ARTICLE IN PRESS

Climate Risk Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Climate risk management for the U.S. cellulosic biofuels supply chain

Matthew Langholtz [a,*], Erin Webb [a], Benjamin L. Preston [a,b], Anthony Turhollow [a], Norman Breuer [c], Laurence Eaton [a], Anthony W. King [a,b], Shahabaddine Sokhansanj [a], Sujithkumar Surendran Nair [a,b], Mark Downing [a]

[a] Environmental Sciences Division, Oak Ridge National Laboratory, United States
[b] Climate Change Science Institute, Oak Ridge National Laboratory, United States
[c] Rosentiel School of Marine and Atmospheric Science, University of Miami, United States

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Bioenergy
Climate change
Climate extremes
Risk management
Adaptation

ABSTRACT

As U.S. energy policy turns to bioenergy, and second-generation biofuels in particular, to foster energy security and environmental benefits, consideration should be given to the implications of climate risk for the incipient bioenergy industry. As a case-in-point, we review evidence from the 2012 U.S. drought, underscoring the risk of extreme weather events to the agricultural sector in general, and the bioenergy supply chain in particular, including reductions in feedstock production and higher prices for agricultural commodities and biofuels. We also use a risk management framework developed by the Intergovernmental Panel on Climate Change to review current understanding regarding climate-related hazards, exposure, and vulnerability of the bioenergy supply chain with a particular emphasis on the growing importance of lignocellulosic feedstocks to future bioenergy development. A number of climate-related hazards are projected to become more severe in future decades, and future growth of bioenergy feedstocks is likely to occur disproportionately in regions preferentially exposed to such hazards. However, strategies and opportunities are available across the supply chain to enhance coping and adaptive capacity in response to this risk. In particular, the implications of climate change will be influenced by the expansion of cellulosic feedstocks, particularly perennial grasses and woody biomass. In addition, advancements in feedstock development, logistics, and extension provide opportunities to support the sustainable development of a robust U.S. bioenergy industry as part of a holistic energy and environmental policy. However, given the nascent state of the cellulosic biofuels industry, careful attention should be given to managing climate risk over both short- and long-time scales.

Introduction

The development and use of biofuels as an energy source has increased rapidly in recent years, both in the United States and internationally. Estimates from the energy industry indicate that global use of biofuels increased by a factor of five from

* Corresponding author. Address: Environmental Sciences Division, Oak Ridge National Laboratory, PO Box 2008, One Bethel Valley Road, Oak Ridge, TN 37831-6253, United States. Tel.: +1 865 574 6520; fax: +1 865 576 9939.

E-mail address: langholtzmh@ornl.gov (M. Langholtz).

http://dx.doi.org/10.1016/j.crm.2014.05.001
2212-0963/Published by Elsevier B.V.

2001 to 2011 (BP, 2012). Over that same time period, the United States emerged as the single largest national producer of biofuels, accounting for 48% of global production. The growth in biofuels has been driven by two energy-related policy challenges. First, biofuel development has been pursued as means of reducing environmental externalities of traditional fossil fuels. Ethanol was adopted as a fuel additive under the U.S. Clean Air Act Amendments (U.S. Environmental Protection Agency, 2012; USEPA, 2012) and the Alternative Motor Vehicle Fuels Act (USGPO, 1988) as a means of reducing particulate air pollution from transportation. Increasing awareness of climate change as another externality of energy use has provided additional incentives to the use of biofuels in order to offset carbon emissions from traditional fossil fuels. Second, and more recently, a growing national emphasis on energy security has been a key driving force for domestic biofuel production. While almost all the 57 billion liters of U.S. ethanol production in 2012 was derived from corn, policies are designed to foster commercialization of biofuels from non-food crops, specifically lignocellulosic biomass. For example, the Energy Policy Act of 2005 (USGPO, 2005) and the Energy Independence and Security Act (EISA) of 2007 (USGPO, 2007) substantially increased the targets for ethanol production, setting a production goal of 136 billion liters of cellulosic biofuels by 2022 (U.S. Environmental Protection Agency, 2005, 2007).

While bioenergy, including biofuels and biopower, has received significant attention in the literature as a technology for offsetting future greenhouse gas emissions from energy (Adler et al., 2007; Campbell et al., 2008; Field et al., 2008; Schneider and McCarl, 2003), the potential vulnerability of bioenergy production to extreme weather events, climate variability, climate change, and overall climate risk[1] has received comparatively little (de Lucena et al., 2009; Dominguez-Faus et al., 2013; Haberl et al., 2011; Poudel et al., 2011; Schröter et al., 2005; Stone et al., 2010; Tuck et al., 2006; Wilbanks et al., 2012). Recent assessments of the implications of climate change for U.S. energy systems, for example, acknowledge the potential climate sensitivity of bioenergy (CCSP, 2007; Wilbanks et al., 2012), yet contain little discussion of the timing and magnitude of future impacts for different bioenergy resources. As with agricultural and forestry production, bioenergy is highly exposed and sensitive to weather and climate (Wilbanks et al., 2012), and thus may be more vulnerable than other energy sources. For example, Eaves and Eaves (2007) found that the price volatility of grain ethanol is higher than that of gasoline imports due to the impacts of weather. Given predictions that extreme weather events will increase in frequency, duration, and/or intensity (IPCC, 2012), climate risk to biofuels derived from agricultural and forest enterprises would also be expected to increase. The current policy emphasis on cellulosic bioenergy production, as well as the important role of bioenergy in enhancing energy security and reducing climate risk, suggests greater attention to the implications of climate risk for the industry is warranted. As a case-in-point, the U.S. drought experienced during 2012, and its impacts on the agricultural sector, represents a 'teachable moment' for the biofuels industry. As an estimated 1 in 30 years event, it was the first significant, national-scale drought event to coincide with the emergence of the U.S. bioenergy industry. The consequences revealed potential vulnerabilities of the bioenergy supply chain, potential trade-offs among different technologies and feedstocks, as well as opportunities for future risk management. With projected demand of approximately 225 million dry Mg of biomass needed by 2022 to meet EISA targets (Langholtz et al., 2012) and the likely continued expansion of cellulosic bioenergy in future decades, robust climate risk management in the bioenergy industry will be an important component of its evolution and its contributions to meeting U.S. energy security and environmental goals.

Here, we review climate risk to the U.S. bioenergy industry, with a particular emphasis on cellulosic biofuels, which are currently an arena of intensive research and development. We frame our review around a risk-management framework to identify direct and indirect climate hazards, assess exposure, and explore key vulnerabilities, with an emphasis on learning from recent experience with extreme weather events such as the 2012 drought. We also identify risk management strategies for the bioenergy supply chain that may be starting points for adaptation efforts as well as key knowledge gaps that must be addressed through future research and development efforts toward a climate-resilient cellulosic bioenergy supply chain.

Framing climate risk to the bioenergy supply chain

The bioenergy supply chain is comprised of a broad range of assets and infrastructure, both public and private, which have differential vulnerabilities to climate risk (Fig. 1). While much of the focus of biofuel analysis targets the land used to produce biofuels, the industry is dependent upon a more elaborate supply chain that is in some ways analogous to that of other forms of energy (Parish et al., 2013). The foundation for the bioenergy supply chain is the production of bioenergy feedstocks on farms, forestlands, or marginal lands. For cellulosic-based fuels, feedstocks could include crop residues such as corn stover (the most abundant U.S. cellulosic feedstock at present) (Kadam and McMillan, 2003), direct production of energy crops including annual (e.g., sorghum) or perennial (e.g. switchgrass and Miscanthus) herbaceous crop, as well as woody biomass crops (McKendry, 2002). Once harvested, these feedstocks are stored onsite or transported to biorefineries or long-term storage facilities. Biorefineries may store feedstocks for short periods of time and facilitate additional preprocessing before biomass enters the biochemical or thermochemical refining process. Depending on the refinery, the products of refining include liquid fuels such as ethanol as well as syngas, which can be converted to a range of products.

[1] We use the term "extreme weather event" to indicate a singular occurrence such as a hurricane or storm, "climate variability" to specify variation from expected climate averages, and "climate change" in the conventional sense indicating long-term (multi-decade) trends. In this paper we use the term "climate risk" to mean risk associated with extreme weather events, climate variability, and/or climate change, and we use the specific terms where the distinctions are relevant.

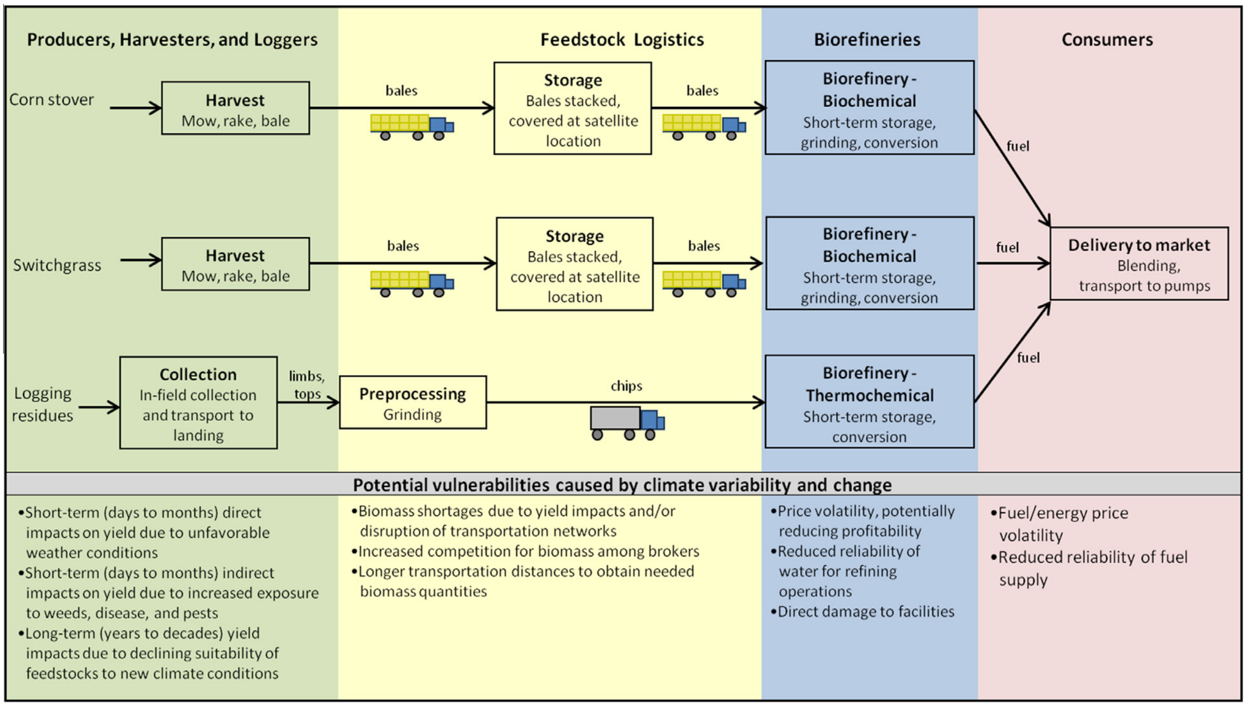

Fig. 1. Examples of conventional biofuel feedstock supply chain.

Refining also can be coupled directly to the generation of heat or electricity (biopower), or refined products (e.g. chemicals, sugars, and fibers) can be delivered to other consumers and end users.

To explore potential climate risks to the bioenergy supply chain, we adapted a risk framework published under the auspices of the Intergovernmental Panel on Climate Change (Lavell et al., 2012). That framework presents risk as function of weather and climate events (or hazards), vulnerability, and exposure (Fig. 2). The weather and climate events are a product of both natural variability and anthropogenic climate change. Meanwhile, the manner in which the industry evolves, through innovation and upscaling, will influence the exposure of different supply chain elements to climate variability and change as well as the capacity of different actors to cope with stress and exploit opportunities for adaptation. The following sections explore each of these aspects of climate risk, from exposure to climate and weather hazards, to the vulnerability of different elements of the supply chain. The various options and strategies available to different actors to manage risks to the supply chain are discussed as well as key knowledge gaps that will need to be addressed to improve future climate risk management and adaptation.

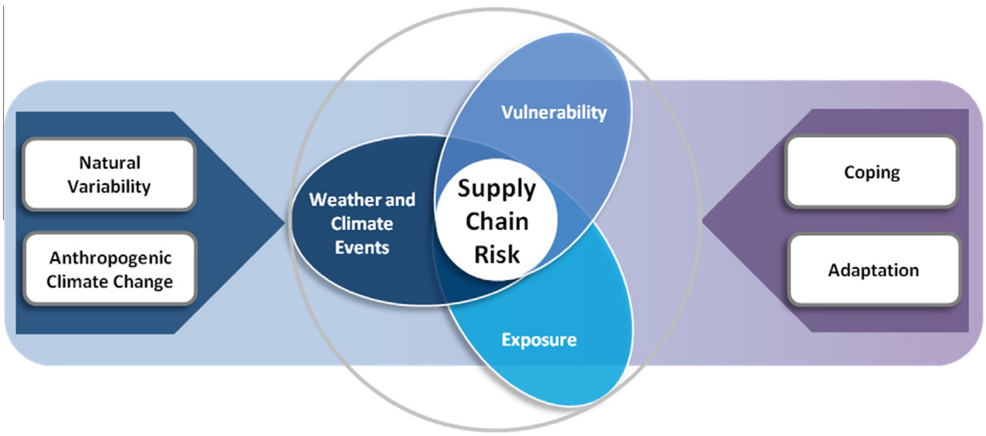

Fig. 2. Bioenergy supply chain risk management framework (IPCC, 2012).

Exposure of cellulosic biofuels to direct and indirect climate-related hazards

To assess the exposure of the cellulosic bioenergy supply chain to climate-related hazards, consideration must be given to two general categories of hazards. First, the supply chain may be exposed directly to hazards such as extremes of weather and climate that result in direct loss and damage to supply chain elements. Second, the supply chain may be exposed indirectly to non-climatic biological and ecological hazards that are nevertheless influenced by climate such as pests and disease. Each of these categories is discussed further below.

Direct climate hazards

Extreme weather events represent significant natural hazards to the bioenergy supply chain. First and foremost, such extreme events pose a significant risk to agricultural and forest lands, which ultimately affects biomass for bioenergy. For example, over 90% of crop loss indemnity payments between 1989 and 2012 were attributed to extreme weather events, equivalent to over $80 billion (Fig. 3; RMA, 2013). Drought alone is by far the single-biggest climate-related threat to agriculture, accounting for 40% of indemnity payments. Such impacts are a function of the location of significant agricultural enterprises on hazardous landscapes. To explore the exposure of current bioenergy feedstocks as well as future feedstocks to climate extremes, we developed a series of hazard indices for the United States based on historical event information from 1950 to 2011 (see supplementary data). These indices included drought (as measured by the Palmer Drought Severity Index (PDSI), hail, wind, tornadoes, tropical cyclones, and wildfire. Indices were developed by calculating the density of events on the U.S. landscape (weighted by event intensity) based upon the location of historical events. Data on historical events were obtained from the National Climatic Data Center (PDSI; NCDC, 2013a), the National Weather Services' Storm Prediction Center (hail, wind, tornadoes, tropical cyclones; NOAA, 2013), and the U.S. Geologic Survey (wildfire; USGS, 2013). Hazard indices were aggregated to the county level and used to identify exposure 'hotspots' for different types of extreme weather events (Fig. 3), based upon observations over the past few decades. While these hazard indices do not represent the entirety of potential climate-related threats to agricultural and forestland systems, they do span the majority of loss events reflected by insurance indemnity payments (Fig. 3). Meanwhile, indices of climatic extremes do not account for future changes in the frequency, intensity, or duration of extreme events, due to persistent challenges in modeling such extremes and the relatively near-term outlook of available biomass projections.

While cellulosic biomass remains an emergent feedstock for bioenergy, its contribution to overall U.S. bioenergy production is projected to grow rapidly over the next few decades in order to meet production targets set by EISA. Hence, to assess cellulosic feedstock exposure to such hazards, we utilized current county-level estimates and future projections of cellulosic feedstock harvests from the POLYSYS bioenergy modeling framework (De La Torre Ugarte and Ray, 2000) and U.S. Department of Energy's Billion-Ton Update (USDOE, 2011). These projections indicate traditional agricultural areas of the United States such as the Great Plains and the upper-Mid West will be key sources of bioenergy feedstocks over the first half of

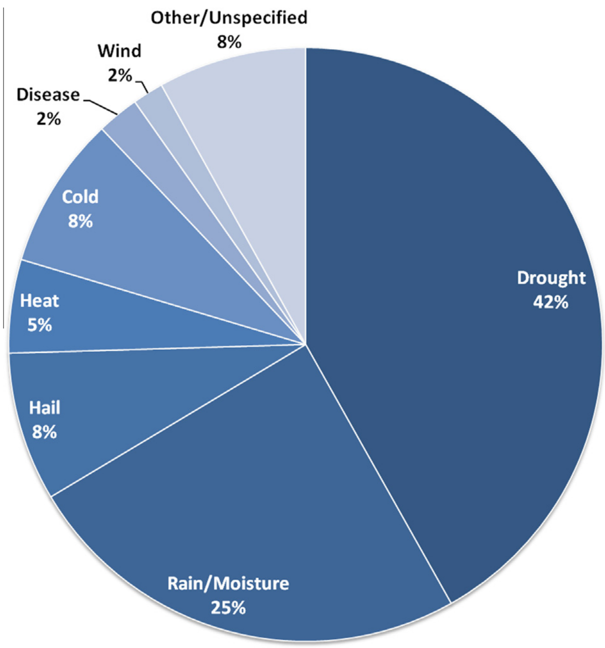

Fig. 3. Attribution of agriculture indemnity payments (1989–2012) to different hazards (RMA, 2013).

the 21st century (Fig. 4). This geographic pattern is largely driven by residues of traditional agricultural crops such as corn, which is particularly prevalent in the upper-Mid West, while other crops (e.g., annual energy crops, perennial grasses) are largely associated with the Great Plains states.

Overlaying the hazard 'hot spots' with the projected distribution of cellulosic bioenergy indicates that the nation's current and projected area supporting cellulosic feedstocks will be exposed to climate risk (Figs. 4 and 5). Baseline estimates of cellulosic feedstocks indicate that the approximately 59 million acres of current production is concentrated in areas that are disproportionately exposed to certain types of climate extremes including drought, hail, wind, and tornadoes (Fig. 5). By 2030, an additional 33 million acres are projected to be harvested, with much of that production also occurring disproportionately in regions that have historically been particularly exposed to these same four hazards. As a consequence, by 2030, the bulk of the harvest area will lie in not just one, but multiple 'hotspots' for extreme weather events (Figs. 4 and 5). While exposure alone does not necessarily translate into a loss, transient and persistent climate hazards associated with climate variability and change are important components of the calculus of risk.

In addition to a greater concentration of feedstocks in regions of the United States exposed to weather extremes, evidence indicates that such extremes have already become more severe (IPCC, 2012; Min et al., 2011; Pall et al., 2011; Sheffield and Wood, 2008; Van Aalst, 2006) and may continue to do so in coming decades (IPCC, 2012). Although robust understanding of the future spatial and temporal dynamics of extreme events remains elusive, changes in the dynamics of extremes would have important implications for exposed biomass (CCSP, 2008a,b; Rosenzweig et al., 2001). Projections of climate change indicate that rising temperatures in future decades are likely to increase evaporation resulting in more frequent drought events (CCSP, 2008b; Dai, 2012; Strzepek et al., 2010; Trenberth et al., 2014). These trends hold for more recent results from the models participating in the IPCC's *Fifth Assessment Report* (AR5) (Dai, 2012; Zhou Tian-Jun, 2013) as well as those of the previous AR4 (Dai, 2011b; Sheffield and Wood, 2008; Strzepek et al., 2010; Wehner et al., 2011). Nevertheless, there is significant debate in the literature regarding the evaluation of drought trends and, in particular, the robustness of different metrics for undertaking such evaluations (Dai, 2011a; Sheffield et al., 2012; Strzepek et al., 2010; Trenberth et al., 2014; Van der Schrier et al., 2011; Vicente-Serrano et al., 2011; Zhou Tian-Jun, 2013). Furthermore, details of the projected drought vary with the emission scenario and the model or models used and there are of course uncertainties surrounding the projections (Burke and Brown, 2008). There is a tendency for the models to overestimate drought duration, frequency and intensity of drought when compared to observations of the 20th century, but the trend of increasing drought across the United States through the 21st century appears robust (CCSP, 2008b). Meanwhile, rainfall is likely to be less frequent, but more intense, resulting in more rainfall extremes. Some studies have translated such changing precipitation regimes into an increase in flood risk (Hamlet and Lettenmaier, 2007; Milly et al., 2002), yet national estimates of flood risk for the U.S. at the scale of agriculture are limited. Wildfires and hurricanes are also projected to become more extreme (Holland, 2012; Knutson et al., 2010; Spracklen et al., 2009; Webster et al., 2005; Westerling et al., 2006). Although such hazards largely affect areas around the margins of cellulosic feedstock production, individual enterprises may be exposed. Projections for other types of hazards that affect U.S. agriculture such as hail are less readily available. Extremes will also affect forestry systems through changes in disturbance regimes including potential dieback of forest stands (Dale et al., 2001, 2011a,b, 2009; Shugart et al., 2003). Despite the well-documented hazard posed by climate extremes to agriculture and forestry enterprises, agricultural models consistently fail to account for the effects of extreme weather events such as hail, floods, or high winds (Archer and Johnson, 2012; Brown and Rosenberg, 1999; Rotter et al., 2011; Soussana et al., 2010; Tubiello et al., 2007; Zhang et al., 2010) – a knowledge gap that ultimately affects risk assessment and strategic planning for bioenergy crops as well.

Indirect climate hazards

In addition to direct exposure to climate, cellulosic feedstocks may also be exposed to the indirect effects of climate change including impacts on weeds, insect pests, and diseases (Royle and Ostry, 1995; Tubiello et al., 2007). McDonald et al. (2009) observe changes in the competitive advantage between damaging weeds in response to higher temperatures (Valerio et al., 2011; Ziska, 2001). In addition, increasing atmospheric CO_2 may alter interactions between plants and insect herbivores (Stacey and Fellowes, 2002; Zvereva and Kozlov, 2006). Similarly, climate change has been implicated in epidemics of forest pests in the Western United States including bark beetles (Bentz et al., 2010) and the Mountain Pine Beetle (Aukema et al., 2008; Hicke et al., 2006; Kurz et al., 2008). Exposure to such pests may be exacerbated by monoculture management conditions that arise in production systems (Tuskan, 1998). While there is significant research and management experience associated with the agriculture and forestry industries with respect to weeds, pests, and disease, there has been limited investigation of potential changes in the spatial distribution and damages associated with such hazards focused on climate/energy feedstock interactions (Perlack et al., 2005).

Key vulnerabilities of the biofuel supply chain

To assess risk to the bioenergy supply chain, consideration must be given to not just whether elements of the supply chain are exposed to climate hazards but also the potential vulnerability of those elements that may create conditions that allow exposure to be translated into harm. As a starting point, we draw on the work of Lynch et al. (2008), O'Neill and Hulme (2009), and O'Neill and Nicholson-Cole (2009) regarding the use of iconic extremes as vehicles for understanding

Please cite this article in press as: Langholtz, M., et al.. Climate Risk Management (2014), http://dx.doi.org/10.1016/j.crm.2014.05.001

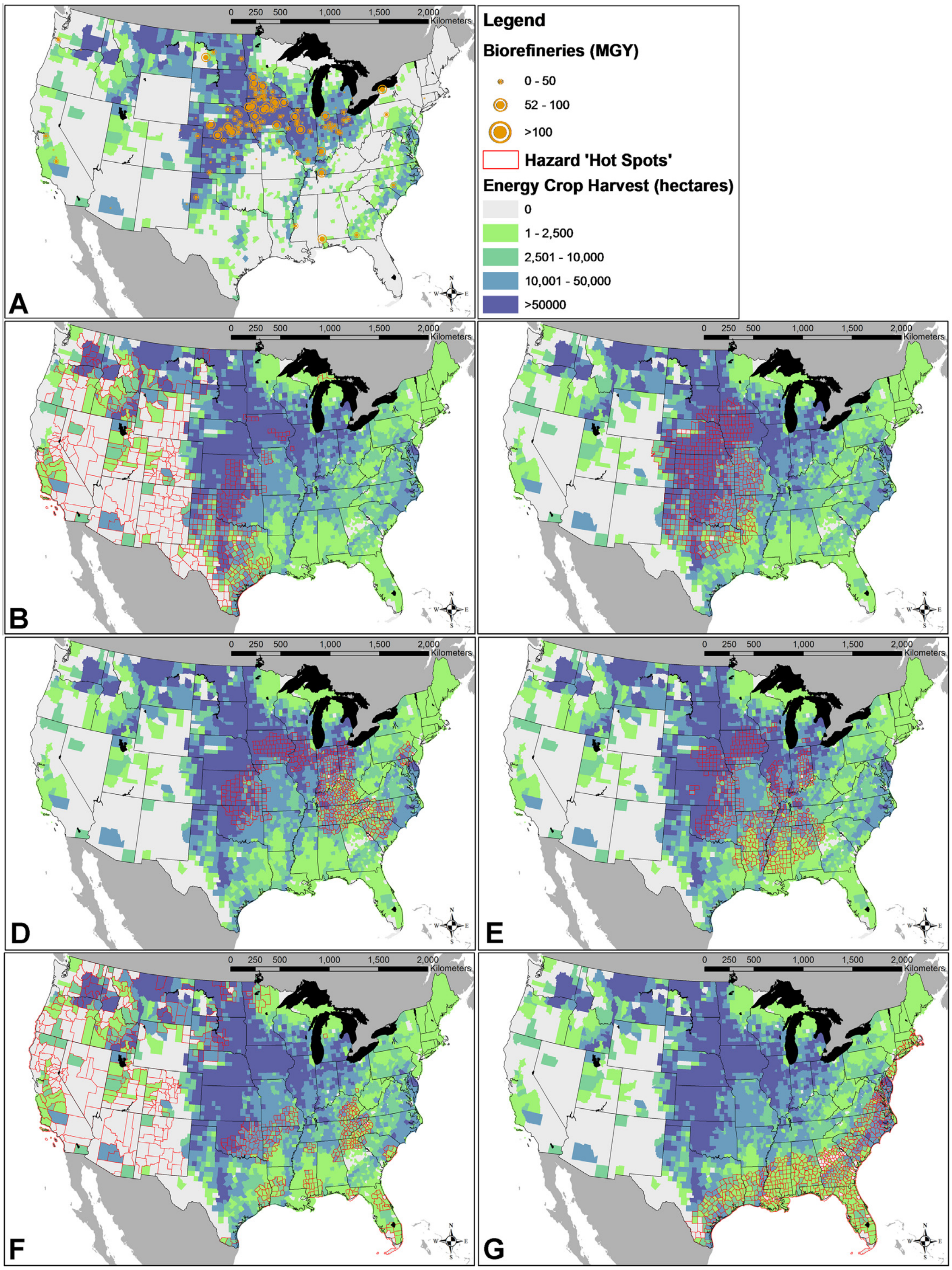

Fig. 4. Spatial distribution of current (2012) and projected (2030) cellulosic bioenergy feedstock harvests in the continental United States as well as comparison of projected with historical 'hotspots' for extreme weather events. Cellulosic feedstocks include annual energy crops, perennial grasses, woody biomass, corn stover, wheat residues, and sorghum residues. (A) current harvest and locations of biorefineries. (B–D) Projected harvests and historical hot spots for extreme weather events (based on observations from 1950 to 2011; see supplementary data for discussion of methods and data sources): (B) severe drought; (C) hail; (D) wind; (E) tornadoes; (F) wildfire; (G) hurricanes.

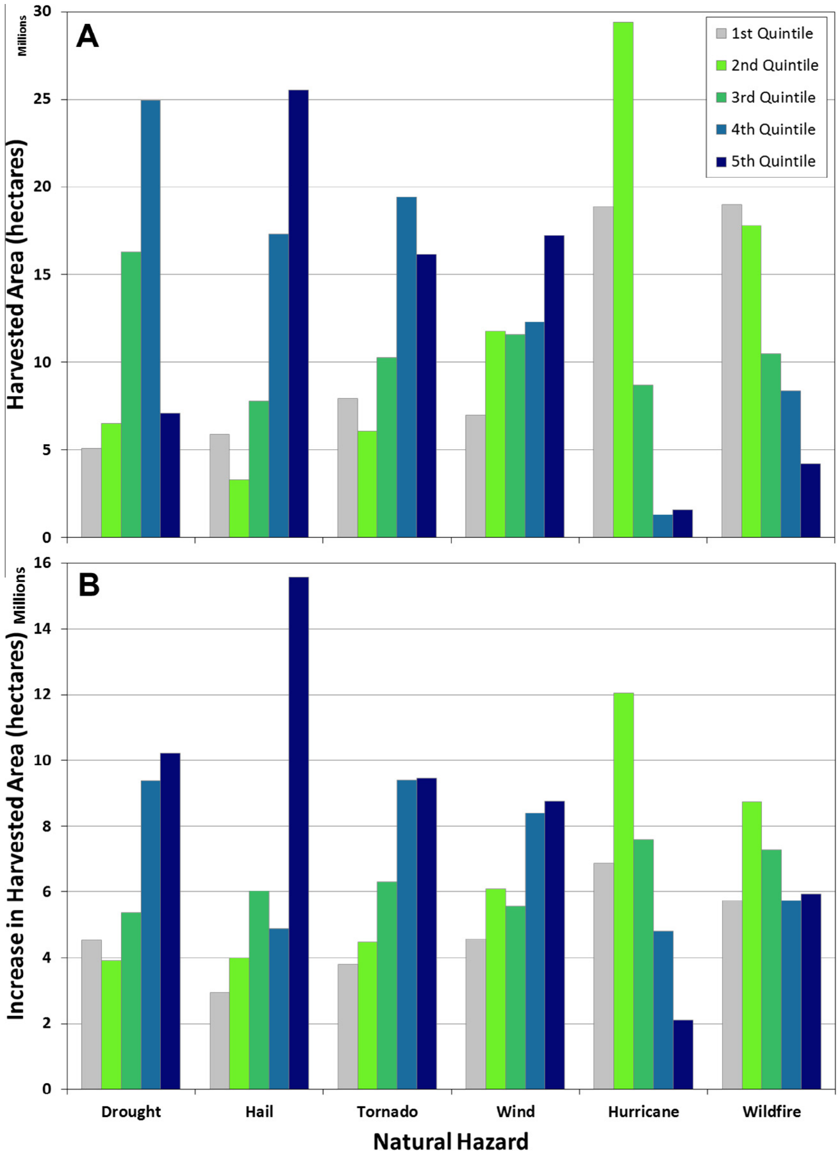

Fig. 5. Distribution of bioenergy feedstock harvest area among U.S. counties classified into different natural hazard exposure categories. (A) Bioenergy crop harvest area in 2012 exposed to different hazards (see supplementary data for discussion of methods and data sources). (B) Exposure of additional harvest area projected by 2030 to different hazards. Harvest areas corresponding to the 1st quintile are associated with the lowest risk of exposure while those of the 5th quintile are associated with the highest risk.

vulnerability and adaptation to climate change. In this context, the drought and its consequences for agriculture and current bioenergy feedstocks is such an iconic event that can be used to frame vulnerability of the cellulosic bioenergy supply chain to climate variability and change. Here, we review this event and use it as the basis for the development of a typology of key vulnerabilities for the supply chain. Each of these vulnerabilities is then discussed further in the broader context of future climate change and the evolution of cellulosic bioenergy.

Evidence from the 2012 drought

The drought of 2012 was characterized by significant rainfall deficits as well as record high temperatures in many parts of western, central, and south central United States, particularly during late June and early July (NCDC, 2013b). In contrast, the western Gulf Coast and Appalachians had normal precipitation (USDA, 2012a,b). By late-2012, the U.S. Department of Agriculture had designated 2245 counties in 39 states as disaster areas due to drought, equivalent to 71 percent of the United States by area (USDA, 2013b). This included many regions that are significant producers of biomass for bioenergy. For many areas of the U.S. South, 2012 was the second consecutive year of significant drought (Blunden and Arndt, 2012). These dry conditions had a significant impact on crop yields and agricultural production, highlighting the potential vulnerability of U.S. agriculture and, by extension, the bioenergy supply chain to climate risk. At the same time, however, the drought revealed how extreme conditions force trade-offs among different agricultural enterprises and how deliberate and autonomous (i.e., market-based) coping mechanisms influence how impacts are distributed.

The impacts of the drought were readily observed as decreases in crop yields and production for much of the central United States (USDA, 2013a), indicating favorable conditions in the Southeast were not sufficient to offset the losses in drought-affected regions. Including grains, oilseeds, and hay, crop production was down by 7%, yet responses of individual crops varied significantly. Corn, for example, experienced a 13% decline in yield in 2012 relative to 2011 and a 16% decrease in yield when compared to the 2001–2012 mean (Fig. 5). This contributed to reductions in corn utilization for both ethanol production and other uses ((AFDC, 2013c; EIA, 2012a); Fig. 6). Meanwhile, hay production declined 9% at the national level. These national-scale impacts mask much more dramatic consequences at the state level (Fig. 5). Overall, grain production declined by 8%, with feed grains (corn, grain sorghum, barley, and oats) declining 12%, while grain sorghum, barley, and oat production all increased relative to the previous year. Wheat production increased 13%. While U.S. soybean production, which accounts for approximately 90% of oilseed production (ERS, 2013c), declined by approximately 3%, production of oilseeds (e.g., soybeans, canola, cottonseed, peanuts, and sunflowers) overall were up, largely due to significant increases in the area planted and harvested in 2012 relative to 2011 (USDA, 2013a). In spite of the severity of the drought of 2012, the 7% decline in crop production in 2012 was surprisingly low. This is due to a range of factors including significant production from irrigated land (ranging in 2008 from 4% of wheat production to 92% of rice), winter wheat was grown and harvested before the drought started, and corn varieties have become better at withstanding drought (Schill, 2012). This highlights the importance of the timing of extreme events and land management practices with respect to the influence of drought on production. The drought of 2012 does not appear to have greatly affected crop production for 2013. There was some concern for the winter wheat harvest in Spring/Summer 2013, but based on planted area, yield of the winter wheat crop harvested in 2013 is forecast to decline by 10% relative to 2012, and is 2% higher than the average yield from 2001 through 2011. Overall crop production (grains and oilseeds) for 2013, as of June 2013, is forecast to be the highest recorded.

The decline in crop production resulted in an increase in crop prices. Prices received by farmers for 2012 crops (based on prices through June 2012 and estimated for the rest of the marketing year) of corn, winter wheat, and soybeans were up by 12%, 14%, and 15%, respectively, while prices for hay were down about 2%, compared to the 2011 marketing year. The price for corn, in particular was the highest since the introduction of ethanol as a fuel additive in the late 1980s (Fig. 6). As of June

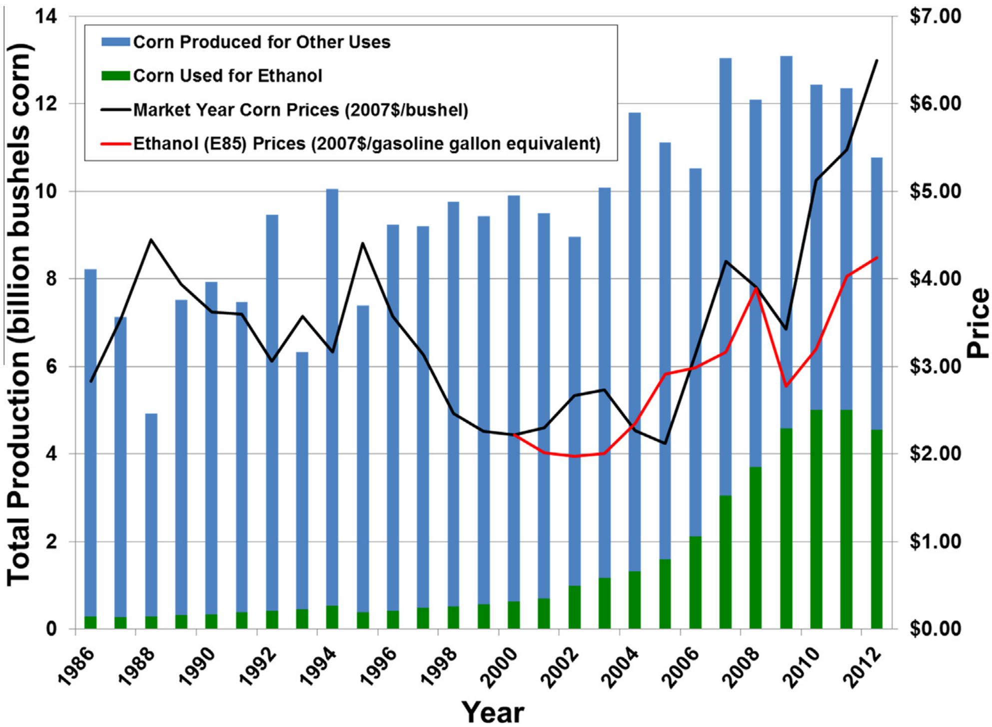

Fig. 6. Historical trends in corn production and ethanol prices were obtained from the Alternative Fuels Data Center (AFDC, 2013a; AFDC2013c). Data on market year corn prices (1986–2011) were obtained from the Alternative Fuels Data Center (AFDC, 2013b) in 2007$ and extended to 2012 with data from the National Agricultural Statistics Service (NASS, 2013). Ethanol prices were obtained in current dollars and converted to constant 2007 dollars following the conversions for inflation-adjusted corn prices reported in (AFDC, 2013b) using the consumer price index.

2013, prices were up for all farm products by 12% from 2011 (calendar year) but up by 42% relative to 2010. These higher prices had downstream impacts on consumers. For example, the crop part of the prices received by farmers was up 14% over 2011 and 51% over 2010. Yet, farm-level costs made up only 16% of consumer food prices in 2008 (Canning, 2011). Hence, the Economic Research Service of the US Department of Agriculture estimated that consumer food prices increased 2.6% in 2012 and are forecast to increase 2.5–3.5% in 2013 (ERS, 2013a). The impact on meat prices was expected to be modest in the short term, because meat producers liquidate some of their animals in response to higher prices and the unavailability of feed (e.g., pastures producing minimal feed). One response of the U.S. government to the 2012 drought was to allow grazing on 1.5 million ha of Conservation Reserve Program (CRP) land, which increased hay equivalent supplies. Livestock and product prices were up 11% over 2011 as of June 2013. Larger impacts can be expected over the long-term. Meanwhile, the high price for corn contributed to ethanol reaching its highest price in over a decade, and was more than twice the price observed in 2000 (Fig. 6). This economic disruption was attributed in part to competition for corn between fuels and food/feed/fiber (Babcock, 2012; Larson et al., 2010).

While crop production was down in 2012, farmer revenues in the United States for crops (in the aggregate) actually increased by 3% because prices increased more than production decreased (see supplementary data). This is an indication that crop demand is inelastic (i.e. the percent increase in price is more than the percent decrease in quantity). Hence, financial impacts to producers at the national level were offset by the market, yet this resulted in adverse impacts on consumers forced to pay higher prices. This affected the profitability of ethanol production as well because the spread between ethanol and corn prices narrowed, shrinking profit margins and, ultimately, ethanol production (EIA, 2012b). Furthermore, these national impacts mask regional disparities, which become evident by examining crop revenues for five states: Indiana, Minnesota, Mississippi, Missouri, and Pennsylvania (see supplementary data). Indiana and Missouri were hard hit by the drought of 2012, while the other states were not. Revenue decreased in Indiana and Missouri by 8%, while revenue increased by about 20–25% in Mississippi and Pennsylvania and 8% in Minnesota (Table 1). However, profit did not increase proportionally with revenues, because production costs increased as well. Therefore, overall crop profit in 2012 was estimated to be down only 4% (ERS, 2013b).

When experience with the 2012 drought is viewed through the lens of bioenergy supply chain, it suggests that bioenergy systems have three critical areas of vulnerability, which are applicable across climate-related impacts in general:

- Vulnerability of cellulosic feedstock production and supply – Reductions in the production and subsequent supply of feedstocks due to adverse impacts of extreme weather and climate change.
- Vulnerability of biofuel supply chain infrastructure – Disruption of biorefining operations and subsequent supply of biofuels due to reduced availability of feedstocks, interruption of transportation networks, and/or direct damage to biorefineries and supporting utilities and resources (e.g., electricity, water).
- Vulnerability to market prices – Volatility in market prices for bioenergy feedstocks and refined products that affects producer and/or consumer welfare and the competitiveness of feedstock production relative to conventional crops.

Each of these vulnerabilities is discussed further below, with particular emphasis on the level of understanding and current knowledge gaps relevant to risk management.

Vulnerability of cellulosic feedstock production and supply

As evidenced by the 2012 drought, the first-order consequences of climate risk will manifest as impacts on the production of cellulosic feedstocks (Porter and Semenov, 2005). The vulnerability of specific cellulosic feedstocks is contingent upon a range of factors that span local growing conditions (e.g., weather, climate and soil), physiological characteristics of individual feedstocks (Barney et al., 2009; Erickson et al., 2008; Oosterhuis et al., 1990), and the management practices of producers (Table 2). Much of current understanding regarding feedstock vulnerability is based on drought. Among annual grasses, for example, biomass sorghum is considered to be an attractive energy crop candidate because of its high yield potential, rapid maturation, high water-use efficiency, and drought tolerance (Rooney et al., 2007; Turhollow et al., 2010). In contrast, other annual grasses such as corn are sensitive to moisture stress, regardless of the growth stage (Bai et al., 2006; Boyer,

Table 1
Crop revenue for 2012 among select drought-affected states as compared with revenue for 2011 (see supplementary data). Major crops include corn, sorghum, barley, oats, wheat, rice, soybeans, and upland cotton.

State	Crop revenue for major crops (millions of US$)		2012 as a percentage of 2011 (%)
	2011	2012	
Indiana	8828	8103	91.8
Minnesota	13,294	14,330	107.8
Mississippi	2473	3010	121.7
Missouri	5895	5477	92.4
Pennsylvania	1610	1999	124.1
United States	167,224	172,106	1.0

1970; Dominguez-Faus et al., 2013; Nagy et al., 1995). However, while current ethanol production from corn is dependent on corn grain, cellulosic biofuels utilize corn residues for which the implications of drought can be quite different. A failed grain harvest may leave significant residue biomass that can be exploited for bioenergy. Producers growing conventional crops such as corn can hedge against uncertainty and/or adversity by exploiting both grain and biomass residue markets, and annual planting provides flexibility to producers in terms of being able to switch crops over relatively short time scales in response to changing environmental conditions. Corn is also routinely covered under crop insurance schemes.

Perennial herbaceous plants, such as switchgrass, which has been identified by the U.S. Department of Energy as a "model" high-potential energy crop (McLaughlin and Kszos, 2005; Wright and Turhollow, 2010), and *Miscanthus x giganteus* are also vulnerable to drought (Barney et al., 2009). Yet, various characteristics of perinneals may offer some competitive advantage under drought stress, one of which is root depth. As observed in the 2012 drought, for example, hay (a perinneal grass) production declined less than corn (an annual grass) (Fig. 7). Among dedicated bioenergy crops, Switchgrass has a relatively extensive and evenly distributed deep root system (>3 m in depth), compared with Miscanthus for which 90% of root biomass occurs in the top 0.35 m soil (Monti and Zatta, 2009). This enables switchgrass to capture water from deep soil, especially during dry periods (Eggemeyer et al., 2009; Monti and Zatta, 2009). Switchgrass has the highest root/shoot ratio across C4 grasses, which is a common characteristic among drought tolerant plants (Xu et al., 2006). Brown et al. (2000) projected switchgrass yields in Kansas would benefit from future higher temperatures and CO_2 concentrations, in contrast with grain crops that would face increasing stress. Woody biomass conveys a particular advantage in that it can continue to be stored *in situ* and used as a feedstock, even in the event of the death of the plant. Disturbance of forestlands due to extreme conditions such as drought or storms (e.g., 'wind wood'), for example, may result in dieback of trees (Shugart et al., 2003), generating significant woody biomass that could be harvested for bioenergy (Curry et al., 2008; Escobedo et al., 2009; Staudhammer et al., 2011). Such characteristics suggest potential advantages of cellulosic feedstocks in general, and switchgrass as well as woody biomass in particular, in terms of resilience to climate risk. Furthermore, once planted, perennial grasses and woody biomass don't require annual replanting and there is flexibility in terms of when they are harvested (Hall and House, 1994). This insulates these feedstocks from the vulnerabilities associated with annual planting and harvesting windows, although it creates some degree of investment lock-in for producers, which discourages switching of crops from one year to the next. In addition, perennial herbaceous grasses and woody biomass may be exposed to weather variability over a longer time period, which may increase its likelihood of experiencing an adverse weather event over its production cycle.

Less information is available regarding absolute and relative vulnerabilities of different feedstocks to other climate hazards. Excess moisture and flooding has been shown to adversely affect a range of current biofuel feedstocks including

Table 2
Characteristics of cellulosic bioenergy feedstocks that influence their vulnerability or resilience to climate variability and change.

Characteristics	Example feedstocks	Advantages	Vulnerabilities
Resilience to extreme conditions	• Varies depending on crop breeding efforts	• Enables plants to cope with climate variability and change	• None
Resistance to disease and pests	• Varies depending on crop breeding efforts	• Enables plants to cope with disease and pests along and/or in combination with climate variability and change	• None
Short (1 year) maturation time	• Sorghum • Corn residue • Energy cane	• Enables production during relatively short windows of favorable weather conditions • Enables relatively rapid switching to alternative crops as conditions change	• Associated with shallow root depths and less able to cope with prolonged adverse conditions
Perennial growth	• Woody biomass • Switchgrass • Energy cane • Miscanthus	• Enables plants to become established (e.g., deep root system) and enhances drought tolerance	• Constrains flexibility in crop switching
Infrequent planting, flexible harvest window	• Miscanthus • Switchgrass • Woody biomass	• Once established, does not require annual replanting, which is prone to climate risk. Enables flexibility around variable weather conditions	• Establishment period may be extended (>2 years) depending on climate variability. Variable time to achieve expected yields
Flexibility in end use	• Corn (grain and residue) • Woody biomass	• Enables crop biomass to enter different markets and therefore hedge against uncertainty • Provides revenue security for producers	• Reduces incentives for exploitation of other energy crops • Reduces security of biomass supply
Insurability	• Corn	• Provides revenue security for producers	• Reduces incentives for exploitation of other energy crops • Moral hazard

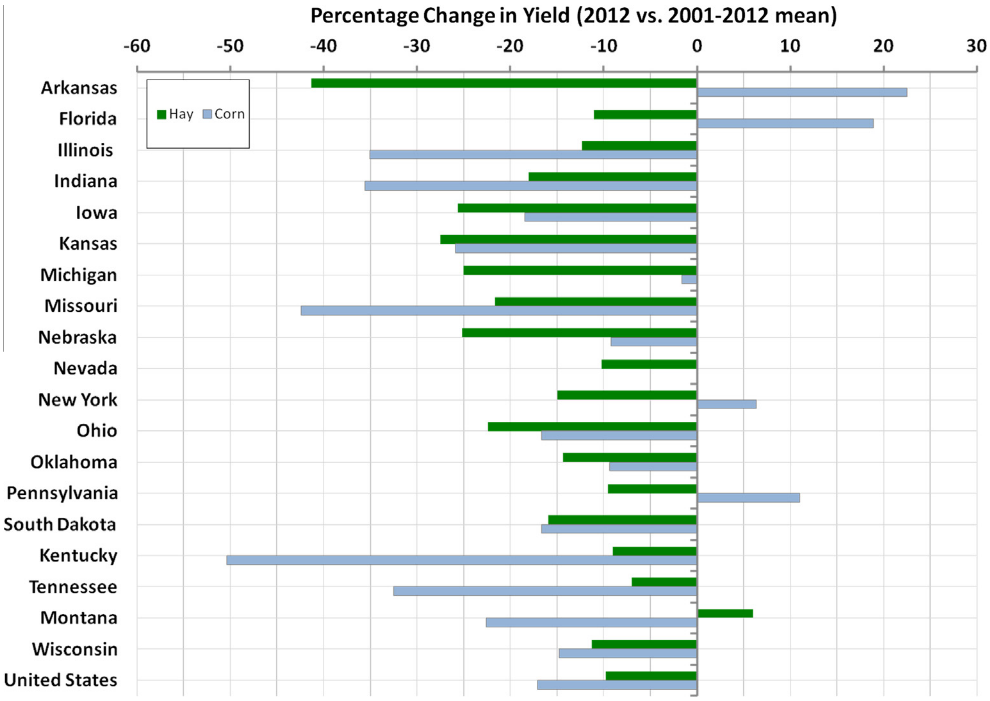

Fig. 7. Corn and hay yields among select U.S. states in 2012 relative to the 10-years mean (2001–2012). Source: data from annual U.S. Department of Agriculture Crop Production Summary reports (USDA, 2013a).

soybeans (Oosterhuis et al., 1990), corn (Subbaiah and Sachs, 2009; Yan et al., 1996; Yordanova and Popova, 2007; Zaidi et al., 2004); and sugarcane (Gilbert et al., 2008; Viator et al., 2012). Naidu and Long (2004); Casler et al. (2007 and 2004) investigate thermal tolerances of Miscanthus and switchgrass; and while insurance indemnities and the literature identify hail as a significant agricultural hazard (Fig. 3; Rosenzweig et al., 2002), there is little evidence to document differential vulnerability among potential feedstocks. Furthermore, vulnerability to extreme weather conditions may decline over time. Various sources of biomass currently being explored as bioenergy feedstocks have not benefited from decades of genetic manipulation to develop cultivars more resilient to climate, pests, and disease (JM-F et al., 2007), and thus their long-term potential for sustainability in the face of climate and weather extremes remains unknown. Hence, there is significant opportunity for more comprehensive evaluation of the vulnerabilities of different feedstocks and cultivars over different spatial and temporal contexts.

In addition to the well-documented effects of acute extreme weather events on agricultural systems, climate change can also have chronic impacts on bioenergy feedstocks through long-term shifts in the suitability of different ecoregions to feedstock production (Barney and DiTomaso, 2010; Tuck et al., 2006) and, in particular, through impacts on water availability. Chiu et al. (2009), for example, estimate that 1 L of ethanol currently requires 248–780 L of irrigation water, although regional requirements vary with irrigation practice (de Fraiture et al., 2008; NRC, 2008; Pimentel, 2003; Pimentel and Patzek, 2005; Wu et al., 2009). Furthermore, as bioenergy has expanded into new areas that are more dependent upon irrigated cultivation, the embodied water in ethanol has increased (Chiu et al. (2009)). In fact, current production of biodiesel and ethanol from conventional crops is associated with rates of water consumption per megawatt hour that are at least an order of magnitude higher than other energy systems (USDOE, 2006). Hence, questions have been raised regarding the value of bioenergy to sustainable energy production (Dominguez-Faus et al., 2009). Given climate change has been identified as a potential threat to water resource availability to other energy sources (e.g., (Averyt et al., 2011; Cooley et al., 2011; EPRI, 2011)), climate change impacts on water availability may exacerbate the high water demands associated with the production of bioenergy feedstocks.

For bioenergy supply chains, consideration must be given to not only the yields generated by feedstocks, but also the efficiency and profitability of biomass harvest and collection operations. The harvesting and transport of biomass incur costs. For biomass feedstocks, like high-yielding dedicated energy crops, reductions in yield per unit area translates into increased harvest costs on a per-ton basis (Sokhansanj et al., 2009). If yield impacts become sufficiently large, the harvesting of biomass may become cost-prohibitive. In addition, such crops tend to be more geographically distributed than traditional commodity crops making transportation costs to biorefineries a larger component of their price. Reduced productivity and/or availability of these crops that expands the supply area only exacerbates transportation costs. These risks can be mitigated to some extent through adaptive agronomic strategies (e.g. fertilizer and pest management regimes).

Please cite this article in press as: Langholtz, M., et al.. Climate Risk Management (2014), http://dx.doi.org/10.1016/j.crm.2014.05.001

Vulnerability of bioenergy supply chain infrastructure

Biorefining infrastructure and the services and natural resources that support those refineries are an important consideration with respect to climate vulnerability. Such vulnerabilities are likely to become increasingly important as the industry expands in the future. Insights regarding infrastructure vulnerability can be acquired from the literature, based on what's been reported for other renewable energies (e.g., solar, wind, hydropower) as well as conventional fossil fuel energy sources (CCSP, 2007; Wilbanks et al., 2012). Such infrastructure can be adversely affected by climate change directly, particularly through changes in extreme events that pose direct hazards to infrastructure. For example, flooding and wind damage may disrupt operations at biorefineries by damaging infrastructure. Biorefineries can also be affected indirectly. Wilbanks et al. (2012), for example, note that declines in feedstock production ultimately affect the availability of feedstocks to biorefineries and subsequent production, although as noted previously, some disturbances can result in generation of biomass that could be used by biorefineries. In addition, the electricity supply of biorefineries as well as the transportation of feedstocks to (or products away from) biorefineries can be disrupted by extreme weather events that affect roads, rail, pipelines, barge traffic, or the energy grid (EIA, 2012b; Wilbanks et al., 2012). Biorefineries, like other conventional energy infrastructure, are also dependent upon significant inputs of water. Water use averages 22.7 and 7.6 liters of water per liter of ethanol for biochemical and thermochemical conversion processes, respectively (Foust et al., 2009), although these values are small relative to the use of water for irrigation (see Vulnerability of bioenergy supply chain infrastructure). Increasing concerns about water availability for future energy generally, and the water needs of bioenergy specifically, suggest water availability over both the short term (i.e., seasonal to inter-annual) and long term (i.e., multi-decadal) as a key consideration for future investments in bioenergy infrastructure.

Vulnerability to market prices

The sustainability of the biofuels supply chain is dependent upon a range of market forces and incentives, with climate risk representing a potential uncertainty in the stability and predictability of markets. Declines in feedstock production, whether transient or persistent, would lead to constraints on the supply of bioenergy feedstocks to the supply chain resulting in higher feedstock prices. As demonstrated by the 2012 drought, those higher prices can act to maintain producer revenue and profits despite production impacts. Autonomous responses of the market can therefore assist producers in coping with adverse conditions. However, impacts for individual producers in particularly hard-hit regions may be greater, particularly for those growing dedicated bioenergy crops for which insurance is unavailable. For consumers of feedstocks, such as biorefineries, however, those higher prices result in higher input costs and can erode the profitability of such enterprises. These costs may be exacerbated if a biorefinery must exploit feedstocks over a larger area (with higher transportation costs) to compensate for reductions in local production (see Vulnerability of bioenergy supply chain infrastructure). The biorefinery must, therefore, recoup those losses in the form of higher prices for refined products, which ultimately has adverse impacts on end use consumer welfare.

Future expansion of bioenergy would potentially influence the market impacts of climate variability and change on the bioenergy supply chain. Much of the market impacts observed to date are a function of a) the lack of diversity in ethanol feedstocks, which are predominantly derived from corn production and b) competition for corn among multiple end users (fuel, feed, and food). For example, corn production has expanded since the introduction of ethanol into liquid fuels (Fig. 6). However, as that expansion has been accompanied by a concomitant increase in demand for corn, prices for corn have grown steadily over the past decade, peaking in 2012 at levels that hadn't been seen since the introduction of ethanol in the late 1980s (Fig. 6). While a positive development for producers, this adversely affects other elements of the supply chain. Expanding the range of feedstocks that can be utilized for bioenergy can enable both producers and downstream consumers to hedge against climate and market uncertainties. As mentioned previously (see Vulnerability of cellulosic feedstock production and supply), greater use of conventional crop residues may provide producers with a source of revenue even when grains or oilseed yields are not sufficient for harvest. Greater use of dedicated energy crops can enable producers to exploit a broader array of landscapes (e.g., marginal agricultural land) and grow feedstocks over different time scales (e.g., perennial and woody biomass). Meanwhile, downstream consumers could make use of a greater range of biomass resources that reduces the impacts of price volatility associated with the success and failures of individual feedstocks. Collectively this could result in a more resilient and competitive marketplace, with ancillary benefits in terms of reducing the adverse externalities on other agricultural commodities, such as livestock, that have been attributed to the existing corn-based ethanol bioenergy system. It should be noted, however, that as both food crops as well as biofuels generated from feedstocks are commodities traded on international markets, domestic prices for food/feed/fiber and biofuel will also be influenced by the impacts of climate risk on agricultural and forestry systems in other global regions.

Supply chain risk management strategies and opportunities

Given the various challenges that remain with respect to scaling up the cellulosic biofuels industry (Richard, 2010), opportunities for risk management should be included in its future development. Yet, managing risk involves addressing complex interactions at the nexus of land, water and energy (Dale et al., 2011b). Spatial and temporal patterns of biomass

Please cite this article in press as: Langholtz, M., et al.. Climate Risk Management (2014), http://dx.doi.org/10.1016/j.crm.2014.05.001

production and industry development remain uncertain as do the policy and market environments at regional, national, and global scales. These uncertainties are exacerbated by those associated with future climate and its influence on extreme weather events (IPCC, 2012). Multiple assessments, for example, have suggested the potential for increased agricultural yields in the United States due to climate change and CO_2-fertilization (Hatfield et al., 2008). Similar results have been reported in Europe (Schröter et al., 2005; Tuck et al., 2006). However, such effects are region and crop specific. Dominguez-Faus et al. (2013), for example, project climate change will lead to declines in U.S. corn production despite increasing irrigation. Hence, as evidenced by the drought of 2012 and the billions of dollars of indemnity payments made to farmers in recent decades, yield impacts during extreme weather events are an inherent vulnerability of biomass-based industries. Reduced yields and crop losses due to drought or flooding, competition with other industries (e.g., livestock feed, fiber, and biopower), and changes in material quality are climate-associated risks assumed by stakeholders along the biofuel supply chain from biomass production, to biofuel conversion, to fuel use. With reduced biomass availability, operations along the supply chain are subject to low utilization of resources (facilities, equipment, labor, etc.) and inefficiencies associated with substituting biomass sources. These factors can significantly increase the price and quality of products, which can influence the competitive position of an emerging industry. Success of a commercial biofuel industry will require strategic planning on behalf of stakeholders in order to optimize potential returns, while managing climate risk (Table 3).

Feedstock production and supply

Cellulosic feedstock producers have flexibility to respond to changes in local weather and climate by employing strategies such as irrigation, selection of drought-tolerant crop varieties, diversifying production, and the use of alternative tillage practices (Malcolm et al., 2012). As the timing of exposure to natural hazards is a factor affecting the impacts of climate risk on feedstock production, feedstocks should be evaluated for their potential to balance productivity, resilience to climate and weather, and supply chain efficiency with respect to logistics (see Supply chain logistics). Our review of the assessment of the vulnerability of cellulosic feedstocks suggests that there are multiple characteristics that influence the relative vulnerability and resilience of different feedstocks. If one focuses on maximizing the resilience of feedstocks themselves, the establishment period (i.e., site preparation, planting, and early growth) is the period when young plants are most vulnerable to drought, flooding, or other events. In this regard perennial grasses and woody biomass offer distinct advantages due to greater capacity to cope with weather extremes. On the other hand, when one focuses on flexibility in crop management, both annuals and perennials offer distinct advantages. The former allows for relatively frequent crop switching to allow for changing weather and/or market conditions. The latter however, allows for flexibility in harvest times, which can also be leveraged to provide market advantage and/or respond to favorable or unfavorable climate conditions. Other common management practices, such as irrigation during establishment and other sensitive periods, could prove an effective strategy for managing drought stress, although this practice may be constrained by water availability. If, however, such irrigation can use water recycled from other uses, this would reduce pressure on water resources (Stone et al., 2010). For woody biomass and forestland, a range of forest management practices may assist in adaptation to reduce vulnerability (Millar et al., 2007; Ogden and Innes, 2007; Spittlehouse and Stewart, 2003). These include strategies to increase resilience to drought, fire and disease, such as forest thinning and species diversification (Blate et al., 2009; CCSP, 2008a), as well as strategies to better enable forest managers to make use of biomass debris generated by such disturbances when they do occur (Curry et al., 2008; Escobedo et al., 2009). Over the long term, investments in research could lead to genetic improvements that make bioenergy crops and tree varieties more resilient to stress (Oliver et al., 2009). Other innovative agronomic practices could be scaled up to improve energy crop production. For example, (Ghimire and Craven, 2011) found that cocultivating the ectomycorrhizal fungus *Sebacina vermifera* with switchgrass resulted in significantly higher biomass yield during drought stress than control plants during normal conditions. Finally, while insurance is increasingly being adopted in the United States as a mechanism for managing climate risk to agriculture (Cabrera et al., 2006), the absence of insurance programs for dedicated biomass feedstocks puts cellulosic feedstocks at a competitive disadvantage with respect to climate risk management relative to conventional crops. The rising public cost of the U.S. crop insurance program as well as criticism of the subsidies has raised questions regarding its long-term sustainability (Glauber, 2013; Goodwin and Smith, 2013; Woodard et al., 2012). If and when reforms to insurance markets emerge, greater consideration for dedicated energy crop producers could be incorporated into that reform process.

Supply chain logistics

Those responsible for arranging and managing the supply chain from the field to the biorefinery, whether it be the producer themselves, a producer cooperative, an intermediate broker, or the biorefinery, could face biomass shortages and higher prices during times of drought. However, the structure of supply chain logistics will be dependent upon how the sector evolves in the future. Advancements in logistics and handling may create opportunities to streamline operations across the supply chain and reduce exposure to climate risk. In the conventional biomass supply chain (Fig. 1), each biorefinery accepts only one crop in only one format (e.g., switchgrass bales or wood chips). In future designs, innovative supply chains could be developed to convert raw biomass into an engineered feedstock handled and traded much like current agricultural commodities. Intermediate facilities, or depots, located near the production fields (within 8–16 km) could grind bales of herbaceous biomass; densify into a stable, flowable physical format (e.g., pellets or cubes); and store until needed by the

Table 3
Summary of risks, strategies, and opportunities in the bioenergy industry due to extreme weather events summarized by stakeholder.

Stakeholder	Risks and opportunities	Strategies and opportunities
Feedstock producer	• Loss of revenue due to adverse impacts on biomass • Loses to insects, pests, late freezes, ice storms, hail, hurricanes, etc. • Geographic shifts in suitable or optimal growing conditions for different feedstocks • Increased availability of biomass residue and debris associated with ecosystem disturbance • Increased productivity associated with some bioenergy crops due to climate shifts and CO_2 fertilization	• Irrigation during drought, particularly during crop establishment • Once established, woody and perennial crops may be less affected by climate variability and extreme events relative to annuals • Selection of more drought-tolerant crops like forage sorghum • Forest management to increase tree resilience • Genetic improvements for drought resistance • No-till or reduced till in annual crops • Adapting DSSs to include impacts of shocks caused by extreme weather events • Expansion of crop insurance to cover a wider array of energy crops
Supply chain management	• Reduced availability leads to higher biomass prices • Increased competition for biomass for other uses (e.g., biopower, bioproducts, livestock feed) • Reduced efficiency of supply chain as transport distances to secure needed volume of biomass increase	• Advanced processing to increase bulk density (for reduced transport costs) and convert biomass into a uniform-format, commodity feedstock • Increase stability during storage making it possible to stockpile feedstock • Develop standards or grading schemes to commoditize biomass feedstocks • Increase capacity to utilize debris from forests and the built environment
Biorefinery	• Feedstock shortages due to lower biomass availability and increased competition • Higher feedstock costs • Input price volatility • Product price volatility • Short-term (seasonal) scarcity • Water availability for conversion processes	• Purchase feedstock from biomass brokers to increase available resources • Diversification of feedstocks that can be used • Conversion and handling technologies capable of accepting feedstock from a variety of biomass sources • Flexibility to change production rate depending on feedstock availability and cost • Enhancing road, rail, and barge access to accept feedstock from further locations • Select less water-intensive conversion technologies
End use consumers	• Public perception of food vs. fuel; social support of renewable fuels • Effects on fuel prices • Retail price shifts • Substitutability of inputs	• Diversification of energy products • Development of alternative and available substitutes • Relax terms of trade • Loosen restrictions on use of inputs for ethanol production (using corn for food instead of for fuel) • Increase vehicle fuel flexibility

biorefinery (Hess et al., 2009; Richard, 2010; Sokhansanj and Hess, 2009; Sokhansanj et al., 2009). Such material could be designed to meet standard physical (e.g., density, particle size) and compositional (e.g., moisture and ash content) criteria optimized for particular conversion processes. Hess et al. (2009) suggest bulk density targets of 256 dry kg/m^3 for bales to be transported locally and greater than 481 dry kg/m^3 for advanced feedstock commodities. In comparison, current balers typically produce bales of switchgrass or stover weighing in the range of 140–190 kg/m^3. In an analysis by Sokhansanj et al. (2009), increasing the bulk density of biomass feedstocks from baled biomass with an average density of 160 dry kg/m^3 to pellets with an average density of 600 kg/m^3 decreased transportation cost by 21%. Richard (2010) estimates that to meet projected demand at a large, commercial-scale biorefinery, a truck would be unloaded every five minutes around the clock. Achieving higher bulk densities will not only reduce transportation and storage costs, but also reduce the frequency of deliveries to the biorefinery, all of which reduce exposure to climatic events that might compromise the transportation infrastructure. Another strategy for dealing with biomass shortages is stockpiling of feedstock. Space requirements and the dry-matter losses could make long-term storage cost prohibitive, yet the issue has received little critical analysis. Future advances in feedstock preprocessing technologies may lead to more stable products that are suitable for multi-year storage. Commoditized feedstocks could also prove beneficial in the event of feedstock shortages, as biorefineries are forced to purchase feedstock from a broader geographical area, including regions with more abundant biomass resources or those not affected by current weather events. Commoditized feedstocks could be cost-effectively transported longer distances by rail or barge and purchased from a wide range of suppliers rather than via direct contract with local producers.

Biorefineries

While there are a range of mechanisms for increasing the resilience and efficiency of the supply chain between producers and biorefineries, additional resilience can be achieved by focusing on the biorefinery itself. As a starting point, meeting the projected growth targets for future cellulosic feedstock production will require significant expansion in the number and size of U.S. biorefineries. Decisions regarding the siting of future facilities can have a significant impact not only on the resilience of individual facilities, but also the broader energy system. Key considerations with respect to siting are (a) proximity to potential hazards (e.g., flood plains); (b) proximity to sufficient biomass resources; (c) proximity to sufficient water and energy resources; and (d) proximity to transportation networks to end use markets (Melo et al., 2009; NCEP, 2006). In addition to citing decisions, biorefinery design and operations can be used to hedge against uncertainty in the supply of feedstocks. For example, designing biorefinery receiving areas and conversion systems capable of handling a wide range of feedstock formats would enable them to capitalize on a broader array of feedstocks within a given distance (Mascia et al., 2010; Scheffran, 2010) Yet, the potential tradeoffs in costs and benefits associated with developing dense, flowable feedstocks versus constructing a biorefinery capable of accepting diverse feedstocks have not been explored. Biorefinery design is also relevant to other potential vulnerabilities such as the security of supply of electricity and water. Advances in recent years have reduced the water usage in thermochemical processes and similar advances are needed, and can be obtained, for biochemical processes. Meanwhile the use of combined heat and power systems within biorefineries can reduce their reliance upon the electricity grid.

End use consumers

Managing risks to end use consumers of bioenergy can be facilitated by enhancing flexibility in upstream elements of the supply chain to minimize the risk of climate or weather induced disruptions to energy supply and prices. This includes broadening the range of feedstocks that can be used in biorefineries, which will reduce upward pressures on prices of individual commodities due to demand for feedstocks when adverse weather and climate conditions arise. Such flexibility in bioenergy logistics will also enhance opportunities for the supply chain to capitalize on short-term (e.g., 'wind wood') and long-term (e.g., CO_2-fertilization effects in herbaceous grasses) benefits of climate variability and change on feedstock production. In addition to the logistics of feedstock management, diversification of available energy products for consumers may reduce pressure on supply-constrained products. For example, ethanol has partially offset the use of gasoline in transportation, and experimental trials are underway with the use of ethanol as a diesel additive as well. Similarly, technologies for transportation have diversified from gasoline and diesel engines to hybrid-electric, plug-in hybrid, and all-electric vehicles. Meanwhile, liberalization of international trade in energy products may stimulate domestic production of bioenergy and streamline the import and export of bioenergy products to better manage domestic supply and demand (Elobeid and Tokgoz, 2008; Lee and Sumner, 2010).

Decision support for risk management

Because the production of cellulosic biofuel feedstocks takes place under conditions of uncertainty, decision science, an area of the social sciences, must be included in the interdisciplinary mix of knowledge that seeks to address the complex problem of managing climate and other risks to the biofuels industry (Garcia-Quijano et al., 2005; Giunipero and Eltantawy, 2004; Mitchell, 2000; Neiger et al., 2009; Parish et al., 2013; Ramachandra et al., 2005). While documenting the effects of climate risk and providing better climate forecasts to potential users would be beneficial to climate risk management, such efforts in themselves are not sufficient (Fraisse et al., 2006; Tribbia and Moser, 2008). Because of the complex interactions among biophysical, social, and institutional factors that affect agricultural systems, end users need decision aids and technical assistance to bridge the gap that still exists between available climate forecasts and their routine applications in agriculture (Meinke et al., 2009; Podesta et al., 1999). To this end, systematic and comprehensive decision support systems (DSS) that are specific to the bioenergy industry will be needed as the industry matures. Such DSSs can help producers to better understand the possible responses to climate forecasts and indicate risks associated with alternative responses in order to obtain benefits from a weather or climate forecast (Letson et al., 2001), not to mention forecasts of market conditions. Examples of some of the types of DSSs that have been developed or adapted for the bioenergy industry to date include: biomass availability data sets (USDOE, 2011), agricultural policy models (English et al., 2006; Ray et al., 1998), supply chain models (Sokhansanj et al., 2008), and crop production models (Nair et al., 2012). However, further refinement of these tools to include system shocks caused by climate variability is needed.

Conclusions

As the U.S. biofuels industry continues to evolve to make significant contributions to future domestic and international energy production, it will inevitably face challenges associated with climate risk. These challenges may be short term or persistent, that may be localized or diffuse, and their impacts may be experienced differentially across the supply chain. Yet, as with conventional agricultural industries, stakeholders along the supply chain can cope and adapt. Some responses may arise autonomously, such as the balancing of reduced feedstock production during adverse growing conditions with higher commodity prices that mitigate revenue and profit impacts. Other responses will be more deliberate. Feedstock producers can opt to grow crops and varieties that are well-suited to drought and other extreme weather events, or they may choose management strategies that increase resilience. Commoditization of biomass feedstocks enables more cost-effective transportation and handling and makes it feasible to ship material from regions that may be spared droughts or extreme events and with high availability, to facilities where feedstocks are limited. These advanced feedstocks also tend to be more stable in storage and may make it possible to stockpile biomass. Biorefineries that are designed with flexibility in feedstock specifications, production rate, and products will benefit during times when feedstocks are limiting. In practice, these strategies will depend on improved understanding of climate risk and the mainstreaming of climate risk management into future development of the industry.

Mainstreaming such risk management practices into the bioenergy supply chain will require increased awareness of both the risks and opportunities associated with climate variability and climate change to stakeholders as well as greater investments in research and development efforts regarding climate risk (Table 1). As a path forward, collaboration is needed between the climate science community and bioenergy feedstock supply and logistics experts to evaluate climate implications on the biofuels supply chain at different scales including feedstock production, logistics, refining, and commodity markets. Near-term efforts could include: (1) experimentation with regionally-downscaled models or coupled climate-crop models to account for climate-associated uncertainty; (2) accounting for future climate variability and climate change uncertainty in national cellulosic feedstock supply and price projections; (3) developing mechanisms for reducing the water and energy requirements of advanced processing technologies; (4) designing economical logistics and storage systems for densified biomass; (5) analyzing tradeoffs associated with different transportation and use of different feedstocks; (6) developing DSSs for different supply chain elements; and (7) employing social science research to insure that research and development products are actionable within the context of drivers beyond climate. Attempts to manage climate risk, however, should also be cognizant of the potential externalities (social, economic, or environmental) that may arise from different management practices (Dale et al., 2013; McBride et al., 2011; Parish et al., 2013; Schubert and Blasch, 2010).This collective knowledge should subsequently become part of the calculus regarding the potential contributions of cellulosic bioenergy to U.S. energy security, air quality, and greenhouse gas mitigation objectives.

Acknowledgements

This project was funded by the U.S. Department of Energy Efficiency and Renewable Energy Bioenergy Technologies Office as well as by program development funds within Oak Ridge National Laboratory's (ORNL) Environmental Sciences Division. ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crm.2014.05.001.

References

Adler, P.R., Grosso, S.J.D., Parton, W.J., 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol. Appl. 17, 675–691.
AFDC, 2013a. Clean Cities Alternative Fuel Price Reports. Alternative Fuels Data Center. U.S. Department of Energy, Washington, DC.
AFDC, 2013b. U.S. Soybean and Corn Prices. Alternative Fuels Data Center. U.S. Department of Energy, Washington, DC.
AFDC, 2013c. U.S. Total Corn Production and Corn Used for Fuel Ethanol Production. Alternative Fuels Data Center. U.S. Department of Energy, Washington, DC.
Archer, D., Johnson, J.F., 2012. Evaluating local crop residue biomass supply: economic and environmental impacts. BioEnergy Res. 5, 699–712.
Aukema, B.H., Carroll, A.L., Zheng, Y., Zhu, J., Raffa, K.F., Dan Moore, R., Stahl, K., Taylor, S.W., 2008. Movement of outbreak populations of mountain pine beetle: influences of spatiotemporal patterns and climate. Ecography 31, 348–358.
Averyt, K., Fisher, J., Huber-Lee, A., Lewis, A., Macknick, J., Madden, N., Rogers, J., Tellinghuisen, S., (2011). Freshwater Use by U.S. Power Plants: Electricity's Thirst for a Precious Resource. A report of the Energy and Water in a Warming World initiative. Union of Concerned Scientists, Cambridge, MA.
Babcock, B., 2012. Preliminary Assessment of the Drought's Impacts on Crop Prices and Biofuel Production. Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa.
Bai, L.P., Sui, F.G., Ge, T.D., Sun, Z.H., Lu, Y.Y., Zhou, G.S., 2006. Effect of soil drought stress on leaf water status, membrane permeability and enzymatic antioxidant system of maize. Pedosphere 16, 326–332.
Barney, J.N., DiTomaso, J.M., 2010. Bioclimatic predictions of habitat suitability for the biofuel switchgrass in North America under current and future climate scenarios. Biomass Bioenergy 34, 124–133.
Barney, J.N., Mann, J.J., Kyser, G.B., Blumwald, E., Van Deynze, A., DiTomaso, J.M., 2009. Tolerance of switchgrass to extreme soil moisture stress: Ecological implications. Plant Sci. 177, 724–732.
Bentz, B.J., Régnière, J., Fettig, C.J., Hansen, E.M., Hayes, J.L., Hicke, J.A., Kelsey, R.G., Negrón, J.F., Seybold, S.J., 2010. Climate change and bark beetles of the western united states and canada: direct and indirect effects. Bioscience 60, 602–613.
Blate, G.M., Joyce, L.A., Littell, J.S., McNulty, S.G., Millar, C.I., Moser, S.C., Neilson, R.P., O'Halloran, K., Peterson, D.L., 2009. Adapting to climate change in United States national forests. Unasylva 231 (232), 1–60.
Blunden, J., Arndt, D.S., 2012. State of the climate in 2011. Bull. Am. Meteorol. Soc. 93, S1–S264.
Boyer, J.S., 1970. Differing sensitivity of photosynthesis to low leaf water potentials in corn and soybean. Plant Physiol. 46 (236).

BP (2012). BP Statistical Review of World Energy, June 2012, London, UK.
Brown, R., Rosenberg, N., 1999. Climate change impacts on the potential productivity of corn and winter wheat in their primary united states growing regions. Clim. Change 41, 73–107.
Brown, R.A., Rosenberg, N.J., Hays, C.J., Easterling, W.E., Mearns, L.O., 2000. Potential production and environmental effects of switchgrass and traditional crops under current and greenhouse-altered climate in the central United States: a simulation study. Agric. Ecosyst. Environ. 78, 31–47.
Burke, E.J., Brown, S.J., 2008. Evaluating uncertainties in the projection of future drought. J. Hydrometeorol. 9, 292–299.
Cabrera, V., Fraisse, C., Letson, D., Podestá, G., Novak, J., 2006. Impact of climate information on reducing farm risk by optimizing crop insurance strategy. Trans. ASABE 49, 1223–1233.
Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The global potential of bioenergy on abandoned agriculture lands. Environ. Sci. Technol. 42, 5791–5794.
Canning, P., 2011. A Revised and Expanded Food Dollar Series: A Better Understanding of Our Food Costs. U.S. Department of Agriculture, Economic Research Service, Washington, DC.
Casler, M.D., Vogel, K.P., Taliaferro, C.M., Wynia, R.L., 2004. Latitudinal adaptation of switchgrass populations this research was funded in part by the U.S. dep. of energy biomass fuels program via the oak ridge national lab. contract no. DE-A105-900R2194. Crop Sci. 44, 293–303.
Casler, M.D., Vogel, K.P., Taliaferro, C.M., Ehlke, N.J., Berdahl, J.D., Brummer, E.C., Kallenbach, R.L., West, C.P., Mitchell, R.B., 2007. Latitudinal and longitudinal adaptation of switchgrass populations. Crop Sci. 47, 2249–2260.
CCSP, 2007. Effects of Climate Change on Energy Production and Use in the United States. In: Wilbanks, T.J., Bhatt, V., Bilello, D.E., Bull, S.R., Ekmann, J., Horak, W.C., Huang, Y.J., Levine, M.D., Sale, M.J., Schmalzer, D.K., Scott, M.J. (Eds.), A Report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, DC.
CCSP, 2008a. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental Protection Agency, Climate Change Science Program, Washington, DC, USA, p. 873.
CCSP (2008b). Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. In: Karl, T.R.M., G.A., Miller, C.D., Hassol, S.J., Waple, A.M., Murray, W.L. (Eds.), Climate Change Science Program, Washington, DC.
Chiu, Y.-W., Walseth, B., Suh, S., 2009. Water embodied in bioethanol in the united states. Environ. Sci. Technol. 43, 2688–2692.
Cooley, H., Fulton, J., Gleick, P.H., 2011. Water for Energy: Future Water Needs for Electricity in the Intermountain West. Pacific Institute, Oakland, California.
Curry, G.L., Coulson, R.N., Jianbang, G., Tchakerian, M.D., Tattersall Smith, C., 2008. An optimization-based system model of disturbance-generated forest biomass utilization. Bull. Sci. Technol. Soc. 28, 486–495.
Dai, A., 2011a. Characteristics and trends in various forms of the palmer drought severity index during 1900–2008. J. Geophys. Res. Atmos. 116, D12115.
Dai, A.G., 2011b. Drought under global warming: a review. Wires Clim. Change 2, 45–65.
Dai, A., 2012. Increasing drought under global warming in observations and models. Nat. Clim. Change.
Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., 2001. Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. Bioscience 51, 723–734.
Dale, V.H., Lannom, K.O., Tharp, M.L., Hodges, D.G., Fogel, J., 2009. Effects of climate change, land-use change, and invasive species on the ecology of the Cumberland forests. Can. J. For. Res. 39, 467–480.
Dale, V.H., Kline, K.L., Wright, L.L., Perlack, R.D., Downing, M., Graham, R.L., 2011a. Interactions among bioenergy feedstock choices, landscape dynamics, and land use. Ecol. Appl. 21, 1039–1054.
Dale, V.H.E., Rebecca, A., Kline, Keith L., 2011b. The land use–climate change–energy nexus. Landscape Ecol. 26, 755–773.
Dale, V.H., Efroymson, R.A., Kline, K.L., Langholtz, M.H., Leiby, P.N., Oladosu, G.A., Davis, M.R., Downing, M.E., Hilliard, M.R., 2013. Indicators for assessing socioeconomic sustainability of bioenergy systems: a short list of practical measures. Ecol. Indic. 26, 87–102.
de Fraiture, C., Giordano, M., Liao, Y., 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 10, 67–81.
De La Torre Ugarte, D.G., Ray, D.E., 2000. Biomass and bioenergy applications of the POLYSYS modeling framework. Biomass Bioenergy 18, 291–308.
de Lucena, A.F.P., Szklo, A.S., Schaeffer, R., de Souza, R.R., Borba, B.S.M.C., da Costa, I.V.L., Júnior, A.O.P., da Cunha, S.H.F., 2009. The vulnerability of renewable energy to climate change in Brazil. Energy Policy 37, 879–889.
Dominguez-Faus, R., Powers, S.E., Burken, J.G., Alvarez, P.J., 2009. The water footprint of biofuels: a drink or drive issue? Environ. Sci. Technol. 43, 3005–3010.
Dominguez-Faus, R., Folberth, C., Liu, J., Jaffe, A.M., Alvarez, P.J.J., 2013. Climate change would increase the water intensity of irrigated corn ethanol. Environ. Sci. Technol. 47, 6030–6037.
Eaves, J., Eaves, S., 2007. Renewable corn-ethanol and energy security. Energy Policy 35, 5958–5963.
Eggemeyer, K.D., Awada, T., Harvey, F.E., Wedin, D.A., Zhou, X., Zanner, C.W., 2009. Seasonal changes in depth of water uptake for encroaching trees *Juniperus virginiana* and *Pinus ponderosa* and two dominant C(4) grasses in a semiarid grassland. Tree Physiol. 29, 157–169.
EIA, 2012a. Drought Increases Price of Corn, Reduces Profits to Ethanol Producers. U.S. Energy Information Agency, Washington, DC.
EIA 2012b. Short-Term Energy Outlook (STEO), Washington, DC.
Elobeid, A., Tokgoz, S., 2008. Removing distortions in the U.S. ethanol market: what does it imply for the United States and Brazil? Am. J. Agric. Econ. 90, 918–932.
English, B.C., De La Torre Ugarte, D.G., Walsh, M.E., Hellwinkel, C., Menard, J., 2006. Economic competitiveness of bioenergy production and effects on agriculture of the southern region. J. Agric. Appl. Econ. 38, 389.
EPRI, 2011. Water Use for Electricity Generation and Other Sectors: Recent Changes (1985–2005) and Future Projections (2005–2030). Electric Power Research Insitute, Palo Alto, CA.
Erickson, K.D., Awada, T., Harvey, F.E., Wedin, D.A., Zhou, X., Zanner, C.W., 2008. Seasonal changes in depth of water uptake for encroaching trees *Juniperus virginiana* and *Pinus ponderosa* and two dominant C4 grasses in a semiarid grassland. Tree Physiol. 29, 157–169.
ERS, 2013a. Changes in food price indexes, 2011 through 2013, updated 25 June 2013. Economic Research Service, U.S. Department of Agriculture, Washington, DC.
ERS, 2013b. Income Statement for the U.S. Farm Sector, 2009-2013F, Updated February 11, 2013. Economic Research Service, U.S. Department of Agriculture, Washington, DC.
ERS, 2013c. Oil Crops Yearbook. Economic Research Service, U.S. Department of Agriculture, Washington, DC.
Escobedo, F.J., Luley, C.J., Bond, J., Staudhammer, C., Bartel, C., 2009. Hurricane debris and damage assessment for Florida urban forests. J. Arboric. 35, 100–106.
Field, C.B., Campbell, J.E., Lobell, D.B., 2008. Biomass energy: the scale of the potential resource. Trends Ecol. Evol. 23, 65–72.
Foust, T.D., Aden, A., Dutta, A., Phillips, S., 2009. An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes. Cellulose 16, 547–565.
Fraisse, C.W., Breuer, N.E., Zierden, D., Bellow, J.G., Paz, J., Cabrera, V.E., Garcia y Garcia, A., Ingram, K.T., Hatch, U., Hoogenboom, G., Jones, J.W., O'Brien, J.J., 2006. AgClimate: a climate forecast information system for agricultural risk management in the southeastern USA. Comput. Electron. Agric. 53, 13–27.
Garcia-Quijano, J.F., Deckmyn, G., Moons, E., Proost, S., Ceulemans, R., Muys, B., 2005. An integrated decision support framework for the prediction and evaluation of efficiency, environmental impact and total social cost of domestic and international forestry projects for greenhouse gas mitigation: description and case studies. For. Ecol. Manage. 207, 245–262.
Ghimire, S.R., Craven, K.D., 2011. Enhancement of switchgrass (*Panicum virgatum* L.) biomass production under drought conditions by the ectomycorrhizal fungus *Sebacina vermifera*. Appl. Environ. Microbiol. 77, 7063–7067.

Gilbert, R.A., Rainbolt, C.R., Morris, D.R., McCray, J.M., 2008. Sugarcane growth and yield responses to a 3-month summer flood. Agric. Water Manage. 95, 283–291.
Giunipero, L.C., Eltantawy, R.A., 2004. Securing the upstream supply chain: a risk management approach. Int. J. Phys. Distrib. Logistics Manage. 24, 698–713.
Glauber, J.W., 2013. The growth of the federal crop insurance program, 1990–2011. Am. J. Agric. Econ. 95, 482–488.
Goodwin, B.K., Smith, V.H., 2013. What harm is done by subsidizing crop insurance? Am. J. Agric. Econ. 95, 489–497.
Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C., Steinberger, J.K., 2011. Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. Biomass Bioenergy 35, 4753–4769.
Hall, D.O., House, J.I., 1994. Trees and biomass energy: carbon storage and/or fossil fuel substitution? Biomass Bioenergy 6, 11–30.
Hamlet, A.F., Lettenmaier, D.P., 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. Water Resour. Res. 43, W06427.
Hatfield, J., Boote, K., Fay, P., Hahn, L., Izaurralde, C., Kimball, B.A., Mader, T., Morgan, J., Ort, D., Polley, W., Thomson, A., Wolfe, D., 2008. Agriculture. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, pp. 362.
Hess, J.R., Kenney, K.L., Ovard, L.P., Searcy, E.M., Wright, C.T., 2009. Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid From Herbaceous Lignocellulosic Biomass. Idaho National Laboratory.
Hicke, J.A., Logan, J.A., Powell, J., Ojima, D.S., 2006. Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. J. Geophys. Res. Biogeosci. 111, G02019.
Holland, G.J., 2012. Hurricanes and rising global temperatures. Proc. Natl. Acad. Sci. 109, 19513–19514.
IPCC, 2012. Summary for policymakers. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge and New York.
JM-F J, MD C, R G, A J, R M, D R, WW W (2007). Biomass-bioenergy crops in the United States: a changing paradigm. Am. J. Plant Sci. Biotechnol. 1–28.
Kadam, K.L., McMillan, J.D., 2003. Availability of corn stover as a sustainable feedstock for bioethanol production. Bioresour. Technol. 88, 17–25.
Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A., Sugi, M., 2010. Tropical cyclones and climate change. Nat. Geosci. 3, 157–163.
Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., Safranyik, L., 2008. Mountain pine beetle and forest carbon feedback to climate change. Nature 452, 987–990.
Langholtz, M., Graham, R., Eaton, L., Perlack, R., Hellwinkel, C., Ugarte, D.G.D., 2012. Price projections of feedstocks for biofuels and biopower in the U.S. Energy Policy 41, 484–493.
Larson, J., English, B., Ugarte, D.D.L.T., Menard, R., Hellwinckel, C., West, T.O., 2010. Economic and environmental impacts of the corn grain ethanol industry on the United States agricultural sector. J. Soil Water Conserv. 65, 267–279.
Lavell A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., Muir-Wood, R., Myeong, S. (2012). Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 25–64.
Lee, H., Sumner, D., 2010. International Trade Patterns and Policy for Ethanol in the United States. In: Khanna, M., Scheffran, J., Zilberman, D. (Eds.), Handbook of Bioenergy Economics and Policy. Springer, New York, pp. 327–345.
Letson, D., Llovet, I., Podesta, G., Royce, F., Brescia, V., Lema, D., Parellada, G., 2001. User perspectives of climate forecasts: crop producers in Pergamino, Argentina. Clim. Res. 19, 57–67.
Lynch, A.H., Tryhorn, L., Abramson, R., 2008. Working at the boundary: facilitating interdisciplinarity in climate change adaptation research. Bull. Am. Meteorol. Soc. 89, 169–179.
Malcolm, S., Marshall, E., Aillery, M., Heisey, P., Livingston, M., Day-Rubenstein, K., 2012. Agricultural Adaptation to a Changing Climate: Economic and Environmental Implications Vary by U. S. Region. U.S. Department of Agriculture, Economic Research Service, Washington, DC.
Mascia, P.N., Portereiko, M., Sorrells, M., Flavell, R.B., 2010. Designing plants to meet feedstock needs. Plant Biotechnology for Sustainable Production of Energy and Co-products. Springer, pp. 57–84.
McBride, A.C., Dale, V.H., Baskaran, L.M., Downing, M.E., Eaton, L.M., Efroymson, R.A., Garten, C.T., Kline, K.L., Jager, H.I., Mulholland, P.J., 2011. Indicators to support environmental sustainability of bioenergy systems. Ecol. Indic. 11, 1277–1289.
McDonald, A., Riha, S., DiTommaso, A., DeGaetano, A., 2009. Climate change and the geography of weed damage: analysis of U.S. maize systems suggests the potential for significant range transformations. Agric. Ecosyst. Environ. 130, 131–140.
McKendry, P., 2002. Energy production from biomass (part 1): overview of biomass. Bioresour. Technol. 83, 37–46.
McLaughlin, S.B., Kszos, L.A., 2005. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. Biomass Bioenergy 28, 515–535.
Meinke, H., Howden, S.M., Struik, P.C., Nelson, R., Rodriguez, D., Chapman, S.C., 2009. Adaptation science for agriculture and natural resource management-urgency and theoretical basis. Curr. Opin. Environ. Sustainability 1, 69–76.
Melo, M.T., Nickel, S., Saldanha-da-Gama, F., 2009. Facility location and supply chain management – A review. Eur. J. Oper. Res. 196, 401–412.
Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. 17, 2145–2151.
Milly, P.C.D., Wetherald, R.T., Dunne, K.A., Delworth, T.L., 2002. Increasing risk of great floods in a changing climate. Nature 415, 514–517.
Min, S.-K., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature 470, 378–381.
Mitchell, C., 2000. Development of decision support systems for bioenergy applications. Biomass Bioenergy 18, 265–278.
Monti, A., Zatta, A., 2009. Root distribution and soil moisture retrieval in perennial and annual energy crops in Northern Italy. Agric. Ecosyst. Environ. 132, 252–259.
Nagy, Z., Tuba, Z., Zsoldos, F., Erdei, L., 1995. CO_2-exchange and water relation responses of sorghum and maize during water and salt stress. J. Plant Physiol. 145, 539–544.
Naidu, S.L., Long, S.P., 2004. Potential mechanisms of low-temperature tolerance of C-4 photosynthesis in Miscanthus x giganteus: an in vivo analysis. Planta 220, 145–155.
Nair, S.S., Kang, S.J., Zhang, X.S., Miguez, F.E., Izaurralde, R.C., Post, W.M., Dietze, M.C., Lynd, L.R., Wullschleger, S.D., 2012. Bioenergy crop models: descriptions, data requirements, and future challenges. Global Change Biol. Bioenergy 4, 620–633.
NASS, 2013. Quick Stats. National Agricultural Statistics Service. U.S. Depatment of Agriculture, Washington, DC.
NCDC, 2013a. Historical Palmer Drought Indices. National Climatic Data Center, Asheville, NC.
NCDC, 2013b. National Overview – Annual 2012. National Oceanographic and Atmospheric Administration, Washington, DC.
NCEP, 2006. Siting Critial Energy Infrastructure: An Overview of Needs and Challenges. National Commission on Energy Policy, Washington, D.C.
Neiger, D., Rotaru, K., Churilov, L., 2009. Supply chain risk identification with value-focused process engineering. J. Oper. Manage. 27, 154–168.
NRC, 2008. Water implications of biofuels production in the United States. National Research Council, National Academy of Sciences Press, Washington, DC.
Ogden, A., Innes, J., 2007. Incorporating climate change adaptation considerations into forest management planning in the boreal forest. Int. For. Rev. 9, 713–733.
Oliver, R.J., Finch, J.W., Taylor, G., 2009. Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO2 and drought on water use and the implications for yield. Global Change Biol. Bioenergy 1, 97–114.
O'Neill, S.J., Hulme, M., 2009. An iconic approach for representing climate change. Global Environ. Change 19, 402–410.

O'Neill, S., Nicholson-Cole, S., 2009. "Fear Won't Do It": Promoting positive engagement with climate change through visual and iconic representations. Sci. Commun. 30, 355–379.
Oosterhuis, D.M., Scott, H.D., Hampton, R.E., Wullschleger, S.D., 1990. Physiological-responses of 2 soybean glycine-max (l) merr cultivars to short-term flooding. Environ. Exp. Bot. 30, 85–92.
Pall, P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G.J., Lohmann, D., Allen, M.R., 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature 470, 382–385.
Parish, E.S., Kline, K.L., Dale, V.H., Efroymson, R.A., McBride, A.C., Johnson, T.L., Hilliard, M.R., Bielicki, J.M., 2013. Comparing scales of environmental effects from gasoline and ethanol production. Environ. Manage. 51, 307–338.
Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., Erbach, D.C., 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
Pimentel, D., 2003. Ethanol fuels: energy balance, economics, and environmental impacts are negative. Nat. Resour. Res. 12, 127–134.
Pimentel, D., Patzek, T.W., 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Nat. Resour. Res. 14, 65–76.
Podesta, G.P., Messina, C.D., Grondona, M.O., Magrin, G.O., 1999. Associations between grain crop yields in central-eastern Argentina and El Nino-Southern Oscillation. J. Appl. Meteorol. 38, 1488–1498.
Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. Lond. B Biol. Sci. 360, 2021–2035.
Poudel, B.C., Sathre, R., Gustavsson, L., Bergh, J., Lundström, A., Hyvönen, R., 2011. Effects of climate change on biomass production and substitution in north-central Sweden. Biomass Bioenergy 35, 4340–4355.
Ramachandra, T., Krishna, S.V., Shruthi, B., 2005. Decision support system to assess regional biomass energy potential. Int. J. Green Energy 1, 407–428.
Ray, D.E., Richardson, J.W., De La Torre Ugarte, D.G., Tiller, K.H., 1998. Estimating price variability in agriculture: Implications for decision makers. J. Agric. Appl. Econ. 30, 21–34.
Richard, T.L., 2010. Challenges in scaling up biofuels infrastructure. Science 329, 793–796.
RMA, 2013. Cause of Loss Historical Data Files. Risk Management Agency, U.S. Department of Agriculture, Washington, DC.
Rooney, W.L., Blumenthal, J., Bean, B., Mullet, J.E., 2007. Designing sorghum as a dedicated bioenergy feedstock. Biofuels Bioprod. Biorefin. Biofpr 1, 147–157.
Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P., Chivian, E., 2001. Climate change and extreme weather events; implications for food production, plant diseases, and pests. Global Change Hum. Health 2, 90–104.
Rosenzweig, C., Tubiello, F.N., Goldberg, R., Mills, E., Bloomfield, J., 2002. Increased crop damage in the US from excess precipitation under climate change. Global Environ. Change 12, 197–202.
Rotter, R.P., Carter, T.R., Olesen, J.E., Porter, J.R., 2011. Crop-climate models need an overhaul. Nature Clim. Change 1, 175–177.
Royle, D.J., Ostry, M.E., 1995. Disease and pest control in the bioenergy crops poplar and willow. Biomass Bioenergy 9, 69–79.
Scheffran, J., 2010. Criteria for a Sustainable Bioenergy Infrastructure and Lifecycle. Plant Biotechnology for Sustainable Production of Energy and Co-products. Springer, pp. 409–447.
Schill, S.R., (2012). Boosting corn's drought performance. Ethanol Producer Magazine, pp. 41–44.
Schneider, U.A., McCarl, B.A., 2003. Economic potential of biomass based fuels for greenhouse gas emission mitigation. Environ. Resour. Econ. 24, 291–312.
Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C.A., de la Vega-Leinert, A.C., Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaanpää, S., Klein, R.J.T., Lavorel, S., Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem service supply and vulnerability to global change in Europe. Science 310, 1333–1337.
Schubert, R., Blasch, J., 2010. Sustainability standards for bioenergy—A means to reduce climate change risks? Energy Policy 38, 2797–2805.
Sheffield, J., Wood, E.F., 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dyn. 31, 79–105.
Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. Nature 491, 435–438.
Shugart, H., Sedjo, R., Sohngen, B., (2003). Forests & Global Climate Change: Potential Impacts on U.S. Forest Resources. Pew Center on Global Climate Change, Arlington, VA.
Sokhansanj, S., Hess, J.R., 2009. Biomass supply logistics and infrastructure. Biofuels Methods Protoc. 581, 1–25.
Sokhansanj, S., Wilkerson, E.G., Turhollow, A.F., 2008. Development of the Integrated Biomass Supply Analysis and Logistics (IBSAL) Model. Oak Ridge National Laboratory, Oak Ridge, TN.
Sokhansanj, S., Mani, S., Turhollow, A., Kumar, A., Bransby, D., Lynd, L., Laser, M., 2009. Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum* L.)-current technology and envisioning a mature technology. Biofuels Bioprod. Biorefin. Biofpr 3, 124–141.
Soussana, J.-F., Graux, A.-I., Tubiello, F.N., 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. J. Exp. Bot. 61, 2217–2228.
Spittlehouse, D.L., Stewart, R.B., 2003. Adaptation to climate change in forest management. BC J. Ecosyst. Manage. 4, 1–11.
Spracklen, D.V., Mickley, L.J., Logan, J.A., Hudman, R.C., Yevich, R., Flannigan, M.D., Westerling, A.L., 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. J. Geophys. Res. Atmos. 114, D20301.
Stacey, D.A., Fellowes, M.D.E., 2002. Influence of elevated CO2 on interspecific interactions at higher trophic levels. Global Change Biol. 8, 668–678.
Staudhammer, C., Hermansen, A., Carter, D., Macie, E., 2011. Wood to energy: using southern interface fuels for bioenergy. USFS Southern Research Station, Ashville, NC, p. 90.
Stone, K.C., Hunt, P.G., Cantrell, K.B., Ro, K.S., 2010. The potential impacts of biomass feedstock production on water resource availability. Bioresour. Technol. 101, 2014–2025.
Strzepek, K., Yohe, G., Neumann, J., Boehlert, B., 2010. Characterizing changes in drought risk for the United States from climate change. Environ. Res. Lett. 5, 9.
Subbaiah C., Sachs M., (2009). Responses to oxygen deprivation and potential for enhanced flooding tolerance in maize. In: JL B, SC H (Eds.), Handbook of Maize: Its Biology, Springer-Verlag, New York, NY, pp. 345–365.
Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nature Clim. Change 4, 17–22.
Tribbia, J., Moser, S.C., 2008. More than information: what coastal managers need to plan for climate change. Environ. Sci. Policy 11, 315–328.
Tubiello, F.N., Soussana, J.-F., Howden, S.M., 2007. Crop and pasture response to climate change. Proc. Natl. Acad. Sci. 104, 19686–19690.
Tuck, G., Glendining, M.J., Smith, P., House, J.I., Wattenbach, M., 2006. The potential distribution of bioenergy crops in Europe under present and future climate. Biomass Bioenergy 30, 183–197.
Turhollow, A.F., Webb, E.G., Downing, M.E., 2010. Review of Sorghum Production Practices: Applications for Bioenergy. Oak Ridge National Laboratory, Oak Ridge, TN.
Tuskan, G., 1998. Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know? Biomass Bioenergy 14, 307–315.
U.S. Environmental Protection Agency (2005). Summary of the Energy Policy Act.
U.S. Environmental Protection Agency (2007). Summary of the Energy Independence and Security Act.
U.S. Environmental Protection Agency (2012). Clean Air Act.
USDA, 2012a. Crop Production, July 11, 2012. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC.
USDA, 2012b. Crop Production, June 12, 2012. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC.
USDA, 2013a. Crop Production 2012 Summary. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC.

USDA, 2013b. USDA Designates 597 Counties in 2013 as Disaster Areas Due to Drought. United States Department of Agriculture, Washington, DC.
USDOE, 2006. Energy Demands on Water Resources. Report to Congress on the Intedependency of Energy and Water. U.S. Department of Energy, Washington, D.C.
USDOE, 2011. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. Oak Ridge National Laboratory, Oak Ridge, TN, p. 227.
USEPA (2012). Notice of Decision Regarding Requests for a Waiver of the Renewable Fuel Standard, [FRL–9754–4]. Federal Register 77:70752-70776.
USGPO, 1988. Alternative Motor Vehicle Fuels Act of 1988. Public Law 100-494, October 14, 1988. U.S. Government Printing Office, Washington, DC.
USGPO, 2005. Energy Policy Act of 2005. Public Law 109-58, August 8, 2005. U.S. Government Printing Office, Washington, DC.
USGPO, 2007. Energy Independence and Security Act of 2007. Public Law 110-140, December 19, 2007. U.S. Government Printing Office, Washington, DC.
USGS, 2013. Federal Wildland Occurrence Data. U.S. Geologic Survey, Denver CO.
Valerio, M., Tomecek, M., Lovelli, S., Ziska, L., 2011. Quantifying the effect of drought on carbon dioxide-induced changes in competition between a C3 crop (tomato) and a C4 weed (Amaranthus retroflexus). Weed Res. 51, 591–600.
Van Aalst, M.K., 2006. The impacts of climate change on the risk of natural disasters. Disasters 30, 5–18.
Van der Schrier, G., Jones, P., Briffa, K., 2011. The sensitivity of the PDSI to the Thornthwaite and Penman-Monteith parameterizations for potential evapotranspiration. J. Geophys. Res. Atmos. 116, 16.
Viator, R.P., White, P.M., Hale, A.J., Waguespack, H.L., 2012. Screening for tolerance to periodic flooding for cane grown for sucrose and bioenergy. Biomass Bioenergy 44, 56–63.
Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2011. Comment on ''characteristics and trends in various forms of the palmer drought severity index (PDSI) during 1900–2008'' by Aiguo Dai. J. Geophys. Res. Atmos. 116, 9.
Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.-R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309, 1844–1846.
Wehner, M., Easterling, D.R., Lawrimore, J.H., Heim, R.R., Vose, R.S., Santer, B.D., 2011. Projections of future drought in the continental United States and Mexico. J. Hydrometeorol. 12, 1359–1377.
Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. Science 313, 940–943.
Wilbanks, T.B., Schmalzer, D., Scott, M., Arent, D., Buizer, J., Chum, H., Dell, J., Edmonds, J., Frando, G., Jones, R., Rose, S., Roy, N., Sanstad, A., Seidel, S., Weyant, J., Wuebbles, D., 2012. Climate Change and Energy Supply and Use. Oak Ridge National Laboratory and U.S. Department of Energy, Oak Ridge, TN.
Woodard, J.D., Schnitkey, G.D., Sherrick, B.J., Lozano-Gracia, N., Anselin, L., 2012. A spatial econometric analysis of loss experience in the U.S. crop insurance program. J. Risk Insur. 79, 261–286.
Wright, L., Turhollow, A., 2010. Switchgrass selection as a ''model'' bioenergy crop: a history of the process. Biomass Bioenergy 34, 851–868.
Wu, M., Mintz, M., Wang, M., Arora, S., 2009. Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline. Center for Transportation Research, Energy Systems Division. Argonne National Laboratory, Argonne, IL.
Xu, B.C., Li, F.M., Shan, L., Ma, Y.Q., Ichizen, N., Huang, J., 2006. Gas exchange, biomass partition, and water relationships of three grass seedlings under water stress. Weed Biol. Manage. 6, 79–88.
Yan, B., Dai, Q.J., Liu, X.Z., Huang, S.B., Wang, Z.X., 1996. Flooding-induced membrane damage, lipid oxidation and activated oxygen generation in corn leaves. Plant Soil 179, 261–268.
Yordanova, R.Y., Popova, L.P., 2007. Flooding-induced changes in photosynthesis and oxidative status in maize plants. Acta Physiol. Plant. 29, 535–541.
Zaidi, P.H., Rafique, S., Rai, P.K., Singh, N.N., Srinivasan, G., 2004. Tolerance to excess moisture in maize (*Zea mays* L.): susceptible crop stages and identification of tolerant genotypes. Field Crops Res. 90, 189–202.
Zhang, X., Izaurralde, R.C., Manowitz, D., West, T.O., Post, W.M., Thomson, A.M., Bandaru, V.P., Nichols, J., Williams, J.R., 2010. An integrative modeling framework to evaluate the productivity and sustainability of biofuel crop production systems. GCB Bioenergy 2, 258–277.
Zhou Tian-Jun, H.T., 2013. Projected changes of palmer drought severity index under an RCP8.5 scenario. Atmos. Oceanic Sci. Lett. 6, 273–278.
Ziska, L.H., 2001. Changes in competitive ability between a C4 crop and a C3 weed with elevated carbon dioxide. Weed Sci. 49, 622–627.
Zvereva, E.L., Kozlov, M.V., 2006. Consequences of simultaneous elevation of carbon dioxide and temperature for plant–herbivore interactions: a metaanalysis. Global Change Biol. 12, 27–41.

Please cite this article in press as: Langholtz, M., et al.. Climate Risk Management (2014), http://dx.doi.org/10.1016/j.crm.2014.05.001