Biofuels and Climate Change: Evaluating the Viability of a Drought Vulnerable Fuel Resource

Halley Finkel

Abstract The rising prices, national security threats and environmental concerns about petroleum have spurred the US government into looking into alternative energy. The country is encouraging biofuels as its replacement transportation fuel and put policies in place that intend the amount of cellulosic biofuels to encompass over 16% of US fuel usage by 2022. Two grasses, *Miscanthus x giganteus* and switchgrass (*Panicum virgatum)*, have been identified as the primary crops for cellulosic biofuels. However, climate change will cause increased drought over the next century that will severely limit the output of these two crops, especially drought-sensitive *Miscanthus*. To test how drought affects these two fuel crops and to compare the two crops to each other, I created temperature and precipitation range maps, gathered information about how drought will affect the continental US over the next century and then applied this information to data collected on the changing yields of *Miscanthus* and switchgrass when each grass was subject to drought. I found that in all US regions, *Miscanthus* will continue to out produce switchgrass through the 2070s, but in drought-prone regions the two have similar outputs. Both crops sustain major losses from drought in the latter half of the century. From this I conclude that *Miscanthus* is a better biofuel crop for most northern US regions currently, but with such high potential for losses from both crops, policy makers will need to think carefully about drought before investing too much in cellulosic biofuels.

Introduction:

Today in the 21st century, natural resource consumption is on the rise, fossil fuels are dwindling and climate change is growing more and more apparent with increased floods, droughts, and natural disasters (IPCC 2007). In this era of change, the need for alternative fuel has become urgent; transportation energy requirements are rapidly growing while oil production seems to have peaked and begun to taper off (Hill *et al.* 2006). Presently, 98% of fuel used for transportation is derived from petroleum, but as stocks start declining, the global economy is left susceptible to fluctuations in oil prices (Gomez *et al.* 2008). Growing concerns about this vulnerability and the negative environmental impacts of petroleum products are causing many Americans to press for a replacement for oil (Moriera 2005). In response to this call for new fuel sources, the United States government has chosen to invest in and support biofuels (Herrera 2006).

Recent US policy decisions have sought to increase ethanol and biofuel production to replace foreign oil. The fact that more than half of US oil comes from the war-torn Middle East creates a national security threat, since so much of the US economy is dependent upon oil an interruption or cessation of that flow could cause serious problems (EIA 2008, elect. comm.). Additionally, with the current consumption rate, massive quantities of money are flowing into potentially hostile countries in exchange for this precious oil. A major concern of both candidates in the 2008 presidential election was finding an alternative to petroleum that would increase national security by reducing reliance on foreign oil producers; since his election President Obama has continued emphasizing the need for alternative transportation energy (CNN 2008). Ethanol seems to be an obvious solution to the country's fuel problem for a number of reasons; it can be produced by domestic agriculture, distributed using our current fuel infrastructure, and pumped using traditional gas stations (Gomez *et al.* 2008). It is easy and relatively cheap to convert standard US automobile engines into flex-fuel engines that can take up to 85% ethanol fuel (Moreira 2005). The biofuel policies of the US government are encouraging companies such as Toyota, Ford, and Volkswagen to increase their production of flex-fuel cars; the numbers of biofuel powered vehicles on the road is predicted to increase by at least ten-fold in the coming decade (Herrera 2006).

The US government has ambitious biofuel goals; policies instituted by the Bush administration aim to replace 30% of the US fuel supply with biofuels by 2030 (Herrera 2006).

The Renewable Fuel Standard set forth in the Energy Independence and Security Act of 2007 calls for an increase of domestic production to 15 billion gallons of conventional corn ethanol per year by 2015 (Schill 2008). Following this standard, in 2008 the US produced 9 billion gallons of corn ethanol, which accounted for 7.76 percent of US transportation fuel usage (Schill 2008, Biopact 2008, elect. comm.). However, recent studies have raised objections against traditional corn ethanol. These objections include corn ethanol's low energy output, the effects that it has on food prices, and the potential it has for releasing more carbon into the atmosphere than petroleum. Manufacturing corn ethanol is energy intensive, so much fuel goes into ethanol production that the net energy gain is only 25%, and most of this is due to the energy output of its byproduct, animal feed (Hill *et al.* 2006). Other biofuel alternatives have higher energy outputs than ethanol; for example, biodiesel yields 93% more energy than it requires in its production (Hill *et al.* 2006). Soaring food prices in 2007 were blamed on the new demand for corn for ethanol production; the price of corn doubled between 2006 and 2007. This caused the prices of staple foods such as grain, milk and meat from corn-fed cows, corn-fed chicken and corn-fed fish to rise dramatically (Odling-Smee 2007). The increase in demand for corn due to ethanol production leads to planting in previously uncultivated areas, which typically involves the destruction of carbon sequestering grasslands or forests to be replaced by annual crops. This causes an increase in carbon flow to the atmosphere, leading to intensified global warming (Searchinger *et al.* 2007). Additionally, if ethanol were to replace all other transportation fuels, it would require an area equivalent to all of the world's arable land (IEA 2006).

Rising academic and social pressure against corn ethanol has forced the government to change its goals (Gomez *et al.* 2008). Corn has been pronounced a first generation biofuel, and the country aims to phase out corn ethanol and move on to second generation biofuels as they become affordable. The most recent Renewable Fuel Standard states that after 2015, corn ethanol will remain at production rates of 15 billion gallons per year while cellulosic biofuels will be expected to increase production to produce 16 billion gallons of fuel per year by 2022 (Schill 2008). Two cellulosic biofuel sources, *Miscanthus* x *giganteus* and switchgrass, "have been identified as the most promising species for biomass energy production in the Midwest" (Bollero *et al*. 2008). *Miscanthus x giganteus* is a sterile tropical grass hybrid from Asia, switchgrass (*Panicum virgatum*) is a native grass to the United States; both produce large amounts of biomass that can be converted into fuel and are expected to make up a majority of the cellulosic ethanol requirements of the Renewable Fuel Standard (Karp and Shield 2008). *Miscanthus* possesses a number of traits that make it a desirable biofuel crop; the grass yields massive quantities of biomass, survives for up to 20 years, will not spread beyond where it is planted due to its sterility and has high water use efficiency (Lewandowski *et al.* 2003). The best crop yields of *Miscanthus* can rise above 30 tons dry matter per hectare (DM/ha), and on average, the grass still produces 24 tons DM/ha in optimum conditions (Lewandowski *et al.* 2003). Switchgrass also has a variety of desirable traits; it has a high yield, native adaptability and is able to survive fairly well on minimal inputs of water and nitrogen (Stroup *et al*. 2003). Its best yields are over 22 tons DM/ha and on average, it produces 16 tons DM/ha in prime conditions (Lewandowski *et al.* 2003).

However, many problems arise from turning crops into fuel, especially with the specter of climate change threatening the global agricultural world. Many recent studies have examined the effects that rising temperature and shifting precipitation patterns will have on crop yields globally and by individual countries. Projections into the future show varied results, especially when the potential positive effect of CO_2 on plant productivity, called carbon fertilization, is taken into account (Cline 2007). Carbon fertilization is “the enhancement of growth of plants as a result of increased atmospheric CO_2 concentration, resulting from the fact that CO_2 is an input into the process of photosynthesis” (Cline 2007, 124). A study from 2007 reevaluated global yields and found that they would drop by 3% with carbon fertilization and by 16% without carbon fertilization. In the US, which is at higher latitudes and generally shielded from many of the severe reductions in yield, production has the potential to rise by 8% with carbon fertilization or drop by 5.9% without carbon fertilization (Cline 2007).

Though carbon fertilization seems to mitigate the effects of temperature increase, it cannot fully compensate for the loss in productivity due to global warming. In particular, C4 crops, which include *Miscanthus* and switchgrass, have limited benefits from carbon fertilization. The structure of C4 plants is advantageous in the current climate; within their bundle sheath cells, C4 plants concentrate CO_2 to a point three to six times greater than atmospheric CO_2. This allows for optimization of carbon availability, so the photosynthetic enzymes are already fully saturated with current CO_2 levels (Long *et al.* 2006). Since carbon fertilization works on the assumption that more CO_2 will help plants, the chance of output gains for switchgrass and *Miscanthus* crops are low, even in higher latitudes like North America.

While many studies have taken the expected effects of climate change into account, namely alterations in temperature and average precipitation, plant based fuels are also vulnerable to the unpredictable elements of climate change: droughts and flooding. Droughts can change agricultural potential more than both temperature and precipitation (Fischer *et al.* 1994). According to the Intergovernmental Panel on Climate Change (IPCC) 2007 report, drought areas and intensity are likely to increase as CO_2 levels continue to rise, and heat waves will bring about greater water limitation (IPCC 2007). Over the next century, extreme drought is projected to cover 30% of global land area at a time, compared to the 1% of land covered by extreme drought in the current day (Burke *et al.* 2006). *Miscanthus* requires large amounts of water to sustain maximum growth, and if it does not get enough water, *Miscanthus* will lose leaf area, reducing its yields considerably (Karp and Shield 2008). In a recent study of the effects of drought on *Miscanthus*, the researchers found that the plant loses up to 40% of its yield when subject to typical summer drought (Richter *et al.* 2008). Switchgrass, which is native to the US, has a variety adapted to drier habitats, but the productivity of switchgrass is still limited by water availability (Karp and Shield 2008). Proponents of switchgrass and *Miscanthus* claim that these second generation biofuel crops can be grown in marginal lands, but it is likely these grasses will not be able to maintain optimal yields with decreased resources (Karp and Shield 2008). Thus, it cannot be assumed that cellulosic biofuels will not compete with current croplands for space, or that they will be able to deliver the impressive outputs necessary for viable biofuel crops when placed in marginal lands. Since the government has mandated that cellulosic biofuels will overtake corn ethanol in the next fifteen years, it is extremely important to fully examine how outputs of the two most important cellulosic sources may change in the coming century. To date, no study has been done that looks at how increased drought due to climate change will affect the economic viability of *Miscanthus* x *giganteus* and switchgrass.

In this study, I examine how US drought patterns will be altered in the coming century by climate change, and how these drought patterns will affect the crop yields of switchgrass and *Miscanthus*. Specifically, I tested outputs in the present day, in a near future scenario and in a more distant future scenario. The near future scenario, hereafter identified as the 2030's, spans from 2025-2040, the distant future scenario will be called the 2070's and spans from 2065-2080. I attempt to answer which biofuel option will be more efficient to produce over the next century in each time period, and then address how much overall output of each crop will decrease and whether or not they will remain viable options for US fuel. I have two hypotheses for this study:

H1: When drought predictions are taken into account *Miscanthus* outputs, currently up to 50% higher than switchgrass outputs, will diminish over the century to amounts below switchgrass outputs.

H2: Drought will reduce the outputs of both cellulosic biofuel sources to a point that neither will be a viable source of fuel for the US.

Alternately, *Miscanthus* could continue to outproduce switchgrass, or the two could become relatively equal. Drought patterns may not affect crop outputs as much as I expect and one or both of these biofuels could turn out to be a viable source of fuel.

To test these hypotheses, I have conducted a meta-analysis. I used a geographic information system (GIS) to delineate the current ranges of temperature and precipitation where *Miscanthus* and switchgrass will be able to grow in the continental US. Then I applied drought data from a climate change model to the present day, the 2030's and the 2070's to find intensity and frequency of droughts. I then calculated the overall change in outputs of *Miscanthus* and switchgrass throughout the current day range in each scenario and time period.

Methods

I examined two potential biofuel crops, *Miscanthus x giganteus*, a tropical hybrid grass from Asia, and switchgrass, a prolific United States native grass (Karp and Shield 2008). To calculate the changing crop yields due to drought through the 21^{st} century, I mapped their potential optimal ranges across the continental US, applied drought predictions to the three time periods of interest and then used these drought measures and studies that looked at water limitation to calculate the average loss of crop outputs.

Range map To create my range map, I used current climate data from 2006-2008. I collected temperature data from Oregon State's Prism Group and precipitation data from WorldClim. Lewandowski *et al*. (2003) states that *Miscanthus* rhizomes will die at soil temperatures below -3.5 degrees Celsius and switchgrass seeds will die at temperatures below -4 degrees Celsius, so I limited the range map to locations in the continental US where soil temperatures do not fall below -3.5 degrees Celsius. For precipitation, I limited my range to locations that rely on rainfall as the primary source of water because drought predictions are inaccurate in regions where snowmelt significantly contributes to the water availability (Dai *et al*. 2004). This disqualified the Southwest and the Southern half of the Pacific Northwest from the range map. Within the range map, I identified separate geographic regions in which I took my samples using a stratified sampling technique. The geographic regions I identified are: the Pacific Northwest, the Northern Plains, the Southern Plains, the Northeast and the Southeast.

Drought predictions For my projections, I used a moderate IPCC scenario called A1B. I chose this scenario because it is a subset of the A1 scenarios, a group of three climate projections that assume the same trends for population and economic growth. The similar conditions in the A1 set control for many confounding variables between other IPCC scenarios. The A1 set differs in one key aspect which is the way that technology will progress in the next century and change greenhouse gas outputs. A1B projects a balanced set of technologies including fossil-fuel energy sources and non-fossil-fuel energy sources (IPCC 2007). I applied this scenario and made projections in three different time periods; the present day, the short term period falling during the 2030s and the longer term period during the 2070s. I have chosen these periods because they match dates used in much of the current literature and will therefore be pertinent to other literature on the subject.

Within each scenario, there are different general circulation models (GCMs) that predict global climate trends. I selected the Hadley CM3 model because of its applicability to the data I collected for my project and because it is a widely used and respected model on which many other studies are based.[1]

Due to the coarseness of the Hadley CM3 GCM, which uses a low resolution, I used a regular stratified sample to select points at the center of every 3.75 degrees of latitude and 2.5 degrees of longitude in each of my regions (Burke *et al.* 2006). The limited ranges caused my regions to be different sizes, thus there are more samples for the larger regions in the plains, and fewer samples for the Northeast, Southeast and Pacific Northwest. Each sample was portrayed as one hectare of cropland on which *Miscanthus* or switchgrass could be grown and I assumed that these sample hectares would experience the projected climate change for that location.

[1] I obtained my drought data from the Met Office in Devon, UK, where the Hadley CM3 model was created.

At each point, I compiled data on the percentage of non-drought years, medium-drought years, high-drought years and severe-drought years. The drought data I obtained from the Met Office used potential evapotranspiration deficit (PED) as its drought index. A drought index integrates a number of hydrological and climatic factors that influence water availability into a single number (Narasimhan and Srinivasan 2005). Recent studies have found that evapotranspiration deficit is the best index for examining crop response (Mullan *et al.* 2004). For this study, I categorize non-drought years as years in which the PED was below 200 mm, medium-drought years as years with PED between 200 mm and 400 mm, high-drought years with a PED between 400 mm and 600 mm, and severe-drought years with a PED of over 600 mm (Mullan *et al.* 2004). I determined these thresholds from a report by New Zealand's Ministry of the Environment and National Institute of Water and Atmospheric Research which states that a drought of 200 PED translates to approximately 50 days of soil moisture deficit (SMD), 400 PED translates to 100 days of SMD and 600 PED translates to 150 days of SMD. By examining the standard deviation of PED accumulated over the year on a timescale graph, I found that 32, 64 and 96 days of drought occur during the summer months for 200, 400 and 600 PED respectively. Summer months are the time at which *Miscanthus* and switchgrass are at the peak of their growing season and very susceptible to drought (Richter *et al.* 2008). Thus, I calculated this to be roughly equivalent to the medium, high and severe drought conditions that I assigned for *Miscanthus* and switchgrass using Clifton-Brown and Stroup water limiting studies.

Calculating yield loss I calculated yield loss for each plant using previous studies that had examined changes in output when water is limited. Clifton-Brown and Lewandowski (2000) found that *Miscanthus* yields drop to 56.4% of optimum yield under medium-drought conditions, and 45.8% of optimum yields under high-drought conditions. For switchgrass, Stroup and Sanderson (2003) found that high-drought conditions cause yields to drop to 58% of optimum yield. As this is a relatively new field, there is a lack of other similar studies, so for this research I calculated yields that I did not have explicit data for by assuming that yield loss is linear with increasing drought. Thus for switchgrass medium-drought causes yield to drop to 79% of optimum yield and severe-drought causes yield to drop to 37% of optimum yield. For *Miscanthus,* severe-drought conditions caused yield to drop to 13% of optimum yield. Once I had collected drought data for each point, I mathematically applied the yield losses for each crop in each level of drought. Then I averaged these losses to find the percent of crop that will be lost each year to drought.

My analysis was limited to averages and graphs. Due to the nature of this study, in which I collected data from other studies and manipulated it to find new trends, there is no data on which statistical tests would be valid or relevant. Trends were marked and percentages were tracked.

Results

Map: The range map of areas where *Miscanthus* and switchgrass could grow is shown below (Figure 1). Low temperature did not disqualify any regions due to the fact that soil temperature did not drop below -3.5 degrees Celsius anywhere in the US at any point in time.

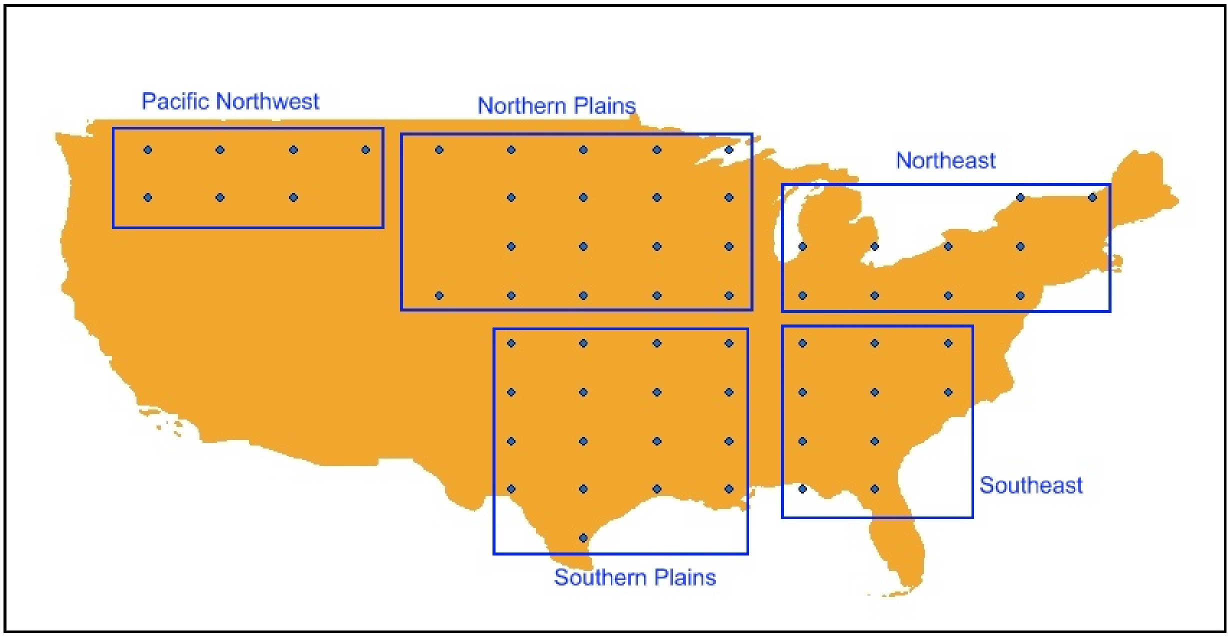


Figure 1: Map of the US displaying ranges where *Miscanthus* and switchgrass crops could plausibly be grown and where drought measures based on precipitation will be relevant.

Present: Present day drought patterns reflected the infrequency of droughts in the Northeast predominantly, limited drought in the Northern Plains and Southeast, and the more prevalent droughts in the Pacific Northwest and Southern Plains. Medium, high, and severe droughts all followed similar trends with medium as the most common in all regions, high less common and severe least common. Droughts had the highest chance of occurring in the Southern Plains, with a moderate drought occurring approximately every 4 years, a high drought every 10 years and an extreme drought every 40 years (Table 1).

2000s

	probability of medium droughts	probability of high droughts	probability of severe droughts
Pacific Northwest	0.152	0	0
Northern Plains	0.039	0.0026	0
Southern Plains	0.27	0.112	0.027
Northeast	0.0022	0	0
Southeast	0.0267	0	0

Table 1: Predictions of drought frequency and intensity during the 2000s.

These current drought patterns caused average *Miscanthus* yields to decrease by 21% in the Southern Plains, the region of greatest drought intensity and frequency, and decreased yields by 0.1% in the Northeast. The Southern Plains produced 19 tons of dry matter (DM) per hectare. Optimal annual yield was 24 tons DM/ha; the Northern Plains, Northeast and the Southeast were all within .5 tons DM/ha of the optimum yield (Figure 2).

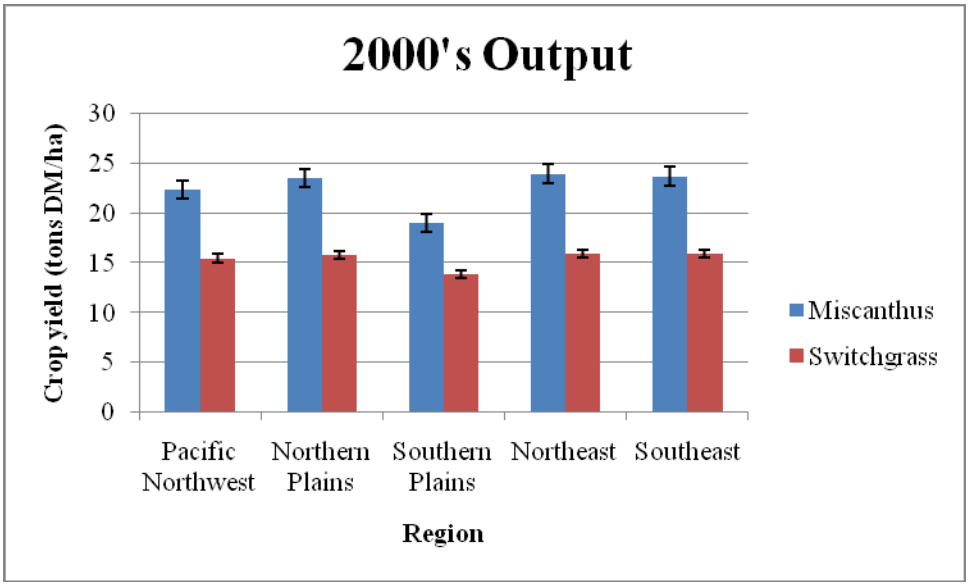


Figure 2: *Miscanthus* and switchgrass crop yields averaged from 1990-2000 with drought affects. Measure of yield taken in tons of dry matter per hectare.

Switchgrass yields dropped by 13% in the Southern Plains and by less than 1% in the least drought prone regions, the Northern Plains, Northeast and Southeast. In these low drought regions, switchgrass crops yielded 16 tons DM per hectare, approximately optimum growth. In the Southern Plains, switchgrass yielded 14 tons DM per hectare (Figure 2).

Short-term (2030s): Predictions show that future drought patterns will display increased droughts fairly evenly distributed across all regions. The Northeast will remain the least prone to drought with medium droughts occurring once every hundred years and extreme droughts essentially never occurring. The Southern Plains is expected to experience heavy drought conditions with medium droughts once every 3 years, high droughts once every 5 years and severe droughts occurring about once every 10 years (Table 2).

	2030s		
	probability of medium droughts	probability of high droughts	probability of severe droughts
Pacific Northwest	0.324	0.0127	0
Northern Plains	0.081	0.012	0
Southern Plains	0.336	0.209	0.099
Northeast	0.011	0	0
Southeast	0.0378	0	0

Table 2: Predictions of drought frequency and intensity during the 2030s.

Miscanthus yields will drop by 36% in the Southern Plains. In the wettest conditions of the country, the Northeast, *Miscanthus* yields will go down only by 0.5%. Yields in the two wetter regions, the Northeast and Southeast, are predicted to both be above 23.5 tons DM/ha. Yields in the driest region, the Southern Plains will decrease to 15.4 tons DM/ha (Figure 3).

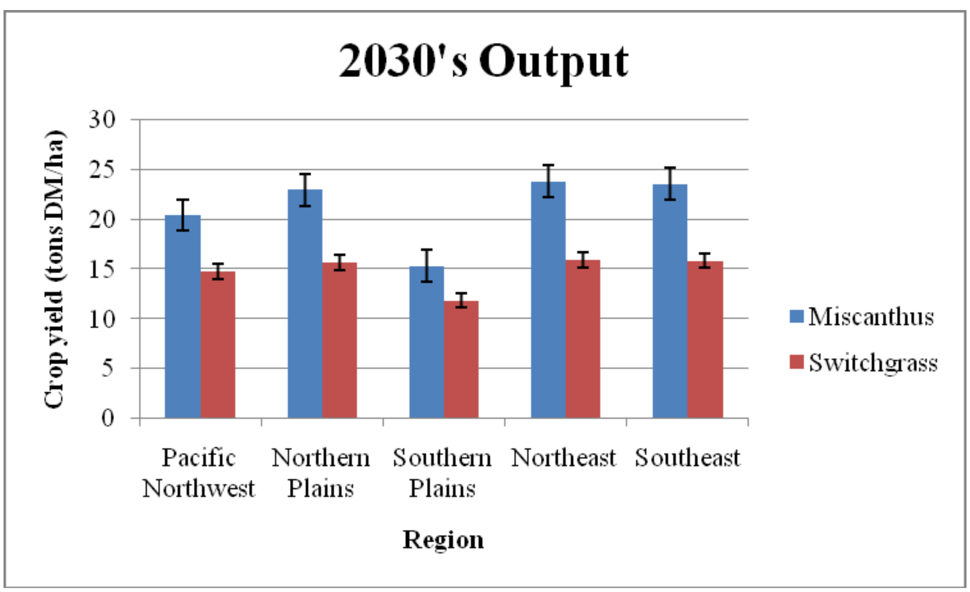


Figure 3: ***Miscanthus*** **and switchgrass crop yields averaged during the 2030s with drought affects. Measure of yield taken in tons of dry matter per hectare.**

Switchgrass yields will decrease by 26% in the Southern Plains and by .3% in the wettest Northeastern region. In the Northern Plains, Southeast and Northeast, yields of switchgrass crops will remain above 15.5 tons of dry matter per hectare, while in the Southern Plains, switchgrass yields will average 12 tons of dry matter per hectare (Figure 3).

Long-term (2070s): Drought patterns in the 2070s show trends towards massively increasing drought in the continental US. The Southern Plains will experience severe drought once every 10 years and the Pacific Northwest and Northern Plains will experience high drought once every 25-35 years. Moderate drought is predicted to occur at least once every 2 years in the Pacific Northwest, more commonly than the drier region of the Southern Plains, which is predicted to experience drought once every 2.5 years or so (Table 3).

2070s

	probability of medium droughts	probability of high droughts	probability of severe droughts
Pacific Northwest	0.48	0.029	0
Northern Plains	0.245	0.04	0
Southern Plains	0.393	0.293	0.118
Northeast	0.084	0.0023	0
South	0.114	0.0045	0

Table 3: Projected drought frequency and intensity during the 2070s.

Projected yields of *Miscanthus* crops will drop by 45% in the Southern Plains and by 4% in the Northeast. The Pacific Northwest will lose about 23% of its *Miscanthus* yields. The Northest will still retain the highest yields of *Miscanthus* with 23 tons DM per hectare and the lowest yields of *Miscanthus* will be in the Southern Plains, with 13 tons DM per hectare (Figure 4).

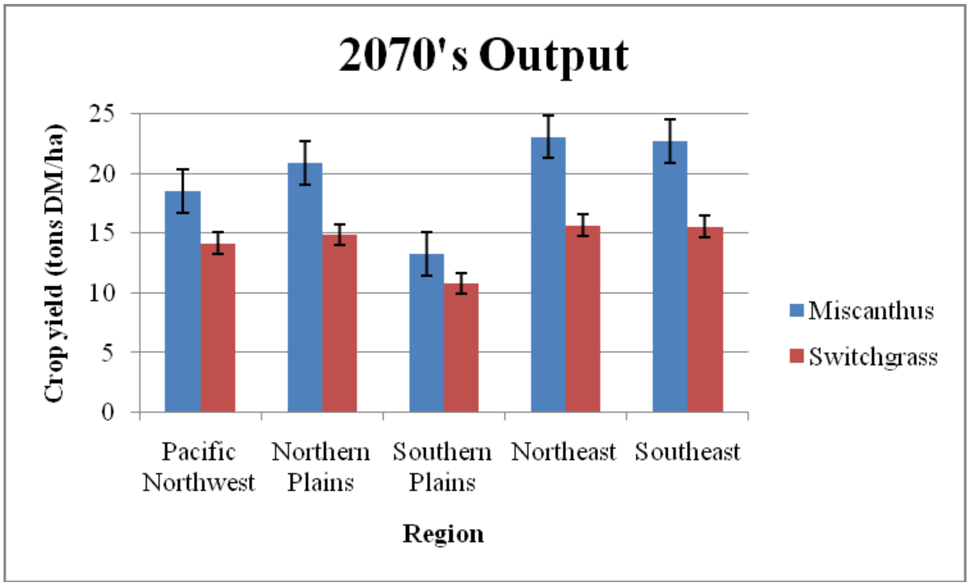
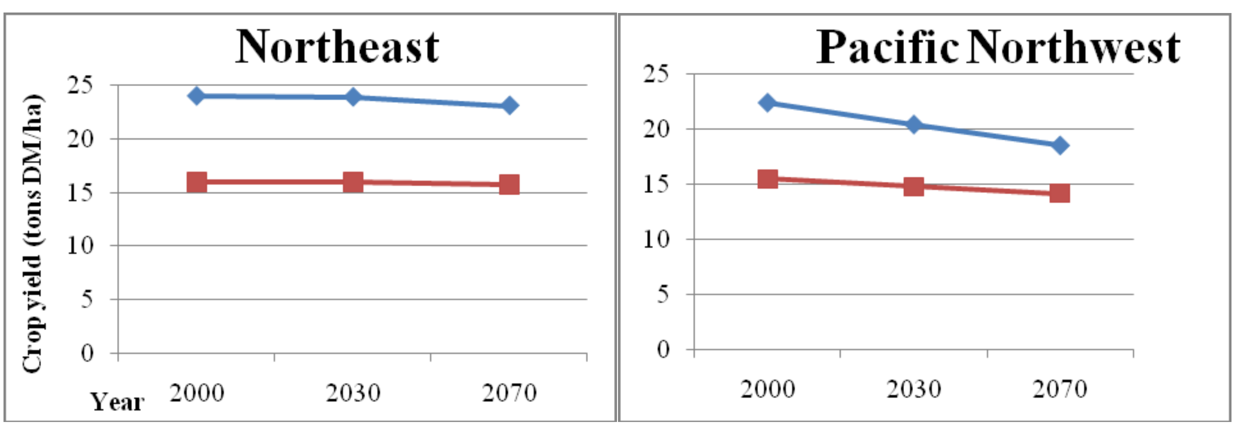


Figure 4: *Miscanthus* and switchgrass crop yields averaged from 2080-2090 with drought affects. Measure of yield taken in tons of dry matter per hectare.

Switchgrass yields will drop by 32% in the Southern Plains while in the Northeast yields will decrease by 2%. In the Southern Plains, switchgrass crops are projected to yield 10.8 tons DM per hectare, in the Northeast, switchgrass crops will still remain mostly unaffected, yielding 15.7 tons DM per hectare (Figure 4).

Comparison: Over the time period of the study, projected *Miscanthus* yields dropped to within 5 tons DM/ha of switchgrass yields in the Pacific Northwest. *Miscanthus* yields remained considerably higher than switchgrass in the Northeast, Northern Plains and Southeast, but in the most drought-prone region, the Southern Plains, *Miscanthus* yields averaged only 2 tons DM/ha above switchgrass yields (Figure 5).



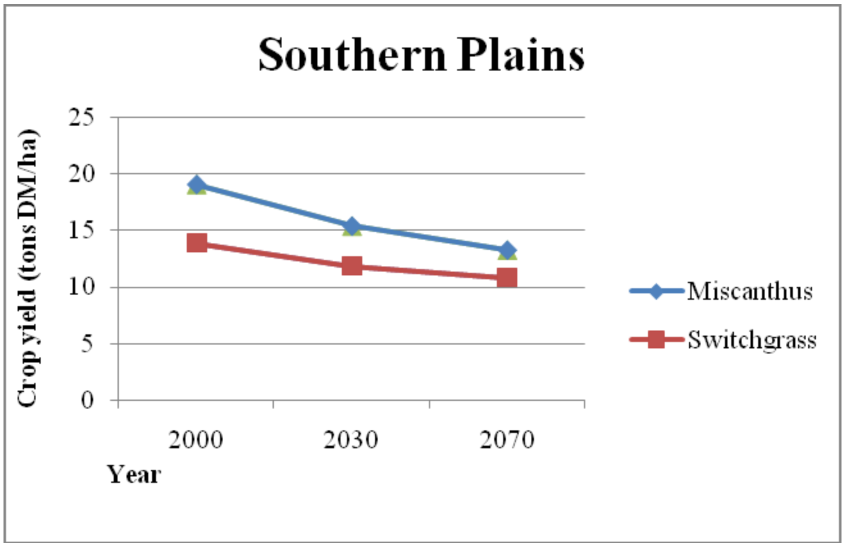


Figure 5: *Miscanthus* crop yields and switchgrass crop yield trends from 2000 to 2070s.

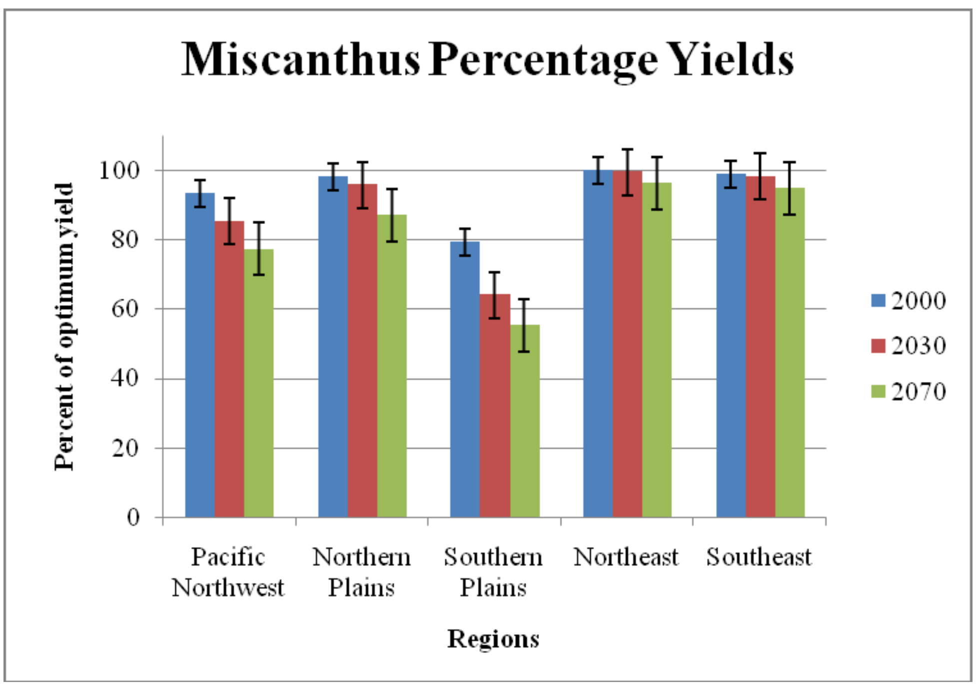


Figure 6: Predicted changes in *Miscanthus* outputs over the course of the 21st century in each region.

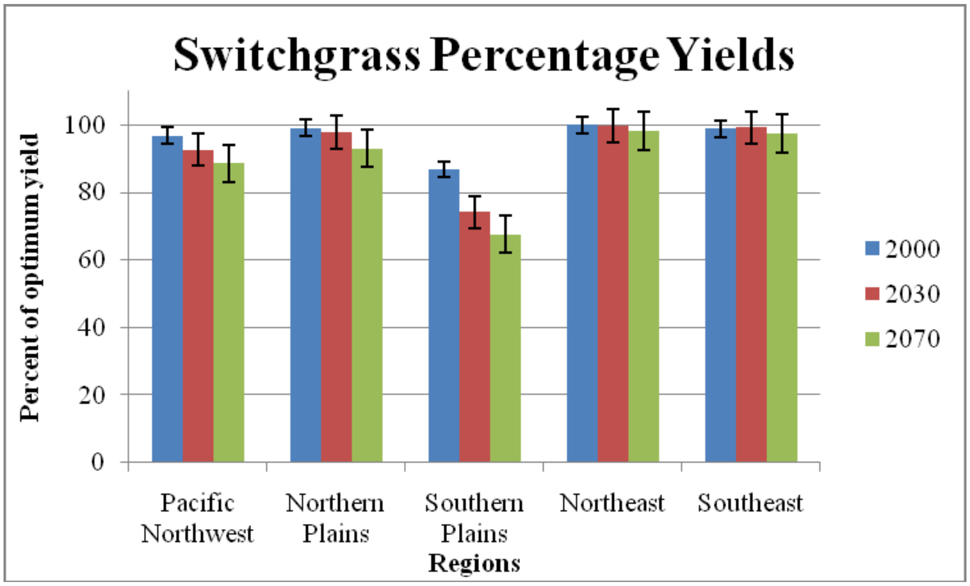


Figure 7: Predicted changes in switchgrass outputs over the course of the 21st century in each region.

Both *Miscanthus* and switchgrass outputs decreased over time. *Miscanthus* yields dropped most precipitously in the Southern plains from 80% of optimum yield to only 55% of optimum yield per year (Figure 6). Switchgrass experienced dramatic decline in the Pacific Northwest as well; yields decreased by 20% over the century (Figure 7). However, in the wettest regions on the Eastern seaboard, percentages barely decreased below optimum yield for both biofuel crops (Figure 6,7).

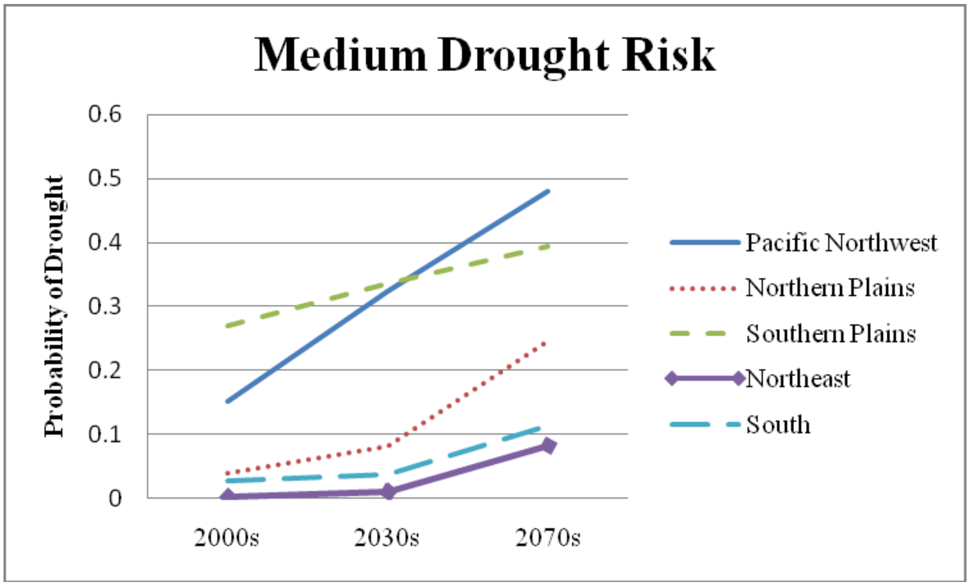


Figure 8: Probability of medium drought in the US over the course of the 21st century.

While drought affected crop yield the most in the Southern Plains, it should be noted that in the projections the Pacific Northwest actually overtook the Southern Plains in the probability of medium drought in the 2070's (Figure 8). Medium drought did not have as visible an effect on grass growth and the Pacific Northwest had far fewer high and severe drought events, so this was not reflected as much in the measures of *Miscanthus* and switchgrass growth.

Discussion

Drought in the US will become considerably more frequent and severe later in the century, particularly in the Southern Plains and Pacific Northwest. *Miscanthus* yields, which have an optimum yield of 24 tons DM per hectare, drop to 13 tons DM per hectare averaged over years of drought loss in the Southern Plains. This is still above switchgrass yields, which under present day conditions is 14 tons DM/ha, and will decrease to 10.8 tons DM/ha in the Southern Plains. In the Pacific Northwest, switchgrass yields and *Miscanthus* yields come within 5 tons DM/ha of each other. In the remaining three regions *Miscanthus* yields remain far above switchgrass yields, in the Northern Plains *Miscanthus* crops decrease by 13%, and switchgrass loses 7% of its optimum output, in the Southeast and Northeast, *Miscanthus* crops lose less than 5% of their yield to drought and switchgrass crops decrease by merely 3%.

Drought Presently, drought is only a minor threat to these two potential cellulosic biofuel crops. Drought occurs relatively infrequently in the modern day, only in the Southern Plains does it happen enough to obviously affect rain-fed crop yields (Table 1, Figure 2). In the middle of the 21^{st} century, drought will become more frequent in all locations, and by the end of the 21^{st} century, high drought is predicted to be extremely frequent in the Southern Plains, and medium drought is projected to occur once every 2 years in the Pacific Northwest and once every 4 years in the Northern Plains (Figure 8, Table 3). This will cause drought to become a much more serious threat to rain-fed agriculture.

Miscanthus Currently, *Miscanthus* yields are high and droughts are so infrequent that the yields far outstrip switchgrass (Figure 2). However, as droughts increase through the course of the century, *Miscanthus* yields will decline at a rapid rate, especially in water-poor regions (Figure 6). By the end of the century, *Miscanthus* crops in the Southern Plains will only be providing 55% of their optimal yield averaged out over years of sufficient rain and drought. It is unlikely that this is an economically sustainable farming practice; with such low average yields, the Southwest will probably not continue to produce *Miscanthus*. Additionally, crop yield will fall in the Pacific Northwest to merely 77% of optimum yield by the 2070's, likely making this region unsuitable for *Miscanthus* by the end of the century.

Switchgrass Switchgrass yields start out close to optimum growth in the present day and are projected to remain near optimum growth due to considerable drought-resistance (Stroup *et al.* 2003). As the century progresses and drought becomes more severe and frequent, switchgrass yields do decrease, most notably in the Southern Plains where they drop by 32% (Figure 7). However, across most of the United States, switchgrass yields will remain within 10 percent of optimum yield. Biofuel farmers would not need to worry about massive losses in crop yield in years of severe drought. However, overall yields would be lower than *Miscanthus* in the first part of the century, so farmers choosing switchgrass would initially accept lower yields so they could experience less profit variability in the long term.

Comparison Examining drought affects on *Miscanthus* and switchgrass crop yields over time in the continental US provided a number of telling trends. As global warming continues to rise, drought will increase across the United States, and *Miscanthus* yields will drop dramatically, while switchgrass yields will remain much more stable. Though *Miscanthus* starts out with a yield that surpasses switchgrass by 50%, by the end of the century, the two provide very similar amounts of dry matter. This refutes my hypothesis that switchgrass would become a more productive biofuel; even though *Miscanthus* would eventually drop near the output of switchgrass in the Southern Plains, *Miscanthus* still would produce greater amounts of biomass than switchgrass in the rest of the country. Trends suggest that this may not remain the case, but for the period that this study covers, switchgrass would not become a more reliable biofuel crop; it would only become an equivalent one in the drier regions of the US.

Previous studies have examined the viability of both of these crops, but have not looked at them in future scenarios, or have not taken drought into account in future scenarios. Lewandowski et al. (2003) identify switchgrass as the best biofuel producer for the US and *Miscanthus* as an ideal biofuel for the UK, but do not mix the two regions and plants. This project refutes Lewandowski et al.'s overall statement that switchgrass would currently be the most productive US biofuel. However as the century wears on, *Miscanthus* is projected to become less prolific in the US, thus Lewandowski's findings become more relevant for the drier regions of the country. Sanderson et al. found high production of switchgrass in the South and Southern Plains (Sanderson *et al.* 1996). The findings in this paper suggest that switchgrass has a greater range of productivity than those southernmost regions, especially in the Pacific Northwest where *Miscanthus* yields eventually come within 5 tons DM/ha of switchgrass yields. Karp and Shield's paper claims that *Miscanthus* can be strongly affected by water loss despite its high water use efficiency and that switchgrass has a potential to lose large amounts of above-ground biomass to drought (Karp and Shield 2008). This paper concurs with these *Miscanthus* findings, but refutes the findings about switchgrass biomass loss.

Limitations This study was limited by a number of factors. The drought data that is used as the basis for these findings is very coarse, due to the fact that more specific data is unavailable. Drought is difficult to calculate, since it is by nature unpredictable. However, more specific calculations of droughts, as well as alternative indices such as the Crop Moisture Index and the Palmer Drought Severity Index could be investigated. Additional research into the relative percentage of dry matter of each plant which would actually be usable for biofuel production would also be necessary, since this study assumes all dry matter is useable.

This analysis was limited by the scenarios and research that I drew upon for my calculations. The IPCC scenarios are imperfect and frequently change, yet they remain the most up to date predictions and are well recognized, which allows this project to fit into the literature by drawing on similar sources. The research that I used to make my yield calculations limited my analysis considerably, since I was restricted to their findings and how they chose to share them, especially in the limited information from the Stroup report on their research in water limitations of switchgrass. Additionally, this project does not account for crop yield decreases due to floods, nor does it allow for possible alternate positive effects of carbon fertilization besides providing additional carbon. Some studies suggest that carbon fertilization changes the size of the stomata openings on plants, which could differentially affect *Miscanthus* and switchgrass.

Finally, this research does not fully address the most economically serious aspect of drought for crop yields. The IPCC report (2007) states that drought will become wider in its range over the next century, so droughts in any region of the country would be likely to be simultaneous with droughts in other regions. Widespread crop loss in these extensive drought years is very likely given the seasonality of drought; the majority of droughts occur in the summer and *Miscanthus* is particularly sensitive to summer drought (Richter *et al.* 2008). Thus, many of the worst crop yields would be realized in the same year, vastly decreasing the fuel output for that year and leaving the entire country reliant on stockpiles and the meager amounts of biomass that can be extracted from the parched soil. It was impossible for this study to fully take this into account due to limited knowledge on future stockpiles and the exact scope and timing of future drought.

Conclusions Though both switchgrass and *Miscanthus* are high producing biofuel crops, in today's climate, *Miscanthus* currently has higher productivity. The findings in this paper show that over the long term, *Miscanthus* productivity will drop significantly across the United States, though it will retain high yields in the least drought prone parts of the country and will still outproduce switchgrass in the 2070's. Switchgrass yields will remain relatively stable and will eventually contribute a similar amount of biomass as the currently higher producing *Miscanthus* crops do in regions that experience more droughts. Drought will have an important effect on how crops will fare over the long term, since both crops lose huge percentages of their optimum output in areas prone to drought. Policy makers and planters alike will need to seriously consider these projected effects of drought when making decisions about biofuels and the future of America's transportation and fuel economy.

Acknowledgements I thank my mentor, John Harte, who was instrumental in the conception of this project and in assisting me in problem-solving throughout. I thank Dr. Eleanor Burke of the Met Office for sharing her data and expertise in IPCC drought predictions. The Geospatial Innovation Facility provided by CNR was a major resource for accomplishing my data collection and I thank the staff for their training and assistance in using GIS mapping. I also thank Inez Fung, Michael O'Hare, Michael Hanemann, the late Alex Farrell, and the ES 196 instructors for their guidance. My final thanks goes to my host of editors and my ES 196 classmates for feedback and encouragement.

References:

Biopact. 2008. U.S. EPA raises biofuel target for 2008 to 7.76 percent. http://news.mongabay.com/bioenergy/2008_02_10_archive.html (accessed February 1 2009)

Bollero G.A., S. P. Long, F. E. Miguez, and F. G. Fernandez. 2008. Model Development to predict feedstock production of *Miscanthus* and Switchgrass as affected by climate, soils and nitrogen management. Unpublished project by Energy Biosciences Institute. http://www.energybiosciencesinstitute.org/index.php?option=com_content&task=view&id=130&Itemid=1 (accessed October 24 2008)

Burke E., S.J. Brown and N. Christidis. 2006. Modeling the Recent Evolution of Global Drought and Projections for the Twenty-First Century with the Hadley Centre Climate Model. Journal of Hydrometerology 7:1113-1125.

Clifton-Brown J.C. and I. Lewandowski. 2000. Water Use Efficiency and Biomass Partitioning of three different *Miscanthus* genotypes with limited and unlimited water supply. Annals of Botany 86: 191-200.

Cline W. R. 2007. Global warming and agriculture: Impact estimates by country. Center for Global Development: Peterson Institute for International Economics, Washington D.C. 186 pp.

CNN. 2008. Transcript of second McCain, Obama debate. CNN Politics.com. Cable News Network. http://www.cnn.com/2008/POLITICS/10/07/presidential.debate.transcript/#cnnSTCText (accessed October 24 2008)

Dai A., K.K. Trenberth and T. Qian. 2004. A Global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming. American Meteorological Society 5: 1117-1130.

Energy Information Administration. 2008. Official Energy Statistics from the US Government- Petroleum Basic Statistics. http://www.eia.doe.gov/basics/quickoil.html (accessed February 1 2009)

Fischer G., K. Frohberg, M. L. Parry, and C. Rosenzweig. 1994. Climate-Change and World Food-Supply, Demand and Trade - Who Benefits, Who Loses. Global Environmental Change-Human and Policy Dimensions 4:7-23.

Gomez L. D., C. G. Steele-King and S.J. McQueen-Mason. 2008. Sustainable liquid biofuels from biomass: the writing's on the walls. New Phytologist 178:473–485.

Herrera S. 2006. Bonkers about biofuels. Nature Biotechnology 24:755-760.

Hill J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences of the United States of America 103:11206-11210.

Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: Synthesis Report. Cambridge University Press, Cambridge. 52 pp.

International Energy Agency. 2006. Energy technology perspectives: scenarios and strategies to 2050. OECD/IEA, Paris. 479 pp.

Karp A., I. Shield. 2008. Bioenergy from plants and the sustainable yield challenge. New Phytologist. 179:15-32.

Lewandowski I., J. M.O. Scurlock, E. Lindvall, and M Christou.2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass and Bioenergy. 25: 335 – 361.

Long S., E. Ainsworth, A. Leakey, J. Nosberger and D. Ort. 2006. Food for Thought: Lower-than-expected crop yield stimulation with rising CO2 concentrations. Science 312:1918-1921.

Moreira N. 2005. Growing Expectations. Science News 168:218-220.

Mullan B., A. Porteous, D. Wratt, M. Hollis. 2005. Changes in drought risk with climate change. National Institute of Water & Atmospheric Research Ltd, NIWA Client Report: WLG2005-23. Wellington.

Narasimhan B., R. Srinivasan. 2005. Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. Agricultural and Forest Meteorology 133:69–88.

Odling-Smee L. 2007. Biofuels bandwagon hits a rut. Nature 446:483-483.

Richter G. M., A. B. Riche, A. G. Dailey, S. A. Gezan and D. S. Powlson. 2008. Is UK biofuel supply from *Miscanthus* water-limited?. Soil Use and Management 24:235-245.

Rosenzweig C., M. L. Parry. 1994. Potential Impact of Climate-Change on World Food-Supply. Nature 367:133-138.

Sanderson M. A., R. L. Reed, S. B. McLaughlin, S. D. Wullschleger, B. V. Conger, D. J. Parrish, D. D. Wolf, C. Taliaferro, A. A. Hopkins, W. R. Ocumpaugh, M. A. Hussey, J. C. Read and C. R. Tischler. 1996. Switchgrass as a Sustainable Bioenergy Crop. Bioresource Technology. 56: 83-93.

Schill S. R. 2008. U.S. ethanol production to meet 2008 RFS targets. Ethanol Producer Magazine 14:30.

Searchinger T., R. Heimlich, R. A. Houghton, F. X. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. H. Yu. 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319:1238-1240.

Stroup J.A., M.A. Sanderson, J.P. Muir, M.J. McFarland and R.L. Reed. 2003. Comparison of growth and performance in upland and lowland switchgrass types to water and nitrogen stress. Bioresource Technology 86:65-72.