IOP Publishing Environmental Research Letters
Environ. Res. Lett. 3 (2008) 034003 (10pp) doi:10.1088/1748-9326/3/3/034003

Impacts of recent climate change on Wisconsin corn and soybean yield trends

Christopher J Kucharik[1,3] **and Shawn P Serbin**[2]

[1] Center for Sustainability and the Global Environment, The Nelson Institute, University of Wisconsin-Madison, 1710 University Avenue, Madison, WI 53726, USA
[2] Department of Forestry and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI 53726, USA

E-mail: kucharik@wisc.edu

Received 4 April 2008
Accepted for publication 21 July 2008
Published 31 July 2008
Online at stacks.iop.org/ERL/3/034003

Abstract
The US Corn Belt supports agroecosystems that flourish in a temperate climate regime that could see significant changes in the next few decades. Because Wisconsin is situated on the northern, cooler fringes of this region, it may be the beneficiary of a warmer climate that could help support higher corn and soybean yields. Here we show that trends in precipitation and temperature during the growing season from 1976–2006 explained 40% and 35% of county corn and soybean yield trends, respectively. Using county level yield information combined with climate data, we determined that both corn and soybean yield trends were enhanced in counties that experienced a trend towards cooler and wetter conditions during the summer. Our results suggest that for each additional degree (°C) of future warming during summer months, corn and soybean yields could potentially decrease by 13% and 16%, respectively, whereas if modest increases in total summer precipitation (i.e. 50 mm) were to occur, yields may be boosted by 5–10%, counteracting a portion of the negative effects associated with increased temperature. While northern US Corn Belt regions such as Wisconsin may benefit from a warmer climate regime and management changes that lengthen the crop-growing period in spring and autumn, mid- to high-latitude crop productivity may be challenged by additional summertime warming unless adaptive measures are taken.

Keywords: corn yield, soybean yield, climate change, Wisconsin

1. Introduction

Worldwide agricultural production is governed by the combination of climate, soil tilth, technology, genetic resources, and farm management decisions such as tillage, manure and fertilizer applications, and crop variety selection [1, 2]. In general, advances in technology and changing agronomic practices are responsible for significant increases in corn and soybean yields across the US Corn Belt [1, 3–7]. For example, Kucharik [8] suggested that trends toward earlier planting [9], helping to support the adoption of longer-season hybrids, contributed between 19 and 53% of state level increases in corn yield across the northern Corn Belt from 1979 through 2005. Additionally, recent climate change may be playing a significant role in observed yield trends. Lobell and Asner [10] suggested that trends toward cooler growing season temperatures from 1982 to 1998 were responsible for up to 20% of US corn and soybean yield increases, thereby decreasing the previous contribution of technology and improvements in agronomic management. On a global scale, warming temperatures have been shown to impact crop productivity and phenological development [11–13], potentially contributing to significant yield and economic losses [14].

An improved understanding of the contributions of various factors to yield trends, such as the introduction of new hybrids versus climate and management changes could help formulate adaptive strategies to take advantage of, or counteract, new

[3] Author to whom any correspondence should be addressed.

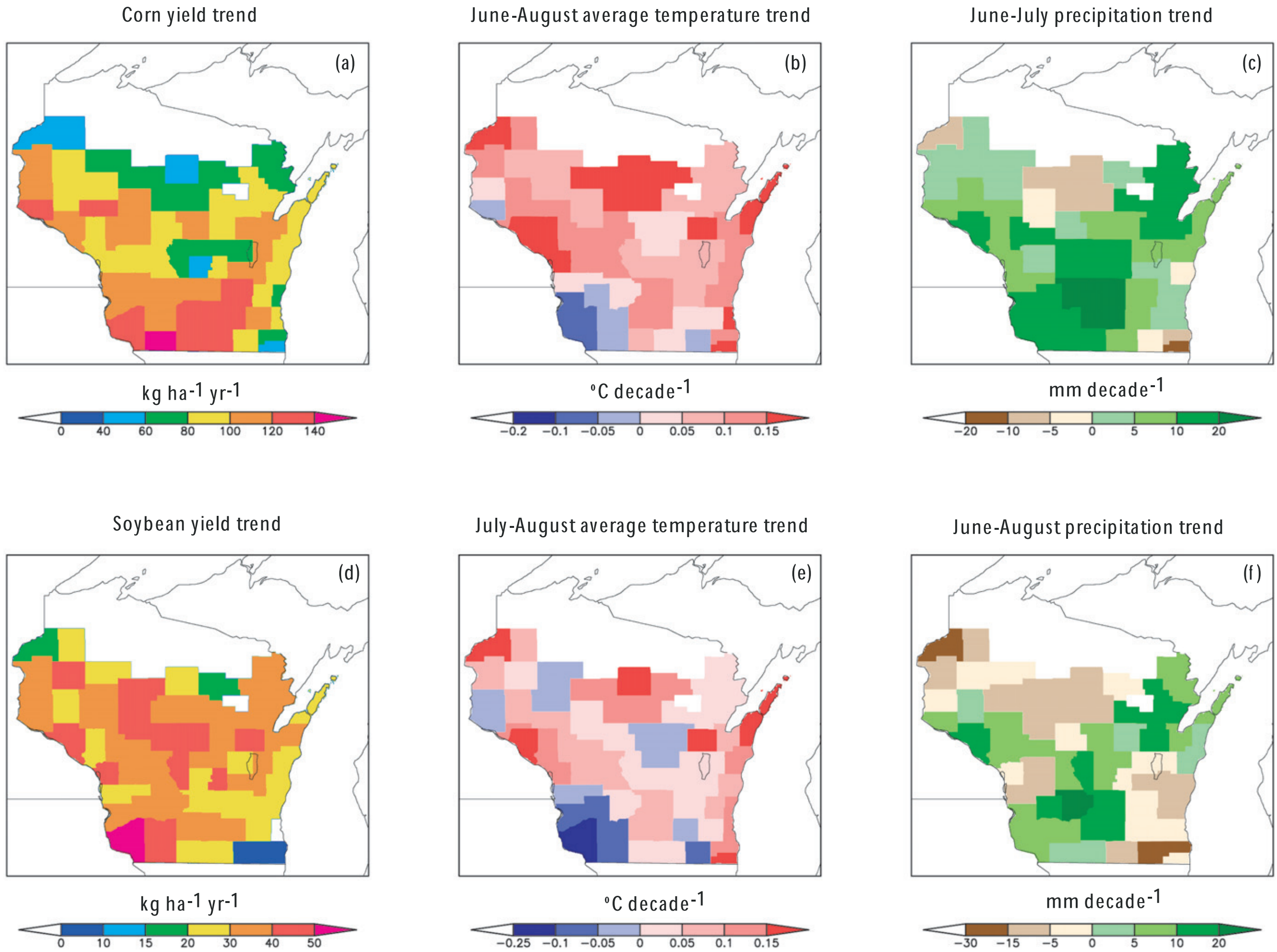

Figure 1. Wisconsin county level trends from 1976–2006 for (a) corn yields, (b) June–August average temperature, (c) June–July total precipitation, (d) soybean yields, (e) July–August average temperature, and (f) June–August total precipitation.

climate regimes in agricultural regions [15, 16]. Across the US Corn Belt, a significant gradient in growing period length (GPL), growing degree-days (GDD), rainfall, and crop varieties exists; therefore, recent climate change may have affected corn and soybean yield trends differently in a spatial context. Furthermore, monthly or seasonal meteorological quantities that are significant drivers to change in one locale may not have the same impact in another location. Consequently, future variability in climate change may dictate the need for one set of adaptive measures in one region, and a different strategy elsewhere. Therefore, it is necessary to continue to synthesize new climate and crop yield data for regions that share similar climate and management regimes, such as crop reporting districts or entire states [17–19].

Here, our investigation focuses on quantifying the previous impact of temperature and precipitation trends on corn and soybean yield trends across Wisconsin from 1976 through 2006 (figure 1). In this region, the latest IPCC [20] projections suggest mean summer (June–August) temperatures will increase 3–4 °C by the end of the current century (e.g., approximately 0.35–0.5 °C decade^{-1}), while the long-term projections for summertime precipitation are more uncertain. However, it appears this region is more likely to experience slightly drier conditions during the growing season based on the suite of IPCC models used in the 4th assessment.

2. Methods

We used an 8 km × 8 km gridded daily climate dataset for the state of Wisconsin [21]. Daily minimum and maximum temperature along with total daily precipitation data were obtained from the NOAA cooperative (COOP) observer network for the period 1950–2006. These observations were interpolated to a terrestrial 5 min × 5 min grid using an inverse distance-weighting algorithm within the ArcGIS software package to generate a continuous 57 yr time series of daily weather. Approximately 133 temperature and 176 precipitation stations were used in the development of the dataset, giving an average distance between observing stations of 25.0 km for temperature, and 21.2 km for precipitation. The 8 km daily and monthly gridded data were linearly interpolated to 1 km to improve edge matching within the boundaries of interest, and county level averages were calculated for all pixels within each county based on political boundaries that corresponded with latitude and longitude information available from the

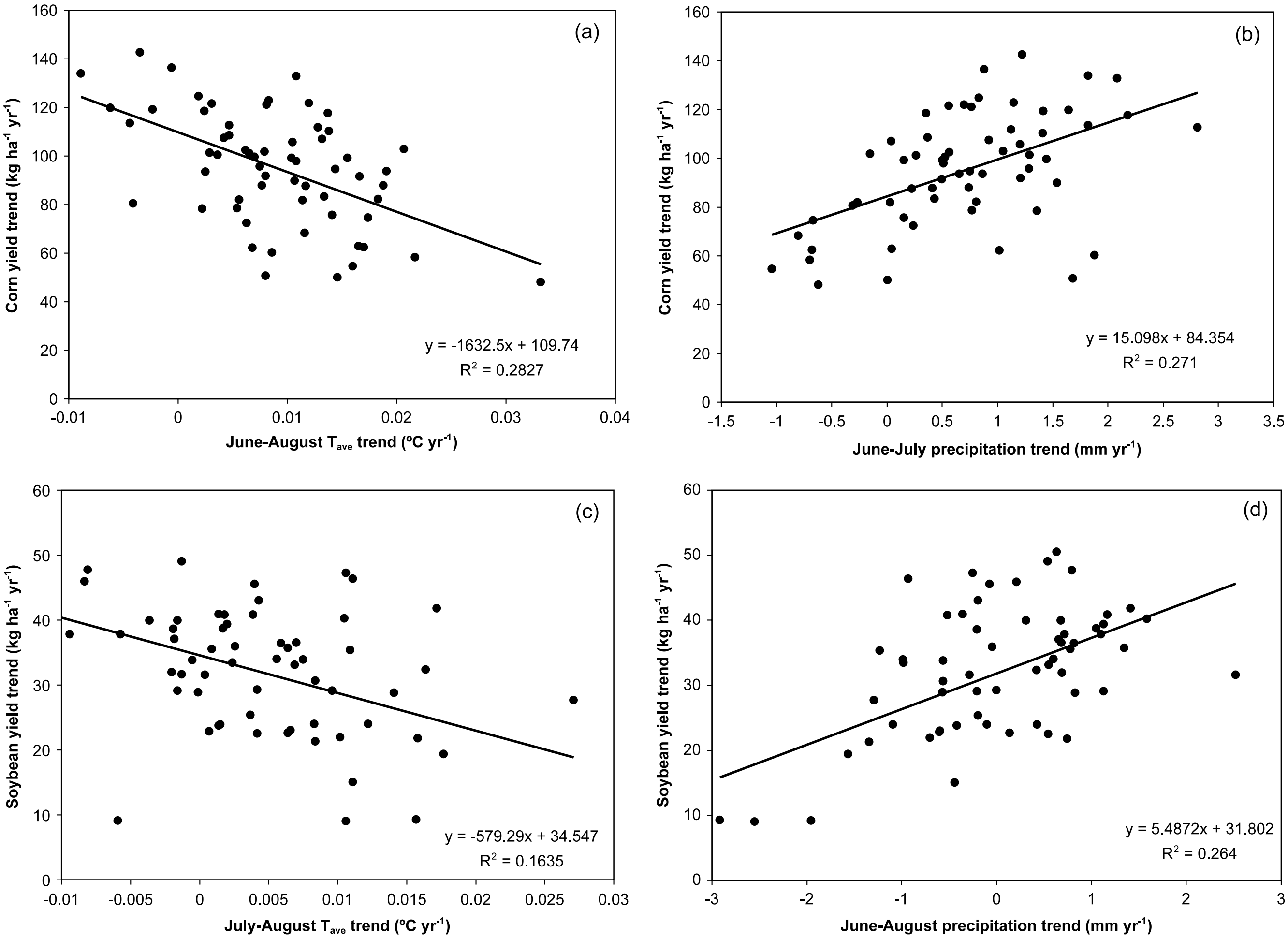

Figure 2. Scatter plots and regression statistics of county trends (61 counties analyzed from 1976–2006) in (a) corn yields and June–August average temperature, (b) corn yields and June–July total precipitation, (c) soybean yields and July–August average temperature, and (d) soybean yields and June–August total precipitation. A best-fit linear regression line is plotted in each graph.

US Census website (www.census.gov/geo/www/cob/co2000.html). Maximum (tmax), minimum (tmin), and average (tavg) temperature and total precipitation (prcp) were determined for each Wisconsin county ($n = 72$) at daily and monthly temporal scales for the entire period. For corn and soybean crop data, we utilized the US Department of Agriculture's (USDA) National Agricultural Statistic Service (NASS) data on Wisconsin county level yields (available at http://www.nass.usa.gov).

We focused on the last 31 yrs (1976–2006) of the data record and calculated monthly climate and corn and soybean yield trends for each county. The beginning year of 1976 was chosen to coincide with the initiation of the most recent period of sustained warming in the 20th century, whereby the rate of annual average temperature increase has been comparable to the rate of projected warming for the rest of the 21st century. We calculated trends for county corn and soybean yields (Mg ha^{-1} yr^{-1}) and the county average monthly tmax, tmin, and tavg temperatures (°C yr^{-1}) and prcp (mm yr^{-1}) for each month of the year using linear regression analysis and the JMP (v.5.01) statistical software package (SAS, Cary NC). The qualitative definition of 'trends' in yield and climate variables is the generalized direction of change in these values over the 31 yr period, while the quantitative measure of the change over time is the slope of the linear regression analyses performed. We determined that 61 counties in Wisconsin had continuous corn and soybean yield records for 1976–2006 (figure 1), and computed a total of 2928 climate variable regressions (12 months $\times$ 4 variables $\times$ 61 counties) and 128 total crop yield regressions as a first step. We also computed multiple month average climate values for *two* and *three* consecutive month periods (e.g., Mar–Apr, Jun–Aug, Aug–Sep, etc), allowing for additional predictor variables to be tested as part of the regression analysis.

In order to study the relationship between crop yield trends and climate trends across Wisconsin, we developed multiple regression models using the monthly, two-month, and seasonal (i.e. three-month) composite tmax, tmin, tavg, and prcp values as predictor variables and corn and soybean yield trends as the response variables [10]. To do so, we first studied the independent regression relationships between all possible climate variable trends and yield trends using all 61 counties as replicates (e.g., figure 2). We selected the most significant predictor variables based on their coefficient of determination (R^2) values. In general, all predictor variables that were ranked high (based on R^2 values) had a significant relationship with corn and soybean yield trends ($P < 0.001$). The analyses were performed separately for corn and soybean, so predictor variables could potentially be different for each crop type. We limited the final selection of variables to one unique temperature related quantity and one unique precipitation variable for each crop that was a key driver to crop phenology and growth. While many other predictor variables might have had a significant relationship with yield trends, we chose a limited set of variables to generalize how corn and soybean yield trends have been influenced by climate trends and explained the greatest amount of variability.

The common belief is that empirical regression models relating crop yields to climate capture the composite effect of all climate change impacts on yield trends, and cannot offer a true explanation of the underlying cause of the changes, whether it be phenological, biophysical, or management related [14]. However, by focusing on a small region of the Corn Belt, we are attempting to minimize the varied contribution of slowing changing factors such as crop management and assume that changes in management are consistent for each Wisconsin county through the period. Improvements in hybrids and technology that are used by farmers are assumed to be uniform across the entire region as we have no reason to believe that farmers in one portion of the state would have a decisive edge over others in obtaining new hybrids or equipment that might help support a trend towards higher productivity.

One of the largest documented management changes in the central US has been a trend towards earlier corn and soybean planting. Wisconsin corn planting dates have shifted to approximately 10 days earlier since the late 1970s [9], and Kucharik [8] suggested that earlier planting across Wisconsin during the 1979–2005 timeframe has contributed 22% to corn yield trends. That contribution is largely believed to be due to the ability to plant longer-season hybrids with higher yield potential via a prolonged growing period length. However, Kucharik [9] noted that the trend towards earlier planting was not strongly correlated with warmer springtime temperatures during this period, and was more likely due to improvements in technology and management that have been implemented statewide.

3. Results

3.1. Spatial patterns of county level crop yield and climate trends

Corn yield trends across Wisconsin varied between approximately 40 kg ha^{-1} yr^{-1} in far northwest, northcentral, and far southeast counties, to 140 kg ha^{-1} yr^{-1} in southwestern and some westcentral counties (figure 1(a)). Several counties in central Wisconsin also had lower yield increases ranging between 50 and 80 kg ha^{-1} yr^{-1}. We determined that the June–Aug tavg trend had the strongest correlation with corn yield trends ($R^2 = 0.28$) (figure 2(a)) compared to all other temperature predictor variables. While the June–Aug tmax ($R^2 = 0.26$) and tmin ($R^2 = 0.11$) variables also had a significant correlation with corn yield trends ($P < 0.01$), they did not explain as much variability at the county level as tavg for the same time period. We note, however, that tmax played a stronger role than tmin during the summer in creating variability in yield trends for Wisconsin corn. For precipitation, the two-month June through July composite prcp trend yielded the highest correlation ($R^2 = 0.27$) (figure 2(b)) with corn yield trends. We also found that trends in April ($R^2 = 0.08$), May ($R^2 = 0.09$), and June ($R^2 = 0.25$) prcp had a significant relationship with corn yield trends ($P < 0.05$); however, a trend towards more precipitation during the springtime planting season was correlated with higher county yield trends.

The majority of Wisconsin counties experienced warming trends in monthly tavg during meteorological summer (i.e. June–August) of between 0.05 and 0.2 °C decade^{-1} (figure 1(b)), with the largest increases in far northcentral, westcentral, and southeast. However, several counties in the southwest corner of the state have experienced a trend towards cooler June–August tavg, up to −0.1 °C decade^{-1}. The observed June–July total prcp trends suggested that the majority of locations have been receiving more precipitation, centered on an axis from the southwest through northeast portion of the state (figure 1(c)). For example, many areas saw increased prcp in June–July, ranging between 5–20 mm decade^{-1}. However, this pattern was not uniform and several northcentral and southeastern counties saw a decreasing trend in prcp during this period of −5 to −15 mm decade^{-1}.

Soybean yield trends have varied between 5 kg ha^{-1} yr^{-1} in the far southeast counties to as high as 50 kg ha^{-1} yr^{-1} in the southwest (figure 1(d)). The northern extent of the soybean growing region saw a yield trend around 15 kg ha^{-1} yr^{-1}, while the large majority of counties in the central portion of the state have seen increases of 30–40 kg ha^{-1} yr^{-1}. We found that the July–Aug tavg trend (figure 1(e)) had the strongest correlation with soybean yield trends ($R^2 = 0.16$) (figure 2(c)) compared to all other temperature predictor variables that were tested. While the July–Aug tmax ($R^2 = 0.11$) and tmin ($R^2 = 0.09$) variables also had a significant correlation with corn yield trends ($P < 0.05$), they did not explain as much variability at the county level as tavg. During springtime, only trends in March tmax and May tmin were correlated with soybean yield trends ($P < 0.05$), and linear regression suggested that warming during these months was correlated with a trend towards decreasing yields. For precipitation, we determined that the three-month composite total for the summer growing season (June–Aug) had the highest correlation with soybean yield trends ($R^2 = 0.26$) (figures 1(f) and 2(d)). For individual months, trends in March ($R^2 = 0.16$), April ($R^2 = 0.08$), and May ($R^2 = 0.09$) precipitation had significant, but weaker correlations with soybean yield trends than summer precipitation. A trend towards higher March and April precipitation was correlated with increased yields, whereas increases in May precipitation were correlated with decreasing yields.

A large number of Wisconsin counties experienced warming trends in monthly tavg during July–Aug of between

0.05 and 0.15 °C decade^{-1} (figure 1(e)), with the largest increases within lakeshore counties, the far northcentral, and westcentral. However, the southwest corner of the state experienced a trend towards cooler July–Aug tavg, up to −0.25 °C decade^{-1}, and several other counties across the state also experienced cooling trends. The June–Aug total prcp trends suggested that a trend towards more precipitation was centered on a small axis from the southwest through northeast portion of the state (figure 1(f)). In this region, and a small portion of the westcentral part of the state, total prcp in June–Aug increased by 5–20 mm decade^{-1}. However, many counties clustered in the northwest, northcentral, and southeastern counties saw a significant trend of decreasing prcp during this period of −5 to −30 mm decade^{-1} (figure 1(f)).

3.2. General relationships of crop yields and temperature and precipitation trends

Overall, the highest corn and soybean yield increases were supported by a trend towards cooler and wetter conditions during the summer (figures 2(a)–(d), figures 3(a)–(b)). We determined 'climate-adjusted' yield trends, or an estimate of what crop yield trends would have been with climate held constant, by choosing the intercept (i.e. the yield trend corresponding to climate trends of either 0.0 °C yr^{-1} or 0.0 mm yr^{-1}) that resulted from linear regression analyses [10]. The linear regression between county level trends in corn yield and trends in interpolated Jun–Aug tavg produced a climate-adjusted average yield trend of 109.7 kg ha^{-1} yr^{-1} (figure 2(a)), which was 15.5% greater than the observed trend of 95.0 kg ha^{-1} yr^{-1} (table 1). This suggests that the trends in corn yields were potentially suppressed by increasing summertime temperatures across the state, and yield trends would have been greater if climate had not changed simultaneously. For the linear regression between county level precipitation (Jun–Jul) and corn yield, the climate-adjusted average yield trend was 84.4 kg ha^{-1} yr^{-1} (figure 2(b)) suggesting that if trends in precipitation had not occurred, yield trends would have been 11.2% lower than observed. The linear regression between county level trends in soybean yield and trends in Jul–Aug tavg produced a climate-adjusted average yield trend was 34.5 kg ha^{-1} yr^{-1} (figure 2(c)) which was 11.3% higher than the observed soybean yield trend of 31.8 kg ha^{-1} yr^{-1}. For the linear regression between county level precipitation (Jun–Aug) and soybean yield, the climate-adjusted average yield trend was 31.8 kg ha^{-1} yr^{-1}, or very comparable to the observed trend (figure 2(d)).

For corn, each degree of warming during June–Aug (tavg) appears to be capable of suppressing yields by as much as −1633 kg ha^{-1} (figure 2(a)), which is equivalent to a 19% decrease compared to current (i.e. 2000–2007 average) state average yields. For Jun–Jul total prcp, every 50 mm of additional precipitation could potentially boost yields by 755 kg ha^{-1} higher (figure 2(b)), or 9% higher compared to the current average state yields of 8.5 t ha^{-1}. For soybeans, based on the independent linear regression models, for each degree of warming during July–Aug (tavg) a decrease in yields of −579 kg ha^{-1} (figure 2(c)) could occur, which is a 22% decrease compared to the current state average yield of 2.6 t ha^{-1}. For June–Aug total prcp, soybean yields were 274 kg ha^{-1} higher with each additional 50 mm of precipitation (figure 2(d)), an 11% increase compared to the current state average.

While the general effects of temperature and precipitation are apparent on corn and soybean yield trends, there appears to be a weak correlation between temperature and precipitation trends (figures 3(a)–(b)). It is not surprising that trends toward warmer conditions are correlated with trends toward less precipitation, which is an important discovery in helping to better understand how climate change is actually occurring. Figure 3 also illustrates that corn and soybean yield trends on a county-by-county basis have been impacted differently by climate trends. For example, figure 3(a) depicts a grouping of county corn yield trends based on a ranking of the top 25% (blue color), middle 50% (green), and bottom 25% (red) of county values. When those rankings are used and plotted in figure 3(b) for soybeans, it is clear that the ordering is no longer applicable. This suggests that climate changes have led to varied impacts on these two crops. In some counties, the climate changes have benefited corn more than soybeans, and vice versa in other locations. Potential reasons for this result will be discussed later.

In figure 4(a), the bottom-end county level corn yield trends in Wisconsin (i.e. ∼50 kg ha^{-1} yr^{-1}) were predominantly found when the Jun–Aug tavg temperature trends were highest (∼0.25–0.3 °C decade^{-1}), and Jun–Jul prcp trends were lowest (∼−5 to −10 mm decade^{-1}). The highest trends in recent corn yields (i.e. >115 kg ha^{-1} yr^{-1}) were mostly found where Jun–Aug tavg trends were negative, and Jun–Jul precipitation was increasing through the period. The same general response was observed for soybeans, although precipitation plays a slightly more dominant role given similar soybean yield trends were found across a larger continuum of Jul–Aug tavg trends (−0.1 to 0.15 °C decade^{-1}) (figure 4(b)). The highest soybean yield trends (>45 kg ha^{-1} yr^{-1}) occurred in counties that saw increases in Jun–Aug precipitation, and a cooling trend in Jul–Aug.

3.3. Contribution of climate trends to yield trends

We used multiple linear regression analysis, with temperature and precipitation trends at the county level as independent, predictor variables, and trends in corn and soybean yields as the dependent variables, to quantify the separate effects of those factors. Overall, approximately 40% of corn and 35% of soybean yield trends could be explained by a combination of the most important climate factors (table 1). The climate-adjusted average corn yield trend was 99.0 kg ha^{-1} yr^{-1}, or 5.3% higher than the observed value. For soybeans, the climate-adjusted average soybean yield trend was 33.5 kg ha^{-1} yr^{-1}, or 9.7% higher than the observed average trend (table 1). Therefore, it appears that climate changes have suppressed yield trends by 5–10% during the 1976–2006 period. However, trends toward warmer

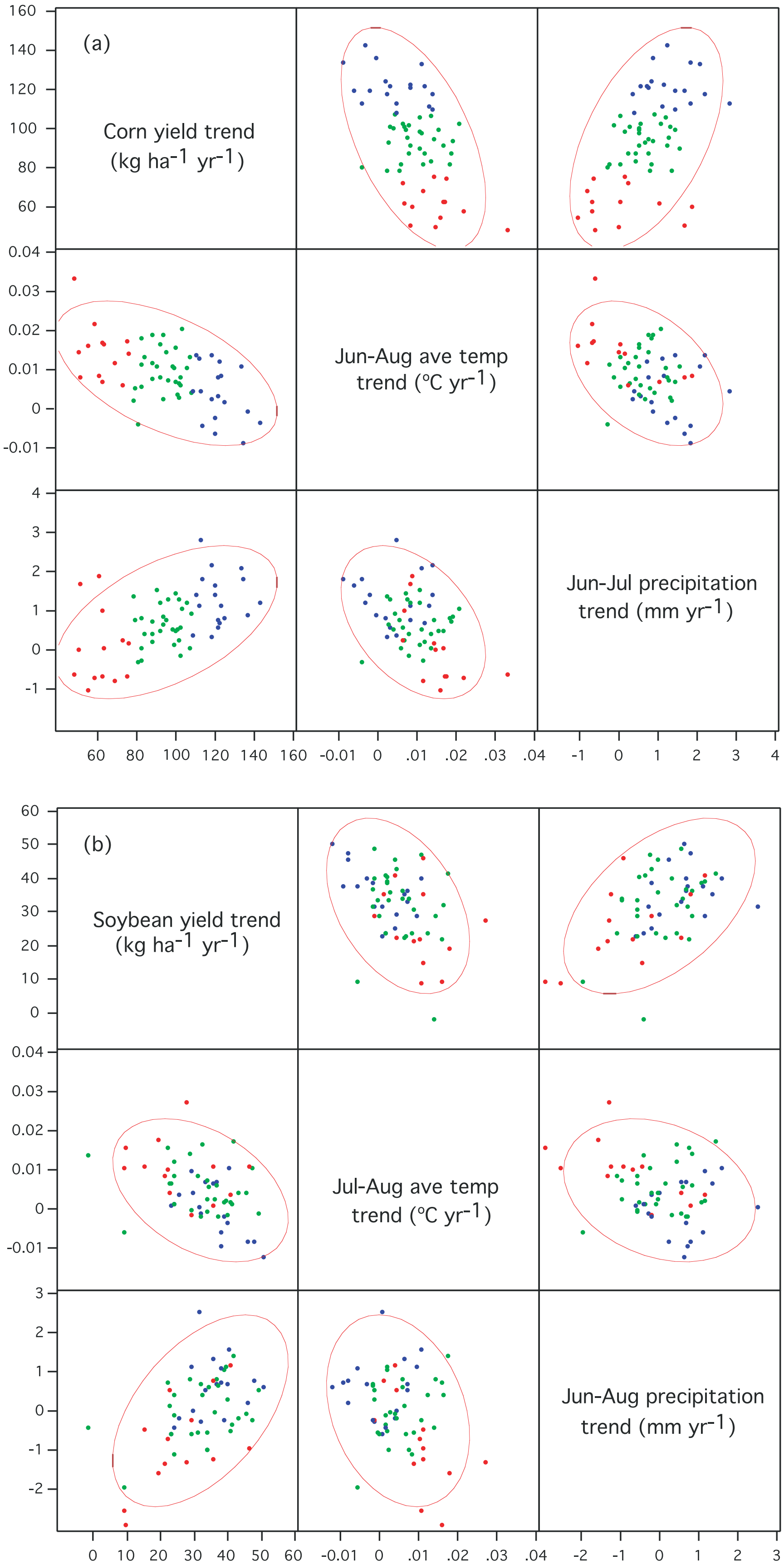

Figure 3. Scatterplot matrix depicting relationships between (a) corn yield trends, June–August average temperature trends, and June–July total precipitation trends; (b) soybean yield trends, July–August average temperature trends, and June–August total precipitation trends. A 95% bivariate normal density ellipse is plotted in each graph. The county data points have been categorized into three groups in (a) and (b) based on ranked corn yield trends; top 25% (blue dots), middle 50% (green dots), and bottom 25% (red dots).

Table 1. Summary of multiple regression statistics and models between trends in crop yields and climate at the county level for 1976–2006.

Crop	2000–07 yield average (t ha^{-1})	Average yield trend (kg ha^{-1} yr^{-1})	Predictor variables	Intercept (kg ha^{-1} yr^{-1})	R^2	P-value	tavg coefficient (kg ha^{-1} °C^{-1})	prcp coefficient (kg ha^{-1} mm^{-1})	Δ yield per tavg ±1 °C (%)	Δ yield per prcp ±50 mm (%)
Corn	8.5	95.0	June–Aug tavg June–Jul prcp	99.0	0.40	<0.0001	−1141	10.1	13.4	5.9
Soybean	2.6	31.8	July–Aug tavg June–Aug prcp	33.5	0.35	<0.0001	−419	5.0	16.1	9.6

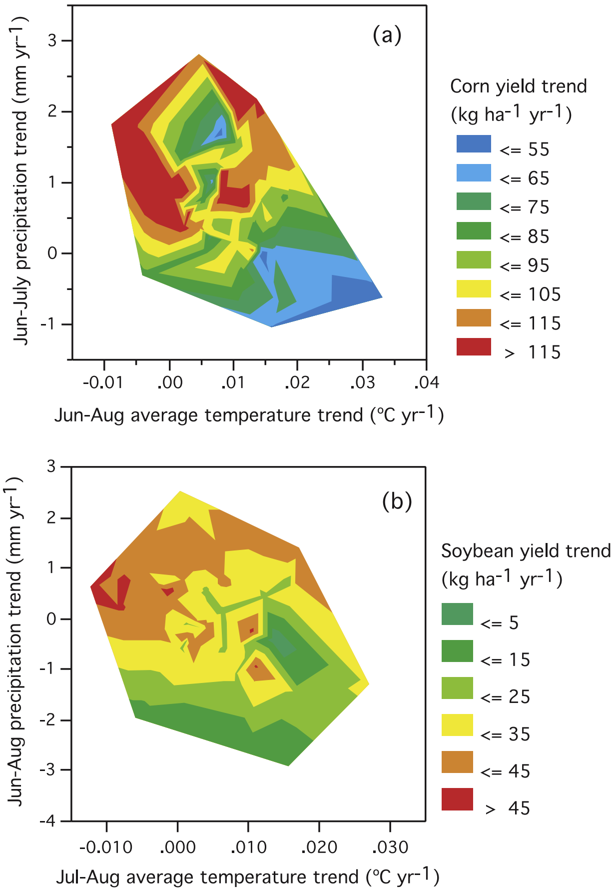

Figure 4. Distribution of trends in county (a) corn and (b) soybean yields when compared simultaneously to county level trends in temperature and precipitation.

conditions during the growing season, which clearly have a negative impact on yield trends for both crops, have been counterbalanced by increases in precipitation during these months in many areas, thereby helping to offset yield losses.

The partial correlations of corn yield trends with the tavg and prcp variables were −0.53 and 0.52, respectively, suggesting that the two contributed almost equally to the end result. Likewise, the partial correlations of soybean yield trends with predictor variables were −0.40 and 0.51 for tavg and prcp, respectively. In the case of soybeans, trends in precipitation had a slightly larger impact on the overall multiple regression results. Cross-correlations between temperature and precipitation were not significant predictors for either corn or soybeans ($P > 0.3$).

The resulting coefficients for tavg and prcp for corn (−1141 kg ha^{-1} °C^{-1}, 10.1 kg ha^{-1} mm^{-1}) from the multiple regression analysis suggest that for every 1 °C perturbation in temperature for Jun–Aug tavg, yields could be affected by 13.4% when compared with the current statewide corn yield average. For every 50 mm change in prcp during Jun–Jul, yields could either increase or decrease by 5.9% (table 1). In comparison, the multiple regression results for soybean suggest yield sensitivity of 16.1% for 1 °C changes in tavg in Jul–Aug, and 9.6% for 50 mm perturbations in Jun–Aug total prcp (table 1) when compared with the current state average soybean yield.

4. Discussion

4.1. Predictor variables

The most influential climate factors we selected were not identical for each crop type, but there are several potential explanations for this outcome. Corn development and growth is more tightly connected to temperature fluctuations for an extended period of time compared to soybeans (in our study June–Aug, compared to July–Aug) because corn is planted approximately two weeks earlier and therefore has a longer growing period length. In terms of precipitation, the June–July period might be a more significant determinant of corn yield variability because leaf area expansion occurs rapidly from mid-June though late-July, and end-of-season corn yield is particularly sensitive to soil moisture stress occurring near the silking stage in mid- to late-July when pollination occurs and the rate of crop growth is peaking [22]. For soybeans there are generally two time periods when soil moisture is critical for optimum growth; (1) during the very early vegetative stage when water stress can impact yield by reducing the number of seeds that develop, and (2) from flowering through the seed-filling period (approximately July through early- to mid-September in Wisconsin), when water stress can accelerate leaf senescence, and shorten the period of seed-filling [23]. Therefore, total precipitation over the June–August timeframe might be a more important determinant of soybean yield variability. Another potential reason for the discrepancy between the selected variables is that the geographic pattern and total amount of corn and soybean harvested areas in each county across the state are not identical; therefore, the apparent impact of climate trends on long-term yield increases at the county level likely varies between these two crops. Finally, the corn cultivars used across counties and changes in corn varieties over the 31 year period may have had a different response to climate changes compared to soybean cultivars.

While we selected very specific multiple month predictor variables as the single most influential determinants driving variability in county level yield trends, we reiterate that other climate variables—which explained a much smaller amount of yield trend variability—were also identified. For corn, these included June, July, August, and September tmax, May, June, Aug, and Sept tmin, and April, May, June, Sept, and October prcp. For soybean, significant relationships were detected between yield and monthly climate trends for March, August, Sept, and Oct tmax, May, Aug, and Oct tmin, and March, Apr, May, June, and Aug prcp. However, a much higher percentage of variability was typically explained (R^2) by meteorological indices that were aggregated over multiple months because single month indices are not likely to best represent the composite effect of weather events over an entire growing season on yield variability. While tmax and tmin variables undoubtedly correspond to specific biological processes such as the impact of heat stress on photosynthesis or cold tolerance, the tavg variables consistently explained a higher percentage of variability in yield trends for all composite indices we studied.

In cases where there was a significant relationship between springtime (March–May) climate and yield trends, a trend towards warmer temperatures was correlated with decreased yield trends, and increases in precipitation contributed to higher yield trends. This result is somewhat surprising given that cooler and wetter springtime conditions would likely delay planting of corn and soybeans and contribute to yield losses. Recent research has shown that for each day of delayed corn planting in Wisconsin, a yield decrease of 63 kg ha^{-1} typically occurs [8]. However, superimposed on our regression analysis is a long-term trend towards earlier planting that has been supported by advances in seed engineering and improved agronomic practices [9]. Therefore, this confounding factor may make it difficult to detect the true impact of trends in springtime temperature or precipitation on yield trends in the US Corn Belt.

4.2. Comparison with other studies of climate change impacts on crop productivity

The results presented here are in agreement with recent studies [10], but contradict other reports concerning the future impact of global climate change on agricultural productivity in the Corn Belt. Our overall corn yield response to warming (13% for 1 °C) in this mid-latitude region is much greater than discussed in the IPCC 4th assessment, where corn yields are projected to decrease by 5–20% with up to 3–4 °C of warming without adaptation. With adaptive measures, yields were projected to be able to remain at or slightly above current levels [20]. An increase in productivity related to global warming has been suggested by other comprehensive assessments, where corn yields were projected to increase 15% by the year 2030 with projected climate changes [24]. A study by Jones *et al* [25] that used the CROPGRO soybean model reported that a +2 °C change in temperature would contribute to only a −0.4% decline in soybean yields in the Madison, Wisconsin region, which is a more favorable outcome compared to our 16% decline in soybean yield trends associated with 1 °C of warming (table 1). The magnitude of the yield response in our study was also significantly greater per 1 °C of warming compared to the Lobell *et al* [14] global scale results that reported a −8.3% decrease (per 1 °C) for maize and −1.3% for soybean. Changnon and Hollinger [17] reported that a 10–25% increase in growing season precipitation may only help to boost corn yields by up to 3% based on field trials in Illinois. In support of that outcome, our analysis suggests that a 50 mm increase in June–Jul prcp, which is about a 25% increase, corresponded to a 5.9% increase in corn yields (table 1).

4.3. Potential confounding effects of increasing atmospheric CO_2

While we did not account for other management changes or trends in atmospheric CO_2 [26], ozone, or pests and disease in this study [27], we presume that these had minimal impact on our overall results given their contributions would have likely been uniform across a small region. Furthermore, new experimental data from carbon dioxide enrichment (FACE) experiments suggest that C_4 photosynthesis (corn) is already saturated at the current levels of atmospheric CO_2, and future increases in CO_2 (550 ppm) will not be effective at boosting productivity [26, 28]. For soybeans, it appears that yields may be increased by 13–17% as CO_2 approaches 550 ppm [26, 28, 29]. Therefore, the impacts of increasing CO_2 on corn yield trends over the past 31 years in Wisconsin appear to be negligible, while a ∼4% contribution to the soybean yield trend has potentially occurred. This potential gain has been roughly offset by the impacts of recent climate change, and as Lobell *et al* [14] discuss, contradicts what previous assessments have stated about the benefits of increased CO_2 on crop productivity compared to the effects of global warming. In addition, research performed by Amthor [30] documented wheat yield response to increased CO_2 and temperature and suggested that warming of only a few degrees may offset the positive impact of higher CO_2 on productivity. This is largely believed to occur due to an acceleration of plant development associated with warmer temperatures, and the sensitivity of grain crops to daily temperature during the grain fill period [31].

5. Conclusions

Our study suggests that crop productivity along the northern perimeter of the Corn Belt could be adversely affected by continued temperature rises during the summer growing season, and the response could be even greater than anticipated if heat and drought combine together. One hypothesis presented here is that farmers may not be switching cultivars as quickly as needed to adapt to recent regional climate change. It appears that a significant amount of spatial variability in climate trends at the county level across Wisconsin has contributed to variable trends of soybean and corn yields. Some regions with the highest yield gains over the past 30 yrs have experienced a trend towards cooler and wetter conditions during the summer, while other areas that have experienced a trend towards drier and warmer conditions have experienced suppressed yield gains. These widely varying climate trends could make it more difficult for farmers to adapt to long-term local climate change. Future studies of regional hybrid performance under varied climate change scenarios are needed so that more precise county or crop district level recommendations for adaptation could be made.

If a trend towards warmer and drier conditions during the spring planting time and fall harvest occurred in the future, this could help boost yields in northern Corn Belt locations like Wisconsin that have a shorter growing season. Farmers in the northern US Corn Belt often plant crop hybrids with lower yield potential that are more suited for a shorter growing season, and farmers may benefit from warmer and drier springtime weather conditions that support earlier planting and the use of higher yield potential cultivars. However, if warming trends continued during summer as documented in this study, it could impede crop productivity gains by accelerating phenological development, causing the plant to mature more rapidly, thereby losing valuable calendar days in the field to accumulate biomass during grain fill. Furthermore, additional heat and soil moisture stress during pollination and an increased frequency of very warm days (e.g., tmax $> 35\,^{\circ}\mathrm{C}$) could counteract the potential benefits of an extension of the growing season via decreased carbon assimilation during the day and increased nighttime respiration. The take home message is that recent warming during the summer in Wisconsin has not been entirely beneficial to supporting increased crop productivity.

As future forecasts are made about the impacts of global climate change on agriculture, we stress the importance of identifying the biological processes or management options that are most likely to be impacted. Previous assessments have stated that mid- and high-latitude corn and soybean growers may ultimately benefit from warming temperatures, but we argue that warming outside of the core of the growing season will be most beneficial to supporting higher yields. We stress that future modeling studies should analyze the potentially competing effects of warming in spring and fall versus summer by simulating the effectiveness of adaptive measures. This will help to improve projections of agricultural productivity by considering specific changes in land management such as planting date, or the effect of switching to different cultivars. There is need for continued regional-scale research in this field because of the large uncertainty in crop productivity responses to climate change and increasing atmospheric CO_2 and O_3. On the path towards continuing long-term yield increases are potential climate roadblocks that pose threats to the expanding biofuels market and global food security.

Acknowledgments

This research was supported by the Wisconsin Focus on Energy Environmental Research Program and a NASA Interdisciplinary Science grant. We extend gratitude to two anonymous reviewers who provided many constructive comments on improving the manuscript.

References

[1] Duvick D N and Cassman K G 1999 Post-green revolution trends in yield potential of temperate maize in the North-Central United States *Crop Sci.* **39** 1622–30
[2] Ramankutty N, Foley J A, Norman J and McSweeney K 2002 The global distribution of cultivable lands: current patterns and sensitivity to possible climate change *Global Ecol. Biogeogr.* **11** 377–92
[3] Naylor R, Falcon W and Zavaleta E 1997 Variability and growth in grain yields, 1950–94: does the record point to greater instability? *Popul. Dev. Rev.* **23** 41–58
[4] Kucharik C J and Ramankutty N 2005 Trends and variability in US corn yields over the 20th century *Earth Interact.* **9** 1–29
[5] Duvick D N 1977 Genetic rates of gain in hybrid maize yields during the past 40 years *Maydica* **22** 187–96
[6] Duvick D N 1992 Genetic contributions to advances in yield of US maize *Maydica* **37** 69–79
[7] Andresen J A, Alagarswamy G, Rotz C A, Ritchie J T and LeBaron A W 2001 Weather impacts on maize soybean alfalfa production in the Great Lakes region 1895–996 *Agron. J.* **93** 1059–70
[8] Kucharik C J 2008 Contribution of planting date trends to increased maize yields in the central United States *Agron. J.* **100** 328–36
[9] Kucharik C J 2006 A multidecadal trend of earlier corn planting in the central USA *Agron. J.* **98** 1544–50
[10] Lobell D B and Asner G P 2003 Climate and management contributions to recent trends in US agricultural yields *Science* **299** 1032
[11] Peng S, Huang J, Sheehy J E, Laza R C, Visperas R M, Zhong X, Centeno G S, Khush G S and Cassman K G 2004 Rice yields decline with higher night temperature from global warming *Proc. Natl Acad. Sci* **101** 9971–5
[12] Nicholls N 1997 Increased Australian wheat yield due to recent climate trends *Nature* **387** 484–5
[13] Tao F, Yokozawa M, Xu Y, Hayashi Y and Zhang Z 2006 Climate changes trends in phenology yields of field crops in China 1981–2000 *Agric. For. Meteorol.* **138** 82–92
[14] Lobell D B and Field C B 2007 Global scale climate-crop yield relationships and the impacts of recent warming *Environ. Res. Lett.* **2** 014002
[15] Howden S M, Soussana J F, Tubiello F N, Chhetri N, Dunlop M and Meinke H 2007 Adapting agriculture to climate change *Proc. Natl Acad. Sci* **104** 19691–6
[16] Lobell D B, Burke M B, Tebaldi C, Mastrandrea M D, Falcon W P and Naylor R L 2008 Prioritizing climate change adaptation needs for food security in 2030 *Science* **319** 607–10
[17] Changnon S A and Hollinger S E 2003 Problems in estimating impacts of future climate change on Midwestern corn yields *Clim. Change* **58** 109–18
[18] Hu Q and Buyanovsky G 2003 Climate effects on corn yield in Missouri *J. Appl. Meteorol.* **42** 1626–35
[19] Lobell D B, Cahill K N and Field C B 2007 Historical effects of temperature and precipitation on California crop yields *Clim. Change* **81** 187–203
[20] IPCC 2007 *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) p 976
[21] Serbin S P and Kucharik C J 2008 Spatio-temporal mapping of temperature and precipitation for the development of a multi-decadal climate dataset for Wisconsin *Agric. Forest Meteorol.* submitted
[22] Tollenaar M and Dwyer L M 1999 Physiology of maize *Crop Yield Physiology and Processes* ed D L Smith and C Hamel (Berlin: Springer) pp 169–204

[23] Brevedan R E and Egli D B 2003 Short periods of water stress during seed filling, leaf senescence, and yield of soybean *Crop Sci.* **43** 2083–8

[24] National Assessment Synthesis Team 2000 *Climate Change Impacts in the US: Overview* (Cambridge: Cambridge University Press) p 154

[25] Jones J W, Jagtap S S and Boote K J 1999 Climate change: implications for soybean yield and management in the USA *Proc. World Soybean Research Conf. VI (Urbana-Champaign)* (Chicago, IL: University of Illinois)

[26] Long S P, Ainsworth E A, Leakey A D B, Nosberger J and Ort D R 2006 Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations *Science* **312** 1918–21

[27] Tubiello F N, Soussana J F and Howden S M 2007 Crop and pasture response to climate change *Proc. Natl Acad. Sci* **104** 19686–90

[28] Leakey A D B, Uribelarrea M, Ainsworth E A, Naidu S L, Rogers A, Ort D R and Long S P 2006 Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought *Plant Physiol.* **140** 779–90

[29] Morgan P B, Bollero G A, Nelson R L, Dohleman F G and Long S P 2005 Smaller than predicted increase in aboveground net primary production and yield of field-grown soybean under fully open air [CO_2] elevation *Global Change Biol.* **11** 1856–65

[30] Amthor J S 2001 Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration *Field Crops Res.* **73** 1–34

[31] Fuhrer J 2003 Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change *Agric. Ecosyst. Environ.* **97** 1–20