Climate Variability and the Productivity of Barley and Oats in Minnesota

by Katherine Klink, Christopher J. Crawford, Jochum J. Wiersma, and Deon D. Stuthman

Minnesota’s crop economy, which totaled more than $12.7 billion in 2009, depends largely on corn and soybeans. However, a variety of other crops, including wheat, sugar beets, dry beans, alfalfa, sunflower, potatoes, oats, and barley, are also frequently grown in Minnesota. All of these crops are important in Minnesota in large part because its climate is conducive to their growth. The term climate in this context refers to long-term conditions, such as the expected date of the last spring freeze or the expected number of days with temperatures above 90°F; weather, on the other hand, refers to short-term conditions, such as the occurrence of a hail storm, heat wave, or cold snap. One convenient way to think of the distinction is via the adage “Climate is what you expect, and weather is what you get.” Cropping systems in Minnesota have been developed based on “what we expect”—the climate—whereas farmers are well aware that crop yields will depend on “what we get”—the weather. Year-to-year variability in weather conditions is a given in Minnesota. The Minnesota climate, however, also may be changing. For example, long-term observations across Minnesota have provided evidence for higher mean temperatures (particularly at night), higher summer dew points, and higher total precipitation. If Minnesota is experiencing a change in “what we expect,” how might that affect the productivity of individual crops and, consequently, the cropping systems now commonplace in Minnesota?

In this work, we investigated how variations in climate—both temperature and precipitation—may affect crop productivity by analyzing long-term records of barley and oat yields in Minnesota. According to the United States Department of Agriculture’s National Agricultural Statistics Service, Minnesota was the nation’s top producer of oats in 2008 and ranked sixth in the nation in that same year in the production of barley, which is a particularly important crop in the...
northwestern part of the state. Minnesota farmers routinely rotate cereals like oats and barley with other crops, such as sugar beets, soybeans, and dry beans, to reduce disease and insect and weed pressure. Both barley and oats are cool-season annual grasses: their optimum growth temperature is between 68 and 70°F, and their growth and development are substantially reduced at temperatures above 82 to 86°F (see sidebar, p. 14). As a result, we expect that both crops will be particularly sensitive to an increase in temperature. Although we studied the effects of both temperature and precipitation on Minnesota barley and oats, temperature effects were of particular importance, as temperature increases in Minnesota have already been observed during the past few decades1 and are projected to continue into the next several decades.2 The research on which this article is based was supported in part by a grant from CURA’s Faculty Interactive Research Program. Additional funding was provided by the College of Liberal Arts at the University of Minnesota.

Methodology

Barley Production in Western and Northwestern Minnesota. The University of Minnesota’s Northwest Research and Outreach Center in Crookston and West Central Research and Outreach Center in Morris (Figure 1) have been the sites of barley field trials for many years. We analyzed 26 years (1980–2005) of temperature and precipitation data for Crookston and Morris, available from the Minnesota State Climatology Office, and compared them with the corresponding yield-trial data recorded by the University of Minnesota’s spring-barley breeding project. We computed mean monthly values of maximum and minimum daily temperatures as well as total monthly precipitation for all months in the dataset. The yield-trial data included in this analysis were for a single variety, Robust (a six-row barley), one of the most widespread malting barleys planted in Minnesota and the surrounding states since its release more than 25 years ago. Robust, like all barley varieties, is a true breeding line, meaning that the genetic makeup of the variety has been the same since its release. Similarly, the agronomic practices and methodologies used in these variety trials have not changed substantially over the past three decades. Consequently, we hypothesize that the changes in productivity of Robust observed in the annual yield trials result from climate variation, rather than variation in crop type or agricultural practices.

Oat Production in and near Minnesota. Our data for oat yields came from a network of oat nurseries in and near Minnesota. Our early-season oat data were from the nurseries at Rosemount and Waseca, Minnesota, and at Beresford and Brookings, South Dakota, and our mid-season oat data were from the nurseries at Rosemount and Morris, Minnesota; Fargo, North Dakota; and Brookings and Watertown, South Dakota (Figure 1). We analyzed 14 years (1996–2009) of temperature and precipitation data at the nursery sites, available from the Minnesota State Climatology Office, and compared them with the corresponding yield-trial data recorded by the oat nurseries. We computed mean monthly values of maximum and minimum daily temperatures as well as total monthly precipitation for all months in the dataset. As with the barley-variety trials, the agronomic practices and methodologies used in the oat-variety yield trials have not changed substantially over the years in our dataset, and we have assumed that changes in yield were not confounded by changes in agricultural practices.

Figure 1. Location of Crop Yield-Trial Sites Used in this Study

Glossary of Terms

Floret: An individual flower within the head.

Glumes: The pair of leaf-like bracts located at the base of a spikelet in the head.

Grain fill: The plant development phase during which seeds are formed.

Kernel: Seed

Panicle: A branched cluster of flowers in which the branches carry single flowers.

Spikelet: A flower of a grass consisting of a pair of glumes and one or more enclosed florets; a subdivision of the head.

Tiller: A shoot originating from the base of the plant.

Tillering: The development phase during which tillers are formed


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Each year, a range of oat varieties are field-tested at the nurseries, and the trials include checks (genetically stable varieties) that represent a baseline against which to compare the performance over time of newer oat varieties. Within the oat-variety trials, entries are grouped by relative maturity into early- and mid-season groups. Early-season oats mature more quickly than the mid-season varieties, and often they are planted at climatically warmer locations where they can mature before temperature (and thus heat stress) reaches its peak in July and August. Mid-season varieties take longer to mature and typically are planted at cooler locations, where the plants can take advantage of a longer growing season without the risk of heat stress during plant development. Early- and mid-season oats are harvested 90–120 days after planting, depending on the variety, the planting date, and the weather during the growing season. For early-season oats, we examined the yield data for four check varieties (Andrew, Clintford, Don, and Otee) at all sites; for mid-season oats, we examined three check varieties (Clintland 64, Gopher, and Ogle) at all sites. For consistency, we used only check varieties in our analysis because the data for these checks were available for each year of our dataset.

Statistical Analyses. We used a stepwise multiple regression procedure to estimate how climate affects barley and oat yields. Multiple regression is a statistical technique that allows us to examine the extent to which a particular outcome (in this case, crop yield) can be predicted based on information about a set of “predictors” (here, temperature and precipitation). Multiple regression helps us to identify the particular aspects of the climate (too-warm maximum temperatures or too little precipitation in a given month, for example) that have the most influence on crop yield at our sites. Stepwise regression is a useful technique when there are many possible predictors (in this case, climate variables), because it allows us to test how different predictors—alone or in combination—are related to crop yield. Because our “predictors” are, to some degree, related to each other (for example, a month with warm maximum temperatures typically also has warm minimum temperatures)—a condition known as multicollinearity—the stepwise regression procedure also allows us to minimize multicollinearity and thereby produce more statistically robust results. The “predictor” variables we use in the stepwise procedure include monthly maximum and minimum temperatures and precipitation during the April–August growing season, as well as precipitation during the prior winter (November–March) because spring snowmelt provides additional soil moisture that may be beneficial for yield.

Research Findings: Analysis of Climate-Crop Yield Relationships

Barley. For the Crookston and Morris yield-trial sites, the stepwise multiple regression results showed, as hypothesized, that climate does have a statistically significant impact on barley yield, with the relationship at Morris being stronger than the relationship we found for Crookston.

At Crookston, our statistical model showed that the mean maximum temperature in May is negatively associated with barley yield and accounted for approximately 12% of the variance in barley yield (Table 1). Early warmth promotes plant growth, but unusually high temperatures also can stress the plant. Therefore, too-warm temperatures at the early stages of barley development can lead to reduced numbers of tillers and fewer spikelets, negatively affecting yield (see sidebar below).

Our results for Morris showed a much stronger climate effect, with the

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Barley and Oat Planting and Growth

Barley is a cool-season annual grass. It is typically planted by mid-April in Morris and by late April in Crookston, and reaches maturity approximately 90–110 days later. The rate of development is primarily driven by temperature, but is also influenced by day length. Barley is a so-called facultative long-day species, meaning that barley requires less than a certain number of hours of darkness in each 24-hour period to trigger a switch from vegetative growth to reproductive growth. Under the climatic conditions encountered in Minnesota and its production practices (such as the recommended window for planting date and recommended seeding rate), the development of six-row barley cultivars can be well predicted by temperature only. It is only in the case of extreme late planting that the growth and development of barley would be negatively affected by having short nights trigger reproductive growth too soon after the seedling emerges. In such an instance, very short plants with fewer leaves would be produced, ultimately resulting in lower grain yields.

The growth and development of barley can be subdivided into a series of sequential phases starting with germination and emergence, followed by the vegetative growth, reproductive growth, and grain-fill phases, and ending with ripening. The minimum temperature for germination is 34–36°F and emergence occurs approximately 3–7 days after planting. Leaves and tillers appear during the vegetative growth stage, and tillering generally starts in early to mid-May in Minnesota. Immediately following the formation of tillers, barley moves into the reproductive growth phase and the initiation of spikelets. Spikelet initiation occurs near the end of May or in early June. Grain fill commences as soon as the fully developed spike has emerged, which in Minnesota typically occurs in late June to early July.

High temperatures during one or more growth phases will result in reduced yield. High temperature coupled with water stress is even more detrimental to yield, because photosynthesis is curtailed as stomata close to preserve water, thereby preventing plant leaves from exchanging oxygen and carbon dioxide. For example, temperature and/or water stresses that hamper photosynthesis during the grain-fill period can result in arrested grain development (lower kernel weight) and in fewer kernels per spike. Crop water usage itself is a function of temperature, nearly doubling with a 20°F increase in temperature.

Oats are also a cool-season crop, with growth and development characteristics and climatic tolerances similar to those of barley as described above.

The three main components of total grain yield for barley and oats are the number of tillers per unit area, the number of spikelets, and the number and weight of kernels.

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3 In Minnesota, both early- and mid-season oats are planted in early to mid-April, and are harvested between early July and mid-August.
statistical model explaining 41% of the variance in barley yield. Yield was particularly sensitive to June and July maximum temperatures, but total precipitation from November of the prior year to March of the current year also had an important influence. Barley is planted in mid-April at Morris and is typically entering the reproductive stage by early June. Unusually warm maximum temperatures during June and July would stress the plant during this stage, resulting in reduced yield. We interpret the positive relationship between yield and accumulated November–March precipitation, which largely falls as snow, to indicate that springtime snowmelt is an important source of moisture for the growing season at Morris, thus helping to increase yield.

Why do we find a different climate-barley yield relationship at Morris than we do at Crookston? The climate at Crookston is slightly cooler than that at Morris (Table 2), with, on average, fewer days with high temperatures near barley’s upper threshold. Any increase in mid- to late growing-season temperatures at Crookston would thus be less likely to cause an increase in the frequency of exceeding those threshold temperatures; instead, the extra warmth may even promote plant development and grain fill. Despite Crookston having a slightly drier climate than Morris, the data suggested that early-season moisture is more important for yields at Morris compared with Crookston because the overall warmer temperatures at Morris

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### Table 1. Climate Variables Used in the Stepwise Multiple Regression Analysis; Standardized Regression Coefficients* for Barley, Early-Season Oat, and Mid-Season Oat Yield Data; and Statistics for Regression Models at Each Study Site

<table>
<thead>
<tr>
<th>climate variables</th>
<th>Crook</th>
<th>Morris</th>
<th>Brook</th>
<th>Beres</th>
<th>Rsmt</th>
<th>Waseca</th>
<th>Fargo</th>
<th>Water</th>
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<td>0.84</td>
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<td>p-value‡</td>
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<td>0.0045</td>
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<td>#</td>
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</tbody>
</table>

* For each site, the magnitude of the standardized regression coefficient reflects the relative importance of each variable for that site’s regression model. Negative coefficients (highlighted in blue) indicate that an increase in that variable results in reduced yield, whereas oat yields were available as bushels per acre. Consequently, for a specific crop, it is important to focus on the relative magnitude of the coefficients more so than their actual values.

† The adjusted r² represents the percentage of variation in crop yield that can be explained by variations in the climate variables used here. For example, the r² value of 0.12 (the barley model for Crookston) means that the variation in mean May maximum temperature can explain (account for) about 12% of the variation in barley yields.

‡ The p-values represent the probability that there is no statistical relationship between (in this case) crop yields and climate. A p-value of 0.05 or lower is typically considered to indicate statistical significance (that is, there is only a 5% chance that climate has no effect on crop yield; stated another way, the relationship observed has only a 5% probability of occurring by chance). The symbol # indicates a p-value <0.0001, meaning there is less than a 0.01% chance that the statistical relationship is a result of chance. Note: Only those climate variables that have a statistically significant influence on crop yield are shown in the table. An empty cell indicates that the addition of those climate variables to the regression model did not improve the model’s representation of the relationship between climate and crop yield and thus excluded from the final model results.

Abbreviations: Tmax is mean monthly maximum temperature (in °F), Tmin is mean monthly minimum temperature (in °F), and Prec is total monthly precipitation (in inches). Sites are Beresford, SD (Beres); Brookings, SD (Brook); Crookston, MN (Crook); Fargo, ND (Fargo); Morris, MN (Morris); Rosemount, MN (Rsmt); Waseca, MN (Waseca); and Watertown, SD (Water).
also increase evaporation, and the extra soil moisture at the start of the growing season helps to offset this evaporative loss. It is possible that we do not see the same relationship at Crookston because its (generally) cooler temperatures result in slightly lower evaporative losses.

In sum, our statistical analyses of the relationship between climate and barley yields for Crookston and Morris suggest that barley is growing well within its climatic tolerance at Crookston, whereas barley at Morris is growing in an environment that is closer to its climatic limits. As a result, barley yield at Crookston had a weaker relationship to climatic variability than at Morris. Nonetheless, if growing-season temperatures were to increase, we would expect future barley yields to decrease at both Morris and Crookston.

**Early-Season Oats.** At each nursery site, we used stepwise multiple regression to develop a statistical model to relate the yield of four check varieties to the suite of climate variables that we expected to have an influence on oat yields. The results showed that climate did have a statistically significant impact on the early-season oat yield at all four sites. Our statistical model showed that climate variability accounted for 30% of the variation in yield at Brookings, approximately 65% of the variation at Beresford and Rosemount, and 84% of the variation at Waseca (Table 1). At three of the four sites, we observed that early-season oat yields were reduced when mean maximum temperatures were unusually warm during the growing season. This relationship was strongest at Waseca, as indicated by it having the largest standardized regression coefficients of all the sites, indicating that the amount of variation that can be explained by the climate variables we examined is highest at this site.

The relationship between yield and mean minimum temperature and total monthly precipitation was more mixed across the sites. For Beresford, increased May precipitation was conducive to higher yields at this somewhat dry location, whereas warm June minimum temperatures were associated with reduced yields, possibly because of the increased respiration (and thus loss of plant biomass) that occurs with higher nighttime temperatures. Brookings was the coolest of the four study sites, but it also was the driest (Table 2), and the fact that precipitation did not emerge as an important factor for early-season oat yields was an unexpected result.

One possible explanation is that the cooler climate at Brookings resulted in less evaporative stress during the relatively shorter early-season oats growing season, with the result that temperature had more of an effect on yield than did precipitation. At Rosemount, warm April minimum temperatures promoted higher yields, whereas high April precipitation had a nearly equal and opposite effect. Warm conditions may promote germination of early-season oats, which are planted in early to mid-April, but wet conditions may inhibit it. Yield at Rosemount was also negatively affected

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### Table 2. Mean Maximum Temperature (Tmax, °F), Mean Minimum Temperature (Tmin, °F), and Total Precipitation (Prec, inches) for April through August

<table>
<thead>
<tr>
<th></th>
<th>BARLEY</th>
<th>EARLY-SEASON OATS</th>
<th>MID-SEASON OATS</th>
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<tbody>
<tr>
<td></td>
<td>Crook</td>
<td>Morris</td>
<td>Brook</td>
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<tr>
<td>Apr–Aug Tmax</td>
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<tr>
<td>Apr–Aug Tmin</td>
<td>48.2</td>
<td>50.2</td>
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<tr>
<td>Apr–Aug Prec</td>
<td>14.2</td>
<td>17.0</td>
<td>13.9</td>
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</table>

Note: To be consistent with the time periods of the yield data, April–August means are computed for 1980 to 2005 for the barley sites, and for 1996 to 2009 for the oat sites. The use of two different averaging periods results in slight differences in mean temperature and precipitation values at Morris (based on 26 years of data for the barley analysis, and on 14 years of data for the oats analysis).

Abbreviations: Tmax is mean monthly maximum temperature (in °F), Tmin is mean monthly minimum temperature (in °F), and Prec is total monthly precipitation (in inches). Sites are Beresford, SD (Beres); Brookings, SD (Brook); Crookston, MN (Crook); Fargo, ND (Fargo); Morris, MN (Morris); Rosemount, MN (Rsmt); Waseca, MN (Waseca); and Watertown, SD (Water).

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4 Analysis by the Minnesota Office of the State Climatologist shows that observed annual and seasonal temperatures have increased in Minnesota, particularly during the last several decades (climate.umn.edu/climateChange /climateChangeObservedNu.htm). Future climatic trends and impacts, particularly temperature increases, are summarized in T.R. Karl, J.M. Melillo, and T.C. Peterson (eds.), *Global Climate Change Impacts in the United States* (Washington, D.C.: U.S. Global Change Research Program, 2009), www.globalchange.gov/publications/reports /scientific-assessments/us-impacts.© Regents of the University of Minnesota. All Rights Reserved.
by high precipitation in June and July, but was increased with higher values of November–March accumulated precipitation. High precipitation on the sandy soils of the Rosemount site can promote leaching of soil nutrients during the growing season (thus reducing yield), whereas increased soil moisture at the beginning of the growing season (reflected by the positive relationship between yield and November–March precipitation) can offset the generally limited amount of water available in these sandy soils. The results for Waseca show that, in combination with cool maximum temperatures during June and July, warm August minimum temperatures had a strong positive effect on yield, as did increased June precipitation (Table 1). For our 1996 to 2009 analysis period, Brookings was the coolest (and driest) of the four early-season oat sites, Beresford was warm and dry, and Rosemount and Waseca were warm and moist (Table 2). Taken together, our regression results showed a similar pattern to what we found for barley: cooler sites (Brookings for early-season oats, Crookston for barley) had a weaker (but still important) relationship between climate and yield, and warmer sites had a stronger relationship (Table 1). We interpreted our early-season oat results as additional support for our hypothesis that cool-season crops grown at climatically cooler sites (Brookings, Crookston) are less likely to encounter temperatures near physiological thresholds, and thus the climate–yield relationship is not as strong as it is at sites that are climatologically warmer. Stated another way, early-season oats grown at warmer sites are more likely to be negatively affected by increasing temperatures than are early-season oats grown at cooler sites, because higher temperatures at already-warm sites are more likely to produce days with temperatures above physiological thresholds than would already-cool sites.

**Mid-Season Oats.** We used step-wise multiple regression to estimate the extent to which climate may affect the yield of three check varieties at five nursery locations in Minnesota, North Dakota, and South Dakota. We found some similarity to the results observed for early-season oats, but we also found some interesting differences.

As for our previous analyses, our regression model for mid-season oats showed that climate has a statistically significant impact on yield at all of the sites. Climate variability accounted for 36% of the variation in yield at Rosemount, 55% at Fargo, approximately 65% at Brookings and Morris, and 77% of the variation at Watertown (Table 1). In general, warm early-season maximum temperatures were associated with increased yield at these sites, whereas warm maximum temperatures later in the season, when temperatures already are high, were associated with decreased yield. Warmer minimum (nighttime) temperatures during the growing season also led to reduced yields because plant growth fueled by photosynthesis (which increases plant biomass and thus yield) was offset by losses due to an increase in plant respiration (a temperature-dependent “breaking down” process, dominant at night, that reduces plant biomass). In contrast to what we found for early-season oats, our mid-season oat analysis showed that, at most of the drier sites we analyzed, yield increased with April precipitation, which helps to increase soil moisture at the start of the growing season.6

For mid-season oats, the relationship between climate and yield was strongest at the drier sites, whereas for early-season oats the relationship was strongest at the warmer sites. For our period of record (1996–2009), mean April through August precipitation at Rosemount was at least five inches higher than at the other sites (Table 2). The Rosemount regression model was the only one of the five mid-season oat models that did not include a precipitation variable; in contrast, the regression model for Brookings, the driest site, included nearly all of the precipitation variables. Mid-season oats emerge and develop under warmer conditions than do the early-season varieties. At many of the drier sites, precipitation appears to be an important predictor of mid-season oat yield, because increased precipitation can help maintain higher soil moisture by offsetting the evaporative losses that occur during these warm (and dry) months. By this reasoning, it seems odd that the regression model for Fargo showed a negative relationship between June precipitation and mid-season oat yields. The 1996–2009 climate record shows that Fargo normally experienced its highest monthly precipitation in June, and excess precipitation can cause temporary flooding. Temporary flooding is not an uncommon occurrence in the Red River Valley basin, with its flat topography and the preponderance of

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5 Mean maximum temperatures for Waseca in June and July had a negative relationship with yield, meaning that cooler temperatures had a positive relationship with yield.

6 High April precipitation can also be detrimental to crops in Minnesota, as often occurred at Morris, when increased early-season soil moisture resulted in delayed planting.
Yield declines when fields are at or above field capacity because an acute lack of oxygen in the root zone disrupts basic physiological processes such as water and nutrient uptake. Unfortunately, it is unclear from the available data whether temporary flooding or biological stresses, such as the incidence of crown rust, impacted mid-season oat yield negatively at the Fargo site.

**Discussion**

Although we understand that temperatures that are too warm and precipitation that is too scarce will have detrimental effects on oat and barley yields, we also understand that weather and climate are not the only factors that affect yield. For example, weeds, disease, and pest outbreaks are also important variables. Our objective with this work was to try to clarify the specific role of climate on crop yield because, although farmers can use herbicides, pesticides, and fungicides to mitigate the impacts of weeds, insects, and disease, climate is less amenable to control. Climate also can affect the likelihood of some insect and disease outbreaks. The reproduction of the *Fusarium* head blight fungus, for example (which affects barley and oats, as well as wheat, rice, and maize), is favored by temperatures in the range of 65 to 86°F and by extended periods of moisture.

Although some variations existed across the sites, taken together our results showed that barley and oats (both early- and mid-season varieties) have similar sensitivities to warm temperatures, as we might expect based on past research and experience. We found, however, that poor yields were associated not only with too-warm maximum temperatures, but also (particularly for oats) with too-warm minimum temperatures. Data from the Minnesota State Climatology Office indicate that between 1980 and 2007 the mean maximum temperatures within the state have increased by approximately 1.4°F, but that mean minimum temperatures have increased even more, by approximately 2.2°F.7 Based on our barley and oat analyses, it is reasonable to conclude that this increase in minimum temperatures could contribute to a decrease in yields over time within Minnesota. Increases in precipitation, on the other hand, could partially offset the effects of warm minimum temperatures, because our results showed that higher springtime precipitation often led to higher yields.

Projections of future climate change produced by the Intergovernmental Panel on Climate Change8 (IPCC) and by the U.S. Climate Change Science Program9 (CCSP) suggest that spring and summer temperatures are highly likely to increase in the upper Midwest, and that minimum temperatures are likely to increase more than maximum temperatures. If these changes in temperature profiles were to occur, cool-season crops such as barley and oats would be subjected to increased frequencies of unusually warm temperatures that our results show are detrimental to the yields of both crops. In addition to changes in temperatures, both the IPCC and CCSP point to the potential for decreases in available growing-season moisture over time, which our results show would also lead to decreases in barley and oat yield.

**Conclusions and Future Directions**

Federal farm policies, market demands, and/or disease outbreaks often have been touted as the primary reasons why Minnesota farmers have reduced their acreage of barley and oats in favor of other crops. Although these factors are no doubt important, our research shows that Minnesota’s changing climate also may be contributing to the decline in yields of both crops and, in turn, a decline in acreage. Concerns about future increases in both temperature and drought frequency have spurred efforts to develop crop varieties that are better adapted to a changing climate. As one example, the American Malting Barley Association is funding research (at the University of Minnesota and elsewhere) to develop winter varieties of malting barley that can mature earlier in the growing season, thereby reducing the likelihood of heat-related declines in yield. Our work to date is an important step toward identifying the primary climatic factors affecting barley and oat yields, and we plan to extend our work to include research on how breeding more climatically tolerant varieties may prevent these and other cool-season crops from disappearing from Minnesota’s landscape.

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