Effect of climate change and use of improved varieties on barley and canola yield in Manitoba

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An, H. and Carew, R. 2015. **Effect of climate change and use of improved varieties on barley and canola yield in Manitoba**. Can. J. Plant Sci. **95**: 127–139. A stochastic production function was estimated to investigate the effect of fertilizer inputs, changes in weather conditions and the use of improved varieties on barley and canola yields and its variability in Manitoba. Adoption of improved barley varieties did not have a significant effect on yield, while the adoption of herbicide-tolerant hybrid canola varieties was positively correlated with yield. An increasingly warmer climate in Manitoba is expected to have a slightly negative effect on mean barley yield and yield variance. In contrast, a warmer climate is expected to have a negligible effect on mean canola yield, but a positive effect on yield variability. Our results showed that a projected 50% increase in growing degree days would lead to a decrease of less than 1% in barley and canola yields.

Key words: Barley, canola, climate change, improved crop varieties, statistical analysis

An, H. et Carew, R. 2015. **Effets du changement climatique et de l'utilisation de variétés améliorées sur le rendement de l'orge et du canola au Manitoba**. Can. J. Plant Sci. **95**: 127–139. Les auteurs ont estimé l'utilité d'une fonction stochastique pour approfondir les conséquences des apports d'engrais, du changement des conditions météorologiques et de l'usage de meilleures variétés sur le rendement de l'orge et du canola et sur sa variabilité au Manitoba. L'adoption de cultivars améliorés d'orge n'a pas d'effet significatif sur le rendement, cependant le recours à des variétés hybrides de canola tolérant les herbicides présente une corrélation positive avec le rendement de cette culture. Le climat de plus en plus chaud au Manitoba devrait avoir une incidence légèrement négative sur le rendement moyen de l'orge et sa variation. Parallèlement, il aura un impact négligeable sur le rendement du canola, mais agira positivement sur la variabilité de ce dernier. Les résultats de l'analyse indiquent qu'une hausse prévue de 50 pour cent du nombre de degrés-jours devrait réduire le rendement de l'orge et du canola de moins d'un pour cent.

Mots clés: Orge, canola, changement climatique, variétés améliorées, analyse statistique

The analysis of the effect of climate change on agricultural production has employed various methods (Chen et al. 2004; Schlenker and Roberts 2009; Cabas et al. 2010), data sets, regional coverage, time periods and weather definitions. Some studies showed that climate change can have adverse effects on crop agriculture (Schlenker and Roberts 2009; Lobell et al. 2012) but in general the results were notable for the differences they found regarding the direction and magnitude of temperature and precipitation effects on crop agriculture. Two of the more common methods used to analyze the effects of climate change on agricultural production are the hedonic approach and the production function approach. The hedonic approach measures the effect of climate variables, such as precipitation and temperature, on the value of farmland used to grow crops while the production function approach estimates the effect of climate variables on crop yield. The advantage of the hedonic method is that it considers the impact climate change has on land values, which is a function of both the quantity and quality (i.e., type) of crops produced. The main weakness of the hedonic approach is that the effects of climate conditions can be confounded with other important (unobservable or omitted) factors that can influence land values.

We used a production function approach to investigate the effect that intra-seasonal climate conditions have had on the mean and variance of barley and canola yields in Manitoba, Canada, over the past decade. In addition, we addressed whether the adoption of herbicide-tolerant hybrid canola varieties or barley varieties protected by Plant Breeder's Rights (PBR) have affected crop yield in the presence of a changing climate. The results show that adoption of improved barley varieties does not have a significant effect on yield, while the adoption of herbicide-tolerant hybrid canola varieties is positively correlated with yield. An increasingly warmer climate in Manitoba is expected to have a slightly negative effect on mean barley yield and yield variance. In contrast, a warmer climate is expected to have a negligible effect on mean canola yield, but a positive effect on yield variability. Last, our results show that a projected 50%

Abbreviations: **GDD**, growing degree days; **ML**, maximum likelihood; **PBR**, Plant breeder's rights increase in growing degree days will lead to a decrease of less than 1% in barley and canola yields.

We investigated these two crops for several reasons. Canola was chosen because of its economic importance to the Canadian prairies, specifically Manitoba. Canola occupied the largest amount of farm land and was the single most valuable crop in Manitoba, with cash receipts totaling Can$1.1 billion in 2011 (Statistics Canada 2012). We selected barley because there were no recent studies in the literature on the effects of climate change on barley yield in Manitoba, while several exist for wheat and canola (Carew and Smith 2006; Carew et al. 2009). In addition, we were interested in how technical change, represented by the use of improved varieties, has impacted yield variability. The case of barley presented an interesting contrast to canola because of the divergent nature of public and private research funding that drives technical change in these two crops. While the public sector still plays an important role in canola varietal development in the area of germplasm preservation and development, new canola varieties are mainly developed by the private sector. On the other hand, new barley varieties are predominantly funded and released by the public sector.

This paper contributes to the existing and growing literature on the effects of climate change on agricultural yield by accounting for the effect of improvements in crop genetics, which is represented by increases in the adoption of herbicide-tolerant hybrid canola varieties and improved barley varieties protected by PBR. Empirically, we contribute to the literature in two ways: first, our measure of temperature is growing degree days (GDD) instead of average temperature. GDD is the standard measure in the agronomy literature and better captures the cumulative impact of temperature on plant growth stages than average temperature and is a better indicator of plant development. Second, we use maximum likelihood (ML) estimation instead of the more traditional feasible generalized least squares approach. ML methods tend to yield more efficient estimates that are also unbiased when the sample size is small (Saha et al. 1997).

Other studies that have used the production function approach have concentrated on analyzing climate change effects on mean yield and variance (Chen et al. 2004; Cabas et al. 2010) rather than considering non-climatic factors such as varietal diversity and improvements in crop varieties. Studies that have examined the effect of plant breeding programs on improving crop yields (e.g., Nalley et al. 2008) have neglected to consider the role of climate change. Examining how improved barley or canola varieties perform in a changing external environment would provide useful information to plant breeders in the development of better varieties and management practices to adapt to climate change. There is evidence that varieties that are higher yielding under ideal conditions may be more sensitive to changes in temperature and precipitation (Anderson and Hazell 1987). Beyond the farm level, there are significant public funds committed to insurance risk management programs in Canada and elsewhere. The cost of funding these programs is substantial and partly affected by the expected performance of producers who face crop yield risks. Therefore, it is imperative that we gain a better understanding of the effects of climate change on crop yield and production risk.

A review by Mooney and Arthur (1990) showed that climate change can have a beneficial effect on Manitoba's agricultural sector by lengthening the growing season and promoting the adoption of longer maturing crop varieties, such as wheat, canola, and barley. A few Canadian studies have examined the effects of climate conditions on crop agriculture. Carew et al. (2009) found that higher temperatures and greater precipitation were associated with increased wheat yield in Manitoba, but that the interaction of high temperatures and precipitation had negative effects on yield. Kutcher et al. (2010) observed that high temperatures and low precipitation resulted in a negative impact on canola yield in Saskatchewan, while greater than average precipitation and cooler than average nocturnal temperatures had a positive effect.

In Ontario, Cabas et al. (2010) used a variety of climate variables in a production framework and showed that temperature and precipitation had significant effects on the mean yield of corn, soybean, and winter wheat and that these effects varied depending on the period within the growing season. They concluded that the positive impact of a longer growing season on crop yield would likely mitigate the negative effects of greater heat and rainfall variability. The Ontario results were consistent with an earlier Manitoba study that showed warmer temperatures were likely to have a beneficial effect on crop agriculture for crops as soybeans, sunflowers and corn as a result of the lengthened growing season and increased heat units (Mooney and Arthur 1990). Weber and Hauer (2003) employed a hedonic approach and concluded that the beneficial gains of climate change on Canadian agricultural land values were likely to be greatest in the prairies and lowest for coastal regions.

Carew and Smith's (2006) study is a precursor to ours in that they looked at the aggregate growing season weather relationship between canola varieties protected by PBR, herbicide-tolerant hybrid varieties and yield in Manitoba. They found that weather variables, such as growing season precipitation and heat units, did not have any effect on mean crop yield. The adoption of canola varieties protected by PBR had a negligible effect on yield, while the use of herbicide-tolerant hybrids led to approximately 7% higher yield.

The next section contains an overview of the canola and barley sectors in Manitoba. This is followed by the Materials and Methods section, in which we describe the conceptual model, data used and the statistical model employed. In the fourth section, we present the Results and Discussion. The final section provides concluding statements and identifies areas for further research.

BACKGROUND ON CANOLA AND BARLEY PRODUCTION

The combination of the enactment of the PBR Act in 1990 and the approval of genetically modified canola in 1996 provided the impetus for the private sector development of crop traits (e.g., herbicide tolerance, specialty oils, hybrid vigor) and the production expansion of canola. Since the early 1990s canola production has increased by 240% from an average of 747 700 tons in 1990–1992 to 2.5 million tons in 2008–2010, while barley production has declined by 48% from 1.6 million tons to 855 667 tons over the same time period (Statistics Canada 2012). The expansion in canola production has been attributed to the adoption of herbicide-tolerant varieties, which increased from 10% of total canola harvested acres in 1996 to 99% in 2010 (Canola Council of Canada 2011). The first hybrid canola variety was approved for commercial release in Canada in 1999, and by 2012 approximately 98% of the canola grown in Manitoba was hybrid. Bayer's Liberty Link (63%) and Monsanto's Roundup Ready (31%) herbicide-tolerant hybrid canola varieties represented the bulk of the herbicide-tolerant canola grown in Manitoba (Kubinec 2012).

Over the past two decades, canola yield has increased at a greater rate than barley yield (Fig. 1). In the past decade, barley yield has been fairly volatile with large yield drops in 2005 and 2010. However, the general yield trend has been positive since 1990. Since the introduction of plant variety protection laws, there has been a total of 81 barley varieties granted PBR over the 1995–2010 period (C. Irving, personal communication, Canadian Food Inspection Agency). Apart from yield, seeded area of both crops has changed over the years. Canola seeded area has risen dramatically, while barley seeded area has seen a concomitant drop (Fig. 2).

It is unclear how intra-seasonal changes in temperature have affected barley and canola yields. Barley, unlike many cereal crops, does not thrive under very warm conditions (Bootsma et al. 2005). Specifically, barley yield suffers when daily maximum temperatures exceed 28°C or when the daily average is greater than 20°C (M. Therrien, personal communication, Brandon Research Centre, Agriculture and Agri-Food Canada, Brandon, MB; Hakala et al. 2012). Barley will go into dormancy at temperatures around 31°C, but has no physiological mechanism to manage excess moisture. Therefore, it was expected that too much precipitation would negatively affect barley yield. For canola, high temperatures (i.e., >29°C) and low precipitation can lead to yield loss, especially during the early part of the flowering period (Kutcher et al. 2010). Canola is similar to barley in that it is also considered a cool-weather crop and grows best under temperature conditions between 12°C and 29°C (Canola Council of Canada 2012).

MATERIALS AND METHODS

We considered a producer with a production technology $y = f(x, z)$, where y is a single output, x is a vector of inputs (e.g., fertilizer), and z is a vector of inputs related to the weather (e.g., temperature and precipitation) over which the producer has no control. We were primarily interested in analyzing the effects of fertilizer inputs, climate change and the use of improved varieties on mean yield and yield variability. We hypothesized that climate variables would have an effect on both the average yield of canola and barley, as well as yield variance. Using crop yield and weather data for the key crop production risk districts in Manitoba, we calculated several aggregate weather measures that were used in a series of crop yield models. We compared several model specifications to evaluate the effects of changes in temperature and precipitation and the robustness of these effects across different statistical models.

Data

Data on crop yield, seeded area, fertilizer use [i.e., nitrogen (N), phosphorus (P), potassium (K), and sulfur

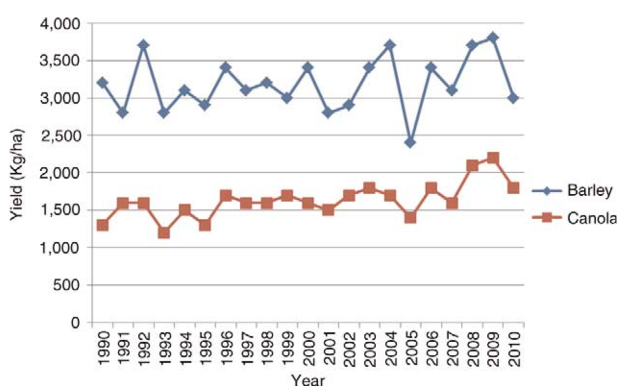

Fig. 1. Barley and canola yield in Manitoba between 1990 and 2010. Hybrid canola was approved for commercial release in 1999.

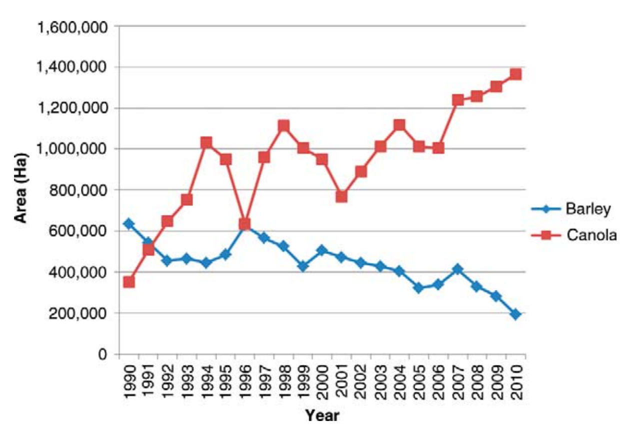

Fig. 2. Barley and canola seeded area in Manitoba between 1990 and 2010. Hybrid canola was approved for commercial release in 1999.

(S)], varietal diversity, insurance premia, the share of PBR varieties and the share of canola herbicide-tolerant hybrid varieties seeded were obtained from the Manitoba Agricultural Services Corporation (MASC, Management Plus Program) for the period 1997–2008. The data set consisted of farm-level data spanning 12 yr for 15 crop production risk districts in Manitoba that differed in agro-climatic characteristics, such as soil quality and weather conditions (Dumanski et al. 1992). Descriptive statistics of these variables are shown in Table 1.

The temperature data, which consisted of the daily maximum and minimum temperatures, were from Environment Canada weather stations corresponding to each of the 15 districts (R. Warren, personal communication, Agriculture and Agri-Food Canada). Some of the production districts had multiple weather stations and therefore multiple temperature readings. In these cases, we used the mean of the maximum and minimum temperatures. We calculated each day's growing degree day (GDD) as:

$$GDD = \frac{temp_{\min} + temp_{\max}}{2} - temp_{base}$$

where $temp_{base} = 5°C$ is the base temperature that is normally used for barley and canola. We used the daily GDD to calculate monthly and total GDD. To account for the effects of extremely high temperatures, we constructed monthly high temperature dummy variables that equal 1 when there was any day within a given month where the daily maximum temperature exceeded 28°C (barley) or 29°C (canola) and a monthly average temperature that was greater than 20°C. During the period of our dataset, only 2 months had any observations that satisfied both criteria: July and August. Therefore, we only included monthly high temperature dummy variables for these two months.

In addition, we also included monthly high-temperature variables that captured the number of days in a given month where the daily maximum temperature exceeded 28°C (barley) or 29°C (canola) and a monthly average temperature that was greater than 20°C. This count variable allowed us to investigate the cumulative effects of extremely hot days on yield. The extreme temperature variable descriptions were selected based on existing studies (Hakala et al. 2012; Robertson et al. 2013) and expert opinion (M. Therrien, personal communication, Brandon Research Centre, Agriculture and Agri-Food Canada). It was expected that at these critical temperatures both barley and canola yields would be negatively affected.

The precipitation data were also from Environment Canada, but were at the growing season level. That is, our precipitation variable represented the sum of growing season precipitation (May–August for barley and May–September for canola) plus the recharged precipitation from October of the previous year to April following Yang et al. (1992).

The relationship between fertilizer use and mean yield was expected to be positive; similarly, fertilizer use and yield variability were also expected to be positively correlated. It is well known that fertilizer increases crop yield, but fertilizer use has also been shown to be associated with increased risk (Paulson and Babcock 2010). Data on insurance premium rates (70% coverage)

Table 1. Summary statistics of dependent and explanatory variables used in empirical analysis

	Canola				Barley			
Variable	Mean	Std. dev.	Min.	Max.	Mean	Std. dev.	Min.	Max.
Yield (kg ha^{-1})	1711	371	265	2581	3139	715	501	4634
Seeded area (ha)	56727	38950	8317	190434	49583	27840	4180	153347
Share of crop insured area (%)	25.2	7.2	8.5	46.7	9.5	3.5	1.4	19.4
Insurance premium rate	10.2	2.9	5.8	20.4	9.0	3.0	4.0	21.0
Share (%) of PBR	–	–	–	–	44.0	27.9	3.6	100
Share (%) of hybrid canola	48.8	25.4	4.4	97.8	–	–	–	–
Margalef diversity index	2.3	0.7	1.1	3.9	1.0	0.5	0.2	2.7
Fertilizer N (kg ha^{-1})	92.5	10.7	59.8	113.9	73.7	7.9	46.3	90.5
Fertilizer P (kg ha^{-1})	33.5	2.9	26.9	40.7	31.9	3.3	20.9	40.4
Fertilizer K (kg ha^{-1})	8.8	5.2	1.7	21.3	9.2	5.5	1.2	29.0
Fertilizer S (kg ha^{-1})	14.3	2.9	6.9	20.9	3.3	1.5	0.8	7.5
Precipitation (mm)	514.5	88.9	304.6	706.3	464.4	92.5	157.6	653.7
May GDD	167.4	58.6	40.4	260.0	164.4	58.7	38.7	256.3
June GDD	330.7	45.8	228.9	425.1	329.2	46.0	228.1	421.6
July GDD	446.1	32.9	363.1	516.4	442.6	33.0	358.3	516.4
August GDD	408.5	57.3	249.4	533.4	407.2	56.9	244.8	533.4
September GDD	235.7	36.2	142.5	308.8	–	–	–	–
May high temp. days (no.)	0.3	0.5	0.0	2.0	0.4	0.6	0.0	3.0
June high temp. days (no.)	1.0	1.2	0.0	5.0	2.4	2.1	0.0	10.0
July high temp. days (no.)	3.7	3.1	0.0	15.0	7.8	3.8	0.0	20.0
August high temp. days (no.)	3.3	3.5	0.0	16.0	5.7	4.6	0.0	21.1
September high temp days (no.)	0.5	0.8	0.0	5.0	–	–	–	–

for barley and canola by Manitoba crop production districts were provided by MASC (D. Wilcox, personal communication, MASC). Higher insurance premium rates were likely positively associated with provincial risk areas that have greater yield variability. The relationship between premium rates and mean yield was less clear. If lower yield was also correlated with greater yield variability, then we would expect a negative relationship between insurance premium rates and yield. If mean yield and yield variability are independent of one another, then we would expect premium rates to increase with mean yield.

The variable PBR represented the percent or share of barley seeded area devoted to varieties granted PBR, while the herbicide-tolerant canola hybrid share represented the percent of canola varieties seeded that were herbicide-tolerant hybrids. Information on the names of granted PBR barley varieties as well as the names of registered herbicide-tolerant canola hybrid varieties in Canada were from the Canadian Food Inspection Agency (2012). The extent of varietal diversity was calculated using a Margalef index, which is also known as a species or variety richness index. The index D_{Mg} was calculated as:

$$D_{Mg} = (S-1)/\text{In } N$$

where S is the actual number of different species grown, or varieties in this case, and N is the total number of hectares of barley or canola seeded. Larger values of D_{Mg} indicate higher degrees of variety diversity. Smale et al. (1998) showed that varietal diversity can influence crop productivity. We hypothesized that diversity was negatively correlated with yield variability, while we were uncertain about the relationship between diversity and mean yield. We expected this relationship to hold across space and time. That is, we hypothesized that districts with greater varietal diversity would have lower yield variability, ceteris paribus; similarly, as the varietal diversity in a particular district increased (decreased) over time, we expected yield variability to decrease (increase) as well, ceteris paribus. A greater number of species or varieties seeded are likely able to withstand shocks in temperature and precipitation better, but it was not clear what the average yield response would be.

Given our dataset, we estimated four models. All four model specifications included non-climatic explanatory variables that control for seeded area, varietal diversity (i.e., Margalef index), fertilizer use, barley varieties protected by PBRs used, adoption of herbicide-tolerant hybrid canola and insurance premium rates. The four model specifications differed in how GDD and critical high temperatures were hypothesized to affect yield. Model 1 was the baseline model and considered the effect of cumulative seasonal GDD on crop yield. In model 2, we used disaggregated monthly GDD as our explanatory variables to better capture the effects of temperature across different growth stages. We also considered the possibility that these temperature effects were not linear. In model 3, we added high-temperature dummy variables to account for the possible effects of extreme heat on crop yield. Lastly, in model 4, we included high-temperature count variables to account for the cumulative effects of multiple hot days.

The first two specifications were chosen based on the existing agricultural economics literature: for example, Chen et al. (2004) used average seasonal temperature as an explanatory variable, and Cabas et al. (2010) used monthly temperature as an explanatory variable. The third and fourth model specifications were chosen based on discussions with barley researchers in Manitoba and some findings in the agronomy literature that suggested extreme temperatures – even in short duration – can have negative consequences. For example, too much heat in canola can result in the termination of the flowering process and any additional yield gains, also known as flower- or bud-blasting.

Statistical Model

To account for the possible effects that climate change may have on both the average crop yield and its variability, we estimated a Just–Pope stochastic production function (Just and Pope 1978, 1979). This approach allowed for the possibility that weather and other explanatory variables could affect both the mean and variance of crop yield shown in Eq. 1. Under this formulation, crop yield in risk region i in year t, y_{it}, was expressed as:

$$\mathrm{y_{it}} = f(x_{it};\ \beta) = h\ (x_{it};\ \alpha)^{1/2}\varepsilon_{it} \qquad (1)$$

where x_{it} is a vector of explanatory variables, β and α are the corresponding vectors of parameters to be estimated, and ε_{it} is a disturbance term with mean zero and variance $\sigma^2_{\varepsilon_i}$. The Just–Pope specification decomposed the crop production function into two components: the mean, or expected, crop yield was:

$$E[y_{it}] = E[f\ (\mathrm{x}_{it};\ \beta) + h\ (x_{it};\ \alpha)^{1/2}\varepsilon_{it}] = f(x_{it};\ \beta)$$

while the variance was $V(y_{it}) = h\ (x_{it};\ \alpha)\sigma^2_{\varepsilon_i}$. This specification allowed explanatory factors, such as temperature, to have differential effects on the mean and variance. That is, climate change may have decreased average crop yield, but it may have also increased (or decreased) the variance of crop yield.

Using farm-level panel data, it was possible to estimate the function in Eq. 1 using three-step feasible generalized least squares (3-FGLS) or one-step maximum likelihood estimation (MLE). The traditional approach has been to use 3-FGLS but Saha et al. (1997) showed that for small samples, the MLE approach yielded more efficient and unbiased estimates. Given that our sample was relatively small (15 regions and 12 years), we used the MLE approach.

Following Saha et al. (1997), the log-likelihood function can be expressed as:

$$\ln L = -\frac{1}{2} \times \left[n\ln(2\pi) + \sum_{i=1}^{n} \ln h(x_{it};\alpha) + \sum_{i=1}^{n} \times \frac{(y_i - f(x_{it};\beta))^2}{h(x_{it};\alpha)} \right] \quad (2)$$

Using non-linear optimization procedures, the parameters α and β were estimated in a single step by maximizing the likelihood function in Eq. 2. We estimated a Cobb–Douglas functional form for the mean yield and variance functions.

RESULTS AND DISCUSSION

In addition to the results presented here, we also ran some preliminary diagnostic and specification tests. Since we were interested in the effects of weather variables and other explanatory factors on the mean and variance of crop output, we first needed to confirm that there was indeed output risk. Therefore, we tested for heteroskedasticity using a likelihood ratio test and rejected the null hypothesis of homoskedasticity at the 1% level for both barley and canola yield specifications. In addition, we ran specification tests to rule out the presence of non-stationarity in the data series and to choose between a random effects (RE) and fixed effects (FE) modeling approach. We found that the data were stationary based on the results of tests proposed by Im et al. (2003). A Hausman test supported the use of a FE model. The results of these tests are provided in the Appendix (Tables A1 and A2). In the following section, the mean yield results for barley and canola are first presented followed by the variance regression results. We have omitted reporting the results of the regional fixed effects dummy variables to avoid unnecessary clutter, and in all the regressions the standard errors were clustered at the crop production risk district level.

Barley Mean Yield Results

The results of the mean regressions using the Just–Pope stochastic production function framework are reported in Table 2 (barley) and 3 (canola). From Table 2, it is evident that the effects of non-weather explanatory variables, such as fertilizer inputs, were generally insignificant for barley. In models 2 and 3, the share of PBR barley varieties was positively correlated with yield, although the significance disappeared in model 4 once we accounted for extreme temperatures. This suggested that technical progress, through the use of improved barley varieties, had a minimal effect on yield. Barley seeded area and the use of potassium fertilizer were both positive and statistically significant but only in models 3 and 1, respectively.

Regarding the effects of the weather variables, precipitation was negative and significant across all model specifications. For a crop like barley, which is sensitive to excessive moisture but fairly resilient to drier conditions, too much rain can have deleterious effects on yield. Unfortunately, our data did not allow us to look at intra-seasonal precipitation effects. In model 1, total GDD had a negative effect while total GDD squared had a positive effect (both are significant at the 1% level), which together suggested that warmer temperature had a negative and diminishing effect on barley yield. We calculated the marginal effect (at the mean) using these two coefficient values, and found that a 1% increase in total GDD resulted in a yield decrease of 0.02%. To put this into perspective, a recent report by Sauchyn et al. (2009) predicted that climate change would increase GDD by 25 to 50% (relative to 1961–1990 levels) in the prairies by 2050. Under these projections, our results suggested that barley yield would decrease by only 0.5 to 1%.

When monthly GDD were considered in models 2–4, the only significant variable was May GDD (negative) and May GDD squared (positive). The marginal effect of a 1% increase in May GDD on yield ranged from –0.002% (models 2 and 4) to –0.004% (model 3). Even at the upper range of the projected increase in GDD, this suggested a decrease in yield of only 0.1 to 0.2% percent. In model 3, the addition of high temperature dummy variables slightly improved the overall fit of the model specification but none of these dummy variables was statistically significant. In model 4, of the monthly high temperature count variables added, only June was statistically significant and resulted in a negative effect on yield, as expected. For each additional high temperature day in June, barley yield decreased by 0.02%. Also, the high temperature dummy variable for July remained negative, but was now statistically significant. A possible explanation for this is that July is the period in which flowering occurs and the seed is set, so any heat stress that occurred this late would lower the expected yield.

Canola Mean Yield Results

The results for the canola model specifications (Table 3) showed a larger number of statistically significant variables. Seeded area was positively related to yield in models 2 and 3, while varietal diversity was negatively correlated with yield in models 2–4. These results suggested that as canola seeded area expanded crop yield increased, while increases in canola varietal diversity led to lower yield. The share of herbicide-tolerant hybrid canola varieties was statistically significant and positively related to yield in all the models analyzed.

Precipitation was significant and negatively related to yield in all four models examined. Unfortunately, our precipitation data were too aggregated to look at intra-seasonal precipitation effects. Therefore, this result should be interpreted with some caution since our precipitation variable represented total growing season precipitation.

Table 2. Mean yield regression results – Barley

	Barley							
	(1)		(2)		(3)		(4)	
Variables	Coeff.[z]	Std. err.[y]	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Constant	0.0337*	0.0183	0.0291**	0.0144	0.0297**	0.0142	0.0321**	0.0155
Area	0.0375	0.0611	0.0893	0.0653	0.1160*	0.0605	0.0641	0.0568
Spatial index	−0.0525	0.0504	−0.0260	0.0390	−0.0031	0.0419	−0.0173	0.0448
PBR share	−0.0031	0.0237	0.0509*	0.0266	0.0476**	0.0239	0.017	0.0235
Insurance rate	0.0824	0.1154	0.1160	0.0940	0.0926	0.0849	0.088	0.0793
Nitrogen	−0.0087	0.2823	−0.0741	0.2317	−0.0324	0.2043	−0.022	0.2039
Phosphorus	0.0011	0.2153	−0.0292	0.1797	−0.0597	0.1692	−0.1561	0.1615
Potassium	0.1374***	0.0451	0.0607	0.0427	0.0417	0.0399	0.0534	0.0378
Sulfur	−0.0228	0.0445	−0.0363	0.0405	−0.0273	0.0392	−0.0305	0.0317
Weather variables								
Precipitation	−0.294***	0.0843	−0.381***	0.0697	−0.350***	0.0741	−0.289***	0.0775
Total GDD	−0.005***	0.0019						
Total GDD squared	1.36E-6***	4.89E-7						
May GDD			−0.0048	0.0034	−0.0062**	0.0029	−0.0046*	0.0027
June GDD			−0.0064	0.0044	−0.0051	0.0041	−0.007	0.0045
July GDD			0.0053	0.0162	−0.0066	0.0174	−0.0195	0.0193
August GDD			−0.0053	0.0042	−0.0025	0.0046	−0.0006	0.0055
May GDD squared			9.96E-6*	5.79E-6	1.19E-5**	4.96E-6	9.37E-6**	4.72E-6
June GDD squared			7.37E-6	4.59E-6	5.72E-6	4.28E-6	9.08E-6*	4.90E-6
July GDD squared			−7.30E-6	1.37E-5	3.36E-6	1.49E-5	1.42E-5	1.65E-5
August GDD squared			4.30E-6	3.79E-6	1.86E-6	4.26E-6	−1.26E-7	5.34E-6
May high temp							−0.0244	0.0228
June high temp							−0.0238**	0.0113
July high temp							0.0002	0.0043
August high temp							0.0012	0.0087
July HT dummy					−0.059	0.0637	−0.1217**	0.0562
August HT dummy					−0.0074	0.0547	0.0118	0.0565
District fixed effects	Yes		Yes		Yes		Yes	
Observations	180		180		180		180	
Log-likelihood	213.9		237.8		244.2		248.3	

[z]Statistical significance of the parameter estimates is indicated as follows: ***$P<0.01$, **$P<0.05$, *$P<0.1$.
[y]Standard errors are clustered at the crop production risk district level.

The timing of precipitation is important, and different crop growth stages have different water requirements. The results showed that total seasonal GDD and total GDD squared were not statistically significant. In models 2–4, May GDD was significant and negatively related to yield while May GDD squared was significant and positive, which suggested that higher temperatures in May had a negative but diminishing effect on canola yield. Using the 2050 projection of a 50% increase in May GDD, our results suggested that canola yield would decrease by 0.4% (model 2) to 0.5% (model 4). The inclusion of the high-temperature dummy variables in model 3 was found to have no qualitative effect on the results. However, the addition of the monthly high temperature count variables improved the overall fit by a large margin and led to a larger increase in the number of statistically significant variables.

In model 4, July and August GDD was significant and positively related to yields, while the significant and negative signs on July and August GDD squared terms suggested that these effects were diminishing. A scenario that resulted in a 50% increase in July or August GDD would decrease canola yield by 0.7%. In addition, the results showed that for each additional high temperature day in June, August and September, canola yield decreased by 0.05, 0.02 and 0.03%, respectively. The presence of a single day (or more) that exceeded the critical temperature in July had a positive effect (0.11%) on canola yield. This was an unexpected result given that the flowering stage has historically occurred in both June and (early) July, typically, and is sensitive to high temperatures. It is possible that producers adapted to warmer temperatures by planting earlier so that the flowering stage ended in late June and was not subject to the higher temperatures of July. However, seeding earlier brings a greater risk of being exposed to spring frost.

In general, most of the coefficients on the effect of GDD on crop yield were statistically insignificant. The most robust result – across crops and specifications – was a negative relationship between yield and May GDD. Total growing season GDD was negatively associated with barley yield, but there was no significant correlation with canola yield. Among the statistically significant results, assuming a scenario in which GDD increased

Table 3. Mean yield regression results − Canola

	Canola							
	(1)		(2)		(3)		(4)	
Variables	Coeff.[z]	Std. err.[y]	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Constant	0.0285*	0.0155	0.0244*	0.0134	0.0189	0.0126	0.0221**	0.0101
Area	0.0362	0.0762	0.1332**	0.0584	0.1227**	0.0593	0.0177	0.0667
Spatial index	0.0178	0.0605	−0.1235*	0.0660	−0.1426**	0.0653	−0.1975***	0.0515
Hybrid share	0.1104***	0.0328	0.1231***	0.0275	0.1127***	0.0283	0.0688***	0.0252
Insurance rate	0.0588	0.0828	0.0256	0.0851	−0.0078	0.0882	−0.2301***	0.0795
Nitrogen	−0.3881	0.2454	−0.2758	0.2315	−0.1738	0.2200	−0.0637	0.1528
Phosphorus	−0.0608	0.2408	0.0745	0.2564	0.1295	0.3248	0.6706***	0.2459
Potassium	0.0426	0.0484	0.0204	0.0449	0.0130	0.0456	−0.0492	0.0390
Sulfur	0.2148*	0.1215	0.0630	0.1080	0.0305	0.1150	0.1167	0.0843
Weather variables								
Precipitation	−0.2548**	0.1040	−0.309***	0.0868	−0.3703***	0.0975	−0.5818***	0.0891
Total GDD	0.0012	0.0019						
Total GDD squared	−3.38E-7	4.08E-7						
May GDD			−0.0096**	0.0038	−0.0122***	0.0041	−0.0124***	0.0029
June GDD			−0.0037	0.0051	−0.0028	0.0052	−0.0041	0.0039
July GDD			0.0115	0.0125	0.0115	0.0158	0.0195*	0.0109
August GDD			0.0072	0.0046	0.0091	0.0061	0.0089**	0.0045
September GDD			0.0038	0.0054	0.0003	0.0077	−0.0013	0.0070
May GDD squared			1.60E-5***	6.06E-6	2.01E-5***	6.59E-6	1.93E-5***	4.87E-6
June GDD squared			3.68E-6	5.39E-6	2.71E-6	5.49E-6	4.73E-6	4.16E-6
July GDD squared			−1.16E-5	1.03E-5	−1.20E-5	1.29E-5	−1.84E-5*	9.50E-6
August GDD squared			−6.51E-6	4.13E-6	−8.10E-6	5.53E-6	−7.17E-6*	4.19E-6
Sept GDD squared			−6.89E-6	7.00E-6	−2.50E-6	9.99E-6	−7.97E-7	8.92E-6
May high temp							−0.0067	0.0198
June high temp							−0.0497***	0.0140
July high temp							−0.0058	0.0049
August high temp							−0.0184***	0.0048
Sept high temp							−0.0339**	0.0149
July HT dummy					0.0194	0.0499	0.1108***	0.0384
August HT dummy					−0.0425	0.0664	0.0209	0.0398
District fixed effects	Yes		Yes		Yes		Yes	
Observations	180		180		180		180	
Log-likelihood	222.9		259.6		261.9		281.3	

[z]Statistical significance of the parameter estimates is indicated as follows: ***$P<0.01$, **$P<0.05$, *$P<0.1$.
[y]Standard errors are clustered at the crop production risk district level.

by 50%, the predicted decrease in barley or canola yield would be less than 1%. Together, these results suggested that future warmer temperatures would likely not have significant effects on barley or canola yields in Manitoba. Furthermore, producers could mitigate any potentially negative effects of warmer temperatures by altering their production practices (e.g., by planting earlier) to minimize the likelihood of exposing their crops to excessively warm temperatures during the more sensitive growth stages.

Barley Yield Variance Results

The results of the yield variance regressions for barley are presented in Table 4. For the model specifications analyzed, all four model specifications suggested that increasing the area planted resulted in lower yield variability. The negative relationship between barley-seeded area and yield variability is consistent with a recent study in Nepal that found that an increase in rice or wheat area decreased yield variability (Kotani and Poudel 2013). Insurance rates were significant and negatively related to yield variability, though the significance disappeared in model 3. All four models showed that higher insurance rates were correlated with high yield variance, which was surprising, since insurance rates typically increase with riskier growing environments. However, due to the nature of the empirical analysis (i.e., fixed effects regression), this result actually showed that holding the risk region constant, yield variance decreased as insurance rates increased. Therefore, it was not necessarily the case that regions with greater yield variance on average were associated with lower insurance rates. The effect of PBR was significant and positively related to yield variability but only in model 1. In all other specifications, it was negative but statistically insignificant. This suggested that once all the various temperature effects were accounted for, an increase in the share of PBR varieties had no effect on yield variability.

Regarding the weather variables, in all the models analyzed, higher precipitation was correlated with greater

Table 4. Yield variance regression results - Barley

	Barley							
	(1)		(2)		(3)		(4)	
Variables	Coeff.[z]	Std. err.[y]	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Constant	−3.529***	0.1054	−3.796***	0.1054	−3.867***	0.1054	−3.912***	0.1054
Area	−1.5298**	0.5990	−1.2259*	0.7301	−1.2462*	0.6647	−2.631***	0.8766
Spatial index	0.2523	0.5353	−0.0199	0.5967	0.287	0.5894	0.8271	0.6761
PBR share	0.5169**	0.2632	−0.0668	0.4048	−0.2195	0.3789	−0.6257	0.4067
Insurance rate	−2.6885**	1.1417	−2.8755**	1.2300	−2.7802**	1.1955	−2.6105**	1.171
Nitrogen	1.8440	2.8721	−0.0100	3.4923	−0.5866	3.4634	−3.7149	3.4351
Phosphorus	−0.3224	2.8831	−2.4972	2.9785	−3.3595	2.835	−4.8649*	2.864
Potassium	−0.0679	0.6516	0.5996	0.6821	1.0066	0.6829	1.7275**	0.7417
Sulfur	0.1116	0.4211	−0.0071	0.4732	−0.0357	0.4725	−0.5953	0.4924
Weather variables								
Precipitation	3.184***	0.8829	3.9082***	1.0237	2.9436***	1.0618	2.1233*	1.1728
Total GDD	0.0406**	0.0169						
Total GDD squared	−1.03E-5**	4.46E-6						
May GDD			0.1009***	0.0352	0.1123***	0.0337	0.1034***	0.0386
June GDD			0.2809***	0.0967	0.2858***	0.0958	0.3132***	0.099
July GDD			−0.2120	0.1832	−0.0584	0.1761	−0.0891	0.191
August GDD			−0.0160	0.0576	−0.0254	0.0645	−0.0057	0.0807
May GDD squared			−0.0002***	0.0001	−0.0002***	5.50E-5	−0.0002***	6.23E-5
June GDD squared			−0.0003***	0.0001	−0.0003***	0.0001	−0.0003***	0.0001
July GDD squared			0.0002	0.0002	3.20E-5	0.0001	0.0001	0.0002
August GDD squared			1.79E-5	0.0001	2.77E-5	6.02E-5	7.15E-7	7.84E-5
May high temp							0.5353*	0.2874
June high temp							−0.0791	0.2131
July high temp							−0.0958	0.0882
August high temp							0.0632	0.1272
July HT dummy					1.9765***	0.5669	2.0316***	0.6111
August HT dummy					−0.1234	0.8069	0.275	0.9023
Prec*July_HTD								
Prec*August_HTD								
District fixed effects	Yes		Yes		Yes		Yes	
Observations	180		180		180		180	
Log-likelihood	213.9		237.8		244.2		248.3	

[z]Statistical significance of the parameter estimates is indicated as follows: ***$P<0.01$, **$P<0.05$, *$P<0.1$.
[y]Standard errors are clustered at the crop production risk district level.

yield variability. Total GDD had the expected positive (and diminishing) effect on yield variability. A 1% increase in total GDD led to a barley yield variance increase of 0.17%. Consequently, a predicted GDD increase of 50% would lead to an increase in yield variance of about 9%. Higher GDD in May and June was significantly positively associated with yield variability; a 1% increase in May and June GDD resulted in yield increases of 0.06–0.07 and 0.28–0.38%, respectively. In the later stages of the growing season barley becomes more resilient to heat, which may partly explain the absence of a statistically significant relationship for July and August. In models 3 and 4, the presence of at least one day in July with extreme heat led to an increase in yield variance of 1.98 and 2.03%, respectively. Lastly, for each additional extreme heat day in May, barley yield variability increased by 0.53%.

Canola Yield Variance Results

In the case of canola (Table 5), the area planted was significant and positively correlated with yield variability in models 1–3. The effect of technology – represented by the share of herbicide-tolerant hybrid canola – was positive and significant in model 1, but negative and significant in model 4. This implied that the development of hybrid canola varieties, which accounted for the bulk of canola planted area in Manitoba, was associated with lower yield variability or greater yield stability once monthly GDD and high temperature effects were taken into consideration. Varietal diversity was negatively related to variance, but was only statistically significant in model 4. Similar to barley, the insurance premium was significant and negatively correlated with canola yield variability. However, as discussed in the barley results section, this did not necessarily mean that production regions with greater yield variance on average had lower insurance rates.

Regarding the weather variables, greater precipitation was associated with increased canola yield variance. Total GDD had no statistically significant effect on yield variability. May GDD was significant and was positively correlated with yield variability, though at a decreasing

Table 5. Yield variance regression results - Canola

	Canola							
	(1)		(2)		(3)		(4)	
Variables	Coeff.[z]	Std. err.[y]	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Constant	−3.629***	0.1054	−4.038***	0.1054	−4.063***	0.1054	−4.279***	0.1054
Area	2.421***	0.8861	2.919***	1.0224	2.823**	1.1265	1.6062	1.2470
Spatial index	−1.0633	0.9008	−1.2612	1.5029	−1.0005	1.4545	−3.832***	1.2716
Hybrid share	0.8210**	0.4187	−0.6200	0.5991	−1.0193	0.6476	−1.3717*	0.7032
Insurance rate	−3.531***	1.2498	−4.852***	1.5850	−5.444***	1.5921	−7.278***	1.6620
Nitrogen	6.1359*	3.6569	9.7173**	4.2078	10.631**	5.2818	27.053***	5.9897
Phosphorus	4.5467	2.8116	1.6639	3.8663	3.2191	5.2840	4.7469	4.4657
Potassium	−1.735***	0.6601	−1.579**	0.8018	−1.962**	0.8598	−3.1881***	0.9921
Sulfur	−2.3306	1.6788	−3.5462*	1.9596	−3.629*	2.1398	−9.8695***	2.0722
Weather variables								
Precipitation	6.269***	0.9673	5.310***	1.5707	3.6042**	1.6262	3.3247**	1.4712
Total GDD	−0.0108	0.0173						
Total GDD squared	3.69E-6	3.87E-6						
May GDD			0.180***	0.0369	0.1796***	0.0378	0.3303***	0.0500
June GDD			−0.0116	0.0911	0.0398	0.0990	0.2811**	0.1169
July GDD			−0.2084	0.1948	−0.2073	0.2126	−0.0640	0.2670
August GDD			−0.183***	0.0525	−0.1805***	0.0686	−0.3790***	0.0841
September GDD			0.0007	0.0814	−0.0440	0.0957	−0.0037	0.0938
May GDD squared			−0.0003***	0.0001	−0.0003***	0.0001	−0.0005***	0.0001
June GDD squared			1.70E-5	0.0001	−3.57E-5	0.0001	−0.0003**	0.0001
July GDD squared			0.0002	0.0002	0.0002	0.0002	−2.50E-6	0.0002
August GDD squared			0.0002***	4.73E-5	0.0002***	0.0001	0.0003***	0.0001
Sept GDD squared			1.21E-5	0.0001	0.0001	0.0001	3.29E-5	0.0001
May high temp							0.0582	0.5740
June high temp							1.4566***	0.3307
July high temp							0.3341***	0.1114
August high temp							−0.3110***	0.1046
Sept high temp							−0.2418	0.2962
July HT dummy					0.9329	0.6877	1.5014**	0.7373
August HT dummy					−0.6816	0.8057	−0.6686	0.7679
District fixed effects	Yes		Yes		Yes		Yes	
Observations	180		180		180		180	
Log-likelihood	222.9		259.6		261.9		281.3	

[z]Statistical significance of the parameter estimates is indicated as follows: ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$.
[y]Standard errors are clustered at the crop production risk district level.

rate, across models 2–4. The marginal effect of a 1% increase in May GDD was an increase in canola yield variance of 0.14–0.28%. In contrast, the marginal effect of a 1% increase in August GDD resulted in a decrease in yield variance of 0.07–0.55%. In model 4, the presence of an extreme heat day in July increased yield variance by 1.50%. Each additional extreme heat day in June and July increased yield variance by 1.46 and 0.33%, respectively. Lastly, each additional extreme heat day in August decreased canola yield variance by 0.31%.

CONCLUSION

We investigated the effects of improved crop varieties and intra-seasonal changes in weather on barley and canola yields in Manitoba. The adoption of herbicide-tolerant hybrid canola varieties was associated with higher mean yield, while the relationship between PBR barley varieties and mean yield was less clear. An increasingly warmer and wetter growing season due to climate change would likely have a small negative effect on the mean yield of barley. Our results further suggested that warmer temperatures would not have a significant effect on canola yield; however, increased precipitation would decrease canola yield and increase yield variability. In general, as the number of days that exceeded critical temperature thresholds increased, mean barley and canola yields would decrease while the yield variance would increase.

These results suggested a couple of options for possible adaptation strategies. First, it seemed that barley producers would have to adapt to a changing climate since higher temperatures in May did not affect barley yield in a statistically significant manner. Since higher temperatures in the later months of the growing season did not have a significant effect either, barley producers may adapt simply by planting earlier in the growing season. It would be somewhat different for canola where higher temperatures in May had a negative effect on yield, but higher temperatures in July and August had positive effects on yield. It was not clear from our results that canola producers would need to make changes to adapt to warmer conditions in general. Current climate models predict a drier future, which – based on our results – might be favorable to both barley and canola production. However, as the frequency of extremely hot days increased, this had a negative effect on yield for barley and canola.

This study had a few limitations. It could be improved and extended, first, with a longer panel data set and examining intra-season precipitation effects on yield variability. It would also be worthwhile to measure the effects of weather on canola and barley yields in other prairie provinces, since there are distinct differences in climate across western Canada. Clearly, the use of more disaggregated intra-seasonal precipitation data would improve the analysis. Other possible extensions include adding other crops, such as spring wheat, and to investigate whether PBR varieties developed by public or private seed developers have differential effects on increasing crop productivity and decreasing risk. In addition, we acknowledge the potential endogeneity of input use and yield that might arise as producers adapt to changing climatic conditions. However, it is outside the scope of this present paper to consider adaptation strategies such as land use or farm land area changes.

Overall, the results suggested that barley and canola mean yields would be resilient to changes in climate conditions but may be susceptible to extreme heat events, especially during the latter part of the growing season. In addition, yield variability in both crops would likely increase as temperatures increased. While the use of improved barley varieties protected by PBR did not result in significant improvements in yield, the resiliency of barley and its unique physiological characteristics suggest that climate change will not negatively affect barley production in the near future. Canola, while more sensitive to extreme warmer temperatures, may also be able to withstand these environmental changes as new late-maturing and drought-tolerant hybrid varieties become available in the market place.

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Appendix

Table A1. Unit root test results

	Yield	Area	Precipitation	Total GDD	May GDD	JuneGDD	July GDD	August GDD	September GDD
No serial correlation[z]									
Barley	−3.930*	−2.560*	−3.236*	−8.066*	−10.966*	−5.221*	−10.841*	−11.937*	n/a
Canola	−3.323*	1.706	−2.989*	−7.448*	−11.645*	−4.785*	−8.830*	−12.161*	−5.741*
Serial correlation[y]									
Barley	−4.048*	−3.049*	6.881*	−4.053*	−4.527*	−3.307*	−2.763*	−4.949*	N/A
Canola	−3.018	−1.545	−6.238*	−3.906*	−4.531*	−3.505*	−2.569*	−4.665*	−2.932*
Cross-sectional correlation[x]									
Barley	−3.201*	−2.142*	−3.004*	−4.499*	−4.939*	−3.627*	−3.169*	−5.141*	N/A
Canola	−3.331*	−2.659*	−3.002*	−3.579*	−3.927*	−3.328*	−2.861*	−3.745*	−3.150*

All tests conducted using the Im et al. (1997) approach.
[z]No serial correlation test uses the t-bar statistic.
[y]Serial correlation test uses W-t-bar statistic.
[x]Cross-section correlation test uses the t-bar statistic.
*Denotes significance at the 1% level

Table A2. Panel model specification tests

	Barley	Canola
Fixed vs. random effects	43.85[z]	35.90[z]
Heteroskedasticity	114.52[y]	107.16[y]

[z]Denotes rejection of null hypothesis of Hausman test at 1% significance.
[y]Denotes rejection of null hypothesis of homoskedasticity at 1% significance.