Estimating yield response to temperature and identifying critical temperatures for annual crops in the Canadian prairie region

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Robertson, S. M., Jeffrey, S. R., Unterschultz, J. R. and Boxall, P. C. 2013. **Estimating yield response to temperature and identifying critical temperatures for annual crops in the Canadian Prairie region**. Can. J. Plant Sci. **93**: 1237–1247. Historical yield and temperature data, by municipal district for the three prairie provinces, are used to estimate the marginal effect of exposure to specific temperatures in defined ranges during the growing season. Incorporating these non-linear temperature effects into the model improves yield forecasting for Canadian prairie annual crops over models that use average temperatures or growing degree days. Critical maximum temperatures at which yields decline, calculated for winter wheat, spring wheat, durum wheat, barley, spring rye, fall rye, oats, canola and flax, range between 28 and 34°C, depending on the crop. Additional critical minimum and maximum temperatures are estimated using the marginal effect of exposure to specific temperatures in defined ranges. Estimates of critical maximum temperatures and their marginal impact on yields are important for research and policy analysis on various issues and problems, including climate change, risk management instruments such as crop insurance, and development of heat tolerant crop varieties.

Key words: Temperature (critical), yield forecasting

Robertson, S. M., Jeffrey, S. R., Unterschultz, J. R. et Boxall, P. C. 2013. **Estimation de la réaction du rendement à la température et identification des températures critiques pour les cultures annuelles dans la région des Prairies canadiennes**. Can. J. Plant Sci. **93**: 1237–1247. On a recouru aux données historiques sur le rendement et la température dans les districts municipaux des trois provinces canadiennes des Prairies pour estimer l'effet marginal de l'exposition à certaines températures dans des plages bien définies, durant la période végétative. Lorsqu'on intègre les effets non linéaires attribuables à la température au modèle, on obtient de meilleures prévisions de rendement que celles résultant des modèles qui recourent à la température moyenne ou aux degrés-jours de croissance pour les espèces annuelles cultivées dans les provinces des Prairies canadiennes. Le maximum de température à partir duquel le rendement diminue a été calculé pour le blé d'hiver, le blé de printemps, le blé dur, l'orge, le seigle de printemps, le seigle d'automne, l'avoine, le canola et le lin. Il se situe entre 28 °C et 34 °C, selon la culture. On estime d'autres minimums et maximums critiques en fonction de l'effet marginal qui résulte de l'exposition à des températures précises, à l'intérieur d'une fourchette définie. Estimer la température maximale critique et son incidence marginale sur le rendement a de l'importance pour la recherche et l'analyse des politiques relatives à divers dossiers ou problèmes, notamment le changement climatique, les outils de gestion du risque comme l'assurance-récolte et le développement de variétés qui tolèreront la chaleur davantage.

Mots clés: Température (critique), prévision du rendement

Weather (i.e., precipitation and temperature/heat) represents an important "input" in crop production, and one that is not controllable by humans. Extreme air temperature events, such as heat waves, droughts, or cold spells all affect yields. For example, major droughts in 1988 and 2001–2002 resulted in reduced crop yields and billions of dollars of agricultural economic losses in the region (Wheaton et al. 1992; Alberta Environment 2004; Wheaton 2011). However, exposure to even a single day of heat above the plant's tolerance level can also have a significant adverse effect on yield. Schlenker and Roberts (2006, 2008) demonstrate that US yields for cotton, corn and soybeans increase with exposure to higher temperatures up to a certain maximum critical temperature, beyond which yields decrease. Agronomic research has shown that exposure to extreme temperatures at crucial times of plant development (e.g., during flowering or anthesis) will negatively affect crop yields (e.g., Angadi et al. 2000; Morrison and Stewart 2002; Ugarte et al. 2007). Wheeler et al. (2000) and Luo (2011)

Abbreviations: **AMAPE**, adjusted mean absolute percentage error; **AVG**, average air temperature; **CRAIN**, cumulative growing season rainfall; **DEG**, cumulative exposure to air temperature increments; **GDD**, growing degree day; **ln**, natural log; **MAE**, mean absolute error; **MRAIN**, monthly rainfall; **PATEMP**, partial aggregation of monthly cumulative exposure to air temperature increments; **RMSE**, root mean square error

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provide reviews of the agronomic literature concerning extreme temperatures and crop yields.

The relationship between crop yield and weather variables (particularly heat or temperature) is important for research examining a variety of issues. For example, predicting land use decisions in agriculture with climate change is contingent on understanding the impact of changes in temperature and precipitation levels on crop yields (e.g., Sands and Edmonds 2005; Kulshreshtha 2011). Agronomic and economic studies also make frequent use of temperature and/or precipitation data to assist in explaining patterns in expected crop yields or crop production risk (e.g., variability in crop yield, susceptibility of yields to droughts, heat waves, frost, etc.). This may be done through formal econometric estimation of production functions (e.g., Carew et al. 2009; Cabas et al. 2010) or other types of statistical analyses (e.g., Harker et al. 2012). This study examines the marginal effects of temperature on yields for annual crops in the Canadian prairies; specifically, winter wheat, spring wheat, durum wheat, canola, flax, fall rye, spring rye, oats, and barley.

A common approach in modeling temperature/heat effects on crop yield is to use average air temperatures over a specified period. For example, Cabas et al. (2010) use mean growing season temperature as an explanatory variable in estimating a production function used to examine the impact of climatic and non-climatic variables on expected crop yields and yield variability in southwestern Ontario. Wang et al. (2009) use mean temperatures to examine the impact of climate change on agriculture in China. Harker et al. (2012) use average growing season temperatures (along with other temperature/heat measures) as explanatory variables in a study that examined the relationship between input levels and canola yields in the Canadian prairies.

A limitation of using average temperatures, however, is that they do not capture the effects of extreme temperatures (e.g., increasingly higher air temperatures) on output. Averaging temperatures removes the marginal yield impact of the extremes by offsetting higher temperature values with lower ones.

An alternative is to use growing degree days (GDD), a measure of accumulated heat over a certain period of time. Growing degree days are calculated as the difference between an average of minimum and maximum temperature, and a base temperature assumed to be required for growth. The base temperature varies by crop and variety (McMaster and Wilhelm 1997). Use of GDD measures of heat is common in the empirical literature. For example, Carew et al. (2009) use GDD as an explanatory variable in their production function study of wheat yields and yield variability in Manitoba. Bootsma et al. (2005) use GDD in their study of the potential impacts of climate change on crop yields in Atlantic Canada.

Growing degree days are relatively simple to calculate and represent an improvement over average temperatures in capturing marginal effects of higher temperatures on yield. However, when using GDD the marginal effects on yield of exposure to various air temperatures inside the range are assumed to be identical, and exposure to temperatures outside the range captured in the calculation has a zero marginal yield effect. The value of GDD increases with heat, as warm days contribute more to GDD than cool days, but the number of warmer days is not tracked.

As noted earlier, exposure to heat above some critical level during the course of the growing season can hinder crop growth rather than promote it. To capture these non-linear effects, it is necessary to know at what temperatures yields begin to decline and by how much. Average temperature yield models cannot incorporate these effects. Depending on how it is calculated, GDD either eliminates the effects of temperature above a critical maximum, effectively assuming a neutral effect on yield, or assumes no critical maximum which implies that yield increases linearly for all increases in temperature. If these effects do matter, then GDD models could be subject to bias in the estimators.

The differential impact of higher temperatures on crop yields has been addressed in some crop yield studies. For example, Harker et al. (2012) use the number of days in July and August with temperatures greater than 30°C as a proxy for extreme temperatures in an analysis of canola yields. Lobell et al. (2011) use two different GDD measures in their analysis of African maize yields in order to model non-linear heat effects; GDD accumulated for temperatures in the range of 8 and 30°C, and a second GDD measured using temperatures greater than 30°C.

An alternative approach to aggregating air temperature data has been explored by Schlenker and Roberts (2006, 2008). They use United States data for minimum and maximum daily temperatures to estimate hourly temperatures for each day, and then calculate hours of exposure to incremental temperature ranges. Historical county level yields are estimated as a function of hours of exposure to incremental temperature ranges, time, and district dummy variables:

$$y_{ijt} = f(DEG_{xjt}, D_{jt}, t) \tag{1}$$

where y_{ijt} is yield for crop i in district j in year t, DEG_{xjt} is the number of hours of exposure to degree range x in district j in year t, and D_{jt} is a vector of district dummies for districts j in year t. Time is included to capture technological change. Schlenker and Roberts' model does not include other inputs such as fertilizer, land management decisions, etc.

Schlenker and Roberts' approach is an adaptation of GDD that captures non-linear impacts of air temperature on crop yields and incorporates marginal yield response from exposure to high temperatures. Using this approach Schlenker and Roberts show that in the United States, corn, soybean and rice exhibit a non-linear

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relationship with temperature. Yields increase until a critical maximum temperature is reached, which varies between 29 and 32°C depending on the crop. Yields decrease with exposure to temperatures above these levels.

The objective in this paper is to test the Schlenker and Roberts approach for crops in the Canadian prairie region against alternative methods of incorporating temperature effects. In particular, Canadian prairie historical yields and weather data at the municipal district level are used to compare yield estimates based on average temperature, GDD and the Schlenker and Roberts (2006, 2008) approach. The models are tested against out-of-sample yields to evaluate which approach is better suited to forecasting future yields under possible climate change scenarios. Results highlight critical crop yield maximum temperatures and annual yield trends for winter wheat, spring wheat, durum wheat, canola, flax, rye, oats, and barley.

MATERIALS AND METHODS

Crop yield and weather data were collected for agricultural municipal districts in the Canadian prairie provinces of Alberta (AB), Saskatchewan (SK) and Manitoba (MB). Daily minimum and maximum air temperatures were used to calculate alternative aggregate weather measures. Alternative measures of precipitation (i.e., seasonal versus monthly totals) were also calculated using daily precipitation data. Different combinations of these aggregated weather data measures were evaluated in crop yield models, which were then compared statistically to assess performance in forecasting crop yields.

Data

County or municipality level crop yield data were obtained from crop insurance corporations in the cases of Alberta and Manitoba, and the provincial government in the case of Saskatchewan. Crops considered in the analysis were winter wheat, spring wheat, durum wheat, canola, fall rye, spring rye, oats, flax, and barley. Rye yields from Manitoba were excluded from the analysis because the data were not separated into fall and spring yields. These crops constitute approximately 85% of annual field crop production in the Canadian prairie provinces and approximately 82% of total field crop land allocation in the Prairie region (Statistics Canada 2010).

Yield data for Saskatchewan and Manitoba were available from 1965 to 2007, while Alberta yield data from 1978 to 2007 were used. Alberta yields prior to 1978 were excluded because they were self-reported and as such were considered to be unreliable. Table 1 shows the highest and lowest individual yield observations, by crop, in the dataset as well as mean yield. Yield data from irrigated lands were also excluded as most crop production agriculture in the region is dryland and it can be argued that the link between irrigated yields and weather variables is different than for dryland yields and, in the case of growing season precipitation, weaker in nature.

Weather data were obtained for the same historical time period as the crop yields. Daily minimum and maximum temperature data were available from Environment Canada for 2347 climate stations across Alberta, Saskatchewan, and Manitoba. Observations from Apr. 14 to Sep. 01 of each year were used to represent growing season weather. For many individual weather stations complete sets of observations for the full time period were not available. Stations with data missing for an entire month between May through August were removed from the dataset. Once this criterion was applied, 847 of the original 2347 climate stations (i.e., approximately 36%) remained in the dataset.

Individual observations were removed for years when there were more than 10 d of missing data in total, or if there were more than 3 consecutive days of data missing. Any remaining missing temperature data were interpolated spatially or temporally. If another weather station in a particular district had available data for that date, then the assumption was made that the values for those two stations were identical for that observation. If no nearby data were available for the same date, missing values were interpolated temporally using temperatures from the day before and after and calculating a simple average.

Table 1. District highest and lowest and average yields, Canadian Prairies (1965–2007)

	High yield		Low yield		Average
	(kg ha^{-1})	Year	(kg ha^{-1})	Year	(kg ha^{-1})
Winter wheat	5346.0	2004	46.0	1988	2589.9
Spring wheat	4588.7	2005	80.9	1988	1991.2
Durum wheat	4917.4	1990	73.0	2002	1859.3
Oats	4364.9	1992	44.7	1980	1911.2
Barley	5000.0	2003	97.4	2002	2377.5
Spring rye	4395.9	2003	96.0	2001	1209.3
Fall rye	4226.8	2007	125.8	1988	1589.3
Flax	2502.2	2004	5.8	2002	976.7
Canola	2913.5	2005	12.7	2002	1201.5

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Hourly temperatures for each date were estimated using an air temperature distribution function described by Cesaraccio et al. (2001). This function requires daily minimum and maximum temperatures as well as daily sunrise and sunset times. Daily sunrise and sunset times for each district in the sample for 2009 were obtained from the United States Naval Observatory (2009) for this purpose. The choice of 2009 as a representative year for establishing sunrise/sunset times was arbitrary, but year-to-year fluctuations in sunrise and sunset times were examined and found to be extremely small.

Growing season precipitation data were also obtained from the Environment Canada database of weather station observations, in the form of daily millimetres of rainfall. These data were summed over the growing season (Apr. 15 to Aug. 31) to obtain total growing season precipitation. Observations with missing data points were eliminated as per the criteria used for temperature data. However, any remaining missing rainfall data were assumed to be zero (i.e., no rainfall for that day). Given that the region is semi-arid, the probability that rainfall is greater than zero in these cases is assumed to be acceptably close to zero for any given day. The resulting growing season rainfall values varied significantly both spatially and temporally. The lowest cumulative rainfall for any growing season for any given weather station was 19.1 mm, and the maximum was 709.4 mm. Average growing season rainfall ranged from 225.2 mm to 269.3 mm for the districts in the dataset.

The weather stations and associated temperature and precipitation data were matched up with the yield data. Weather stations were plotted on a map using geographic information systems, with yield, temperature and rainfall data then being intersected with weather station location data. A total of 13 332 observations were obtained using this method, each characterized by the location of the weather station, the associated weather at that station and the yield in the district in which the station is located. In cases where a municipal district did not contain a weather station the yield data for that district were excluded from the analysis. Conversely, some districts contained multiple weather stations. In these instances, data from each weather station in the district were treated as separate observations, with each being associated with the district crop yield; that is, there were multiple observations for that particular district, one per weather station. This was most frequently the case in Alberta where the municipal districts are generally larger.

Weather Variables

Temperature and precipitation data from the individual weather stations were used to create aggregate weather measures. These measures were in turn employed in generating alternative specifications of the crop yield models. Three alternative temperature measures and two alternative growing season precipitation measures were calculated. Each of these is discussed below.

Average Temperature Variables

Average temperature (AVG) is the first aggregate temperature variable, and is calculated for each month in the growing season as follows:

$$AVG_{mk} = \frac{\sum_{n=1}^{d}\left(\frac{TMAX_{nmk} + TMIN_{nmk}}{2}\right)}{d} \quad (2)$$

where AVG_{mk} is the average temperature in the mth month for the kth weather station, $TMAX_{\mathrm{nmk}}$ and $TMIN_{\mathrm{nmk}}$ are the maximum and minimum temperatures, respectively, for the nth day of the mth month for the kth weather station, and d is the number of days in the month. For each weather station, five monthly averages were calculated in each year, one for each month of the growing season.

Growing Degree Days Variables

The second temperature variable is created using a cumulative GDD calculation. GDD represent a measure of the "heat" accumulated during the growing season, calculated as follows:

$$GDD_k = \sum_{n=1}^{D} max\left\{\left(\frac{TMAX_{nk} + TMIN_{nk}}{2} - B\right), 0\right\} \quad (3)$$

where $\mathrm{GDD_k}$ are the growing degree days accumulated through the growing season for the kth weather station, $TMAX_{\mathrm{nk}}$ and $TMIN_{\mathrm{nk}}$ are defined as before, B is a baseline temperature below which it is assumed no growth occurs, and D represents the number of days in the growing season. One GDD value was calculated per weather station for each year. For the purposes of this analysis, B was set equal to 10°C. Although not presented and discussed in this paper, GDD crop yield models were also estimated using B values set at 5 and 0°C. The only effect was on the value of the intercept of the estimated models.

Degree Increment Variables

The third temperature variable, consistent with the Schlenker and Roberts approach, is hours of exposure to different levels of temperature through the growing season (DEG). Hourly temperature estimates (discussed earlier) were converted to binary variables, T_{xhnmk}, representing the occurrence ("yes" = 1, "no" = 0) of temperature interval x at the hth hour on the nth day of the mth month for the kth weather station. Initially "x" represented 1°C temperature intervals/increments from 0°C to 40°C, with $x = 1, 2, \ldots, 40$ corresponding to intervals 0–0.9, 1.0–1.9, …, 39.0–39.9. One additional variable captured all hours over 40°, as multicollinearity was found in the data in this range. Observations of

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temperatures below 0°C were dropped from the vector to prevent additive multicollinearity between variables. The individual T values were summed over hours, days and months to obtain aggregate temperature interval values, calculated as follows:

$$DEG_{xk} = \sum_h \sum_n \sum_m T_{xhnmk} \tag{4}$$

DEG_{xk} represents cumulative hours of exposure to temperature interval x over the course of the growing season for the kth weather station. There were 41 DEG variables calculated for weather station in each year; that is, for all temperatures from 0 to $\geq$40°C.

Rainfall Variables

Two alternative growing season rainfall variables were calculated for use in the crop yield models. The first is a cumulative growing season rainfall variable, calculated as total rainfall for the entire growing season for each weather station. Recognizing that there may also be a relationship between the timing of precipitation and its effect on yields, cumulative monthly rainfall variables were also calculated and used in some versions of the crop yield models.

Production Function Model Estimation and Comparison

Crop yields are influenced by a number of different factors. These include discretionary inputs such as seed, plant nutrients (i.e., chemical fertilizer), pesticides, labour, capital, etc., along with non-discretionary factors such as soil quality, weather events (e.g., hail), moisture and heat. The current study focuses on the influence of weather in the form of temperature/heat and precipitation on crop yields in the Canadian prairie region. Other explanatory variables are not included due to a lack of data (e.g., input levels are not available at a municipal district level), although the impact of soil quality is proxied through the inclusion of district dummy variables (as discussed below).

Several alternative models were estimated and compared in terms of their ability to forecast crop yields for the Canadian prairie provinces. The models use combinations of different temperature and rainfall variables as explanatory variables, but all take the following general form:

$$ln(y_{ikt}) = \alpha_i + \beta_{ikt} TEMP_{kt} + \mu_{ikt} RAIN_{kt} + \gamma_i D + \delta_i t + \varepsilon_i \tag{5}$$

where y_{ikt} is the yield for the ith crop and kth weather station, in year t. By using logged yields, coefficient estimates may be interpreted as the percentage change in yield resulting from a one unit change in the explanatory variable. Yield was modeled as a function of temperature (***TEMP***), rainfall (***RAIN***), a vector of district dummies (***D***) and a time trend (***t***). ***TEMP*** may be a single variable in the case of GDD, a vector of monthly average temperatures (AVG), or cumulative hours of exposure to temperature intervals (DEG). RAIN is either a single variable representing cumulative growing season rainfall (in mm), or a vector of monthly cumulative rainfall variables. The district dummies are included to capture agronomic and climate influences that are specific to each municipal district.

Six versions of Eq. 5 were estimated and evaluated to compare the alternative approaches to modeling temperature effects on crop yields. Basic AVG, GDD and DEG models (i.e., AVG-CRAIN, GDD-CRAIN and DEG-CRAIN, respectively) were formulated and estimated using corresponding specifications of ***TEMP***, along with the cumulative growing season rainfall specification of ***RAIN***. AVG-MRAIN, GDD-MRAIN and DEG-MRAIN models were estimated using cumulative monthly rainfall variables in ***RAIN***. In each case the district dummy for Newell County in Alberta was excluded from the estimation; that is, it was used as the base district.

The estimated versions of Eq. 5 included up to 344 district dummy variables (depending on the geographic distribution of each crop's acreage), 41 or more temperature variables, one or more variables for rain and a time trend. There were up to 12 333 observations for each crop, based on availability of yield and weather data in each year. Due to the large number of coefficients estimated for the various versions of the crop yield model, most individual coefficients are not reported here. Detailed results are available, upon request, from the authors.

The models were estimated for the nine crops using 85% of the data, selected randomly. The remaining 15% of the observations were used to compare the models in terms of their ability to forecast yields. Specifically, the coefficient estimates from each model were used to calculate predicted yields for the 15% of the observations not used in the regression analysis. These out-of-sample forecasts for each version of the crop yield model were then compared with the actual yields. The size of the full dataset and the number of observations used in the statistical estimation procedures are reported in Table 2.

Predictive accuracy was evaluated using three different statistical measures: root mean square error

Table 2. Total sample and sub-sample size used for parameter estimates

	Total observations	Observations used for estimates	Percent of total
Winter wheat	1934	1642	84.9
Spring wheat	12332	10430	84.6
Durum wheat	5600	4763	85.1
Oats	12333	10491	85.1
Barley	12579	10707	85.1
Spring rye	327	269	82.3
Fall rye	4667	3938	84.4
Flax	7755	6565	84.7
Canola	10776	9141	84.8

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(RMSE), mean absolute error (MAE) and adjusted mean absolute percentage error (AMAPE) for the forecasted yield for each crop. Adjusted R^2 values for each model were reported as well. Each of these measures has advantages and disadvantages in terms of its use. RMSE is the square root of the average squared values for the forecast errors, and places greater weight on larger errors. RMSE measures predictive accuracy attributable to both variability and bias. Mean absolute error is the average of the absolute values for the forecast errors, with each error being weighted equally regardless of magnitude. As such, MAE is a simple measure of bias in the sample average. AMAPE is the average of the absolute values of the errors relative to the average of observed and forecasted yield, in percentage terms. If the ''cost'' of the error is more accurately represented by the percentage error rather than the absolute value of the error, the use of AMAPE is appropriate. A detailed description of these measures is provided by Kennedy (2003, page 361).

RESULTS AND DISCUSSION

Each model was tested for heteroskedasticity and autocorrelation using, respectively, White and Breusch-Pagan-Godfrey and Durbin Watson tests (Shazam 2001; Greene 2003). There was no evidence of autocorrelation, but all of the models displayed heteroskedasticity. This was corrected by using White's heteroskedastic-consistent covariance matrix (Shazam 2001).

The adjusted R^2 and out-of-sample predictive accuracy measure values are provided in Table 3. For RMSE, MAE and AMAPE, lower values represent better predictive accuracy, while the opposite is true for adjusted R^2. The Schlenker and Roberts DEG approach with monthly rainfall variables (i.e., DEG-MRAIN) performs as well as or better than the other approaches in terms of forecasting crop yields for most crops and most of the measures (Table 3). Even in cases when other models perform better for specific measure/crop combinations, predictive capabilities for the DEG-MRAIN formulation are comparable with the best-performing alternative. It may then be concluded that cumulative temperature exposure measures are superior to either average temperature or growing degree day measures, in terms of predicting crop yields in the Canadian prairie region.

Critical Temperatures – DEG-MRAIN Model

Based on these results, the DEG-MRAIN model was re-estimated using the full data set (Table 4) to identify maximum and minimum critical temperatures for crop yields in the Canadian Prairie region. All nine crops exhibit negative marginal yield effects for exposure at or above critical air temperatures that range from 28 to 34°C, depending on the crop. These values, shown in Table 5, provide an indication of heat tolerance associated with the various crops. Oats and barley are least tolerant to heat, with yield decreases occurring for every hour of exposure to heat above 28°C. Conversely, fall rye is the most heat tolerant, with yield decreases occurring only for temperatures above 34°C. Marginal yield effects for spring wheat and canola yields are positive for temperatures below a critical level of 29°C, with yield decreases of 0.06% and 0.08%, respectively, for every hour of exposure to 29°C. The results for wheat and canola are generally consistent with agronomic research on critical temperatures, which report values in the range of 27 to 31°C for these crops (e.g., Ferris et al. 1998; Morrison and Stewart 2002; Ugarte et al. 2007; Teixeira et al. 2013).

For fall rye, yields increase with temperatures up to approximately 29 or 30°C, then show no significant negative yield effects until temperatures exceed 34°C. Thus, fall rye is heat tolerant in that the plant is able to sustain (but not increase) yield at higher air temperatures even though these higher temperatures would damage other crops.

The estimated model can also be used to test for the existence of critical minimum temperatures. The existence of a minimum critical temperature is consistent with the principle underlying GDD calculations. For example, 5°C is often chosen as the base temperature in a GDD calculation; the assumption is that no growth occurs below this critical temperature.

Evidence regarding the existence of critical minimum temperatures for Canadian prairie crop yields is ''mixed'', based on the DEG-MRAIN model results. The coefficient estimates for temperatures from 3 to 5°C are negative (Table 4), and so critical minimum temperatures can be identified (Table 5). However, the coefficients for temperature exposure variables between 0 and 5°C are not consistently negative, and at least one of the positive values is statistically significant for each crop. This implies that only limited support exists for negative yield effects for critical minimum temperatures, at least based on the range of temperatures present in the data set.

Critical Temperatures – Monthly Cumulative Temperature Exposure Model (DEG-MTEMP)

Consistent with Schlenker and Roberts (2006, 2008), the structure of the DEG-MRAIN model imposes an implicit assumption of non-separability in terms of air temperature effects. In other words, it does not matter in which month exposure to specific temperature levels occurs in terms of marginal impacts on yield. However, it may be the case that this assumption obscures heterogeneous monthly temperature effects. To test this assumption, an alternative DEG model, referred to as DEG-MTEMP, was estimated. DEG-MTEMP has monthly cumulative temperature exposure variables and rainfall variables. DEG-MTEMP was not estimated for winter wheat and spring rye due to insufficient numbers of observations (i.e., lack of sufficient degrees of freedom).

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Table 3. Out-of-sample forecasting accuracy measures, by crop and model[z,y]

	AVG-CRAIN	GDD-CRAIN	DEG-CRAIN	AVG-MRAIN	GDD-MRAIN	DEG-MRAIN
Winter wheat						
RMSE	0.338	0.357	0.343	0.343	0.326	0.328
MAE	0.232	0.245	0.240	0.240	0.224	0.226
AMAPE	0.031	0.033	0.032	0.032	0.030	0.030
Adjusted R^2	0.533	0.470	0.504	0.544	0.501	0.522
Spring wheat						
RMSE	0.294	0.302	0.286	0.288	0.294	0.280
MAE	0.215	0.220	0.208	0.212	0.217	0.206
AMAPE	0.029	0.030	0.028	0.029	0.029	0.028
Adjusted R^2	0.369	0.322	0.393	0.388	0.353	0.417
Durum wheat						
RMSE	0.357	0.372	0.360	0.360	0.354	0.344
MAE	0.259	0.266	0.261	0.261	0.257	0.251
AMAPE	0.035	0.036	0.036	0.036	0.035	0.034
Adjusted R^2	0.402	0.361	0.423	0.320	0.286	0.456
Oats						
RMSE	0.353	0.361	0.340	0.350	0.357	0.337
MAE	0.250	0.256	0.242	0.249	0.253	0.238
AMAPE	0.034	0.035	0.033	0.034	0.035	0.033
Adjusted R^2	0.334	0.295	0.383	0.352	0.323	0.403
Barley						
RMSE	0.323	0.339	0.319	0.331	0.341	0.314
MAE	0.228	0.241	0.225	0.237	0.245	0.222
AMAPE	0.666	0.667	0.667	0.031	0.032	0.667
Adjusted R^2	0.334	0.277	0.361	0.340	0.294	0.372
Spring rye						
RMSE	0.444	0.518	0.451	0.426	0.471	0.430
MAE	0.331	0.386	0.336	0.309	0.350	0.32
AMAPE	0.051	0.059	0.051	0.047	0.054	0.050
Adjusted R^2	0.606	0.542	0.636	0.616	0.585	0.648
Fall rye						
RMSE	0.348	0.362	0.351	0.351	0.337	0.338
MAE	0.255	0.261	0.255	0.255	0.251	0.251
AMAPE	0.036	0.036	0.036	0.036	0.035	0.035
Adjusted R^2	0.349	0.305	0.356	0.380	0.356	0.390
Flax						
RMSE	0.417	0.426	0.420	0.414	0.419	0.414
MAE	0.298	0.303	0.295	0.297	0.300	0.293
AMAPE	0.046	0.046	0.045	0.045	0.046	0.046
Adjusted R^2	0.267	0.239	0.279	0.279	0.264	0.295
Canola						
RMSE	0.387	0.401	0.380	0.380	0.384	0.378
MAE	0.250	0.260	0.248	0.248	0.250	0.250
AMAPE	0.037	0.038	0.037	0.037	0.037	0.037
Adjusted R^2	0.328	0.290	0.363	0.341	0.306	0.372

[z]AVG, GDD and DEG refer to models using temperature variables calculated using average monthly temperature, cumulative GDD and temperature increments, respectively. CRAIN refers to models using cumulative growing season rainfall variables, while MRAIN refers to models using monthly rainfall variables.
[y]RMSE, MAE and AMAPE refer to root mean square error, mean average error, and adjusted absolute percentage error measures, respectively.

To determine if the assumption of non-separability of temperature effects from DEG-MRAIN is appropriate, the two versions of the Schlenker-Roberts DEG model (i.e., DEG-MRAIN and DEG-MTEMP) were compared statistically. A non-nested J-test (Greene 2003) was used to test whether the two models, one with seasonal cumulative temperatures and the other with monthly cumulative temperatures, are statistically equivalent. The J-test results indicate that DEG-MTEMP provides information that is not captured in DEG-MRAIN (P value $=0.00$ in added variables in all six models) but the reverse is not true in general (P value >0.21 for spring wheat, durum wheat, flax, fall rye and barley; P value $=0.01$ for oats; P value $=0.04$ for canola).

t-tests were also used for the DEG-MTEMP models to test the null hypothesis that coefficients for each one degree increment in temperature are equal for different months. An equivalent set of t-tests was also performed for the monthly rain coefficient estimates. The test results indicate that non-separability generally does not hold

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Table 4. DEG-MRAIN model results (seasonal cumulative temperature increment and monthly rainfall variables)[z]

Variable[y]	Winter wheat	Spring wheat	Durum wheat	Oats	Barley	Spring rye	Fall rye	Flax	Canola
Constant	5.12***	5.77***	3.33***	5.45***	5.61***	1.97	5.68***	4.53***	4.89***
Time	0.018***	0.0088***	0.0089***	0.0088***	0.010***	−0.0063	0.012***	0.0098***	0.014***
AprRain	0.0020***	0.00054***	0.0010***	0.000060	−0.00016	0.0038**	0.0010***	−0.00036	0.00043*
MayRain	0.0020***	0.00097***	0.0013***	0.00075***	0.00019*	0.0055***	0.0023***	0.00058***	0.0012***
JunRain	0.00022	0.0010***	0.0020***	0.0012***	0.00038***	0.0037***	0.0012***	0.0011***	−0.00009
JulRain	−0.00033	0.00017**	0.0012***	0.00094***	0.00047***	0.0018**	0.00039***	0.0013***	0.00030***
AugRain	−0.00036	−0.00097***	−0.0013***	−0.00088***	−0.0010***	0.00043	−0.0015***	−0.00076***	−0.00054***
DEG0	0.0015	0.0016***	0.0031***	0.0022***	0.0018***	0.0035	0.0020***	0.0032***	0.00094**
DEG1	0.0028***	0.00048	0.0019***	0.00028	0.00073**	0.00044	0.0011*	0.000080	0.00013
DEG2	0.0012	0.00074**	0.0017***	0.00086**	0.00099***	0.0068***	0.0012*	−0.000090	0.00095**
DEG3	−0.00061	−0.000030	0.0016***	0.000050	−0.00013	−0.00089	0.00015	0.00022	−0.00027
DEG4	−0.000090	0.000050	0.0011**	0.00031	−0.000080	0.0042*	0.00078	0.00068	0.00011
DEG5	−0.000090	−0.00046*	−0.000060	−0.00032	0.000090	−0.00064	−0.0011**	−0.00015	0.000040
DEG6	0.0012	0.00087***	0.0015***	0.00077***	0.00062**	0.0018	0.00090*	0.00087**	0.00076**
DEG7	0.00075	0.00035	0.00043	0.00010	0.00058**	0.0017	0.00092**	0.00019	0.00053*
DEG8	0.0017***	0.00060***	0.0013***	0.00095***	0.00077***	0.0019	0.0012***	0.00032	0.00066***
DEG9	0.00028	0.00056***	0.0012***	0.00065**	0.0011***	0.0024	0.00039	0.0011***	0.0010***
DEG10	0.00065	0.00059***	0.00072**	0.00075***	0.00061***	0.0019	−0.00039	0.00086**	0.00068***
DEG11	0.00127**	0.00086***	0.0019***	0.0013***	0.0012***	−0.0020	0.00020	0.0012***	0.00075***
DEG12	0.00023	0.00056***	0.0015***	0.00064***	0.00058***	0.0030*	0.00096***	0.00071**	0.00025
DEG13	0.00023	0.00086***	0.0017***	0.00096***	0.00075***	−0.0012	0.00060*	0.00077**	0.00088***
DEG14	−0.00021	0.00042**	0.00052*	0.00062***	0.00064***	−0.00093	0.00060*	0.00051	0.00074***
DEG15	0.00060	0.00062***	0.0011***	0.00059***	0.00081***	0.0038***	0.00089**	0.0013***	0.00060***
DEG16	0.00046	0.00020	0.0015***	0.00059***	0.00050***	0.0068***	0.00048	0.00054*	0.00022
DEG17	0.0023***	0.00061***	0.0014***	0.0011***	0.00067***	0.0012	0.00098***	0.00076**	0.00080***
DEG18	0.000060	0.00033*	0.00096***	0.00070***	0.00054***	−0.0010	−0.00001	0.00065**	0.00064***
DEG19	−0.00031	0.00034**	0.00097***	0.00053***	0.00059***	0.0022	0.00047	0.00051*	0.00092***
DEG20	0.0023***	0.00049***	0.0012***	0.00061***	0.00091***	0.0025**	0.00038	0.0013***	0.00089***
DEG21	0.000070	0.00021	0.00085***	0.00030	0.00047***	0.0023	−0.00042	0.00085***	0.00069***
DEG22	0.00058	0.00027	0.0011***	0.00034*	0.00058***	0.0012	0.00035	0.00050*	0.00035
DEG23	0.00054	0.00054***	0.0012***	0.0010***	0.00075***	0.00023	−0.00009	0.00071**	0.00099***
DEG24	0.000070	0.00063***	0.0013***	0.00076***	0.0010***	0.0025*	0.00045	0.0013***	0.0012***
DEG25	0.00015	0.00019	0.00081**	0.00017	0.00046**	0.0017	−0.00073*0	0.00038	0.00069***
DEG26	0.00061	0.00047**	0.00047	0.00051**	0.00050**	−0.0041**	−0.00062	0.00063*	0.00020
DEG27	0.0014**	0.00073***	0.0017***	0.0010***	0.00073***	0.0027	0.00089**	0.0011***	0.00031
DEG28	0.00021	0.00024	0.00058	−0.00026	0.000060	0.0024	0.00050	0.0010**	0.00015
DEG29	−0.00042	−0.00056*	−0.00023	−0.00097***	−0.00098***	0.0025	0.00030	0.00085*	−0.00088**
DEG30	−0.00020	−0.00056	−0.000050	−0.00069	−0.00082*	0.00028	0.00043	−0.00049	−0.00049
DEG31	−0.00013	−0.00090*	0.00058	−0.0023***	−0.0011**	−0.0029	−0.0012	−0.00033	−0.00080
DEG32	0.00072	0.00099*	0.0019**	0.0012*	0.0015**	0.0031	0.0020**	0.0013	0.00073
DEG33	0.00082	−0.00035	0.00092	−0.00018	−0.000070	−0.0031	0.00064	0.00048	−0.0014
DEG34	−0.0041	−0.0024***	−0.0011	−0.0027***	−0.0017*	0.0061	−0.00051	−0.0045***	−0.0019
DEG35	−0.0047	−0.0043***	−0.0010	−0.0042***	−0.0046***	−0.023***	−0.0051**	0.0012	−0.0032*
DEG36	0.011**	−0.0067***	−0.0038	−0.0098***	−0.0078***	0.025**	−0.0023	−0.0035	−0.011***
DEG37	−0.0075	−0.0063*	−0.0058*	−0.0035	−0.0048	−0.019	−0.010**	−0.0089*	−0.0048
DEG38	0.0034	−0.011**	−0.0078	−0.0034	−0.011*	−0.029	−0.0096	−0.0072	−0.0083
DEG39	0.0069	0.0059	0.0082	0.015*	0.0135*	−0.041	0.0052	0.0026	0.020*
DEG40	0.019	−0.017**	−0.014*	−0.0053	−0.011	N/A	−0.037***	−0.0081	0.0062
Adj R^2	0.52	0.42	0.34	0.40	0.38	0.67	0.39	0.31	0.36
Obs.	1642	12332	5600	12333	12579	327	4667	7755	10776

[z]The statistical significance of the parameter estimates is indicated as follows: * = $0.10 \geq P$ value ≥ 0.05; ** = $0.05 \geq P$ value ≥ 0.01; *** = P value < 0.01.
[y]Variables are defined as follows: Time = time trend; APRRAIN-AUGRAIN = total cumulative rainfall (mm) by month; DEG0-DEG39 = total hours of exposure to temperature increments, where DEG0 is between 0.0°C and 0.9°C, DEG1 is between 1.0°C and 1.9°C, etc.; DEG40 = total hours of exposure to temperature of 40°C and above; Adj R^2 is the adjusted R^2 statistic; Obs. is the number of observations.

(i.e., the null hypotheses are rejected) for temperature or rainfall, with the exception being for temperature increments above 35°C. Equivalence of air temperature coefficients for variables for each month was collectively tested using a series of F-tests, with the null hypothesis of equality being rejected (i.e., P values = 0.00).

These statistical tests provide a strong indication that temperature and rainfall effects through the growing season are separable and that the marginal yield effects differ by month. The exception is for temperatures over 35°C, which are shown to be non-separable. Rainfall has a statistically different effect on yields depending on the

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Table 5. Critical maximum/minimum temperatures (°C) from DEG-MRAIN model, by crop (seasonal cumulative temperature increment and monthly rainfall variables)

Crop	Critical maximum temperature	Critical minimum temperature
Winter wheat	29	5
Spring wheat	29	5
Durum wheat	29	5
Oats	28	5
Barley	28	5
Spring rye	30	4
Fall rye	34	5
Flax	30	5
Canola	29	3

month in which the precipitation occurred. The *F* and *t*-test results suggest that a model with monthly cumulative values provides additional information over a model with seasonal weather variables and is therefore a better model of crop yields.

Critical maximum and minimum temperatures for the DEG-MTEMP model, by crop, are summarized in Table 6. In general, critical maximum temperatures are higher in the summer months than in spring; that is, heat tolerance for annual crops in the Canadian prairie region increases as the plants mature through the growing season. For minimum temperatures, critical values range from 5 to 16°C in April or May, but in general no critical minimum temperatures are evident in later months of the growing season. The low incidence of very cool air temperatures during the latter part of the growing season makes it more difficult to identify critical minimum temperatures.

The DEG-MTEMP formulation produced estimates for canola, barley, oats and spring wheat that were influenced by multicollinearity in the data. In particular, condition indices (Kennedy 2003, p. 213) calculated for the temperature variables indicated strong multicollinearity. This issue was addressed by estimating a revised model (DEG-PATEMP) for these four crops, in which some of the temperature increment variables were aggregated. These model results are discussed in the following section.

Table 6. Critical maximum/minimum temperatures (°C) from DEG-MTEMP model, by crop (monthly cumulative temperature increment and rainfall variables)

Crop	April	May	June	July	August
Critical maximum temperatures					
Spring wheat	30	34	29	N/A	40
Durum wheat	24	19	35	34	38
Oats	30	36	N/A[z]	N/A	38
Barley	31	34	31	N/A	38
Fall rye	23	20	34	37	37
Flax	26	26	35	35	42
Canola	32	32	34	N/A	38
Critical minimum temperatures					
Spring wheat	7	5	10	N/A	N/A
Durum wheat	5	15	N/A	3	N/A
Oats	5	N/A	N/A	N/A	N/A
Barley	5	N/A	8	N/A	N/A
Fall rye	5	16	N/A	1	N/A
Flax	7	14	N/A	1	N/A
Canola	5	5	N/A	N/A	N/A

[z]N/A indicates that no critical maximum or minimum temperature was identified from the model estimates for the particular crop.

Partial Aggregation of Cumulative Temperature Exposure Variables (DEG-PATEMP)

As noted earlier, in order to address multicollinearity problems a revised model (DEG-PATEMP) for canola, barley, oats and spring wheat was estimated, in which some of the temperature increment variables were aggregated. Different variable combinations were tested, with the final version being a model that included aggregated temperature variables for intervals above 30°C in June, July and August, and monthly values for all other variables.

Coefficient estimates from the DEG-PATEMP models were used to establish critical temperatures for the four crops (Table 7). In the spring months, critical maximum temperatures for spring wheat, canola, oats and barley range between 24 and 26°C. For the summer months of the growing season (i.e., June, July and August), critical maximum temperatures are 35–36°C. For all four crops, *P* values of parameter estimates for temperature increment variables above 34°C are greater than 10%, indicating that crop growth is close to zero (i.e., insignificant) in that range of temperatures. These results (i.e., critical temperatures increasing through the growing season from early to late summer) are consistent with previous agronomic research (e.g., Ferris et al. 1998; Angadi et al. 2000; Morrison and Stewart 2002; Ugarte et al. 2007; Kutcher et al. 2010) that concludes the anthesis or flowering stage of plant development is

Table 7. Critical maximum/minimum temperatures (°C) from DEG-PATEMP model, by crop (partially aggregated monthly cumulative temperature increment and monthly rainfall variables)[z]

Crop	April	May	June/July/August		
Critical maximum temperatures					
Spring wheat	24	25	35		
Oats	24	26	36		
Barley	24	26	35		
Canola	24	25	36		
Critical minimum temperatures					
	April	May	June	July	August
Spring wheat	7	14	N/A[y]	N/A	N/A
Oats	12	5	N/A	N/A	N/A
Barley	12	5	N/A	N/A	N/A
Canola	12	13	N/A	N/A	N/A

[z]Temperature increments were aggregated for temperatures above 30°C for June, July and August.
[y]N/A indicates that no critical maximum or minimum temperature was identified from the model estimates for the particular crop.

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most "sensitive" to high temperatures and that tolerance to heat increases through the growing season.

Critical minimum temperatures are 7–12°C in April and May (Table 7), whereas no critical minimum temperatures are identified for June, July and August, again likely due to relatively few observations of low temperatures during those months. Results for the DEG-PATEMP model, therefore, do not provide a clear signal for minimum critical temperatures.

While not the focus of the analysis, results for the different yield model formulations can be used to estimate yield growth rates over the sample period. In particular, coefficients for the time variables can be interpreted as the annual percentage change in yield (when multiplied by 100). These coefficients are provided in Table 8 for the three DEG models. All coefficients are statistically significant (P values ≤ 0.01) and positive, with the exception of spring rye, for which the growth rate is slightly negative (-0.63% yr^{-1}). The time variable coefficients for individual crops are consistent across the different versions of the DEG yield model. Yield growth for most of the crops over the sample time period is between 0.8% yr^{-1} to just over 1.0% yr^{-1}. The exceptions are canola, with a growth rate of 1.3–1.4% yr^{-1} and winter wheat, which has a growth rate (i.e., approximately 1.8% yr^{-1}) that is approximately double that of spring and durum wheat.

The results here support the hypothesis of progressive technical change in crop yields over the study period, and the magnitude of the growth rates is consistent with previous analysis. Stewart et al. (2009) estimate total factor productivity (TFP) growth rate in prairie crop production (1980–2004) to be 1.77%. While TFP is not identical to technical change, Stewart et al. (2009) report that technical change represents the largest component of the crop TFP growth. There is little information available regarding yield growth rates for individual crops in the Canadian prairie region. The estimates for durum wheat reported here are consistent with results from McCaig and Clark (1995).

Table 8. Time trend regression coefficients for models DEG-MRAIN, DEG-MTEMP and DEG-PATEMP, by crop[z,y]

Crop	DEG-MRAIN	DEG-MTEMP	DEG-PATEMP
Winter wheat	0.018	N/A[x]	N/A
Spring wheat	0.0088	0.0081	0.0081
Durum wheat	0.0089	0.0077	N/A
Oats	0.0088	0.0084	0.0084
Barley	0.010	0.010	0.010
Spring rye	−0.0063	N/A	N/A
Fall rye	0.012	0.010	N/A
Flax	0.0098	0.0095	N/A
Canola	0.014	0.013	0.013

[z]Model DEG-MRAIN uses seasonal cumulative temperature increment variables; model DEG-MTEMP uses monthly cumulative temperature increment variables; model DEG-PATEMP uses partially aggregated temperature increment variables (i.e., temperatures above 30°C aggregated for June, July and August); all three models use monthly cumulative rainfall.
[y]All coefficients have P values <0.01.
[x]N/A denotes that the model was not estimated for that particular crop.

CONCLUSIONS

The primary objective of this paper was to estimate the effect of extreme daily temperatures during the growing season on yields for major Canadian prairie cereal and oilseed crops, including winter wheat, spring wheat, canola, durum wheat, barley, oats, flax, fall rye and spring rye. A second objective was to test the accuracy of out-of-sample forecasting for three alternative aggregate temperature variables: monthly average temperature, GDD and the Schlenker and Roberts (2006, 2008) approach using cumulative exposure to incremental temperature ranges.

The Schlenker and Roberts (2006, 2008) approach (DEG-MRAIN model), using growing seasonal hourly air temperatures and monthly cumulative rainfall values, provided superior out-of-sample forecasting when compared with models using average air temperature or GDD. Disaggregation of the hourly air temperatures to monthly totals (DEG-MTEMP) proved to be statistically superior to the use of seasonal totals (i.e., DEG-MRAIN). In response to multicollinearity problems associated with the DEG-MTEMP model, a third version (DEG-PATEMP) was estimated in which air temperature variables above 30°C for June, July and August are combined into seasonal aggregated totals.

Overall, the Schlenker and Roberts approach provides evidence that crops in the Canadian prairie region are sensitive to temperatures in the 25–30°C range in April and May, but (depending on the crop) are able to withstand temperatures of up to 35 or 36°C in June, July and August. Evidence for critical minimum temperatures is less clear, but the signs of the coefficients, taken from the variables that exhibit the highest significance, indicate that critical minima range from 5 to 14°C in April and May, but are not a factor in June, July and August.

The results from this analysis of crop yield response to cumulative hourly temperatures are useful for research in a number of different areas, as well as for policy analysis. For example, studies of climate change often rely on average temperatures. However, this analysis demonstrates that the Schlenker and Roberts (2006, 2008) approach is superior in estimating the impact of critical maximum air temperatures on Canadian prairie crop yield. The relationship between yields and critical temperatures is also important in the study of agricultural production risk for the purposes of developing or assessing risk management instruments (e.g., crop insurance and other business risk management programs). As noted in the introductory discussion, agronomic research often makes use of heat and/or temperature measures in "controlling" for environmental influences when studying the effects of experimental

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treatments (e.g., seeding rate, nutrient levels) on yields. Having a means to capture the effects of extreme temperature events would be of value to these researchers. Finally, understanding the relationship between yields and critical temperatures is important in terms of motivating research into heat tolerant crops in the Canadian prairies as a means to adapt to future climate change.

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