A Bio-Economic Crop Yield Response (BECYR) Model for Corn and Soybeans in Ontario, Canada for 1959–2013

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This paper presents estimates of the effects of changing climate on crop yields for grain corn and soybeans in Ontario, Canada, for 1959–2013. We were able to use a database that is more comprehensive with respect to explanatory variables than some previous efforts had available. Our model includes climate variables, prices, land quality, groundwater level, CO2 concentration, and a time trend. Our results indicate that trends in temperature and precipitation during our study period have not yet resulted in appreciable threats to crop yields in the region.

Climate change is a widely discussed topic, and its effect on crop production has drawn attention. The projected reduction in crop yields due to the changing climate in some regions has raised concern1–3. Several studies have estimated the effects of changing climate on crop yields1,3–11. These models include variables reflecting the effects of weather, technology and land quality. Many models, however, have not included prices, groundwater level, or CO2 concentration. In Table 1, we compared the variables included those previous econometric crop yield modelling research for corn and soybeans with the variables included in our study. From Table 1, we can see that we used a database that is more comprehensive with respect to explanatory variables than some previous efforts had available. We have estimated county-level yield models for grain corn and soybeans for 29 counties in southern Ontario, Canada, for the period from 1959 to 2013. Our Bio-Economic Crop Yield Response (BECYR) model includes historical weather, price, land quality, groundwater level, local CO2 concentration and a time trend.

We use a unique weather dataset12 developed for this study. The weather data are from a new interpolated spatial climate dataset12, which was not available for previous studies. Previously, weather station data have been used in studies of this type. The limitation of weather station data is that there may be some distance between existing weather stations and the locations where crops are grown. The dataset that we have been able to access is based on a mathematical algorithm that interpolates weather station data for locations between stations. Daily temperature and precipitation are interpolated to the county-level based on the daily weather observations at 4267 weather stations across Canada12. We consider four definitions of the growing season12,13. We tested all four definitions and our modeling was based on the definition that gave us the best overall fit with our data. The growing season is characterized as starting on the day following the last occurrence of −2.2 °C at the beginning of the growing season in the spring and ending on the day preceding the first occurrence of −2.2 °C at the end of the growing season in the fall12. The growing season definition starts at the end of April and ends in the middle of October on average, which is consistent with the agronomic practices for corn and soybeans in studied region. For details of selecting the growing season definitions, please see the Supplementary Information.

According to our data and using the above definition, the length of the growing season in Ontario increased at an average rate of 1.45 days per decade for 1950–201313. Past studies found that longer growing season contributes to higher crop yields9,14. So, we hypothesize that part of the increase in crop yields that has previously been attributed to advances in technology may be attributable to the increased length of the growing season.

Besides, we construct a proxy variable to represent local CO2 concentration. There is seasonal variation of CO2 concentration in Ontario. The CO2 level reaches a peak between November and April (Fig. 1) and drops from May

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till July/August. Unfortunately, measurements of CO₂ concentration in Ontario are only available for the period from 2005 to 2016. However, CO₂ data in Mauna, Hawaii, are available back to 1958. But, the seasonality of the Hawaiian data is different from the Ontario data. The CO₂ in Hawaii peaks in May (Fig. 1) and drops from June to October. Then, it increases slowly from October to June. And the range of CO₂ variation in Ontario is larger than in Hawaii. The difference in seasonal variation might be due to the local climate. Hawaii is located in the tropics and the temperature is more uniform through the year compared to Ontario. So, photosynthesis happens all the year round in Hawaii but is limited during the winter in Ontario.

| Studied Crops, Time Periods, and Regions | Estimation Method and Functional Form | Variables Included |
|-----------------------------------------|--------------------------------------|--------------------|
| This Paper Corn & Soybeans 1950–2013: 29 counties in Ontario, Canada | Ordinary Least Squares (OLS) method Quadratic functional form | ✓ ✓ ✓ ✓ ✓ (FE/cropland area) |
| Houck & Gallagher (1976) Corn 1951–1971: US | OLS method Linear functional form | ✓ ✓ ✓ ✓ (Cropland area) |
| Kaufmann & Snell (1997) Corn 1969,1974,1978,1982, and 1987: counties in 8 states in the US | OLS method Quadratic functional form for weather | ✓ ✓ ✓ (Cropland area) |
| Rickard & Fox (1999) Corn 1889–1995: Ontario, Canada | OLS method Log-linear functional form Quadratic functional form | ✓ ✓ ✓ (Cropland area) |
| Schlenker & Roberts (2009) Corn, Soybeans 1950–2005: counties on the east of the 100° meridian in the US | Nonparametric method Step functional form for heat 8th degree Polynomial for heat Piecewise linear functional form for heat Quadratic functional form for time trend | ✓ ✓ ✓ ✓ (FE) |
| Cabas et al. (2010) Corn, Soybeans 1981–2006: 8 counties in southwestern Ontario, Canada | Feasible Generalize Least Square method Just and Pope production function | ✓ ✓ ✓ (FE) |
| Tolhurst & Alan (2015) Corn, Soybeans 1955–2011: counties in Illinois, Indiana, and Iowa, US | Nonparametric method Quadratic functional form for precipitation | ✓ ✓ |
| Miao et al. (2016) Corn & Soybeans 1977–2007: counties on the east of the 100° meridian in US | Instrumental Variable method Quadratic functional form | ✓ ✓ ✓ ✓ (FE) |

Table 1. Comparison of Variables Included in Previous Econometric Crop Yield Modeling Research for Corn and Soybeans. FE represents the county fixed effect. It is commonly used to estimate the county specific effect on crop yields, such as land quality. Groundwater level could be included in the county fixed effect, but it is not explicitly mentioned in past studies.

Figure 1. Actual and Proxy of Monthly CO₂ Concentration (ppm) in Hawaii and Ontario for 1959–2016. Black line: the actual CO₂ data in Mauna, Hawaii (1959–2016) from National Oceanic and Atmospheric Administration. Blue line: the actual CO₂ data in Egbert, Ontario (2005–2016) from The World Data Center for Greenhouse Gases. Redline: the proxy of CO₂ data in Egbert, Ontario (1959–2004). Discontinuities are due to missing values. The actual Hawaii and Ontario CO₂ data show a similar increasing trend, but the CO₂ concentration in Ontario varies more than in Hawaii. In addition, the CO₂ level in Ontario reaches a peak between November and April and drops from May till July/August. The CO₂ concentration in Hawaii peaks in May and drops from June to October. Variation in the CO₂ concentration in Ontario reflect the reduction in photosynthesis during the winter months. Photosynthesis is less variable during the year in Hawaii. So, we regressed the monthly Ontario CO₂ concentration on the linear corresponding value for Hawaii from 2005 to 2016. We then used the estimated coefficients from the regression to calculate the proxy serving for Ontario for 1959–2004, by substituting the Hawaii observations into the regression equation. See Table S6 for the estimated results and Fig. S2 for the residual plot in the CO₂ regression model.
In the absence of Ontario data for our study period and given the lack of seasonal synchronization of the Hawaiian and Ontario data, we elected to construct a proxy of historical Ontario CO₂ concentration for the period from 1959 to 2004. Figure 1 shows the actual CO₂ concentration in Ontario and Hawaii as well as the proxy of CO₂ concentration in Ontario. The proxy of CO₂ concentration and actual CO₂ concentration in Ontario has a similar pattern of seasonal variation. Figure 2 shows the residuals from the regression. Those residuals are generally small, so the fitted CO₂ presents the actual CO₂ well.

Most studies treat the effect of elevated CO₂ on crop yields as linear16–19, while recent studies find a nonlinear effect of elevated CO₂ on plant biomass20–22. Idso23 reported that the CO₂ effect on sugar cane yield is nonlinear. But no study has found a nonlinear effect of CO₂ on corn and soybean yields (Table 1). This is important to investigate because the prediction of future crop yields might be biased if CO₂ effect is not correctly modeled. To compare the linear and nonlinear CO₂ effects, we apply three versions of our models: 1) No CO₂ effect, 2) Linear CO₂ effect, and 3) Quadratic CO₂ effect.

Results and Discussion

Crop yield response to a pest dummy variable. There was an outbreak of soybean aphids in Ontario in 2001. To measure the effect of this pest event on yields, our soybean models include a dummy variable for the year 2001. Table 2 shows the estimated effects of weather, physical, and economic variables on grain corn and soybean yields. Table 2 shows that the dummy of 2001 has a statistically significant negative effect on soybean yields as expected. Soybean yield was reduced by about 30% in 2001 due to the outbreak.

Crop yield response to technology and CO₂. Most studies treat the effect of elevated CO₂ on crop yields as linear16–19. Table 3 summarizes some of these results for corn and soybeans and compares them with our results from Table 2. For corn, we find that yield increases by 0.04% per ppm (± 0.8% per ppm at 95% C.I.) of CO₂. Past studies17,18 report that the changes in yields for corn range from −0.10% to 0.27% per ppm of CO₂. For soybeans, we find that yield increases by 0.32% per ppm (± 1.26% per ppm at 95% C.I.) of CO₂. This increase is higher than previously reported results, which range from −0.0012% to 0.28% per ppm of CO₂16–19. But our confidence interval covers this range. We also find that the linear CO₂ effect on soybean is larger than that for corn. This is consistent with current crop physiology theory, which suggests that increasing CO₂ is more beneficial for C₃ crops than C₄ crops18,20.

Our results from a quadratic CO₂ effect, however, tell a more complex story. We find that corn yield decreases until CO₂ reaches 353 ppm, which was the average concentration during the growing season that occurred in 1994. Then, corn yield starts to increase at an increasing rate with CO₂ concentration. Reich et al.20 also find similar nonlinear CO₂ effect. However, our quadratic CO₂ effect on corn yield is larger than the effect reported by Reich et al.20. The decrease of yields with higher CO₂ could be a results of multicollinearity problem between the time trend and CO₂ variables. Even though the nonlinear effect of CO₂ on corn yields is found in recent studies, the nonlinear effect of CO₂ is still a question in the field of plant physiology. Reich et al.20 indicated that the plant biomass response to elevated CO₂ might be related to the soil N availability, but the explanation of this possible relationship is unknown yet. More researches are needed to answer this question.

For soybeans, we find that yield decreases until CO₂ reaches 360 ppm, which is the level that occurred in Ontario in 1998. Then, soybean yield starts to increase at an increasing rate with CO₂ concentration. Previous literature has reported inconsistent findings of a nonlinear effect of CO₂ on soybeans20,21. So, we have elected to use a linear CO₂ effect model in our results.

We acknowledge that collinearity between our proxy variable for CO₂ and our time trend means that it is difficult to separate the individual contributions of these variables on crop yields. The correlation coefficient of these two variables is 0.99. For corn, the Variance Inflation Factor (VIF) of time trend is 19 and the VIF of CO₂ is
| Versions of Crop Yield Model | Corn Yield Model | Soybean Yield Model |
|-----------------------------|----------------|-------------------|
| (Dependent Variable = Grain Corn Yields) | (Dependent Variable = Soybean Yields) |
| **Effects of CO₂** | | |
| **Independent Variables** | No CO₂ Effect | Linear CO₂ Effect | Quadratic CO₂ Effect |
| Precipitation Before Growing Season | −0.1091*** | −0.1088*** | −0.08372*** |
| (0.04055) | (0.04156) | (0.04095) |
| Precipitation During Growing Season | 0.1697*** | 0.1697*** | 0.1631*** |
| (0.01649) | (0.01646) | (0.01645) |
| Degree Days During Growing Season | 0.1869*** | 0.1867*** | 0.1866*** |
| (0.02179) | (0.02210) | (0.02160) |
| Corn Price Lagged One-Year | 25.70*** | 25.71*** | 21.82*** |
| (2.057) | (2.05) | (1.958) |
| Fertilizer Price Index | −71.29*** | −71.33*** | −92.88*** |
| (8.952) | (8.789) | (9.069) |
| Trend | 0.2906* | 0.2563 | 2.737*** |
| (0.1691) | (0.3211) | (0.4153) |
| Local CO₂ During Growing Season | 0.04453 | 0.04453 | −16.35*** |
| (0.4454) | (1.77) |
| Square of Precipitation Before Growing Season | 0.0002489*** | 0.0002483*** | 0.0001937*** |
| (0.00008557) | (0.00008762) | (0.00008565) |
| Square of Precipitation During Growing Season | −0.0001594*** | −0.0001596*** | −0.0001517*** |
| (0.00001669) | (0.00001668) | (0.00001733) |
| Square of Degree Days During Growing Season | −0.00006497*** | −0.00006496*** | −0.00006460*** |
| (0.000009012) | (0.000009010) | (0.000008757) |
| Square of Corn Price Lagged One-Year | −4.002*** | −4.009*** | −3.589*** |
| (0.3407) | (0.3424) | (0.3330) |
| Square of Fertilizer Price Index | 22.59*** | 22.60*** | 28.90*** |
| (2.755) | (2.723) | (2.821) |
| Square of Trend | 0.02325*** | 0.02275*** | −0.01624*** |
| (0.002395) | (0.006010) | (0.007021) |
| Square of Local CO₂ During Growing Season | 0.02315*** | 0.02315*** | 0.02384*** |
| (0.002384) |
| Interaction of Precipitation and Degree Days | 0.0002266*** | 0.0002265*** | 0.0002201*** |
| (0.00002119) | (0.00002121) | (0.00002066) |
| Adjusted R-Square | 0.7869 | 0.7864 | 0.7919 |
| F-Value | 503.0 | 466.7 | 453.4 |
| **Effects of CO₂** | | |
| **Independent Variables** | No CO₂ Effect | Linear CO₂ Effect | Quadratic CO₂ Effect |
| Dummy of 2001 | −11.53*** | −11.36*** | −11.09*** |
| (0.9217) | (1.000) | (0.9876) |
| Precipitation Before Growing Season | 0.03554 | 0.03759 | 0.04349* |
| (0.02401) | (0.02498) | (0.02545) |
| Precipitation During Growing Season | 0.07197*** | 0.07143*** | 0.07058*** |
| (0.01073) | (0.01047) | (0.01048) |
| Degree Days During Growing Season | 0.05434*** | 0.05310*** | 0.05020*** |
| (0.007541) | (0.008941) | (0.009281) |
| Soybean Price Lagged One-Year | 7.582*** | 7.607*** | 7.405*** |
| (0.6085) | (0.6106) | (0.6094) |
| Fertilizer Price | −50.25*** | −50.55*** | −53.39*** |
| (4.79) | (4.635) | (4.623) |
| Trend | 0.03450 | −0.05598 | 0.0310*** |
| (0.07523) | (0.1765) | (0.2175) |
| Local CO₂ During Growing Season | 0.1208 | −3.352*** |
| (0.2431) | (0.7144) |
| Square of Precipitation Before Growing Season | −0.00005486 | −0.00005929 | −0.00007115 |
| (0.00005219) | (0.00005418) | (0.0000553) |

Continued
CO2 concentration is the combination of annual all items CPI. The degree days during the growing season refers to the degree days above 10 °C during the growing season. The crop price in Ontario and fertilizer price index in Canada is adjusted the inflation by annual all items CPI (2002 = 100). CO2 concentration is the combination of the proxy of CO2 (1959–2004) and actual CO2 (2005–2013) in Ontario.

Effects of CO2 Concentration (a: N = 1594, b: N = 829) indicate significant coefficients with a significance level of 0.01, 0.05, and 0.1, respectively. The values in parentheses are standard errors. Precipitation during the growing season increases corn and soybean yields on average. Precipitation and temperature levels associated with peak yields are elected to study the time period from 2009–2013. To explore if recent precipitation and degree days had exceeded the water and heat levels associated with peak yields, we elected to study the time period from 2009–2013.

For corn and soybeans, the VIF of time trend is 18 and the VIF of CO2 is 33. All the above values indicate that there is a multicollinearity problem between time trend and CO2 variables. So, we cannot compare the individual contributions of our proxy variable for CO2 and the time trend on crop yields.

Crop yield response to weather variables. Our results (Table 2) indicate that corn and soybean yields respond to the precipitation before the growing season in different ways. Corn yield decreases with more precipitation before the growing season while soybean yield increases. Precipitation before the growing season can impair the timeliness of tillage operations and reduce soil temperature. Soybeans can be planted later than corn in Ontario without incurring a yield penalty. So excess moisture in the spring can shift planted area away from corn and toward soybeans and it can reduce yields in the land that is planted with corn. In average, the increasing precipitation before the growing season reduces 0.00045% of corn yield per year and increases 0.0017% of soybean yield per year.

A longer growing season leads to an increase in precipitation during the growing season and also an increase in degree days during the growing season because there are more days for which precipitation and temperature are measured. Degree days during the growing season is the accumulation of the positive difference between daily average temperature and base temperature (10 °C) during the growing season. According to the plant physiology theory, when plants received either insufficient or excess moisture and heat, the physiology processes of plant would be impeded. This can delay corn planting and germination. Soybeans can be planted later than corn in Ontario without incurring a yield penalty. So excess moisture in the spring can shift planted area away from corn and toward soybeans and it can reduce yields in the land that is planted with corn. In average, the increasing precipitation before the growing season reduces 0.00045% of corn yield per year and increases 0.0017% of soybean yield per year.

Table 2. Corn and Soybean Yield Models in Ontario 1959–2013 Using Fixed Effects Models with Alternative Effects of CO2 Concentration (a: N = 1594, b: N = 829) indicate significant coefficients with a significance level of 0.01, 0.05, and 0.1, respectively. The values in parentheses are standard errors. Precipitation during the growing season increases corn and soybean yields on average. Precipitation and temperature levels associated with peak yields are elected to study the time period from 2009–2013. To explore if recent precipitation and degree days had exceeded the water and heat levels associated with peak yields, we elected to study the time period from 2009–2013. For corn and soybeans, the VIF of time trend is 18 and the VIF of CO2 is 33. All the above values indicate that there is a multicollinearity problem between time trend and CO2 variables. So, we cannot compare the individual contributions of our proxy variable for CO2 and the time trend on crop yields.

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We find that corn and soybean yields increase at a decreasing rate as crop prices increase (Table 2). We also find that corn yield response to economic variables. Agricultural economists have argued that crop yields are influenced by output and input prices. However, price variables have been omitted from several recent studies on the effects of climates on crop yields (Table 1). The effect of the crop price on yields is theoretically ambiguous. Higher expected crop prices might induce farmers to use purchased inputs like fertilizer more intensively, increasing yield. But a higher expected crop price might also induce farmers to increase area planted to that crop, expanding production onto less suitable soils, reducing yields. A higher fertilizer price would result in less intensive fertilizer use and lead to a reduction in yields. Thus, the remaining land with high corn yield might increase the average corn yield. Therefore, the effect of fertilizer price on yields is theoretically ambiguous. As corn and soybeans are planted in the spring, farmers do not know the crop prices that they will receive until after they plant. We used the crop price lagged one-year in our models to represent farmers’ expectations. We find that corn and soybean yields increase at a decreasing rate as crop prices increase (Table 2). We also find that corn and soybean yields have been beneficial for corn yields in the U.S since 1981.

### Table 3. Comparison of The Linear and Non-Linear Effects of CO₂ on Crops in Selected Elevated CO₂ - Plants Relationship Studies

| Studies            | Time Period | Regions          | Method                                      | Comparison of Results                                                                 |
|--------------------|-------------|------------------|---------------------------------------------|---------------------------------------------------------------------------------------|
| ...                |             |                  |                                             | Non-linear: The direction and turning point of CO₂ effect on plants                    |
| ...                |             |                  |                                             | linear: The percentage increase in crop yields per ppm                                 |
| Kimball (1983)     | Various years | Various Countries | Review enclosure studies                     | 0.039–0.13%                                                                            |
| Cure & Acoc (1986) | Various years | Various Countries | Review enclosure studies                     | −0.10–0.27%                                                                            |
| Long et al. (2006) | 1992–2005    | Various Countries | Free-Air Concentration Enrichment Experiment (FACE) | 0%                                                                                   |
| Ziska & Bunce (2007)| Various years | Various Countries | Review enclosure and FACE studies            | −0.00012–0.28%                                                                       |
| This Paper         | 1959–2013   | Ontario, Canada   | Bio-Economic Crop Yield Response Model (BECYR) | 0.04% ± 0.80%                                                                         |
|                     |             |                  |                                             | 0.32% ± 1.26%                                                                         |
| ...                |             |                  |                                             | ...                                                                                    |

The document discusses the effects of climate change on crop yields in Ontario and the United States, including the use of FACE (Free Air Concentration Enrichment) studies to investigate the effect of CO₂ in the field that completely open to the atmosphere. The linear CO₂ effect in this paper is based on average Ontario crop yields for 1959–2013 (e.g. coefficient of CO₂ concentration / Ontario corn yields 1959–2013). The 95% confidential interval is calculated. The quadratic CO₂ effect in this paper is calculated by solving the first-order condition of crop yields in terms of the CO₂ concentration.
global food security. The above discussion suggests that for a temperate climate country like Canada, threats to crop production from climate have yet to materialize. This suggests the possibility that climate is causing changes in regional or national crop yields in Canada. Weber and Hauer31 found that all provinces in Canada would benefit from climate change. Long-term CO₂-plant experimental data are not easy to obtain. Our BECYR model constructs a synthetic CO₂ proxy. This method contributes the estimation of crop yield model when actual long-term CO₂ data are unavailable.

Table 4. The Change in Crop Yields Attributable to Each Time-Variant Variable per Year in Average as A Share of the Grain Corn and Soybean Yields in 1959. The percentage of crop yields in 1959 results from each variable is calculated as the change in crop yield attributable to one variable divided by the fitted crop yield in 1959. We combine the effects of precipitation and degree days because of the interaction effect between precipitation and degree days.

| Crops       | Grain Corn | Soybeans |
|-------------|------------|----------|
| **Effects of CO₂ Variables** | No CO₂ Effect | Linear CO₂ Effect | No CO₂ Effect | Linear CO₂ Effect |
| Precipitation before growing season | −0.0045% | 0.0017% | 0.00045% | 0.0017% |
| Precipitation and degree days during the growing season | 0.085% | 0.084% | 0.13% | 0.13% |
| Crop price lagged one-year | −0.2% | −0.2% | −0.3% | −0.3% |
| Fertilizer price index | 0.022% | 0.022% | 0.065% | 0.065% |
| Time trend | 1.1% | 1.0% | 0.77% | 0.43% |
| CO₂ concentration | 0.043% | 0.34% |

We used the current year index of fertilizer price as the input price in our models. We find both positive and negative effects of fertilizer price on crop yields for our study period. We find that when the fertilizer price index is lower than approximately 160 (100 = dollars in year 2002), corn and soybean yields decrease at a decreasing rate as the fertilizer price goes up (Table 2). When the fertilizer price index is higher than approximately 160 (100 = dollars in year 2002), crop yields increase at an increasing rate as the fertilizer price gets higher (Table 2). In average, decreasing fertilizer price increases 0.022% per year in corn yield and 0.065% per year in soybean yield (Table 4).

Conclusion
This paper builds on previous research on the effects of climate on corn and soybean yields in Ontario, Canada. We constructed a database that is more comprehensive with respect to explanatory variables included in the estimation. Our model includes climate variables, prices, land quality, groundwater level, CO₂ concentration, and a time trend. We use a unique annual panel dataset for 29 counties in Ontario for the time period from 1959 to 2013. Our results indicate that historical trends in temperature and precipitation have not yet resulted in appreciable threats to crop production in Ontario, Canada. However, the prospect of more frequent extreme climate events calls for further research on the effect of climate on crop yields. We are undertaking spatial stochastic simulation modeling to investigate this possibility.

A growing body of evidence suggests that changes in climate are or will constitute a threat to crop production in some major crop producing regions of the world11,32,33, including the United States1–3. The effect of changing climate on crop production is regional specific. Our research as well as previous work at the national level in Canada11 suggest that historical trends in temperatures and precipitation have not yet had an adverse effect on crop yields in Canada. Weber and Hauer11 found that all provinces in Canada would benefit from climate change. The above discussion suggests that for a temperate climate country like Canada, threats to crop production from climate have yet to materialize. This suggests the possibility that climate is causing changes in regional or national comparative advantage in agriculture. This may have important implications for future agricultural trade and global food security.

Past studies11,34,35 use a fixed fertilization effect of CO₂ from experimental studies to predict future crop production. However, the fertilization effect of CO₂ may change by time period, crops, and studied locations. Long-term CO₂-plant experimental data are not easy to obtain. Our BECYR model constructs a synthetic CO₂ proxy. This method contributes the estimation of crop yield model when actual long-term CO₂ data are unavailable.

Method and Data
We model crop yield as a function of precipitation and degree days during the growing season, precipitation before the growing season, cropland quality, groundwater level, crop price, fertilizer price, local CO₂ concentration and a time trend. Grain corn and soybeans are the two most valuable field crops in Ontario. Our panel data extend from 1959 to 2013 for 29 counties in Ontario, Canada. A quadratic functional form is used for every variable except the dummy variables to test for non-linear effects. We estimated two types of model: a pooled regression model and a fixed county effects model. The time-invariant variables, cropland quality and groundwater, are included in the pooled regression model but not in the fixed county effects model. The advantage of a Fixed Effects model is that it to capture the effect of county-level variation in local factors, such as soil type, groundwater, topography and others. Due to poor data quality for these local factors, the pooling regression models are less likely to capture their effects. In addition, the F-test of fixed effect model is higher than that of pooling regression model. So, our study focusses on the results from county level fixed effect models.

The Fixed Effects model allows the intercept term to vary across the 29 counties. Note that, the time-specific effect is not discussed here since we focus on the specific effects across counties and we have included the variable of time trend. This model assumes that county-specific effect is unique for each county but constant over time. Allowing the intercept to vary across counties is useful to capture the effects of other factors not included in each
county. So, parameters $\alpha_i$ vary across counties but not over time, and parameters $\beta, \gamma$ and $\theta$ are constant for all counties and years. The model also includes an individual error term $e_{i,c}$, which varies across both counties and times. Equation (1) shows the Fixed Effects model for corn yield with quadratic CO2 effect:

$$Y_{i,c} = \alpha_0 + \alpha_1 D_1 + \alpha_2 D_2 + \cdots + \alpha_{29} D_{29} + \beta_1 PBGS_{i,c} + \beta_2 PRECI_{i,c} + \beta_3 DD_{i,c} + \beta_4 P_{i-1} + \beta_5 PF_i + \gamma_1 T_i + \gamma_2 CO_{i,t} + \gamma_3 PBGS_{i,c}^2 + \gamma_4 PRECI_{i,c}^2 + \gamma_5 DD_{i,c}^2 + \gamma_6 P_{t-1}^2 + \gamma_7 PF_i^2 + \gamma_8 T_i^2 + \gamma_9 CO_{i,t}^2 + \theta (PRECI_{i,c} - PRECI_{i,c}^2) DD_{i,c} - DD_{i,c} + e_{i,c}$$

where

$Y_{i,c}$ is the annual corn grain yield in year $t$ and county $c$;

$D_c$ ($c = 1, 2, \ldots, 29$) is the dummy variable for each of the 29 counties;

$PBGS_{i,c}$ is the total precipitation during the growing season, which in this context is the 3 months prior to growing season in year $t$ and county $c$;

$PRECI_{i,c}$ is the mean of $PRECI_{i,c}$ for all studied counties and years;

$DD_{i,c}$ is the degree days during the growing season with 10°C base temperature in year $t$ and county $c$;

$P_{t-1}$ is the corn price in Ontario for the previous year $t-1$;

$PF_i$ is the fertilizer price index in Canada for the current year $t$;

$T_i$ is the time trend;

$CO_{i,t}$ is the proxy of CO2 concentration in Ontario for the year $t$;

$DD_{i,c}$ is the mean of $DD_{i,c}$ for all studied counties and years.

The model considers the linear and quadratic effect of each factor as well as the centering interaction between precipitation and degree days. The centering interaction is used to reduce the correlation between the variables and their interaction term. The estimated results are robust for heteroskedasticity and autocorrelation.

For validation, we did hold-out validation and out-of-sample simulation. The results from both methods indicate that our crop yield models for grain corn and soybeans are reliable. For details of the validation, please see the Supplementary Information.

Many counties in Ontario experienced changes in county boundaries from 1959 to 2013. There is a concern that yield data at the county level significantly change due to the historical county boundary changes. Xu28 had determined the effect of county boundary changes on yield data and adjusted county boundaries. We used the adjusted county boundaries from her work for our crop yields and climate data.

Data on corn yields (Bushels/Acre) and soybean yields (Bushels/Acre) were collected from 1959 to 2013. The yield data were obtained from Agricultural Statistics for Ontario. Due to county boundary changes described above, we did retroactive adjustment to the original crop yields data for the years prior to the boundary changes for each county. For the counties with county boundary adjustment, the harvest area weighted average crop yields data are calculated for the new county boundary. Equation (2) shows the formula of the harvest area weighted average crop yields:

$$Yield_{New} = \frac{Yield_1 \times Area_1 + Yield_2 \times Area_2}{Area_1 + Area_2}$$

where

$Yield_{New}$ is the harvest area weighted average crop yields in the new combined county;

$Yield_k$ ($k = 1, 2, \ldots$) is the crop yield in county $k$;

$Area_k$ is the crop harvest area in county $k$.

For soybeans, yield data are not available for all counties over the whole study period. From the 1950s to 1970s, the planting of soybeans was restricted to southern Ontario due to that region having the longest and warmest growing season in Canada.86. Advanced breeding technology allowed farmers to grow soybeans outside of Southern Ontario starting in the 1980s. For this reason, very few soybeans were planted outside of Southern Ontario prior to that period. As a result, the data for soybean production and harvest area is very small in the early period and missing in some years. There is a concern that these data for small-scale soybeans production cannot well represent the soybean production in Ontario and therefore widens the variance of soybean yields. Therefore, we excluded soybean yields data for counties with harvest area less than 1,500 acres per year. In addition, to keep the continuity of soybean yields data, we excluded the soybean yields data in the early period until no data were missing. So, the Soybean yield data are missing in some years in some counties until the year of 1996. We estimated soybean yield model for two different periods: 1) the period of 1959–2013, which is unbalanced panel; and 2) the period of 1996–2013, which is balanced panel. The results from these two tests are similar. The estimated coefficients show the same sign and level of significance. Since the results are similar, we used the model estimated the period of 1959–2013, as it is based on more observations which allow us to better measure the effect of changing climate on crop yields over time.

Climate data were obtained from Natural Resources Canada (NRCan). The data includes historical precipitation before the growing season (mm) ($PBGS$), precipitation during the growing season (mm) ($PRECI$) and degree days during the growing season ($°C$) ($DD$) for the period.
Economic factors include real crop prices and fertilizer price index. We use the Consumer Price Index (CPI) from Statistics Canada, CANSIM Table 326-0021 to convert nominal crop and fertilizer prices to real prices to adjust inflation. As corn and soybeans are planted in the spring, farmers do not know the crop prices that they will receive until after they plant. So, the 1-year lag of crop price is used as the expected crop price in the models for corn and soybeans. Corn price data (dollars per metric ton) in Ontario from 1949 to 2012 were obtained from Statistics Canada CANSIM Table 001-0010 and Table 002-0043 for 1949 to 1984 and 1985 to 2012, respectively. Soybean price data (dollars per metric ton) in Ontario from 1949–2012 were obtained from Statistics Canada CANSIM Table 001-0010, Publication 22-007 and CANSIM Table 002-0043, for 1949 to 1984, 1985 to 1991, 1992 to 2012, respectively. The monthly price data are averaged to obtain annual data.

The composite fertilizer price index in Canada is used as the nominal fertilizer price (PFt). The fertilizer price index (index 1998=100) in Canada from 1959 to 2013 was obtained from Statistics Canada Publication 62-004, CANSIM Table 328-0001, CANSIM Table 328-0014 and CANSIM Table 328-0015, for 1959 to 1961, 1961 to 1998, 1998 to 2002, and 2002 to 2013. The quarterly fertilizer price index is averaged to obtain annual observations.

Technology development plays an important role in crop production, such as the development in plant breeding, and management practices in production systems. A time trend is used as a proxy of technology in this study for each crop. The time trend is a number sequence from 1 to 55.

The monthly CO2 data in Egbert, Ontario for 2005–2016 is collected from The World Data Center for Greenhouse Gases (WDCGG). The monthly CO2 data in Mauna, Hawaii is collected from the National Oceanic and Atmospheric Administration (NOAA). We used the following procedure to construct a proxy of historical Ontario CO2 concentration for the period from 1959 to 2004. We first calculated the correlation coefficients for monthly average CO2 concentration in Ontario and Hawaii for 2005–2016. The 12 correlation coefficients are all above 0.85. Then, we regressed the monthly Ontario CO2 concentration on monthly Hawaii CO2 concentration for 2005–2016. We used a linear monthly fixed effects model. We found that the adjusted R-square is 0.97, which shows a high goodness of fit. In addition, the estimated coefficients for Hawaii CO2 concentration and monthly fixed effects are all statistically significant. We then used the estimated coefficients to construct a proxy for Ontario CO2 concentration for 1959–2004. For the details of the methods and estimation results, see the Support Information (Tables S5–S6).

Data availability
The data and R code used in this paper are available at the University of Guelph data depository system (https://doi.org/10.5683/SP2/6OJSHE). All the other method and materials are present in the paper or supplementary information.

Received: 23 September 2019; Accepted: 1 April 2020; Published online: 24 April 2020

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Acknowledgements

We thank Brady Deaton, Rebecca Shortt and Deborah Brooker for their comments and suggestions on this paper. Funding supported by the Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA) UofG2013-1552 and UofG2017-2868.

Author contributions

G.F. supervised and conceptualized the overall research. G.F. acquired funding for the project. Q.X. conducted literature review, collected and analyzed data, estimated models by econometric methods, conducted validation of the model. D.W.M. provided the interpolated weather dataset. D.W.M., G.P., and Z.L. provided an understanding of agronomy background, soil quality, weather variables, and economic analysis to help Q.X. and G.F. create the model. Q.X. wrote the first draft and all authors jointly revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41598-020-63765-3.

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