Canadian Journal of Soil Science
Revue canadienne de la science du sol

**Evaluation of the Environmental Policy Integrated Climate
(EPIC) Model on Predicting Crop Yield in the Canadian
Prairies, a Case Study**

Journal:	<i>Canadian Journal of Soil Science</i>
Manuscript ID	CJSS-2017-0044.R2
Manuscript Type:	Article
Date Submitted by the Author:	21-Jul-2017
Complete List of Authors:	Lychuk, Taras; Agriculture and Agri-Food Canada, Brandon Research and Development Centre Moulin, Alan; Agriculture and Agri-Food Canada, Research Branch Johnson, Eric; University of Saskatchewan, Plant Sciences Olfert, Owen; AAFC, Brandt, Stewart; Northeast Agricultural Research Foundation, ; Izaurrealde, Cesar; University of Maryland at College Park, Geographical Sciences; University of Maryland
Keywords:	EPIC model, Agricultural inputs, Cropping diversity, Modeling, Canadian Prairie

SCHOLARONE™
Manuscripts

Evaluation of the Environmental Policy Integrated Climate (EPIC) Model on Predicting Crop Yield in the Canadian Prairies, a Case Study

Taras E. Lychuk^{1,*}, Alan P. Moulin¹, Eric N. Johnson², Owen O. Olfert³, Stewart A. Brandt⁴,
Roberto C. Izaurralde⁵

*Corresponding Author: Tel: (204) 578-6640 Fax: (204) 578-6524

E-mail: Taras.Lychuk@agr.gc.ca

¹Agriculture and Agri-Food Canada, Brandon Research and Development Centre, 2701 Grand
Valley Road, Brandon, Manitoba R7A 5Y3, Canada.

²University of Saskatchewan, Department of Plant Sciences, 51 Campus Drive, Saskatoon,
Saskatchewan S7N 5A8, Canada

³Agriculture and Agri-Food Canada, Saskatoon Research and Development Centre,
107 Science Place, Saskatoon, Saskatchewan S7N 0X2, Canada

⁴Northeast Agricultural Research Foundation, P.O. Box 1240,
Melfort, Saskatchewan S0E 1A0, Canada

⁵University of Maryland, College Park, Department of Geography, 2181 LeFrak Hall,
College Park, MD 20740, United States of America

ABSTRACT

The Environmental Policy Integrated Climate (EPIC) model was updated with relevant weather, tillage, and crop management operations from the 1994-2013 Alternative Cropping Systems (ACS) study to assess simulations of annual and long-term yield of wheat, barley, and canola. Linear regression and coefficients of determination (R^2), root mean square error of prediction (RMSE), the d index and paired sample t -test were used to assess the relationship between simulated and experimental values. Simulations indicated that the model captured long-term yield trends, but was less accurate at predicting annual variations. These variations were due to variability of soil properties at the research field, terrain attributes, extreme weather events, and the model's overestimation of available nitrogen (N) under low-N input systems. The R^2 , RMSE, and the d index values on long-term yield were $R^2 = 0.74$, $\text{RMSE} = 205 \text{ kg ha}^{-1}$, $d = 0.75$ for wheat; $R^2 = 0.90$, $\text{RMSE} = 226 \text{ kg ha}^{-1}$, $d = 0.73$ for barley; $R^2 = 0.98$, $\text{RMSE} = 238 \text{ kg ha}^{-1}$, $d = 0.76$ for canola, indicating good model performance. The EPIC model effectively simulated crop yields affected by agricultural inputs and cropping diversity, and may be used to assess future cropping decisions and agronomic management.

Short Title: Lychuk et al. (2017) Evaluation of the EPIC model on predicting crop yield

Key words: EPIC model, agricultural inputs, cropping diversity, modeling, Canadian Prairies.

Abbreviations: ACS - Alternative Cropping System Study; GS - growing season; EPIC - Environmental Policy Integrated Climate Model; ORG - Organic input; RED - Reduced input; HI - High input; LOW - Low diversity; DAG - Diversified annual grains; DAP - Diversified annual perennials.

Farmers in the Canadian Prairies may diversify their production in order to reduce their reliance on fertilizers and pesticides, increase environmental sustainability, and to manage pests and plant diseases (Brandt and Ulrich 2001). A long-term interdisciplinary field experiment was conducted from 1994 to 2013 at a research site in the Canadian Prairies (Scott, Saskatchewan) to enhance understanding of the roles of agricultural inputs and cropping diversity in sustaining crop production and soil quality (Brandt et al. 2010). This 19-year study combined rotations and agricultural input systems typical of the Canadian Prairies. The rotations used by producers on the Canadian Prairies include summer fallow and cereal monocultures; a diversity of cereal and broadleaf crops with minimal use of summer fallow; and a combination of annual and perennial crops. In this study, three levels of rotation and diversity were combined with organic, low and high categories of agricultural inputs resulting in a 3 by 3 matrix (Brandt et al. 2010). Farms typical of each of the diversity levels may be found within any input level. This long-term study was comprehensive as it captured farm practices typical of the Canadian Prairies within one of the 9 crop diversity x input level systems.

The Environmental Policy Integrated Climate (EPIC, Version 1102) model (Gassman et al. 2005; Izaurrealde et al. 2012; Williams 1995) was calibrated and validated using input parameters from

this field study. The validated model was later used to estimate changes in wheat, barley, and canola yields under future climate scenarios at the research site, as described in a companion paper by Lychuk et al. (2017b). Originally created in 1984 to quantify the effects of erosion on soil productivity (Williams et al. 1984), EPIC has evolved into a comprehensive biophysical process model that simulates crop and biomass production, soil processes, and interactions in the system based on detailed farm management practices and climate data. In the past, the EPIC model has been successfully applied in simulations for the analysis of cropping systems in small grains and oilseed rotations in Canada, USA, and other countries (Balkovič et al. 2013; Lee and Archer 2014; Lychuk et al. 2014; Lychuk 2014; Moulin and Beckie 1993). The model can simulate biomass production and yields of hundreds of plant species including crops, native grasses and trees; inter-crops, and cover-crop mixtures for a large number of scenarios. These scenarios include complex rotations with management operations such as tillage, irrigation, fertilization and liming. The model accounts for the effects of tillage practices on surface residues; soil bulk density; residue and nutrients mixing in the surface layer; water and wind erosion; soil hydrology; soil temperature and heat flow; carbon (C), nitrogen (N), and phosphorus (P) cycling; effects of fertilizer and irrigation on crop growth; fate of pesticides; and economics. A coupled carbon-nitrogen sub-model was implemented to simulate terrestrial C dynamics as affected by environmental and management factors. For more detailed information on EPIC algorithms and an in-depth description of the model refer to Izaurre et al. (2006).

Simulation models allow researchers and scientists to assess short- and long-term management concerning crop production and environmental quality. Successful validation of a process-based model like EPIC with experimental yields and soil data typical of farming practices in the Canadian Prairies, would allow researchers to assess yield dynamics and changes in soil and

environmental quality parameters due to climate change. The objective of this modeling study was to assess EPIC with respect to simulations of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and canola (*Brassica napus* L.) yields in response to agricultural inputs and cropping diversity as validated with experimental data from the ACS study. Details on the utilization of this validated model to assess yield changes in future wheat, barley, and canola under future climate scenarios at the research site are presented in a companion paper (Lychuk et al. 2017b).

MATERIALS AND METHODS

Description of the Alternative Cropping System (ACS) Study

The Alternative Cropping System (ACS) experiment was established in 1994 at the Agriculture and Agri-Food Canada Research Farm at Scott, Saskatchewan (52°22'N; 108°50'W; elevation 713 m). The ACS study completed its final cycle in 2013. The soil is a Dark Brown Chernozem (coarse-loamy textured mesic Typic Haploboroll, US Soil Classification) (Table 1) developed from a modified glacial till (Clayton and Ellis 1952). Slopes vary from 1 to 3% from east to west and northwest. Nine cropping systems, with 6-year rotations, were initiated in 1995. The nine cropping systems were combinations of three input management strategies applied to three levels of cropping diversity (Table 2). The three input levels were: (1) organic (ORG, non-chemical pest control and nutrient management practised under conventional tillage to reflect practices used by organic growers); (2) reduced (RED, no-till practices and integrated long-term management of pests and nutrients); and (3) high (HI, pesticides and fertilizers used “as required” under conventional tillage). The three diversity levels were: (1) a low crop diversity system (LOW, wheat, oilseed and fallow or green manure based rotations); (2) a diversified annual grains system (DAG, diversity of cereal, oilseed and pulse crops); and (3) a diversified annual perennial systems (DAP, mix of grain and forage crops). The experimental design was a

split-plot with four replications, the input levels, crop diversity and crop phases were the main, sub, and sub-sub plots, respectively. The size of the experimental site was 16 ha, and the dimensions of each subplot were 40 m x 12.8 m. Fertilizer, cultural and crop protection practices for the study were described in a companion paper by Lychuk et al. (2017b) and by Brandt et al. (2010).

Description of the EPIC Model Parameters

The EPIC model (Williams 1995) was used to simulate wheat, barley and canola grain yields, and was initialized with baseline physical and chemical properties (Table 1) including bulk density, sand and silt contents, pH, organic C contents, $\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$, and spring and fall soil moisture. These baseline soil variables were measured at 160 locations in a systematic unaligned grid across the experimental area in 1994 prior to establishment of experimental treatments and interpolated for each plot with ordinary kriging (Davis 2002), after the site area was uniformly seeded to barley and fertilized to minimize spatial variability of residual fertility. Details of soil sampling and determination of nutrient status procedures are provided in Lychuk et al. (2017b).

The baseline soil organic C fractions in the EPIC model were set as microbial (4%), slow (26%) and passive (70%). The daily weather data (maximum and minimum temperatures, solar radiation, relative humidity, wind speed, and precipitation) from the Environment Canada (Environment Canada 2014) weather station located at the Scott Research Farm were used for the simulations. The growing season precipitation and average maximum and minimum GS temperatures (Environment Canada 2014) are presented in Fig. 1 and 2.

The model simulations included all the crops grown in the rotations, with relevant tillage and crop management operations including fertilizer and pesticide application timing, sequence, rates

and depth, as well as planting and harvesting operations and their dates from 1995 to 2013. One set of input parameters was used for each crop (wheat, barley, and canola) based on data compiled for a range of varieties grown in the US and Canada (Table A1). In total, six wheat, five barley, and nine canola varieties were grown during the 19-year rotation study (Table A2).

Statistical analysis

Simulated annual and long-term yields based on average of 6-yr study cycles were compared with study data using a paired sample *t*-test based on the experimental errors for each combination of input and diversity in the study. A similar analysis was used to compare annual mean yields for the three crops across all combinations of input and diversity, and for average yields for each level of input and diversity. Simulated and experimental available NO₃-N for the different input levels were also compared using a paired sample *t*-test. Linear regression and coefficients of determination (R^2), root mean square error of prediction (RMSE) (Willmott and Matsuura 2005), and the *d* index (Willmott 1984) were also used to assess the relationships between simulated and experimental annual and long-term yields. The RMSE and *d* index were calculated as follows:

$$\text{RMSE} = \left[n^{-1} \sum_{i=1}^n (y_i - x_i)^2 \right]^{0.5} \quad (1)$$

$$d = 1 - \left[\frac{\sum_{i=1}^n (y_i - x_i)^2}{\sum_{i=1}^n (|y_i - x_{\text{avg}}| + |y_i + x_{\text{avg}}|)^2} \right] \quad (2)$$

where y = simulated yield, x = experimental yield, and x_{avg} = the average of experimental yields.

The *d* index is a descriptive measure used to evaluate model performance. A *d* statistic of < 0.7, 0.7 to 0.8, 0.8 to 0.9, and > 0.9 indicates poor, moderate, good and excellent agreement of model performance in relation to the experimental data (Willmott 1984). A *P* value of ≤ 0.05 was

considered statistically significant. The percent errors were calculated as (simulated mean – experimental mean) x 100% / experimental mean. All statistical analyses were completed with JMP®, Version <11.0.0> (SAS Institute Inc., Cary, NC)). Ordinary kriging was done in ArcGIS Version <10.1> (Environmental Systems Research Institute, Redlands, CA). A paired *t*-test was used to compare 1981-2010 GS normal maximum temperature and yearly GS maximum temperatures. A Wilcoxon signed-rank test was used to compare the 1981-2010 GS normal minimum temperatures and precipitation, and the yearly GS minimum temperatures and precipitation.

RESULTS

Wheat

Experimental and simulated wheat yields (Fig. 3) were similar in most years. The EPIC model simulated yields for a given set of climatic, soil, and agronomic conditions so year-to-year variability in simulated yields was primarily a function of weather (Moulin and Beckie 1993). The differences between experimental and simulated yields were greatest in 2005 and 2010 due to hail damage that was not taken into account by model simulations. In order to quantify how accurately the model predicted yields on an annual basis over the 19-yr period, the simulated wheat yields were linearly regressed against the measured yields (Fig. 4). The yields were significantly correlated with a coefficient of determination (R^2) of 0.63, a *d* index of 0.88 and a RMSE of 543 kg ha⁻¹.

Simulated and experimental long-term yields were better correlated than the annual yields, with a coefficient of determination (R^2) of 0.74 ($P \leq 0.05$), a *d* index of 0.75 and a RMSE of 205 kg ha⁻¹ (Table 3). The differences between simulated (2365 kg ha⁻¹) and experimental (2023 kg ha⁻¹) long-term yields were not significant based on a paired *t*-test ($P = 0.05$). The correlations

between the simulated and experimental yield data, for the nine combinations of agricultural inputs and cropping diversity, were also significant (Table 3), showing good model performance. Crop yield was not significantly different from the simulated means in the 9 treatment combinations. The comparisons between the simulated and experimental long-term yields varied by treatment level, in the analyses with coefficients of determination, the d index and the RMSE. These parameters varied from very good and good, to moderate model performance (Table 4). The simulated and experimental yields (Table 4) for all levels of input and diversity were not significantly different according to the paired t -test ($P = 0.05$).

Barley

Similar to the annual trends in wheat yields, the differences between experimental and simulated yields were greatest for 2005 and 2010 (Fig. 5) due to extreme weather conditions which were not simulated by the EPIC model. When the simulated annual yields were regressed against the measured yields (Fig. 6), the yields were significantly correlated with a $R^2 = 0.68$, a d index of 0.91 and a RMSE of 647 kg ha^{-1} . The simulated and experimental long-term barley yields were also significantly correlated (Table 3), with a higher coefficient of determination ($R^2 = 0.90$), a d index of 0.73 and a RMSE of 226 kg ha^{-1} .

The experimental (2551 kg ha^{-1}) and simulated (2236 kg ha^{-1}) long-term yields were not significantly different (paired t test, $P = 0.05$). The experimental and simulated long-term yields in the input x diversity treatment combinations were also compared (Table 3). The simulated yields in the ORG-DAP were significantly greater than the experimental yields, but there were no significant differences for all other comparisons.

A long-term yield comparison for each level of input system and diversity showed that the experimental and simulated yields were significantly different for the ORG input, which was confirmed by the lowest d index (0.50). The simulated yields were not significantly different than the experimental yields for all the other levels of input and diversity in a paired t -test ($P = 0.05$) (Table 4). The R^2 , the d index, and RMSE parameters indicated good to moderate model performance (Table 4). It should be noted that barley was not grown under the LOW diversity treatment.

Canola

The model overestimated yields for 2005 and 2010, similar to the results for wheat and barley (Fig. 7) due to the absence of simulated hail damage in the model. In addition, the model underestimated yields in 2013. The simulated and experimental annual yields were significantly correlated (Fig. 8), with $R^2 = 0.47$, d index of 0.78 and RMSE of 439 kg ha⁻¹. Simulated and experimental long-term canola yields were much better correlated than the annual yields ($R^2 = 0.98$) (Table 3), with a d index of 0.76 and a RMSE of 238 kg ha⁻¹. There were no significant differences between experimental (1492 kg ha⁻¹) and simulated (1075 kg ha⁻¹) long-term canola yields (paired t test, $P = 0.05$). Combinations of input and diversity were also simulated to assess the accuracy of the EPIC model to simulate long-term yields. Canola was grown only in the first 6-year cycle of the ORG treatment. There were no significant differences between the simulated and experimental long-term canola yields for all treatment combinations with the exception of the ORG-LOW, ORG-DAP and RED-DAP treatments (Table 3). Experimental yields in the ORG input (662 kg ha⁻¹) were significantly different than the simulated (1131 kg ha⁻¹). Simulated long-term canola yields were not significantly different for all the other levels of input

and diversity (paired t -test, $P = 0.05$) (Table 4). The R^2 , the d index and the RMSE parameters varied from very good and good, to moderate model performance (Table 4).

DISCUSSION

The EPIC model was less accurate at simulating the annual variability of yields for all three crops, but adequately determined long-term yield and accounted for the effects of agricultural input systems and rotations on long-term crop yield. These results were similar to those reported by other researchers (Causarano et al. 2008; Chung et al. 1999; He et al. 2006; Kiniry et al. 1995; Moulin and Beckie 1993; Toure et al. 1994; Wang et al. 2005) who found that EPIC simulations were similar to long-term predicted yields, but were less accurate at simulating year-to-year yield variability.

Several factors were correlated with experimental yield and may have affected simulation accuracy. They were: (1) terrain attributes, such as slope and micro-topography in the research field, (2) soil variability, and (3) extreme weather conditions (flood, hail, very intense rainfall) as well as some other factors described below.

Lychuk et al. (2017a) reported that terrain attributes such as slope and micro-topography accounted for a significant proportion of yield variation in the ACS study. Elevation differences at the research site were as great as 3.5 m between the highest and lowest points. Terrain attributes such as slope and surface curvature were related to the spatial distribution of total N in the field in previous research (Selles et al. 1999). The correlation of terrain attributes with wheat yields varied depending on the relative location of the plots within the study area and total precipitation. The effects of terrain attributes were especially evident in years with deficit or excess moisture. For example, in 1998 and 2010, the driest and the wettest years of the study,

about 50 to 60 percent of the variations in wheat yields were attributed to input and diversity, with the remaining portion explained by the effects of terrain attributes such as the wetness index and percent slope. The EPIC model was not designed to account for the effects of micro-topography apart from unified slope, a steepness factor, and the field aspect. This may partially explain the differences between experimental and simulated yields in this modeling study.

The experimental annual yields varied considerably during the study due to GS temperatures and precipitation which were significantly different from the 1981 – 2010 GS climate normals (Lychuk et al. 2017a). Despite the large fluctuations in temperatures and precipitation during the study, the EPIC model was able to reproduce annual variations in wheat and barley yields as a function of the weather with acceptable R^2 values of 0.63 and 0.68, respectively, and a lower R^2 for canola of 0.47. For canola, the lower coefficient of determination was attributed due to a lack of input information in EPIC for all the growth parameters in the nine varieties of canola grown in the study (below). In addition, the reduced canola yields simulated in 2013 were attributed to an uneven distribution of soil moisture in the plot area (Lychuk et al. 2017a) and a dry seed-bed due to the pre-seeding tillage for the HI inputs as observed in previous years (Brandt and Ulrich 2001). The EPIC model did not account for the spatial variability of the terrain attributes such as elevation, redistribution of runoff in the plot area, or related soil processes, but it did account for the available moisture content as a result of timing, and the type and intensity of field operations.

Intense hail storms in early July of 2005 and August of 2006 caused extensive damage to all grain crops (Brandt and Ulrich 2008a; Brandt and Ulrich 2008b). Another rain-storm and hail event in mid-July of 2010 also damaged crops. These events accounted for the discrepancies between the experimental and simulated yields in 2005 and 2010 for the three crops (Fig. 3,5,7). The EPIC model was not designed to predict the occurrence of extreme events like hail and did

not account for damage to crops during those years. In general, EPIC's yield predictions for years with extreme weather conditions which damaged and reduced crop production were poorly correlated with the experimental data. These results were in partial agreement with Causarano et al. (2007) who observed that the disagreement between EPIC simulated and experimental yields were greater in dry and wet years in the Coastal Plain of Central Alabama.

The organic systems yielded less than the high or reduced systems throughout the study (Lychuk et al. 2017a), however, the model overestimated barley and canola yields under the ORG input. The long-term simulated yields for barley and canola under the ORG input may have been greater than the experimental yield (Table 3) due to EPIC's simulation of the N cycle. In the organic input system, where N fertilizer was not applied after 1994, EPIC did not accurately predict soil $\text{NO}_3\text{-N}$ when observed (57 kg ha^{-1}) and simulated (74 kg ha^{-1}) values in subsequent years (0-120 cm) were compared (paired *t*-test, $P < 0.05$). He et al. (2006), also concluded that the EPIC model overestimated corn yield for an unfertilized rotation in a long-term rotation study at Arlington, WI USA. However, Moulin and Beckie (1993) observed that the EPIC model underestimated annual wheat yield in unfertilized rotations in a simulation of annual wheat yields in a 30-yr rotation study at Melfort, Saskatchewan. The model reported no N stress days for the ORG input, although N deficiencies with organic inputs undoubtedly limited crop yields for these non-N fixing crops. Simulations in EPIC were more accurate when fertilizer was applied. Overall, the yields in the reduced and high input systems were greater, due to more available N relative to the organic system (Brandt and Ulrich 2000). In the HI and RED input systems where N fertilizer was applied annually, the EPIC model simulated N in the soil profile with greater accuracy. Experimental $\text{NO}_3\text{-N}$ (0-120 cm) was 79 kg ha^{-1} for the HI, and 72 kg ha^{-1} for the RED. The values predicted by EPIC, 83 kg ha^{-1} in the HI and 77 kg ha^{-1} in the RED

input, were not significantly different from the experimental values (paired t -test, $P = 0.05$). Furthermore, the simulated and experimental yields were significantly correlated for all three crops under the HI and RED input systems (Table 4).

The yield was also affected by a gradient in soil texture (data not shown). Sand content was higher towards the northeast end of the site and was finer-textured in the middle and the south end (Selles et al. 1999). This variability affected moisture availability, as well as nutrient distribution (Malhi et al. 2009; Selles et al. 1999). Residual herbicide activity also accounted for some of the discrepancies between the simulated and experimental annual wheat yields as the EPIC model did not simulate herbicide damage. Residues of Edge herbicide (60 percent ethalfluralin as a dispersible concentrate or 5 percent ethalfluralin as granular, Dow AgroSciences) that had been applied for weed control in the preceding canola crop reduced yield (Brandt and Ulrich 2001) during the first six years of the field study. Damage also resulted from the uneven distribution of herbicide when plots were tilled in one direction. Additional environmental factors which affected accuracy of simulated yield include late or early frosts on yield and the impacts of disease or insects.

The simulated annual yields for wheat, barley and canola may have also varied due to crop growth parameters of the 20 crop varieties grown during the experiment (Table A2). The contemporary varieties grown in this field study were not previously validated for the EPIC model as there were not enough information, technical capabilities and resources to develop variety-specific parameters (especially for canola). These and other parameters (Table A1) that define crop growth may have varied between individual crop varieties, and may have contributed to the variability of simulated yields. However, the generalized crop parameters facilitated analysis with the model. The overall goal of the ACS study was to assess effects of different

levels of agricultural inputs and cropping diversity on crop yields, but the assessment of different wheat, barley, and canola varieties on yields were not a focus of this study. Consequently, this modeling study assessed the ability of the EPIC model to reproduce crop yield as a function of agricultural inputs and cropping diversity, although differences between experimental and simulated yields may have been affected by the presence of several varieties over time in the rotations. Finally, the EPIC model assumes a high level of technology and optimal crop management with regard to harvest efficiency, fertilizer application and tillage operations (Brown and Rosenberg 1999). One or all of the factors discussed in this section may combine to cause the model to overestimate experimental yields, especially for annual yield comparisons.

CONCLUSIONS

The EPIC model accurately simulated yield trends of all three crops, and replicated the relative differences between agricultural input systems and cropping diversity over the long term. The EPIC model was less accurate at predicting annual variations in crop yields due to the impacts of soil variability, terrain attributes, overestimation of available N in the organic input system, extreme weather events like hail storms which damaged the crops, and variability between contemporary crop varieties for which the model was not previously validated. The EPIC N model sub-routine should also be updated in order to accurately simulate N mineralization and cycling under low N input systems. Despite the shortcomings with predicting the variability of annual yields, the EPIC model may be used to aid with future long-term cropping decisions and agronomic planning in the Canadian Prairies. Successful validation of a process-based model like EPIC for experimental yield and soil properties data under typical farming practices in the region allows researchers to assess yield dynamics and changes in future soil and environmental

quality. The next step in this research is to validate simulated soil nitrate, P and soil organic C content with experimental data from the ACS study.

ACKNOWLEDGEMENTS

The authors are grateful to A. Kapiniak and L. Sproule (AAFC, Scott Research Farm), A. Waddell and A. Kopeechuk (AAFC, Brandon Research and Development Centre), and Ross Weiss (AAFC, Saskatoon Research and Development Centre) for their technical assistance and to Dr. A. Glenn (AAFC, Brandon Research and Development Centre) for the internal review of the manuscript. Dr. T. Lychuk was supported by a post-doctoral fellowship from Agriculture and Agri-Food Canada under Growing Forward 2.

REFERENCES

- Balkovič, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., Stürmer, B. and Xiong, W. 2013. Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation. *Agricultural Systems* **120**:61-75.
- Brandt, S. A., Thomas, A. G., Olfert, O. O., Leeson, J. Y., Ulrich, D. and Weiss, R. 2010. Design, rationale and methodological considerations for a long term alternative cropping experiment in the Canadian plain region. *European Journal of Agronomy* **32**(1):73-79.
- Brandt, S. A. and Ulrich, D. 2000. Crop production. *in* D. Ulrich, ed. Integrated Management of Disease, Insect and Weed Pests in Alternative Crop Production Systems Volume 8 - 2000 Research Results. Agriculture and Agri-Food Canada, Saskatoon Research Center, Saskatoon.
- Brandt, S. A. and Ulrich, D. 2001. Crop Productivity with Alternative Input Use Cropping Diversity Strategies. *in* S. A. Brandt, A. G. Thomas, eds. Scott Alternative Cropping System Project Review: The First Six Years. Agriculture and Agri-Food Canada, Saskatoon Research Center, Saskatoon.
- Brandt, S. A. and Ulrich, D. 2008a. Crop production. *in* J. Y. Leeson, A. G. Thomas, eds. Alternative Cropping Systems Volume 14 - 2005 Research Results. Agriculture and Agri-Food Canada, Saskatoon Research Center, Saskatoon.
- Brandt, S. A. and Ulrich, D. 2008b. Crop production. *in* J. Y. Leeson, A. G. Thomas, eds. Alternative Cropping Systems Volume 12 - 2005 Research Results. Agriculture and Agri-Food Canada, Saskatoon Research Center, Saskatoon.
- Brown, R. A. and Rosenberg, N. J. 1999. Climate change impacts on the potential productivity of corn and winter wheat in their primary united states growing regions. *Climatic Change* **41**(1):73-107.
- Causarano, H. J., Doraiswamy, P. C., McCarty, G. W., Hatfield, J. L., Milak, S. and Stern, A. J. 2008. EPIC modeling of soil organic carbon sequestration in croplands of Iowa. *Journal of Environmental Quality* **37**(4):1345-1353.
- Causarano, H. J., Shaw, J. N., Franzluebbers, A. J., Reeves, D. W., Raper, R. L., Balkcom, K. S., Norfleet, M. L. and Izaurralde, R. C. 2007. Simulating field-scale soil organic carbon dynamics using EPIC. *Soil Science Society of America Journal* **71**(4):1174-1185.
- Chung, S. W., Gassman, P. W., Kramer, L. A., Williams, J. R. and Gu, R. 1999. Validation of EPIC for two watersheds in southwest Iowa. *Journal of Environmental Quality* **28**(3):971-979.
- Clayton, J. S. and Ellis, J. G. 1952. Soil survey of the experimental stations and substations of the Canada Department of Agriculture in Saskatchewan. Saskatchewan Soil Survey, SK:81 pp.
- Davis, J. C. 2002. Statistics and data analysis in geology. 3rd edition ed. John Wiley and Sons, Toronto.
- Environment Canada. 2014. Environment Canada climate and weather data (Station: Scott CDA, <http://climate.weather.gc.ca/>).
- Gassman, P. W., Williams, J. R., Benson, V. W., Izaurralde, R. C., Hauck, L. M., Jones, C. A., Atwood, J. D., Kiniry, J. R. and Flowers, J. D. 2005. Historical Development and Applications of the EPIC and APEX Models. ASAE/CSAE Annual International Meeting. American Society of Agricultural and Biological Engineers, Ottawa, ON.
- He, X., Izaurralde, R., Vanotti, M., Williams, J. and Thomson, A. 2006. Simulating long-term and residual effects of nitrogen fertilization on corn yields, soil carbon sequestration, and soil nitrogen dynamics. *Journal of Environmental Quality* **35**(4):1608-1619.
- Izaurralde, R., McGill, W. and Williams, J. 2012. Development and application of the EPIC model for carbon cycle, greenhouse-gas mitigation, and biofuel studies. Pages 409-429 *in* M. A. Liebig, A. J. Franzluebbers, R. F. Follett, eds. Managing agricultural greenhouse gases: Coordinated agricultural research through GRACEnet to address our changing climate. Elsevier, Amsterdam.

- Izaurralde, R. C., Williams, J. R., McGill, W. B., Rosenberg, N. J. and Jakas, M. C. Q. 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecological Modelling* **192**(3-4):362-384.
- Kiniry, J. R., Major, D. J., Izaurralde, R. C., Williams, J. R., Gassman, P. W., Morrison, M., Bergentine, R. and Zentner, R. P. 1995. EPIC model parameters for cereal, oilseed, and forage crops in the northern Great Plains region. *Canadian Journal of Plant Science* **75**(3):679-688.
- Lee, J. and Archer, D. W. 2014.** Simulating soil carbon change in oilseed cropping system in North Dakota. Proc. American Society of Agricultural and Biological Engineers Annual International Meeting 2014.
- Lychuk, T., Izaurralde, R., Hill, R., McGill, W. and Williams, J. 2014. Biochar as a global change adaptation: predicting biochar impacts on crop productivity and soil quality for a tropical soil with the Environmental Policy Integrated Climate (EPIC) model. *Mitigation and Adaptation Strategies for Global Change* **20**(8):1437-1458.
- Lychuk, T. E. 2014. Evaluation of Biochar Applications and Irrigation as Climate Change Adaptation Options for Agricultural Systems Ph.D Dissertation. University of Maryland, College Park, USA. 220 pp.
- Lychuk, T. E., Moulin, A., Lemke, R., Gossen, B., Leeson, J. Y., Kirk, A., Johnson, E., Olfert, O., Brandt, S. and Thomas, A. G. 2017a. Effects of Crop Inputs, Diversity, Environment and Terrain on Yield in an 18-year Study in the Semi-Arid Canadian Prairie. *In press*. *Canadian Journal of Plant Science*.
- Lychuk, T. E., Moulin, A. P., Izaurralde, R. C., Lemke, R. L., Johnson, E. N., Olfert, O. O. and Brandt, S. A. 2017b. Climate Change, Agricultural Inputs, Cropping Diversity, and Environmental Covariates in Multivariate Analysis of Future Wheat, Barley, and Canola Yield in Canadian Prairies, a Case Study. *Canadian Journal of Soil Science* **97**(2):300-318.
- Malhi, S. S., Brandt, S. A., Lemke, R., Moulin, A. P. and Zentner, R. P. 2009. Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and nutrient balance in the Canadian Prairie. *Nutrient Cycling in Agroecosystems* **84**(1):1-22.
- Moulin, A. P. and Beckie, H. J. 1993. Evaluation of the CERES and EPIC models for predicting spring wheat grain yield over time. *Canadian Journal of Plant Science* **73**:713-719.
- Selles, F., Campbell, C. A., McConkey, B. G., Brandt, S. A. and Messer, D. 1999. Relationships between biological and chemical measures of N supplying power and total soil N at field scale. *Canadian Journal of Soil Science* **79**(2):353-366.
- Toure, A., Major, D. J. and Lindwall, C. W. 1994. Comparison of five wheat simulation models in southern Alberta. *Canadian Journal of Plant Science* **75**:61-68.
- Wang, X., He, X., Williams, J. R., Izaurralde, R. C. and Atwood, J. D. 2005. Sensitivity and uncertainty analyses of crop yields and soil organic carbon simulated with EPIC. *Transactions of the American Society of Agricultural Engineers* **48**(3):1041-1054.
- Williams, J. R. 1995. The EPIC model. Pages 909 - 1000 in V. P. Singh, ed. *Computer Models of Watershed Hydrology*. Water Resources Public, Highland Ranch, CO, USA.
- Williams, J. R., Jones, C. A. and Dyke, P. T. 1984. A modelling approach to determining the relationship between erosion and soil productivity. *Transactions - American Society of Agricultural Engineers* **27**(1):129-144.
- Willmott, C. J. 1984. On the evaluation of model performance in physical geography. Pages 443-460 in G. L. Gaile, C. J. Willmott, D. Reidel, eds. *Spatial statistics and models*. D. Reidel Publishing, Boston, MA.
- Willmott, C. J. and Matsuura, K. 2005. Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climate Research* **30**(1):79-82.

Fig. 1 Summary of growing season (April 15 – August 31) precipitation from 1995 to 2013

Fig. 2 Average maximum (Tmax) and minimum (Tmin) growing season (April 15 – August 31) temperatures from 1995 to 2013

Fig. 3 Experimental and simulated annual mean wheat grain yield

Fig. 4 Regression of simulated on experimental annual wheat grain yield (1995-2013)

Fig. 5 Experimental and simulated annual mean barley grain yield

Fig. 6 Regression of simulated on experimental annual barley grain yield

Fig. 7 Experimental and simulated annual mean grain canola yield

Fig. 8 Regression of simulated on experimental annual canola grain yield (1995-2013)

Fig. 1 Summary of growing season (April 15 – August 31) precipitation at Research Farm in Scott, Saskatchewan from 1995 to 2013

Fig. 2 Average maximum (Tmax) and minimum (Tmin) growing season (April 15 – August31) temperatures at Research Farm in Scott, Saskatchewan from 1995 to 2013

Fig. 3 Experimental and simulated annual mean wheat yield for the long-term rotation study at Scott, Saskatchewan

Fig.4 Regression of simulated on experimental annual wheat grain yield (1995-2013) at the Agriculture and Agri-Food Canada Research Station in Scott, Saskatchewan.

Fig. 5 Experimental and simulated annual mean barley yield for the long-term rotation study at Scott, Saskatchewan

Fig. 6 Regression of simulated on experimental annual barley grain yield (1995-2013) at the Agriculture and Agri-Food Canada Research Station in Scott, Saskatchewan.

Fig. 7 Experimental and simulated annual mean canola yield for the long-term rotation study at Scott, Saskatchewan

Fig. 8 Regression of simulated on experimental annual canola grain yield (1995-2013) at the Agriculture and Agri-Food Canada Research Station in Scott, Saskatchewan.

Table 1. Characteristics of the soil profile by depth increment used for model initiation

Property	Depth Increment, m				
	0-0.07	0.07-0.15	0.15-0.30	0.30-0.60	0.60-0.90
Physical^a					
Soil texture, g kg ⁻¹					
Sand	696	696	654	632	579
Clay	99	99	107	119	132
Bulk density, Mg m ⁻³	1.16	1.33	1.36	1.52	1.74
May soil temperature (5cm/10cm), °C ^b	10.93/9.92	-	-	-	-
Spring soil moisture, mm ^c	-	37.77	34.07	45.29	45.93
Harvest soil moisture, mm ^c	-	24.54	24.71	35.52	37.91
Organic carbon, % ^a	3.2	2.6	1.2	0.8	0.4
Chemical					
pH ^a	5.1	5.6	6.0	6.5	6.5
NO ₃ -N, kg ha ^{-1a}	-	38.42	11.78	11.93	18.84
PO ₄ -P, kg ha ^{-1a}	-	34.50	9.30	6.27	4.01

^a Data from A.P. Moulin and F. Selles, Agriculture and Agri-Food Canada, Brandon Research Center and Semiarid Prairie Agricultural Research Center (unpublished data)

^b Data from R. Weiss, Agriculture and Agri-Food Canada, Saskatoon, SK and Scott Experimental Farm (unpublished data)

^c Data from S.A. Brandt and R. Weiss, Agriculture and Agri-Food Canada, Saskatoon, SK and Scott Experimental Farm (unpublished data)

Table 2. Description of the nine cropping systems in the Alternative Cropping System (ACS) study^a

Diversity level ^b	Input level ^c	Crop sequence
LOW	ORG	GM ^d -Wheat-Wheat-GM-Mustard ^e -Wheat
	RED	GM ^d -Wheat-Wheat-Chem. Fallow ^f -Canola-Wheat
	HI	Fallow ^g -Wheat-Wheat-Fallow ^g -Canola-Wheat
DAG	ORG	GM-Wheat-Pea-Barley ^h -GM ⁱ -Mustard ^e
	RED	Canola-Fall rye ^j -Pea-Barley-Flax-Wheat
	HI	Canola- Fall rye ^j -Pea-Barley-Flax-Wheat
DAP	ORG	Mustard ^e -Wheat-Barley-Alfalfa ^k -Alfalfa-Alfalfa
	RED	Canola-Wheat-Barley-Alfalfa ^k -Alfalfa-Alfalfa
	HI	Canola-Wheat-Barley-Alfalfa ^k -Alfalfa-Alfalfa

^aSource: (Brandt et al., 2010)

^bLOW - low; DAG - diversified annual grains; DAP - diversified annual perennials

^cORG – organic, non-chemical pest control and nutrient management; RED – reduced, integrated long-term management of pests and nutrients utilizing chemicals and no-till practices; HI – high, pesticides and fertilizers “as required” based on conventional recommendations associated with pest thresholds and soil tests

^dGM - green manure (Indian Head Lentil) partial fallow

^eAfter the first cycle canola was replaced with mustard

^fChem. fallow - summer fallow with weeds controlled by herbicides

^gFallow - summer fallow with weeds controlled by tillage

^hBarley was under seeded to sweet clover in first two cycles

ⁱSweet clover in first two cycles

^jIn the third cycle, fall rye was replaced with soft white spring wheat

^kIn the first cycle, alfalfa and brome were under seeded to oat in the forage establishment year

Table 3. Comparison of 19-year means for simulated and experimental wheat, barley and canola grain yield from long-term rotations (1995-2013) at Agriculture Canada Research Station, Scott, Saskatchewan based on treatment combinations of Organic (ORG), Reduced (RED), High (HI) input and Low (LOW), Diversified Annual Grains (DAG), and Diversified Annual Perennials (DAP) diversity rotations

Input x Diversity Treatment Combination	Wheat Grain Yield					
	Experimental	Simulated by EPIC	RMSE ^a	Error, % ^b	R^2 ^c	d^d
	-----kg ha ⁻¹ -----					
ORG-LOW	1513	2276	246	50	0.58	0.42
ORG-DAG	1933	2393	283	24	0.90	0.83
ORG-DAP	1654	2348	146	42	0.94	0.64
RED-LOW	2115	2421	687	14	0.38	0.70
RED-DAG	2192	2292	650	5	0.52	0.83
RED-DAP	1963	2393	732	22	0.54	0.75
HI-LOW	2250	2472	601	10	0.56	0.81
HI-DAG	2269	2234	500	2	0.66	0.87
HI-DAP	2067	2294	574	11	0.65	0.86
All	2023	2365	205	17	0.74	0.75
Barley Grain Yield						
ORG-LOW	-	-	-	-	-	-
ORG-DAG	1734	2455	440	42	0.72	0.69
ORG-DAP	1614 _a	2623 _b	109	62	0.75	0.25
RED-LOW	-	-	-	-	-	-
RED-DAG	2460	2572	1097	5	0.30	0.71
RED-DAP	2435	2681	1152	10	0.33	0.72
HI-LOW	-	-	-	-	-	-
HI-DAG	2677	2563	907	4	0.50	0.81
HI-DAP	2505	2654	950	6	0.28	0.70
All	2236	2551	226	14	0.90	0.73
Canola Grain Yield						
ORG-LOW ^c	753 _a	1161 _b	303	54	0.52	0.64
ORG-DAG ^c	530	874	366	65	0.53	0.60
ORG-DAP ^c	703 _a	1358 _b	150	93	0.57	0.37
RED-LOW	1487	1816	173	22	0.86	0.72
RED-DAG	1108	1490	240	34	0.75	0.71
RED-DAP	1130 _a	1729 _b	252	53	0.88	0.68
HI-LOW	1577	1841	269	17	0.87	0.75
HI-DAG	1165	1493	358	28	0.48	0.69
HI-DAP	1224	1667	274	36	0.91	0.77
All	1075	1492	238	39	0.98	0.76

^aRoot mean square error;

^b% error calculated from (Simulated-Experimental)/Experimental*100

^cR² coefficient of determination;

^dd index;

^eUnder ORG input, canola was grown only in the first 6-year cycle of the study

^{a,b}Letters indicate significant differences between experimental and simulated yield per crop at the 5% level according to the paired t test or Wilcoxon sign rank test

For Review Only

Table 4. Comparison of 19-year means between experimental and simulated wheat, barley and canola grain yield from long-term rotations (1995-2013) at Agriculture Canada Research Station, Scott, Saskatchewan based on Organic (ORG), Reduced (RED), High (HI) input and Low (LOW), Diversified Annual Grains (DAG), and Diversified Annual Perennials (DAP) diversity rotations

Input / Diversity	Wheat Grain Yield					
	Experimental	Simulated by EPIC	RMSE ^a	Error, % ^b	R^2 ^c	d^d
	-----kg ha ⁻¹ -----					
ORG	1693	2313	108	37	0.86	0.65
RED	2137	2407	33	11	0.98	0.76
HI	2237	2374	141	6	0.64	0.85
LOW	1964	2365	49	20	0.99	0.68
DAG	2211	2411	227	9	0.60	0.84
DAP	1891	2319	293	18	0.09	0.38
Barley Grain Yield						
ORG	1674 ^a	2539 ^b	302	52	0.54	0.50
RED	2447	2626	798	7	0.31	0.72
HI	2590	2608	684	1	0.36	0.75
LOW	-	-	-	-	-	-
DAG	2284	2489	184	8	0.93	0.75
DAP	2187	2613	373	16	0.72	0.65
Canola Grain Yield						
ORG ^e	662 ^a	1131 ^b	98	71	0.65	0.30
RED	1241	1678	201	35	0.73	0.48
HI	1322	1666	120	26	0.70	0.59
LOW	1272	1606	43	26	0.99	0.80
DAG	934	1285	38	38	0.99	0.72
DAP	1019	1584	125	55	0.89	0.46

^aRoot mean square error;

^b% error calculated from (Simulated-Experimental)/Experimental*100

^c R^2 coefficient of determination;

^dd index;

^eUnder ORG input, canola was grown only in the first 6-year cycle of the study

^{a,b}Letters indicate significant differences between experimental and simulated yield per crop at the 5% level according to the paired t test or Wilcoxon sign rank test

APPENDIX

Table A1. Select growth parameters of wheat, barley, and canola used in the Environmental Policy Integrated Climate model runs for the 1994 – 2013 Alternative Cropping System study at Scott Research Farm

Crop	Crop Parameter								
	Biomass-Energy Ratio (baseline CO ₂ = 330 ppm) ^a	Harvest Index	Optimal temperature for plant growth, °C	Minimum temperature for plant growth, °C	Maximum potential leaf area index	Maximum Stomatal Conductance (mm s ⁻¹) ^b	BN1/BP1 ^c	BN2/BP2 ^d	BN3/BP3 ^e
Wheat	35.00	0.42	15.0	0	5.0	0.0070	0.0663/ 0.0084	0.0250/ 0.0032	0.0148/ 0.0019
Barley	35.00	0.42	15.0	0	3.5	0.0070	0.0590/ 0.0057	0.0220/ 0.0022	0.0131/ 0.0013
Canola	34.00	0.23	21.0	5	3.5	0.0078	0.0440/ 0.0073	0.0182/ 0.0037	0.0164/ 0.0023

^aPotential (unstressed) growth rate (including roots) per unit of intercepted photosynthetically active radiation.

^bMaximum stomatal conductance at high solar radiation and low vapor pressure deficit

^cNitrogen/phosphorus uptake parameter. Normal fraction of N/P in crop biomass at emergence

^dNitrogen/phosphorus uptake parameter. Normal fraction of N/P in crop biomass at mid-season

^eNitrogen/phosphorus uptake parameter. Normal fraction of N/P in crop biomass at maturity

Table A2. Wheat, barley, and canola cultivars grown in the 1994 – 2013 Alternative Cropping System study at Scott Research Farm

Wheat	Barley	Canola
AC Lillian	CDC Copeland	InVigor 5020
AC Ecatoria	AC Merit	InVigor 5020 (Prosper)
AC Abbey	Harrington	InVigor 5030
AC McKenzie	Harper	InVigor 2663
AC Barrie	Brier	Polish
CDC Makwa		Hudson
		Reward
		Cyclone
		Premiere