Long-term trends in corn yields and soil carbon under diversified crop rotations

M. Jarecki, B. Grant, W. Smith, B. Deen, C. Drury, A. VanderZaag, B. Qian, J. Yang, and C. Wagner-Riddle

This is the peer reviewed version of the following article: Jarecki, M., Grant, B., Smith, W., et al. Long-term trends in corn yields and soil carbon under diversified crop rotations. J Environ Qual 47, 635–643 (2018). doi:10.2134/jeq2017.08.0317 which has been published in final form at https://doi.org/10.2134/jeq2017.08.0317. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.

Long-term trends in corn yields and soil carbon under diversified crop rotations

Marek Jarecki[1], Brian Grant[2], Ward Smith[2], Bill Deen[3], Craig Drury[4], Andrew VanderZaag[2], Budong Qian[2], Jingyi Yang[4] and Claudia Wagner-Riddle[1*]

[1]School of Environmental Sciences, University of Guelph, Guelph, ON, Canada; [2]Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, Ottawa, ON, Canada; [3]Department of Plant Agriculture, University of Guelph, Guelph, ON, Canada; [4]Harrow Research and Development Centre, Agriculture and Agri-Food Canada, Harrow, ON, Canada.

*corresponding author: cwagnerr@uoguelph.ca

Abbreviation list: SOC, soil organic carbon; CC, continuous corn; CCSS, corn-corn-soybean-soybean; CCSW, corn-corn-soybean-winter wheat; CCSW+Rc, corn-corn-soybean-winter wheat + red clover; CCAA, corn-corn-alfafa-alfalfa; COAA, corn-oats-alfalfa-alfalfa; RCP, representative concentration pathways.

Keywords: Corn yield, Diversified crop rotation, DNDC model, Historical and future trends in soil organic carbon

Core ideas:

- Corn grown in rotation had higher yield than grown in monoculture
- Improvements in the DNDC model captured the yield increases in diversified rotations
- Diversified rotations had higher SOC stock than corn in monoculture
- DNDC-predicted and observed values agreed well for yield and soil carbon
- Benefits from diversified rotations were predicted by DNDC for future scenarios

Abstract

Agricultural practices such as including perennial alfalfa, winter wheat, or red clover in corn rotations can provide higher crop yields and increase soil organic carbon (SOC) over time. How well process-based biogeochemical models such as DNDC capture the beneficial effects of diversified cropping systems is unclear. To calibrate and validate DNDC for simulation of observed trends in corn yield and SOC we used long-term trials: continuous corn (CC) and corn-oats-alfalfa-alfalfa (COAA) for Woodslee, ON, 1959-2015; continuous corn (CC), corn-corn-soybean-soybean (CCSS), corn-corn-soybean-winter wheat (CCSW), corn-corn-soybean-winter wheat + red clover (CCSW + Rc) and corn-corn-alfalfa-alfalfa (CCAA) for Elora, ON, 1981-2015. Yield and SOC under 21st century conditions were projected under future climate scenarios from 2016 to 2100. The DNDC model was calibrated to improve crop nitrogen stress and was revised to estimate changes in water availability as a function of soil properties. This improved yield estimates for diversified rotations at Elora (mean absolute prediction error, MAPE, decreased from 13.4-15.5% to 10.9-14.6%) with lower errors for the 3 most diverse rotations. Significant improvements in yield estimates were also simulated at Woodslee for COAA with MAPE decreasing from 24.0 to 16.6%. Predicted and observed SOC were in agreement for simpler rotations (CC or CCSS) at both sites (53.8 and 53.3 Mg C ha^{-1} for Elora; 52.0 and 51.4 Mg C ha^{-1} for Woodslee). Predicted SOC increased due to rotation diversification and was close to observed values (58.4 and 59 Mg C ha^{-1} for Elora; 63 and 61.1 Mg C ha^{-1} for Woodslee). Under future climate scenarios the diversified rotations mitigated crop water stress resulting in trends of higher yields and SOC content in comparison to simpler rotations.

Introduction

In contemporary agriculture, crops grown in rotation are often displaced by crops grown in monocultures (Meyer-Aurich et al., 2006a; Liebman et al., 2013; Gaudin et al., 2015). This trend is worrisome as long-term monoculture can lead to nutrient depletion and degradation of soil quality (Karlen et al., 2013). Practices such as including perennial alfalfa, winter wheat, or red clover in corn crop rotations have been shown to increase soil organic carbon (SOC), and to produce higher and more stable crop yields over time (Meyer-Aurich et al., 2006a; Drury et al., 2008; Gaudin et al., 2013). Indeed, the positive influence of diversified rotations on crop productivity and soil health has been demonstrated with long-term trials (>20 years) (Congreves et al., 2015). However, long-term field experiments represent limited sets of climate, soil and crop management conditions. Accurate prediction of crop yields, nutrient dynamics, and SOC sequestration in various conditions, including future climate scenarios can be achieved by implementation of biogeochemical models, provided proper evaluation is carried out using results from long-term trials (Grant et al., 2016).

The DNDC biogeochemical model by Li et al. (2000) is a widely-recognized tool with a large spectrum of simulated outputs. The DNDC model has been tested for its ability to predict soil temperature, soil water content, soil nitrogen (N) content, and nitrous oxide (N_2O) emissions at experimental sites in eastern and western Canada (Smith et al., 2002, 2008). It has also been employed in multi-model comparisons for crop production and N_2O emissions (Ehrhardt et al., 2017) and carbon (C) dynamics (Smith et al., 2012, Grant et al., 2016) along with assessing the effects of climate change on crop production (Smith et al., 2013, He et al., 2017). These investigations have prompted the development of improved model processes for the Canadian version of DNDC (DNDC v.CAN) including crop biomass growth (Kröbel et al., 2011), evapotranspiration (Dutta et al., 2016a), soil temperature (Dutta et al., 2017), ammonia volatilization after slurry application (Congreves et al., 2016) and ammonia emissions after urea application (Dutta et al., 2016b). Although the DNDC model has been employed under a wide range of cropping systems in Canada (Abalos et al., 2013, Kröbel et al., 2011, Smith et al., 2012, 2013) and elsewhere (Ehrhardt et al., 2017; Brilli et al., 2107; Zhang and Niu, 2016), it has not been utilized to specifically assess the effect of crop rotation diversity on corn yields and SOC under historical climate or future climate change.

Future atmospheric conditions will be characterized by increased variability in temperature and precipitation and elevated atmospheric carbon dioxide (CO_2) concentration (IPCC, 2007). Current evidence of more stable crop yields over time in diversified crop rotations (Gaudin et al., 2013) and increased SOC (Meyer-Aurich et al., 2006b; Drury et al., 2008) suggests that these systems may be more suitable for future conditions than monocultures. IPCC (2014) elaborated four representative concentration pathways (RCP) scenarios that can be used for assessing future predictions. The scenarios include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with high greenhouse gas emissions (RCP 8.5) based upon radiative forcing levels of 2.6, 4.5, 6.0 and 8.5 W m^{-2} by the end of the 21st century, respectively (Van Vuuren et al., 2011; IPCC, 2014). He et al (2017) considered two contrasting scenarios: the intermediate RCP4.5 and high RCP8.5 as appropriate 21st century pathways for predicting crop yields and soil greenhouse gas emissions. No study to date has assessed future corn yield and SOC trends under these contrasting scenarios.

The objectives of this study were to: (1) evaluate DNDC model predictions of corn yield trends in monoculture and in diversified rotations over time at two locations, and modify the model to provide improved yield estimates in diversified rotations; (2) assess DNDC SOC predictions for corn monoculture and diversified rotations for two long-term field trials on contrasting soil; (3) implement the improved DNDC model to predict corn yield and SOC dynamics in various cropping systems over the 21st century under future scenarios: RCP4.5 and RCP8.5.

Materials and Methods

Site Description

Data from two long-term crop rotation trials with contrasting soil types located in Elora (35 years) and Woodslee (57 years), Ontario were selected for this study. The Elora trial was established in 1981 at the Elora Research Station (43°39'N, 80°25'W, elevation 376 m) on a Typic Hapludalf (Gray Brown Luvisol) silt loam soil (270, 560 and 170 g kg^{-1} of sand, silt and clay, respectively), with pH of 7.3 and SOC of 22 g kg^{-1} (Ramnarine et al., 2014). The Woodslee trial was established in 1959 at the Agricultural and Agri-Food Canada (AAFC) Experimental Farm (42°13'N, 82°44'W, elevation 186 m) on poorly drained Brookston clay loam, with 280, 350 and 370 g kg^{-1} of sand, silt and clay, respectively, and pH of 6.1 and SOC of 25 g kg^{-1} (Drury et al., 1998; Tan et al., 2002). A complete description of sites and experiments is given in Gaudin et al. (2015) for Elora and Drury and Tan (1995) for Woodslee. Climate characteristics are shown in Table S2 and Fig S1.

Cropping Systems

Five cropping systems were selected from the Elora trial: continuous corn (*Zea mays* L.) monoculture (CC), corn-corn-soybean-soybean (*Glycine max* L.) (CCSS), corn-corn-soybean-winter wheat (*Triticum aestivum* L.) (CCSW), corn-corn-soybean-winter wheat with red clover (*Trifolium pratense* L.) as a cover crop inter-seeded under wheat (CCSW+Rc) and corn-corn-alfalfa-alfalfa (*Medicago sativa* L.) (CCAA). For Woodslee, two cropping systems were studied: corn monoculture and corn-oats (*Avena sativa*)-alfalfa-alfalfa. Both sites were managed with conventional tillage which consisted of fall moldboard plowing and disking in spring before planting annual crops and first-year alfalfa (Table S1). Nitrogen fertilizer was applied as starter at planting and as side-dress at the corn 6th leaf stage (Table S1). Details on other agronomic practices are given in Gaudin et al. (2015) for Elora and in Drury and Tan (1995) for Woodslee.

DNDC Model Description

The DNDC model framework includes processes for soil, climate, crop production, C and N dynamics, and trace gas emissions reported at a daily time step. Model inputs are setup based on readily available measurements to characterize soil characteristics (bulk density, texture, soil hydraulic parameters, SOC), climate (air temperature, precipitation, wind speed, solar radiation, humidity), crop production (crop type, potential yield, biomass fractions, C:N ratio, water demand, optimal temperature) and agricultural management (tillage, residue, irrigation, plant/harvest dates, fertilizer).

Crop production is regulated using a simple optimal C growth function driven by temperature degree days. The optimal production is reduced by N and water availability, temperature stress based on a cardinal approach developed in Canada (Yan and Hunt, 1999) and heat stress during anthesis (Smith et al., 2013). The model was updated to include information from Free-Air CO_2 Enrichment studies regarding the effects of CO_2 on C assimilation in plants, crop water use efficiency, and crop N use (Smith et al., 2013). Crop C inputs and C dynamics are managed by the C decomposition sub-model which is characterized by four major pools (litter, labile humus, passive humus and microbial biomass). Each pool utilizes a predefined base decomposition rate that is modified as a function of soil texture, moisture, temperature and N content. A more detailed description of the model's mechanisms and framework design can be found in Li et al. (2012) and Grant et al. (2016).

Input Datasets

Long-term daily temperature, precipitation, solar radiation, wind speed and relative humidity data were obtained from Environment Canada (2017), Elora Research Meteorological Station and from the Harrow Experimental Farm AAFC records. The two sites had slightly different climatic conditions with Elora over 1981-2015 being slightly cooler (growing degree days 1009 vs. 1405) and wetter (annual precipitation 1009 vs. 844 mm) than Woodslee over 1959-2015 (Table S2). Inputs of soil physical properties, planting, fertilization, and tillage operations were obtained from Gaudin et al. (2015) for Elora and from Drury et al. (1995) for Woodslee (Table S1).

Model Calibration and Development for Diverse Crop Rotations

The model simulations were parameterized to ensure that appropriate C residue inputs from corn, winter wheat, soybean and alfalfa were being returned to the soil. Initial calibration of crop parameters (biomass fractions) were leveraged from Janzen et al. (2003) and Bolinder et al. (2007) with some slight adjustment to get the best calibration fit for yields. Crop N uptake and removal was managed through adjustment of crop biomass C:N ratios to ensure that the soil N status would result in a slight N stress under the continuous corn simulations. Yield parameter calibration was conducted using the CCSW rotation at Elora and the first 10 years of the CC rotation at Woodslee (Tables1 and S3). No other calibration was conducted.

It has been reported that under diverse crop rotations certain soil properties may be impacted including, soil pore space, bulk density and biopore volume all of which could influence soil water availability (Bolton et al., 1982; Drury and Tan, 1995; Munkholm et al., 2013; Gaudin et al., 2015). To account for these effects, we incorporated a pedo-transfer function to recalculate changes in soil properties based on changes in SOC (Saxton and Rawls, 2006). These changes in soil properties were applied as relative differences to ensure that initial measured bulk densities and soil hydraulic properties could be utilized. Observed crop yields were compared to simulated values using the standard DNDC model (DNDC ‘before’) and after the revision to account for increased N stress under continuous corn using slightly lower C:N ratio (grain C:N adjusted from 35 to 30) and the improved water availability through the use of the pedo-transfer function (DNDC ‘after’).

To ensure that each of the cropping systems had similar N stress levels under future climate we also developed a new “Farm Agent” algorithm to manage future crop N stress. Using a 10-year running average of the crop N stress index (N uptake/N demand) the farm agent would apply up to 10% change in fertilizer annually to ensure that the climate induced impacts of improved growth potential, increased N leaching, higher N mineralization and trace gas losses did not induce high crop N stress. This generally resulted in higher N fertilizer rates being applied under future conditions.

Model Evaluation

DNDC performance was validated by comparing observed and simulated corn yield for 35 years at Elora and 57 years at Woodslee. For SOC, in years with accessible data, the comparison between measured and simulated C concentration and C stock in the soil profile was completed. Observed SOC concentration and stock were utilized from published data for the top 0-0.20 m or for 0-0.50 m depending on data availability (Table S4). A record of SOC measurements was available for selected rotations and from different sources for Elora. Data from 1995 were available from Wanniarachchi et al. (1999); for 2005 from Yang et al. (2008). Data for 1998, 2000 and 2015 were derived directly from experimental documentation (Deen, 2017). Depending on the rotation, SOC concentration measurements were available in the following years: for CC in 1995, 1998, 2000, 2005; for CCSS and CCSW in 1998, 2000 and 2015; for CCSW+Rc in 1998 and 2000; and for CCAA in 2000 and 2015 (Table S1). For Woodslee, SOC measurements included years 1994, 2002 and 2004-2007 (Drury et. al., 1998; Drury et al., 2004; Reynolds et al., 2014).

SOC stock was computed for each soil layer *i* sampled by a soil core segment (SOC_i, Mg ha^{-1}) according to Ellert et al. (2008):

$$\mathrm{SOC}_i = \rho_i \, C_i L_i \times 10 \qquad (1)$$

where ρ_i is the bulk density of the soil layer (Mg m^{-3}), C_i is the organic carbon concentration of the soil layer (mg C g^{-1} dry soil), L_i is the length of soil layer (m) and 10 is a unit conversion factor. The SOC stock was computed for 0-0.2 m and 0.2-0.5 m soil layers depending on data availability. Total SOC stock for the soil was calculated by adding up all SOC for each soil layer in the profile. When the density of a particular core segment was not reported, the Saxton soil water characteristic calculator was employed with soil texture and SOC concentration as input data (Saxton and Rawls, 2009).

Agreement between observed and predicted corn yield values was evaluated using the following statistical evaluators: mean absolute percentage error (MAPE, %), root mean squared error (RMSE), the Nash–Sutcliffe model efficiency (EF) (Nash and Sutcliffe, 1970) and the coefficient of determination (R^2), each defined as follows:

$$\text{MAPE} = \frac{100}{n} \sum_{t=1}^{n} \left| \frac{o_t - p_t}{o_t} \right| \tag{2}$$

Where t is time step (year), o_t is the observed value of the quantity being predicted, p_t is the predicted value, and n is the number of years with available data;

$$\text{RMSE} = \left[n^{-1} \sum_{t=1}^{n} (p_t - o_t)^2 \right]^{0.5} \tag{3}$$

$$EF = \frac{\sum_{t=1}^{n} (o_t - \bar{o})^2 - \sum_{t=1}^{n} (p_t - o_t)^2}{\sum_{t=1}^{n} (o_t - \bar{o})^2} \tag{4}$$

and $\bar{o}$ is the mean of the observed data. Model efficiency EF=1 indicates full agreement between the predicted and observed data, whereas EF < 0 indicates that predicted values are worse than the observed mean ($\bar{o}$).

Statistical comparisons of SOC concentrations could not be conducted due to lack of treatment replication both of measured and simulated values; however, the standard error of the mean was used to infer if predicted SOC concentration means were different between cropping systems (Reynolds et al. 2014).

Future Scenarios

The variations in yield and SOC stock over time were simulated by DNDC for the historical climate during the trial period (1981-2015 in Elora and 1959-2015 in Woodslee) and for future climate scenarios over the 21st century (2016-2100). Two scenarios were selected from the four simulated RCPs: RCP4.5 which represents a medium stabilization scenario and RCP8.5 which represents a very high baseline emission scenario. Temperature, precipitation and atmospheric CO_2 concentration for these climate scenarios are listed in Table S5.

To evaluate trends in corn yield and SOC stock over the 21st century with RCP4.5 and RCP8.5 scenarios, a linear regression analysis with time as an independent factor was used (Sellers and Zenter, 1993). Significance of the difference between two slopes *(t value)* was calculated using:

$$t = \frac{b_1 - b_2}{\sqrt{s_{b1}^2 + s_{b2}^2}}, df = n_1 + n_2 - 4 \qquad (5)$$

where b_1 and b_2 are the slopes of regressions 1 and 2, and s_{b1} and s_{b2} are the standard errors for these slopes, df is degrees of freedom based on n_1 and n_2 which are the sample sizes for regression 1 and 2 (Soper, 2017).

Results and Discussion

Long-term yield variation

Variation in yield over time both in Elora and Woodslee was high. In Elora over 35 years, the differences between the lowest and peak corn yield varied depending on cropping system from 2.3 times in CC (5.04 Mg ha^{-1} in 1992 vs 11.74 Mg ha^{-1} in 2013 with a mean = 8.57 and σ =1.69

Mg ha^{-1}) to 2.9 times in CCAA (4.85 in 1992 vs 13.96 in 2008 with a mean = 9.21 and σ =1.86 Mg ha^{-1}) (Figure 1, Table 1). Expressed as coefficient of variation (CV) the variability in yield was similar for these two cropping systems (CC and CCAA) at ~20%. In Woodslee, annual corn yield experienced greater amplitude than in Elora. For corn yield in CC over 57 years, the observed maximum yield was 8.5 times greater than the lowest (9.82 in 1992 vs 1.15 Mg ha^{-1} in 1999 with an average of 5.99 and σ = 1.74 Mg ha^{-1}) (Figure 2, Table 1). The COAA cropping system markedly increased both minimum and maximum corn yield with peak yield only 3.4 times higher than the minimum (12.67 Mg ha^{-1} in 1992 vs 3.70 Mg ha^{-1} in 1991 with an average of 8.22 and σ = 2.00 Mg ha^{-1}) (Figure 2, Table 1). The CV for yield over 57 years was 29% for CC and 24.3% for COAA, highlighting the more stable yields over time for the diversified rotation at this site.

Comparison between observed and DNDC-predicted corn yield in monoculture and in diversified crop rotations

Changes to DNDC enhanced agreement between observed and predicted results at Elora for CCSS, CCSW, CCSW+Rc and CCAA rotations, expressed in lower deviation (RMSE and MAPE), greater R^2 and better model efficiency (EF) (Table 1). In Woodslee, model revision (DNDC 'after') was captured the significant improvement in yield over time observed for corn grown in rotation with oats and alfalfa (COAA) while DNDC 'before' did not predict this increase in yield over time (Fig. 2b). Consequently, RMSE and MAPE were reduced, R^2 became more significant (0.38) and model efficiency increase from negative to 0.21 (Table 1). Results for CC (R^2 = 0.40 and EF 0.35, Table 1) were better than previously reported for Woodslee by Liu et al. (2010) (R^2 = 0.36 and EF =-0.70) with the DSSAT-CERES-Maize model. Simulations over shorter time periods (4-6 years) have shown better agreement with observed yield for the Woodslee site (Liu et al. 2014; He et al. 2017). However, our RMSE values are slightly better than obtained with the crop model BioStar in Germany (2.1 Mg ha^{-1}) for corn yield (Bauböck, 2014). Large year to year variation in yield due to weather variability and potentially other factors, such as disease and pest incidence, over the long duration of the simulation period provided the most challenging aspect in good yield prediction performed by DNDC.

Comparison between observed and DNDC-predicted soil organic carbon

Distribution of predicted SOC concentration in the soil profile was evaluated for CC at both sites and COAA at Woodslee, as profile data was not available for the other cropping systems. Although DNDC predicted higher than measured SOC concentration for 0.20 to 0.40 m depth at both sites (Fig. S2), SOC stock in the 0-0.5 m depth agreed well between measured and predicted values in 1998, 2000, 2005 and 2015, with 17% lower than predicted values for Elora CC (Fig. S3). At Woodslee, the 0-0.50 m carbon stock predicted by DNDC was very close to observed values for CC and COAA (Fig S3). Measured and DNDC-predicted 0-0.5 m SOC stock for CC at Elora over all available years agreed well at 82.1 Mg C ha^{-1} (σ = 5.97 Mg C ha^{-1}) and 84.0 Mg C ha^{-1} (σ = 0.68 Mg C ha^{-1}), respectively. For Woodslee, mean observed 0-0.5 m SOC stock was 90.5 vs predicted of 88.7 Mg C ha^{-1} for CC, and 105.1 observed vs 105.5 Mg C ha^{-1} predicted for COAA. Smith et al. (2012) simulated SOC change in residue removal experiments for 14 sites (11 in Western Canada, 1 in Guelph, ON, and 2 in the mid-western USA). They observed DNDC slightly underestimated changes in SOC between cropping systems but differences in relation to observations remained within the 95% confidence limits, demonstrating the ability of DNDC in predicting reasonable SOC stock values.

Increased SOC stocks after long-term diversified crop rotations were predicted well by the DNDC model at both sites (Table 2). At Elora, observed and predicted 0-0.2 m SOC stocks for simpler rotations (CC and CCSS) averaged 53.8 and 53.3 Mg C ha^{-1}, while diversified rotations (CCSW, CCSW+Rc and CCAA) were 58.4 and 59 Mg C ha^{-1}, respectively (Table 2). The largest discrepancy between observed and modelled SOC stock was observed for CCAA with slightly higher observed (4%) than predicted value (58.26 vs 55.81 Mg C ha^{-1}, Table 2). For Woodslee, predicted and measured 0-0.2 m SOC stocks were very similar (Table 2), and both showed increased SOC for the diversified rotation COAA in comparison to CC (Table 2). The modelling results agree with previous observations at the Woodslee site showing higher SOC stock in COAA than in CC (Drury et. al., 1998; Drury et al., 2004; Reynolds et al., 2014). Reynolds et al. (2014) described the COAA rotation as having minimal to moderate soil degradation, whereas CC presented excessive degradation relative to uncultivated soil. In general, SOC sequestration has been observed to be higher in crop rotations than in monocultures due to high production of crop residues and differences in crop residue quality (Franzluebbers et al., 1995; Drury et al. 1998).

Simulations for future climate scenarios

Simulations for future climate over the 21st century (2016-2100) using RCP4.5 showed distinct changes in yields and associated SOC stocks between cropping systems both in Elora and Woodslee (Fig. 3). For Elora, CC and CCSS did not show any trend (regression was not significant) over time and the corn yields were at the same level until the end of the 21st century (Fig. 3a, Table 3). DNDC predicted lower corn yield for CC and CCSS contrasted with CCSW, CCSW+Rc and CCAA where the yield was high. For CCSW, CCSW+Rc and CCAA, a significant increase in corn yield was observed over the first 45 years of simulation (until 2060). For the remaining time (2060-2100) corn yield levelled off (Fig. 3a). An increase in yield over time was noted in CCSW, CCSW+Rc and CCAA with larger increases for CCAA compared to CCSW or CCSW+Rc as indicated by significant differences in slopes (Table 3). Meyer-Aurich et al. (2006a) did observe improved yields at Elora when wheat was included in a corn-soybean rotation but underseeding red clover into wheat had no effect on yields.

Decreased 0-0.2 m SOC stocks were predicted for CC and CCSS at Elora, with larger decreases for the CCSS rotation (Fig 3b, Table 3). Such trend was observed with measured values where SOC stock in the 0-0.34 m soil layer was less for CCSS than in CCAA (Meyer-Aurich et al. (2006b). In contrast, more diversified rotations had the largest increases in SOC stock over time: CCSW+Rc> CCAA>CCSW (Fig. 3b, Table 3). Results from Iowa (Farahbakhshazad et al., 2008) showed that DNDC-modelled soil carbon storage increased over 20 years when cover crops were added to a corn-soybean rotation, due to higher biomass C input, although crop yields stayed the same. Farahbakhshazad et al., (2008) used the DNDC model to explore how alternative cropping practices affect environmental processes such as SOC storage and nitrate leaching, but extensive validation of C inputs and SOC was not conducted for a range of cropping systems.

Our findings that corn yields and SOC may increase in the future under diversified rotations, relative to monoculture and CCSS, is an important result that has not been demonstrated in other modelling studies in Canada. The results are plausible considering DNDC was validated using long-term experimental data which already included variability in climate and marginal increases in atmospheric CO_2 concentration. The improved performance in the diversified rotations is strongly related to crop water stress. Although precipitation increases under the climate scenarios, the simulated evapotranspiration increases at a greater rate at higher temperatures. Note that the Canada DNDC model has recently been improved and validated for simulating evapotranspiration in eastern Canada (Dutta et al., 2016a). Some crops have lower water requirements than corn (such as oats) or are grown in periods where more water is available due to low soil evaporation at cooler temperatures (such as winter wheat or red clover). This reduces water stress in the system and promotes higher growth which increases residue C inputs. As a consequence, SOC under climate change is predicted to decline slightly under CC and the CCSS rotation (soybean has high water use/biomass and low soil carbon inputs), but to increase under the diversified rotations. The increased evaporative stress for the rotational corn is offset by reduced or more efficient water use by the other crops but also by the higher soil water holding capacity calculated by the revised DNDC model as SOC increases.

At Woodslee, future corn yield was also predicted to be significantly lower when grown in monoculture (CC) than in the diversified COAA rotation (Fig 3c), with trends of increased yields in COAA relative to CC. Smith et al. (2013) pointed out that DNDC predicts significant increases in monoculture corn yield over time due to large projected increases in heat units and increases in crop water and N use efficiency under elevated CO_2. However, improved evapotranspiration (Dutta et al., 2016) or the pedo-transfer function to adjust water holding capacity in response to changes in SOC was not considered in their study. Future prediction of SOC stocks at Woodslee were in line with trends observed during the experimental period with COAA having significantly higher SOC than CC (Fig. 3d). At the end of the simulation period (2100) Woodslee SOC showed greater increase for COAA (26%) than for CC (16%) compared to divergences between the systems in 2015 (Fig 3d). Both COAA and CC regressions showed positive trends in SOC stock, with larger increases over time predicted for COAA (Table 3).

Results obtained for the RCP8.5 scenario (assuming high concentration of CO_2 of 850 ppm, Table S5), showed no distinct difference in corn yield and SOC stock from RCP4.5 at Elora (Figs. 3 and S4, Tables 3 and S6). In Woodslee, scenario RCP8.5 showed a slight increase in corn yield of 6.5 % for CC and COAA comparing to RCP4.5, and there was no clear difference in SOC stock (+ 0.6 % in CC and + 2.1% in COAA) (Figs 3 and S4, Tables 3 and S6). The crop trend confirmed previous modelling results using a different long-term trial in Woodslee where the RCP8.5 corn yield was higher by 5.4% than the RCP 4.5 (He et al., 2017). This growth in corn yield under future climate scenarios can be explained by the benefits from higher temperature and CO_2 fertilization effect on C_4 crops (Denger, 2015; He et al., 2017). Crop water, and N efficiency increases in DNDC under elevated CO_2 in accordance with recent Free-Air CO_2 Enrichment studies (Smith et al., 2013).

Conclusion

The DNDC model was modified and evaluated using observed crop yields and climatic parameters to improve yield estimates in diversified rotations. After revision, the DNDC prediction of corn yield and SOC stock was more accurate in all cropping systems. The corn rotations with winter wheat (CCSW, CCSW+Rc), or alfalfa (CCAA) in Elora or oats and alfalfa (COAA) in Woodslee generated greater corn yields and higher SOC stock than CC. Future scenarios for Elora showed intermediate trends in increased corn yield in CCSW, CCSW+Rc and CCAA, but there was no predicted increase for CC or CCSS rotation. SOC stock also increased under diversified rotations, but projections for CC and CCSS indicated negative trends in SOC stock. At Woodslee, future scenarios for corn yield and SOC stock were positive both for CC and

COAA; however, the increase in corn yield and SOC stock under the COAA rotation was considerably greater than under CC. Increases in corn yield for RCP8.5 in relation to RCP4.5 were predicted for Woodslee due to the positive influence of increased atmospheric CO_2. This study indicates that corn yields and SOC content under diversified rotations will be more resilient and could increase under the impacts of future climate change in comparison to CC or CCSS rotations, primarily due to the mitigation of crop water stress.

Acknowledgements

Funding for this research was provided by the New Directions program, Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Additional funding was received from the Natural Science and Engineering Research Council, Discovery grant program.

References

Abalos, D., W.N. Smith, B.B. Grant, C.F. Drury, S. MacKell, and C. Wagner-Riddle. 2016. Scenario analysis of fertilizer management practices for N_2O mitigation from corn systems in Canada. Sci. Total Environ. 573: 356-365.

Bauböck, R. 2014. Simulating the yields of bioenergy and food crops with the crop modeling software BioSTAR: the carbon-based growth engine and the BioSTAR ET0 method. Environ. Sci. Eur. 26: 1–9.doi:10.1186/2190-4715-26-1.

Bolinder M.A., H.H. Janzen, E.G. Gregorich, D.A. Angers a, A.J. VandenBygaart. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agric. Ecosyst. Environ. 118: 29–42

Bolton, E. F., V.A. Dirks, and M.M. Mcllonnell. 1982. The effect of drainage, rotation and fertilizer on corn yield, plant height, leaf nutrient composition and physical properties of Brookston clay soil in southwestern Ontario. Can. J. Soil Sci. 62:297-309.

Brilli L, L. Bechini, M. Bindi, M. Carozzi, D.Cavalli, R. Conant, C.D. Dorich, L. Doro, F. Ehrhardt, R. Farina, R. Ferrise, N. Fitton, R. Francaviglia, P. Grace, I. Iocola, K. Klumpp, J. Léonard, R.Martin, R.S. Massad, S. Recous, G. Seddaiu, J. Sharp, P. Smith, W.N. Smith, J.F. Soussana and G.L. Bellocchi. 2017. Review and analysis of strengths and weaknesses of agro-ecosystem models in representing C and N fluxes. Sci. Total Environ. 598, 445-470.

Congreves, K. A., B. B. Grant, B. Dutta, W. N. Smith, M. H. Chantigny, P. Rochette, and R. L. Desjardins. 2016. Predicting ammonia volatilization after field application of swine slurry: DNDC model development. Agric. Ecosyst. Environ. 219: 179-189.

Congreves, K.A., A. Hayes, E. A. Verhallen, and L.L. Van Eerd. 2015. Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems. Soil Till. Res.152: 17–28.

Deen, B. 2017. Elora crop rotation trial documentation (1981-2015). Unpublished data.

Degener, J.F. 2015. Atmospheric CO_2 fertilization effects on biomass yields of 10 crops in northern Germany. Front. Environ.Sci.3:48. doi: 10.3389/fenvs.2015.00048.

Drury, C. F., X.M.Yang, W.D., Reynolds, and N.B. McLaughlin. 2008. Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. Can. J. Soil Sci. 88: 163-174.

Drury, C.F, X.M. Yang, W.D. Reynolds, and C.S. Tan. 2004. Influence of crop rotation and aggregate size on carbon dioxide production and denitrification. Soil Till. Res. 79: 87–100.

Drury, C.F., T. O. Oloya, D. J. McKenney, E. G. Gregorich, C. S. Tan, and C. L. van Luyk. 1998. Long-Term effects of fertilization and rotation on denitrification and soil carbon. Soil Sci. Soc. Am. J. 62:1572-1579.

Drury, C. F. and C.S. Tan. 1995. Long-term (35 years) effects of fertilization, rotation and weather on corn yields. Can. J. Plant Sci. 75: 355-362.

Dutta, B., B. B. Grant, K. A. Congreves, W.N. Smith, C.Wagner-Riddle, A. C. VanderZaag, M. Tenuta, and R. L. Desjardins. 2017. Characterising effects of management practices, snow cover, and soil texture on soil temperature: Model development in DNDC." Biosystems Engineering. In press.

Dutta, B., W. N. Smith, B. B. Grant, E.Pattey, R. L. Desjardins, and C. Li. 2016a. Model development in DNDC for the prediction of evapotranspiration and water use in temperate field cropping systems. Environ. Modell. Softw. 80: 9-25.

Dutta, B., K. A. Congreves, W. N. Smith, B. B. Grant, P. Rochette, M. H. Chantigny, and R. L. Desjardins. 2016b. Improving DNDC model to estimate ammonia loss from urea fertilizer application in temperate agroecosystems. Nutri. Cycl. Agroecosyst.: 275-292.

Ellert, B.H., H.H. Janzen, A.J. Vander Bygaard and E. Bremmner. 2008. Measuring change in soil organic carbon storage. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis. 2nd ed. CRC Press Taylor & Francis Group 6000 Broken Sound Parkway NW, Suite 300 Boca Raton, FL. p. 25-38.

Ehrhardt, F., J.F.Soussana, G. Bellocchi, P. Grace, R. McAuliffe, R., S. Recous, R. Sándor, P. Smith, V. Snow, M.D.A. Migliorati, B. Basso, A. Bhatia, L. Brilli, J. Doltra, C.D. Dorich, L. Doro, N. Fitton, S.J. Giacomini, B. Grant, M.T. Harrison, S.K. Jones, M. Kirschbaum, Klumpp, P. Laville, J.Léonard, M. Liebig, M. Lieffering, R.Martin, R.S.Massad, E. Meier, L.

Merbold, A.D. Moore, V. Myrgiotis, P. Newton, E.Pattey, S.Rolinski, J.Sharp, W.N.Smith, L.Wu, and Q.Zhang. 2017. Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N_2O emissions. Glob Change Biol. Accepted Author Manuscript. doi:10.1111/gcb.13965Environment Canada. 2017. Environment Canada, Meteorological Services of Canada, 4905 Dufferin Street, Downsview, Ontario M3H 5T4.

Farahbakhshazad, N., D.L. Dinnes, C.S. Li, D.B. Jaynes, and W.Salas. 2008. Modeling biogeochemical impacts of alternative management practices for a row-crop field in Iowa. Agric. Ecosyst. Environ. 123: 30–48.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer, 1994. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58: 1639–1645.

Gaudin, A.C.M., T.N. Tolhurst, A.P. Ker AP, K. Janovicek, C.Tortora, and R.C. Martin. 2015. Increasing Crop Diversity Mitigates Weather Variations and Improves Yield Stability. PLoS ONE 10 (2): e0113261. doi: 10.1371/journal.pone.0113261.

Gaudin, A.C.M., S. Westra, C.E.S. Loucks, K. Janovicek, R.C. Martin and W. Deen. 2013. Improving resilience of northern field crop systems using inter-seeded red clover: a review. Agronomy 2013, 148-180; doi:10.3390/agronomy3010148.

Grant, BB., W.N.Smith, C.A. Campbell, R.L. Desjardins, R.L. Lemke, R. Kröbel, B.G. McConkey, E.G. Smith, and G.P. Lafond. 2016. Comparison of DayCent and DNDC Models: Case Studies Using Data from Long-Term Experiments on the Canadian Prairies. In: S. Del Grosso, L. Ahuja and W. Parton, editors. Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forest Systems to Guide Mitigation and Adaptation. Advances in Agricultural Systems Modeling 6. ASA, CSSA, SSSA. 21-58. doi:10.2134/advagricsystmodel6.2013.0035.

He, W., J.Y. Yang, C.F. Drury, W.N. Smith, B.B. Grant and P. He. 2017. Estimating the impacts of climate change on crop yields and N_2O emissions for conventional and no-tillage in Southwestern Ontario. Agri. Systems, http://dx.doi.org/10.1016/j.agsy.2017.01.025.

IPCC, 2014. Climate Change: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

IPCC, 2007. Fourth Assessment Report: Climate Change 2007. https://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html (accessed 15 June 2017).

Janzen, H.H., K. Beauchemin Y. Bruinsma and E.G. Smith.2003. The fate of nitrogen in agroecosystems: An illustration using Canadian estimates. Nutr. Cycl. Agroecosys. 67:85-102.

Karlen D.L., C.A. Cambardella, J.L. Kovar, and T.S. Colvin. 2013. Soil quality response to long-term tillage and crop rotation practices. Soil Till. Res. 133: 54-64.

Kröbel, R., W.N. Smith, B.B. Grant, R.L. Desjardins, C.A. Campbell, N.Tremblay, C.S. Li, R.P. Zentner, and B.G. McConkey. 2011. Development and evaluation of a new Canadian spring wheat sub-model for DNDC. Can. J. Soil Sci. 91: 503:520.

Li, C., W. Salas, Z. Ruihong, C. Krauter, A.Rotz, and F. Mitloehner. 2012. Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutri. Cycl. Agroecosyst. 93: 163-200.

Li, C., J. F. Aber, F. Stange, K. Butterbach-Bahl, and H. Papen. 2000. A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development. J. Geophys. Res. 105:4369–4384. doi:10.1029/1999JD900949

Liebman, M., M.J. Helmers, L.A. Schulte and C. A. Chase. 2013. Using biodiversity to link agricultural productivity with environmental quality: Results from three field experiments in Iowa. Renewable Agr. Food Syst. 28: 115–128 doi:10.1017/S1742170512000300

Liu, S., Yang, J. Y., Drury, C. F., Liu, H. L. and Reynolds, W. D. 2014. Simulating maize (Zea mays L.) growth and yield, soil nitrogen concentration, and soil water content for a long-term cropping experiment in Ontario, Canada. Can. J. Soil Sci. 94: 435-452.

Liu, H.L., J. Y. Yang, C. F. Drury, W. D. Reynolds, C. S. Tan, Y. L. Bai, P. He, J. Jin, and G. Hoogenboom. 2010. Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. Nutr. Cycl. Agroecosyst. 89: 313-328.

Meyer-Aurich A., K. Janovicek, W. Deen, and A. Weersink. 2006a. Impact of tillage and rotation on yield and economic performance in corn-based cropping systems. Agron. J. 98:1204–1212.

Meyer-Aurich A, A. Weersink, K. Janovicek, and B. Deen. 2006b. Cost efficient rotation and tillage options to sequester carbon and mitigate GHG emissions from agriculture in Eastern Canada. Agr. Ecosys. Environ.117:119-127.

Munkholm L.J., R.J. Heck, and B. Deen. 2013. Long-term rotation and tillage effects on soil structure and crop yield. Soil Till Res. 127:85-91 .DOI: 10.1016/j.still.2012.02.007

Nash, J. E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models, Part I - A discussion of principles. J. Hydrol. 10:282-290.

Ramnarine R., R. P. Voroney, C. Wagner-Riddle, and K. E. Dunfield. 2014. Conventional and no-tillage effects on the distribution of crop residues and light fraction organic matter. Soil Sci. Soc. Am. J. 79:74–80.

Reynolds, W. D., C.F. Drury, X.M. Yang, C.S. Tan, and J.Y. Yang. 2014. Impacts of 48 years of consistent cropping, fertilization and land management on the physical quality of a clay loam soil. Can. J. Soil Sci. 94: 403-419.

Saxton, K.E., and W. Rawls. 2009. Soil water characteristics hydraulic properties calculator. http://hrsl.ba.ars.usda.gov/soilwater/Index.htm (accessed 15 May 2017).

Saxton, K.E. and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc.Am. J. 70: 1569-1578.

Selles, F. and R.P. Zentner. 1993. Spring wheat yield trends in long-term fertility trials. Can. J. Plant Sci. 73: 83-92.

Smith,W.N., B.B. Grant, R.L. Desjardins, R. Kroebel, C. Li, B. Qiana, D.E. Worth, B.G. McConkey, and C.F. Drury. 2013. Assessing the effects of climate change on crop production and GHG emissions in Canada. Agric. Ecosyst. Environ. 179: 139– 150.

Smith,W.N., B.B. Grant, C.A. Campbell, B.G. McConkey, R.L. Desjardins, R. Kröbel, and S.S. Malhi. 2012. Crop residue removal effects on soil carbon: Measured and inter-model comparisons. Agric. Ecosyst. Environ.161: 27– 38.

Smith, W. N., B.B. Grant, R.L.Desjardins, P. Rochette, C.F. Drury, and C. Li. 2008. Evaluation of two process-based models to estimate soil N2O emissions in Eastern Canada. Can. J. Soil Sci. 88: 251-260.

Smith, W. N., R.L. Desjardins, B. Grant, C.Li, R.Lemke, P. Rochette, M.D. Corre, and D. Pennock. 2002. Testing the DNDC model using N_2O emissions at two experimental sites in Canada. Can. J. Soil Sci. 82: 365–374.

Soper, D.S. 2017. Significance of the difference between two slopes calculator [Software]. Available from http://www.danielsoper.com/statcalc (accessed 15 Jun. 2017).

Tan C.S., C.F. Drury, W.D. Reynolds, P.H. Groenevelt, and H. Dadfar. 2002. Water and nitrate loss through tiles under a clay loam soil in Ontario after 42 years of consistent fertilization and crop rotation. Agric. Ecosyst. Environ 93: 121–130.

Van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A.Thomson, K. Hibbard, G.C. Hurtt, T. ram, V. Krey, J. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose. 2011. The representative concentration pathways: an overview. Clim.Chang. 109: 5–31.

Wanniarachchi S.D., R. P. Voroney, T. J. Vyn, R. P. Beyaert, and A. F. MacKenzie. 1999. Tillage effects on the dynamics of total and corn-residue derived soil organic matter in two southern Ontario soils. Can. J. Soil Sci. 89: 473-480.

Yan, W., L.A. Hunt. 1999. An equation for modelling the temperature response of plants using only the cardinal temperatures. Ann. Bot. 84, 607–614. doi:http://dx.doi.org/10.1006/anbo.1999.0955.

Yang X. M., C. F. Drury, M. M. Wander and B. D. Kay. 2008. Evaluating the effect of tillage on carbon sequestration using the minimum detectable difference concept. Pedosphere 18: 421–430.

Zhang Y, and H. Niu. 2016. The development of the DNDC plant growth sub-model and the application of DNDC in agriculture: A review. Agric. Ecosys. Environ. 230: 271–282.

Table 1. Statistical evaluation of observed and DNDC-simulated corn yields for Elora and Woodslee before and after model revision. Average corn yields over 35 and 57 years are shown for Elora (1981-2015) and Woodslee (1959-2015), respectively, for cropping systems: CC = continuous corn, CCSS = corn-corn-soybean-soybean, CCSW = corn-corn-soybean-winter wheat, CCSW+Rc = corn-corn-soybean-winter wheat with red clover as a cover crop after wheat, CCAA = corn-corn-alfalfa-alfalfa, and COAA = corn-oats-alfalfa-alfalfa. RMSE = root mean squared error, MAPE = mean absolute percentage error, R^2 = coefficient of determination for regression between observed and modelled yields, and EF = model efficiency.

Site/ System	Average corn yield			RMSE		MAPE		R^2		EF	
	Obs.	Model									
		before	after	before	after	before	after	before	after	before	after
Elora	-------------------Mg ha^{-1}-----------------					-------%------					
CC	8.57 (1.69)	8.39 (1.49)	8.49 (1.66)	1.13	1.17	11.8	11.6	0.58	0.56	0.54	0.51
CCSS	8.69 (1.81)	8.41 (1.39)	8.46 (1.26)	1.47	1.42	15.5	14.6	0.37	0.38	0.32	0.37
CCSW	8.77 (1.79)	9.05 (1.38)	9.02 (1.43)	1.28	1.19	13.4	12.6	0.50	0.56	0.46	0.54
CCSW+Rc	9.21 (1.92)	8.55 (1.24)	9.40 (1.36)	1.60	1.35	15.4	12.2	0.40	0.50	0.28	0.49
CCAA	9.21 (1.86)	8.71 (1.29)	8.78 (1.66)	1.46	1.41	13.5	10.9	0.44	0.50	0.36	0.40
Woodslee											
CC	5.98 (1.74)	6.34 (1.17)	6.29 (1.36)	1.39	1.40	25.8	24.7	0.40	0.40	0.35	0.35
COAA	8.22 (2.00)	6.54 (1.29)	7.65 (1.79)	2.57	1.76	24.0	16.6	0.20	0.38	-0.50	0.21

Table 2. Observed and predicted mean soil carbon stock in 0-0.2 m layer at Elora and Woodslee with standard error of mean shown in brackets. n = number of samples.

Location	Cropping system	n	Observed	DNDC
			--------------------- Mg C ha^{-1}----------------	
Elora	CC	5	54.13 (1.06)	53.74 (0.39)
	CCSS	3	53.46 (0.515)	52.97 (0.26)
	CCSW	3	58.60 (1.61)	59.93 (2.84)
	CCSW+Rc	2	58.40 (2.04)	61.17 (1.45)
	CCAA	2	58.26 (0.55)	55.81 (1.26)
Woodslee	CC	3	52.02 (1.31)	51.36 (0.248)
	COAA	3	62.96 (1.03)	61.09 (0.566)

Table 3. Regression analysis of predicted corn yield and 0-0.2 m soil organic carbon stock under representative concentration pathway (RCP) scenario RCP 4.5 for the 2016-2100 period at Elora and Woodslee. Results are shown for CC = continuous corn; CCSS = corn-corn-soybean-soybean, CCSW = corn-corn-soybean-winter wheat, CCSW+Rc = corn-corn-soybean-winter wheat + red clover, CCAA = corn-corn-alfalfa- alfalfa, COAA = corn-oats-alfalfa-alfalfa. Linear regression slopes followed by different letters for each site indicate significant trends over time among cropping systems.

Site	Factor	Rotation	R^2	*slope*	*St error*	*t value*	*P-value*
Elora	Corn Yield	CC	0.01	4.38c	4.73	0.93	0.36
		CCSS	0.00	-0.67c	4.67	-0.14	0.89
		CCSW	0.66	36.61b	2.41	15.19	0.00
		CCSW+Rc	0.67	36.98b	2.39	15.46	0.00
		CCAA	0.59	46.50a	3.52	13.22	0.00
	SOC	CC	0.32	-11.78e	1.56	-7.54	0.00
		CCSS	0.90	-35.38d	1.06	-33.46	0.00
		CCSW	0.97	41.74c	0.72	58.14	0.00
		CCSW+Rc	0.99	108.5a	0.96	112.7	0.00
		CCAA	0.95	101.1b	2.04	49.5	0.00
Woodslee	Corn yield	CC	0.06	9.53b	3.15	3.02	0.00
		COAA	0.23	23.72a	3.50	6.64	0.00
	SOC	CC	0.32	4.91b	0.60	8.20	0.00
		COAA	0.98	218.64a	1.91	114.6	0.00

Figure captions:

Fig. 1. Comparison of simulated and observed corn yield from 1981 to 2015 under five cropping systems at Elora for: a) continuous corn (CC), b) corn-corn-soybean-soybean (CCSS), c) corn-corn-soybean-winter wheat (CCSW), d) corn-corn-soybean-winter wheat + red clover (CCSW+Rc) and e) corn-corn-alfalfa-alfalfa (CCAA). Simulated values were obtained with the DNDC model before and after model revision to account for long-term effects of diversified rotations on soil conditions.

Fig. 2. Comparison of simulated and observed corn yield from 1959 to 2015 at Woodslee for: a) continuous corn (CC), and b) corn-oats-alfalfa-alfalfa rotation (COAA). Simulated values were obtained with the DNDC model before and after revision to account for long-term effects of diversified rotations on soil conditions.

Fig. 3. Predictions of corn yield (a. and b.) and 0-0.2 m SOC stock (c. and d.) under representative concentration pathway (RCP) scenario RCP 4.5 over 2016 to 2100 at Elora (a. and c.) and Woodslee (b. and d.) for various cropping systems. Predictions were averaged over selected periods starting in 2016 with error bars representing standard error of means (n=25 for 2016-2040, and n = 20 for other periods). CC = continuous corn; CCSS = corn-corn-soybean-soybean, CCSW = corn-corn-soybean-winter wheat, CCSW+Rc = corn-corn-soybean-winter wheat + red clover, CCAA = corn-corn-alfalfa- alfalfa, COAA = corn-oats-alfalfa-alfalfa.

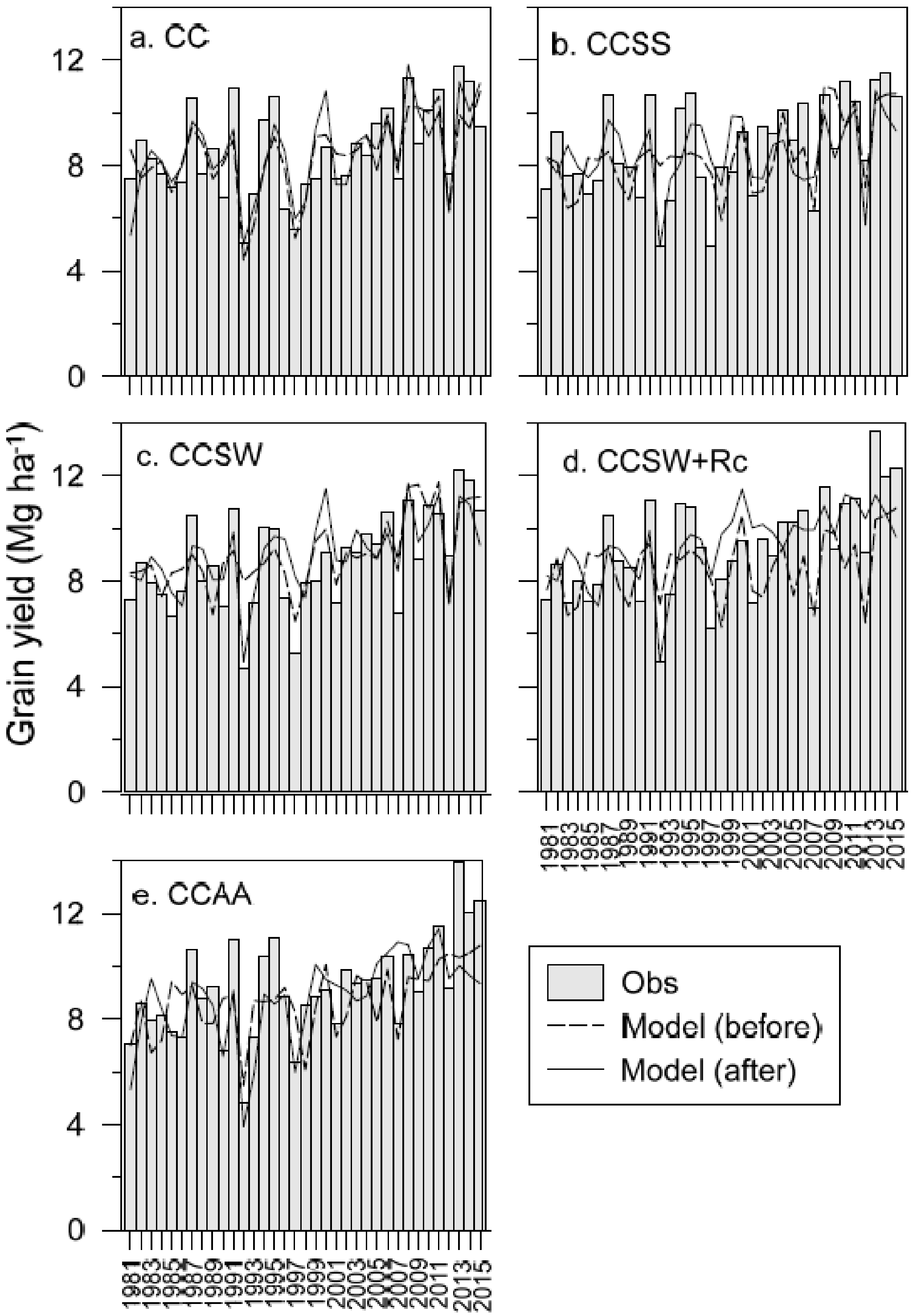
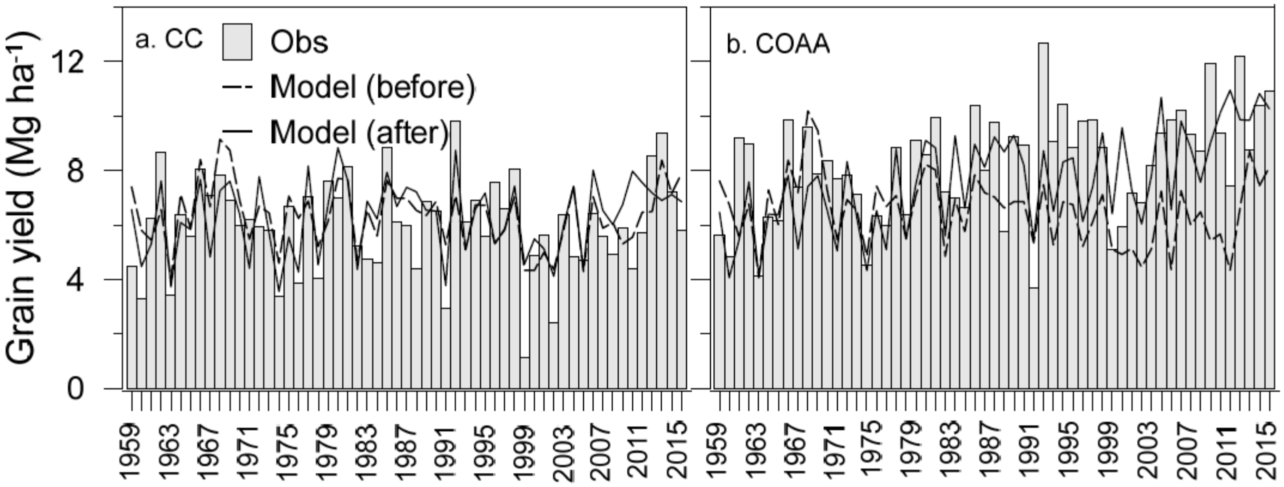
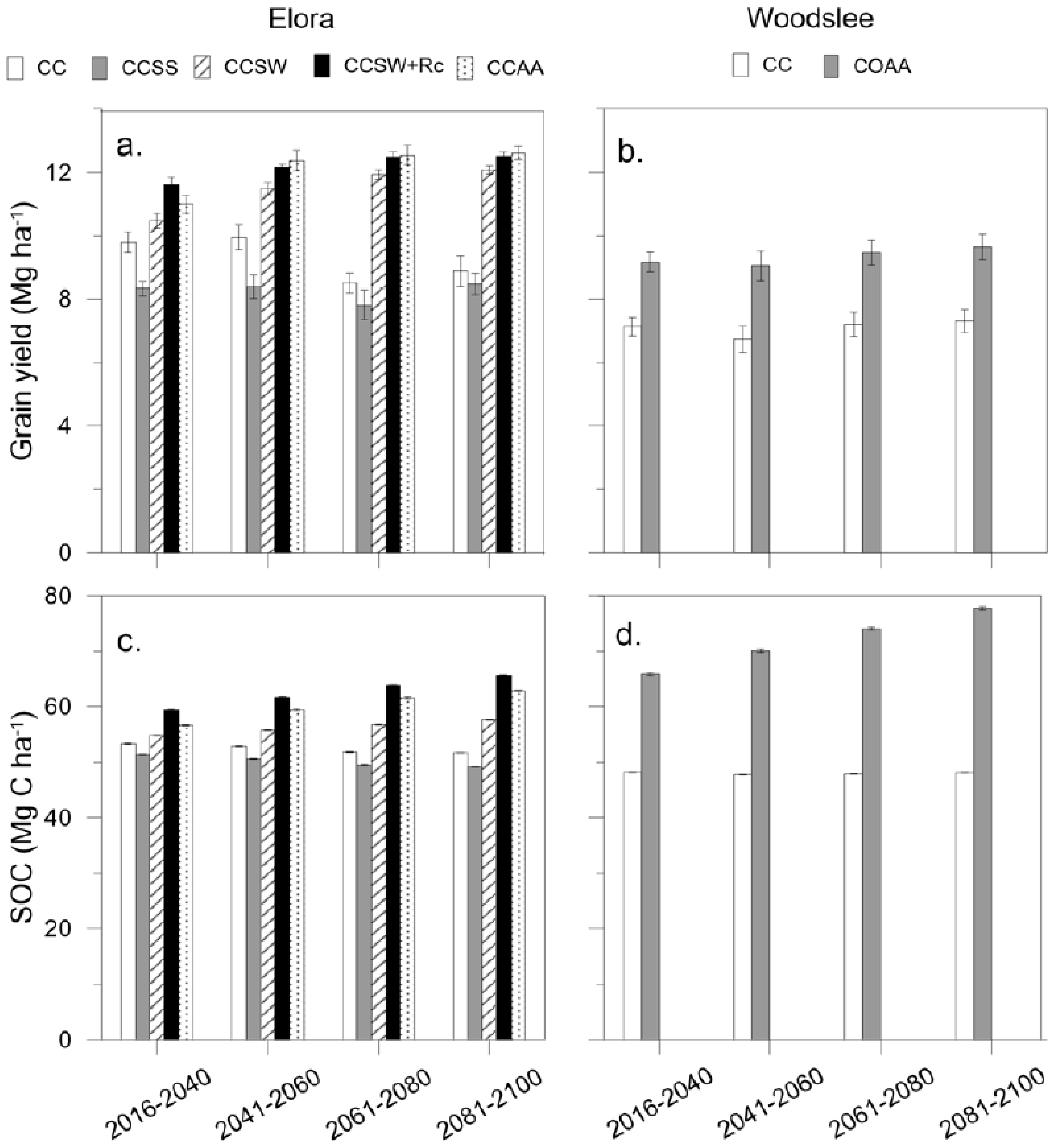

a. CC
b. CCSS
c. CCSW
d. CCSW+Rc
e. CCAA
Grain yield (Mg ha^{-1})
0
4
8
12
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Obs
Model (before)
Model (after)

Fig 1



Grain yield (Mg ha-1)
0
4
8
12
a. CC
Obs
Model (before)
Model (after)
b. COAA
1959
1963
1967
1971
1975
1979
1983
1987
1991
1995
1999
2003
2007
2011
2015

Fig 2



613

614 **Fig 3**

615

Supplemental Material

Long-term trends in corn yields and soil carbon under diversified crop rotations

Marek Jarecki[1], Brian Grant[2], Ward Smith[2], Bill Deen[3], Craig Drury[4], Andrew VanderZaag[2], Budong Qian[2], Jingyi Yang[4] and Claudia Wagner-Riddle[1]

[1]School of Environmental Sciences, University of Guelph, Guelph, ON, Canada; [2]Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, Ottawa, ON, Canada; [3]Department of Plant Agriculture, University of Guelph, Guelph, ON, Canada; [4]Harrow Research and Development Centre, Agriculture and Agri-Food Canada, Harrow, ON, Canada.

Table S1. Soil and crop management inputs for corn grown in monoculture and in crop rotations at Elora and Woodslee, Ontario Canada.

Soil Inputs (0-0.20 m)

Site	pH	Clay	SOC	BD	Wilting point	Field capacity	Saturated Hydraulic Conductivity
		g kg^{-1}		Mg m^{-3}	% Vol		mm h^{-1}
Elora	7.3	170	22	1.30	12.8	31.1	23.8
Woodslee	6.1	370	25	1.35	23.4	37.6	6.02

Crop management inputs

	Planting	Fertilizer application		Tillage application	
		Starter	Side-dress	Spring	Fall
Elora	May	At planting 8 kg N ha^{-1}	6th leaf stage 140-150 kg N ha^{-1}	Disc before planting	Moldboard plowing end of Oct to mid-Nov
Woodslee	mid- May to June	One day before planting 16.8 kg N ha^{-1}	6th leaf stage 112 kg N ha^{-1}	Disc before planting	Moldboard plowing end of Oct to mid-Nov

Table S2. Climate means for the period over which long-term cropping experiments were conducted at the two sites in Ontario, Canada.

Site	Elora	Woodslee
Period	1981-2015	1959-2015
Annual precipitation (mm)	1009	844
Precipitation May-Sep (mm)	426	410
Annual maximum temperature (°C)	11.4	13.9
Annual minimum temperature (°C)	1.8	4.7
Growing degree-days[†]	1009	1405
Solar radiation (MJ m^2)	13.4	13.6
Wind speed (m s^{-1})	4.0	3.4
Relative humidity (%)	81	75

[†] Growing degree-days May to September was computed by averaging daily maximum and minimum temperatures and subtracting base temperature (10°C). When average temperature was <10°C, degree day value = 0.

Table S3. Calibration results for DNDC model runs at the Woodslee site using the first 10 years of continuous corn yield.

A. Corn yield (Mg ha^{-1}) 1959-1968			
Year	Observed Yield	Before calibration	After calibration
1959	4.46	5.93	6.57
1960	3.30	4.36	4.48
1961	6.23	5.00	5.31
1962	8.69	4.36	7.62
1963	3.24	3.99	3.72
1964	6.37	4.35	6.10
1965	5.59	5.20	5.83
1966	8.07	4.45	7.68
1967	7.08	6.31	4.83
1968	7.81	5.34	7.27
Average	6.10	4.93	5.94
Standard deviation	1.90	0.76	1.36
B. Statistical evaluation			
Root mean square error (RMSE, Mg ha^{-1})		2.18	1.16
Mean absolute percentage error (MAPE, %)		38.0	16.8
Coefficient of determination (R^2)		0.02	0.59
Model efficiency (EF)		-0.47	0.58

Table S4. Sources of soil organic carbon measurements per depth used to compared with DNDC model outputs for the two studied sites.

†Carbon concentration was recalculated from SOC content

Site/year	Available sampling depth (m) for each cropping systems					Source
Elora	CC	CCSS	CCSW	CCSW+Rc	CCAA	
1995	0-0.5	NA†	NA	NA	NA	Wanniarachichi et al. (1999)
1998	0-0.5	0-0.5	0-0.5	0-0.5	NA	Deen (2017) (unpublished)
2000	0-0.5	0-0.5	0-0.5	0-0.5	0-0.5	Deen (2017) (unpublished)
2005	0-0.5	NA	NA	NA	NA	Yang et al. (2008)
2015	0-0.5	0-0.5	0-0.5	NA	0-0.5	Deen (2017) (unpublished)
Woodslee		CC		COAA		
1994		0-0.5		0-0.5		Drury et al. (1994)
2002‡		0-0.15		0-0.15		Drury et al. (2004)
2004-2007		0-0.50		0-0.50		Reynolds et al. (2014)

‡ Not available

Table S5. Atmospheric conditions for historical (1981-2015 for Elora; 1959-2015 for Woodslee) and future projections (up to 2100) at two representative concentration pathways (RCP4.5 and RCP 8.5) in Ontario, Canada. Historical years correspond to duration of long-term cropping system trials.

		Average annual temperature		Annual precipitation		CO_2 concentration	
	Scenario	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Location		-------------°C------------		------------mm------------		-------mg m^{-3}-----	
Elora	1981-2015	6.6	6.6	1009	1009	367	367
	2016-2040	8.1	8.6	1002	949	431	443
	2041-2060	9.3	9.7	1003	1031	487	545
	2061-2080	9.9	10.8	992	1081	523	682
	2081-2100	10.1	12.8	1044	1070	534	850
Woodslee	1959-2015	9.3	9.3	844	844	359	359
	2016-2040	10.9	11.4	878	848	407	411
	2041-2060	12.1	12.5	857	947	462	493
	2061-2080	12.5	13.8	826	976	509	609
	2081-2100	12.8	15.1	908	966	534	850

Table S6. Regression analysis of predicted corn yield and 0-0.2 m soil organic carbon stock under representative concentration pathway (RCP) scenario RCP 8.5 for the 2016-2100 period at Elora and Woodslee. Results are shown for CC = continuous corn; CCSS = corn-corn-soybean-soybean, CCSW = corn-corn-soybean-winter wheat, CCSW+Rc = corn-corn-soybean-winter wheat + red clover, CCAA = corn-corn-alfalfa- alfalfa, COAA = corn-oats-alfalfa-alfalfa. Linear regression slopes followed by different letters for each site indicate significant trends over time among cropping systems.

Site	Factor	Rotation	R^2	*Slope*	*St error*	*t value*	*P-value*
Elora	Corn Yield	CC	0.01	4.04c	4.54	0.89	0.38
		CCSS	0.00	-1.52c	4.41	-0.34	0.73
		CCSW	0.71	40.17b	2.33	17.24	0.00
		CCSW+Rc	0.74	40.60b	2.20	18.17	0.00
		CCAA	0.62	53.13a	3.81	13.95	0.00
	SOC	CC	0.47	-15.53e	1.52	-10.24	0.00
		CCSS	0.95	-39.80d	0.86	-46.10	0.00
		CCSW	0.96	46.18c	0.85	54.26	0.00
		CCSW+Rc	0.99	116.6a	0.98	118.9	0.00
		CCAA	0.94	92.47b	2.16	42.9	0.00
Woodslee	Corn yield	CC	0.17	16.58b	3.09	5.37	0.00
		COAA	0.38	32.10a	3.49	9.20	0.00
	SOC	CC	0.62	9.30b	0.60	15.20	0.00
		COAA	0.99	238.5a	1.33	179.0	0.00

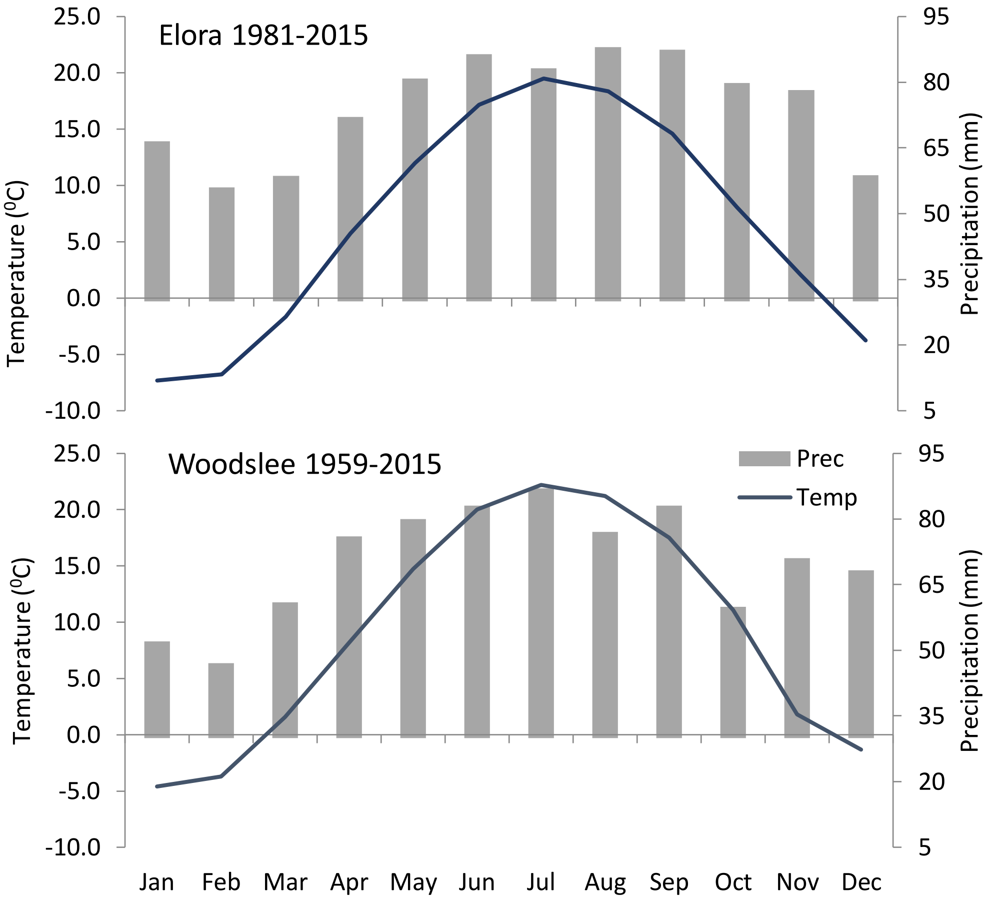


Fig. S1. Average monthly temperature and precipitation at two locations in Ontario, Canada, over the experimental period used for modelling.

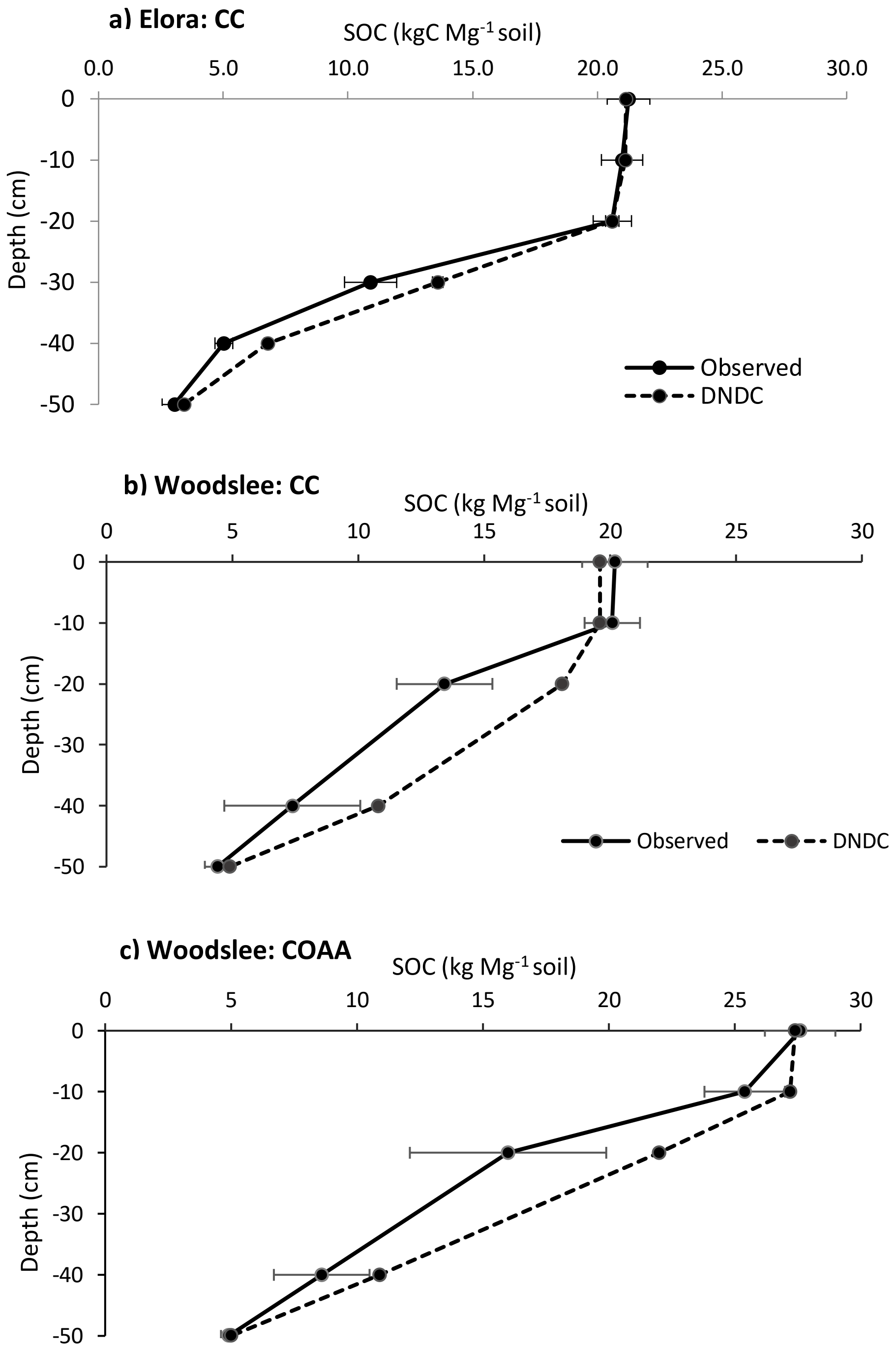


Fig. S2. Observed and DNDC-predicted SOC concentration with depth in a) continuous corn (CC) at Elora, b) continuous corn (CC) at Woodslee and c) corn-oats-alfalfa-alfalfa (COAA) at Woodslee. The horizontal bars represent standard error (n=4) of the mean. Values for Elora are means for 1995, 1998, 2000 and 2005 and for Woodslee 2004-2007.

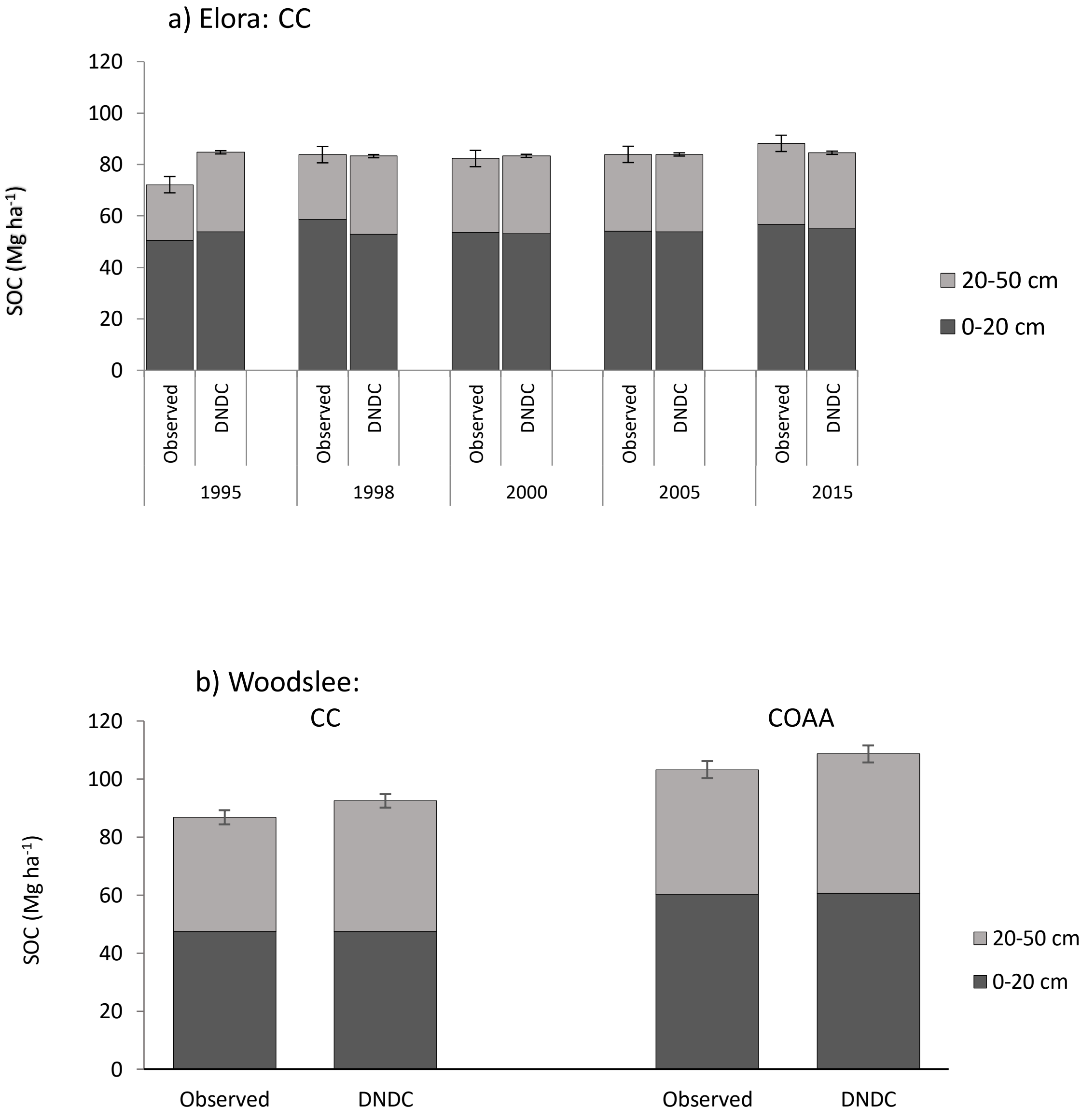


Fig. S3. Observed and DNDC predicted soil organic carbon (SOC) stock for 0-20 and 20-50 cm layer for a) continuous corn (CC) at Elora, b) continuous corn (CC) at Woodslee and c) corn-oats-alfalfa-alfalfa (COAA) at Woodslee. Error bars represent standard error (n=5 for Elora, n=3 for Woodslee).

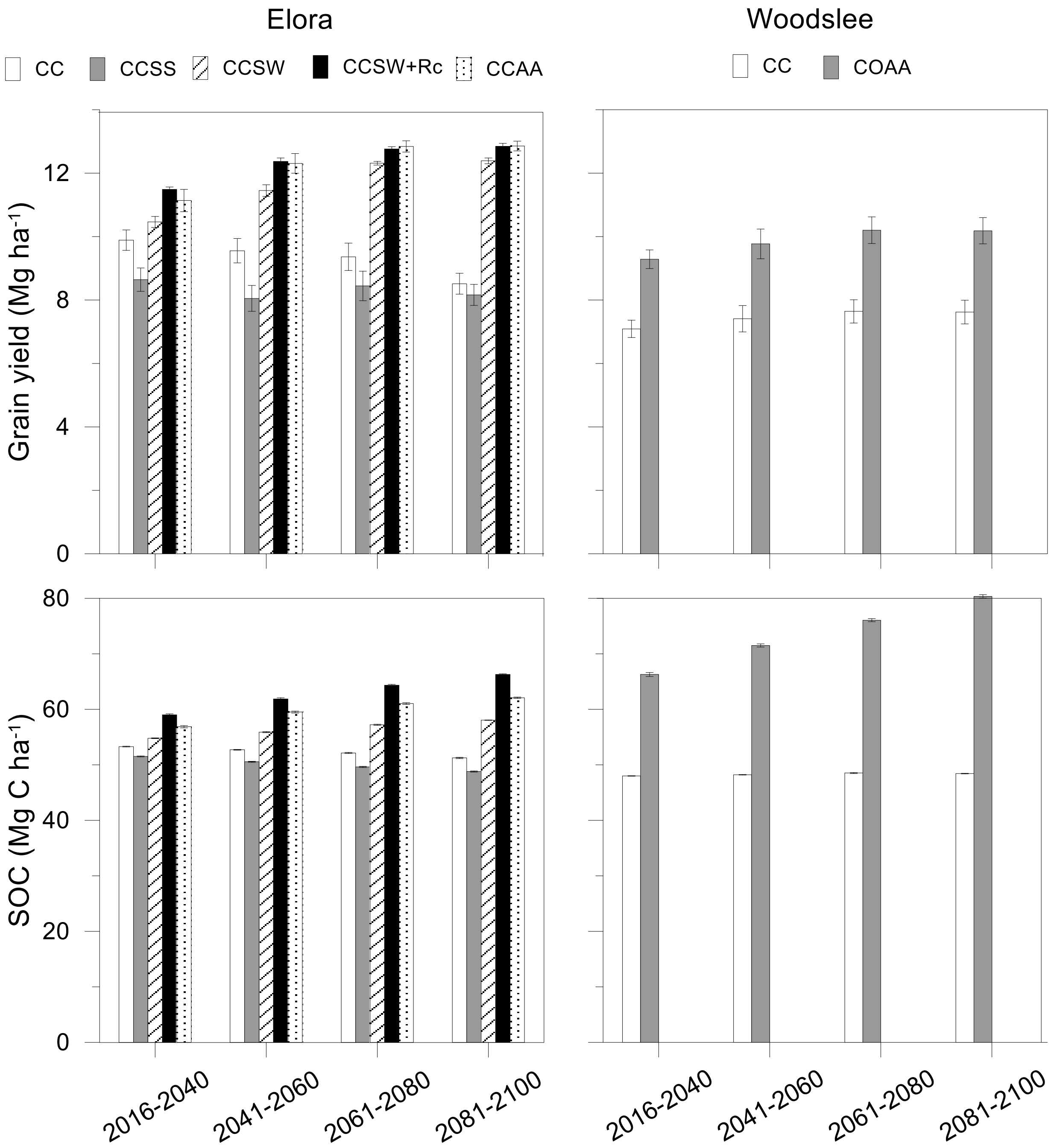


Fig. S4. Predictions of corn yield (top graphs) and 0-0.2 m SOC stock (bottom graphs) under representative concentration pathway (RCP) scenario RCP 8.5 over 2016 to 2100 at Elora (left panel) and Woodslee (right panel) for various cropping systems. Predictions were averaged over selected periods starting in 2016 with error bars representing standard error of means (n=25 for 2016-2040, and n = 20 for other periods). CC = continuous corn; CCSS = corn-corn-soybean-soybean, CCSW = corn-corn-soybean-winter wheat, CCSW+Rc = corn-corn-soybean-winter wheat + red clover, CCAA = corn-corn-alfalfa- alfalfa, COAA = corn-oats-alfalfa-alfalfa.