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Estimating the impacts of climate change on crop yields and N_2O emissions for conventional and no-tillage in Southwestern Ontario, Canada

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A B S T R A C T

Accurately predicting the impacts of higher temperatures, different precipitation rates and elevated CO_2 concentrations on crop yields and GHG emissions is required in order to develop adaptation strategies. The objectives of this study were to calibrate and evaluate a regionalized denitrification-decomposition (DNDC) model using measured crop yield, soil temperature, moisture and N_2O emissions, and to explore the impacts of climate change scenarios (Representative Concentration Pathways (RCP) 4.5 and RCP 8.5) on crop yields and N_2O emissions in Southwestern Ontario, Canada. This simulation study was based on a winter wheat-maize-soybean rotation under conventional tillage (CT) and no tillage (NT) practices at Woodslee, Ontario, Canada. The model was calibrated using various statistics including the d index (0.85–0.99), NSE (Nash-Sutcliffe efficiency, NSE > 0) and nRMSE (normalized root mean square error, nRMSE < 10%) all of which provided "good" to "excellent" agreement between simulated and measured crop yields for both CT and NT practices. The calibrated DNDC model had a "good" performance in assessing soil temperature. However, there were no differences in simulated soil temperatures between CT and NT treatments and this was attributed to deficiencies in the temperature algorithm which does not consider the insulation effect of surface crop residues in the DNDC model. The DNDC model provided a reasonable prediction of soil water content in the 0–0.1 m depth, but it overestimated soil water content during dry conditions mainly because the model was unable to characterize preferential flow through clay cracks. Under future climate scenarios, soybean and maize yields were significantly increased compared to the baseline scenarios due to the benefits from higher optimum temperature for maize and increased CO_2 for soybean. The mean annual N_2O emissions for winter wheat significantly increased by about 38.1% for CT and 17.3% for NT under future RCP scenarios when using the current crop cultivars. However, when a new cultivar with higher TDD (thermal degree days) was used, the mean winter wheat yield increased by 39.5% under future climate scenarios compared to current cultivars and there were significant reductions in N_2O emissions. The higher crop heat units cultivars and longer growing season length would contribute to increased biomass accumulation and crop N uptake. Hence there would be co-benefits with the development of high TDD cultivars in the future as they would not only increase crop yields but also reduce N_2O emissions.

1. Introduction

Dynamic crop and soil models are widely used in agricultural systems to provide a detailed estimation of crop growth, nutrient cycling and water movement (Tsuji et al., 1998; Liu et al., 2011; Li et al., 2015a,b). Many soil and crop models have been used to estimate cultivar performance and optimize management practices under different climatic conditions (i.e., humid, semi-arid, dryland regions) and cropping systems (i.e., monocropping, rotation) (Jeuffroy et al., 2013; Uzoma et al., 2015; He et al., 2016). They have also been used to predict the impacts of future climate change scenarios on crop production, greenhouse gas emissions and water quality (Xu-Ri et al., 2012; Smith et al., 2013a; Wang et al., 2015). The DNDC (Denitrification–Decomposition) (Li et al., 1992a,b) model is a process-based model which is capable of simulating soil fluxes of agricultural greenhouse gases (e.g.,

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nitrous oxide, carbon dioxide) as well as other important crop and soil factors including crop yields, soil water, temperature and nitrate leaching (Ludwig et al., 2011; Li et al., 2012; Deng et al., 2016).

Global greenhouse gas (GHG) emissions increased from 1970 to 2010 with larger absolute increases between 2000 and 2010 due to human activities such as fossil fuel combustion, land use change, deforestation and cement production (IPCC, 2014). Increasing concentrations of GHGs is likely to increase temperatures, change precipitation patterns and increase the frequency of extreme events (Islam et al., 2012). Greenhouse gas emissions have increased by about 70% overall from 1970 to 2010 with carbon dioxide (CO_2) being responsible for nearly 78% of this increase as one of the largest contributing GHGs (IPCC, 2014). Agricultural crop production is likely to be markedly impacted by changes in the atmospheric CO_2 concentrations, temperature and precipitation because of the variations in photosynthesis, respiration rates, water use efficiency and soil C and N biochemical transformations (Wang et al., 2014; Long et al., 2015).

Conventional tillage (CT) management practices (moldboard plowing) can have negative effects on soil nutrient loss and can cause the degradation of soil structure as well as increased greenhouse gas emissions (Chen et al., 2011; Liu et al., 2013; Drury et al., 2006, 2012). Compared with CT, conservation tillage practices (i.e., reduced tillage, zone tillage, no tillage etc.) can reduce water and wind erosion, increase soil water use efficiency and improve soil quality such as increased near-surface organic matter content, improved microbial activity and decreased fuel and labour input costs (Huggins and Reganold, 2008; McLaughlin et al., 2008; Yang et al., 2008; Shi et al., 2012; Ziadi et al., 2014; Chi et al., 2016). Conservation tillage can impact CO_2 and N_2O emissions depending on different cropping practices and local soil and climatic variations (Drury et al., 2006; Rochette et al., 2008; Chi et al., 2016).

The DNDC model has been successfully applied to several studies under different tillage systems. Farahbakhshazad et al. (2008) conducted sensitivity analysis using the DNDC model in a corn-soybean rotation system in Iowa during a 20 year period, and no-tillage practices were found to significantly increase SOC storage and reduce N leaching rate, but slightly decreased crop yields and increased N_2O emissions. A similar sensitivity study reported that conventional tillage with a tillage depth of 20 cm elevated N_2O emissions in a winter wheat-maize rotation system in China (Li et al., 2010). In contrast, the DNDC model underestimated N_2O fluxes up to 55% from reduced tillage plots in Ireland due to an overestimation of the water filled pore space and the effect of SOC on the flux (Abdalla et al., 2009). In addition, Beheydt et al. (2008) reported that the DNDC model showed a significant overestimation of N_2O emissions for CT practice and an underestimation for minimum tillage in a Belgium maize study. The differences in performance of the DNDC model were mainly due to uncertainties in model parameterization and calibration, and limitations in model inherent structure, as well as the differences in soil types, management practices and climatic conditions (Ludwig et al., 2011).

Winter wheat-maize-soybean rotation is a common practice in Southwestern Ontario, Canada. In previous studies, crop rotation could reduce the amount of N_2O emissions released from soil compared with monoculture cropping (Drury et al., 2008). In addition, tillage practices have been found to influence greenhouse gas emissions; conservation tillage could decrease N_2O emissions by 15–40% compared with conventional tillage (Drury et al., 2006; Drury et al., 2012). However, DNDC has not been previously used to evaluate a winter wheat-maize-soybean rotation under different tillage practices in Canada. It is essential to calibrate and evaluate DNDC model performance under different tillage practices. This information can then be used to develop best management practices and it could also be used to examine the impacts of climate change on crop production and environmental risks. Hence, the objectives of this study were to: (1) calibrate and evaluate a regionalized Canadian version of the DNDC model using measured crop yields, soil temperatures, water contents and N_2O emissions; and (2) explore the impacts of climate change on crop yields and N_2O emissions for a winter wheat-maize-soybean rotation under conventional tillage and no tillage systems in Southwestern Ontario, Canada.

2. Materials and methods

2.1. Field experiment

The field experiment was established in the fall of 1999 at Woodslee, Ontario, Canada (42°21′N, 82°75′W). The mean annual temperature was 9.3 °C with a 50-yr average annual precipitation of 843 mm. The soil is a Brookston clay loam with an average soil texture (0–0.15 m) of 28% sand, 35% silt and 37% clay. The soil physical and chemical properties were measured (Table 1) at the beginning of the field experiment as reported by Drury et al. (2006, 2012). Different tillage treatments were evaluated in this study. The crop rotation was winter wheat-maize-soybean with each phase of rotation present in each year in three adjacent fields. There were two tillage treatments with four replicates and each plot was 20 m long by 9 m wide. The tillage practices included conventional tillage (CT) (fall moldboard plowing with a secondary tillage in the spring) and no tillage (NT). The experimental design was a split-plot randomized complete block with the main plot units being tillage treatment and a factorial combination of two fertilizer dates (at planting and sidedress) (Drury et al., 2006, 2012).

Winter wheat (AC Essex) was planted at a seeding rate of 400 seeds m^{-2} in 7 cm rows. Fertilizer (6-24-24) was applied to the winter wheat phase just before planting to provide 12 kg N ha^{-1} and an additional 71 kg N ha^{-1} was applied in the spring. Maize was planted at a seeding rate of 7.6 seeds m^{-2} in 76 cm rows. When maize was planted, a starter fertilizer was applied (8-32-16) to provide 22 kg N ha^{-1}, 88 kg P_2O_5 ha^{-1}, and 44 kg K_2O ha^{-1}. The starter fertilizer was applied in bands that were 5 cm beside and 5 cm below the seed, which is composed of urea, monoammonium phosphate, and KCl. During the 6 to 8 leaf growth stage, 160 kg of N ha^{-1} from 2000 to 2002 and 130 kg of N ha^{-1} from 2004 to 2006 was applied to corn as a sidedress N fertilizer. Soybean was planted at a seeding rate of 61.5 seeds m^{-2} without fertilizer application. Management practices and planting/harvest dates are listed in Table 2. In this experiment, soil temperature (0–0.1 m) was measured during each growing season using a HI93510 thermometer (Hanna Instruments Canada Inc., Laval, Quebec). Gravimetric soil water content (0–0.1 m) was measured three times per week and determined on grab samples in the laboratory. Soil core samples (0–30 cm depth) were collected at the beginning, middle, and end of the growing season from each treatment to determine inorganic soil N (NH_4^+ and NO_3^-). Nitrous oxide emissions were measured a total of 106 times during the growing season in the corn phase of the rotation over six years using 48 rectangular acrylic field chambers, which consist of a “collar” (internal dimensions of 53.5 cm length, 17.7 cm width, 15 cm height) fitted with a removable gas-tight LiO. Detailed measurement information is described in Drury et al. (2006, 2012).

2.2. DNDC model

The DNDC model (Denitrification–Decomposition) is a process-oriented model describing carbon and nitrogen biogeochemistry in agroecosystems. It has been widely used to simulate greenhouse gas emissions, crop growth, C and N dynamics and soil water balance under different management practices and weather conditions (Li et al., 1992a,b; Ludwig et al., 2011; Li et al., 2012; Smith et al., 2013a; Abdalla et al., 2014). The DNDC model consists of two components. The first component consists of soil, climate, crop growth and decomposition sub-models which are used to predict crop growth, soil temperature, soil water content as well as soil C and N dynamics and these are modelled on a daily basis. The second component is based upon nitrification, denitrification and fermentation sub-models and these are used to simulate trace gases emissions from plant-soil systems including

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