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A multi model evaluation of long-term effects of crop management and cropping systems on nitrogen dynamics in the Canadian semi-arid prairie

B. Dutta [a,*], B.B. Grant [a], C.A. Campbell [a], R.L. Lemke [b], R.L. Desjardins [a], W.N. Smith [a]

[a] Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, 960 Carling Avenue, Ottawa, ON K1A 0C6, Canada
[b] Saskatoon Research and Development Centre, Agriculture and Agri-Food Canada, 107 Science Place, Saskatoon, , Saskatchewan S7N 0X2, Canada

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ABSTRACT

Process-based biogeochemical models such as the DeNitrification-DeComposition (DNDC) and DayCent models can provide reliable estimations of components of the nitrogen (N) cycle but have rarely been evaluated for a more complete N balance. This is important in order to assess the long-term effects of management practices on soil and environmental quality. Using published data collected from a long term study in the Canadian semi-arid prairie, the Canadian DNDC version (DNDC v.CAN) and DayCent models were evaluated for their ability to simulate the long term nitrogen dynamics and budgets as well as nitrogen use efficiencies (NUEs) in a loam/silt loam soil for three distinct spring wheat (*Triticum aestivum* L.) cropping systems. Both DNDC v.CAN and DayCent models predicted the spring wheat grain yields, above-ground plant biomass and nitrogen uptake well. The predicted NUEs in DNDC v.CAN, calculated using two approaches with respect to grain yield and grain N concentration, indicated good correlations to the observed values with r ≥ 0.70 and low biases and average relative errors. The N balances were also simulated well in the two models, however DayCent showed a higher estimate of the deficit between N inputs and outputs, termed 'Unaccounted N', in all three systems compared to DNDC v.CAN. For both model simulations and the observed data, N outputs in the form of grain N uptake and N losses (nitrogen leaching, N gas emissions) were greater than N inputs except in the ContW (NP) system. In general, a multiple linear regression for estimations of NUEs with respect to N balance and N inputs across all three cropping systems showed that, DNDC v.CAN correlated better with the observed data compared to DayCent. Thus, based on model performance in this study, DNDC v.CAN as a process-based model offers promise as a tool for analyzing different cropping systems with varying N rates in terms of N dynamics and subsequent environmental impacts and benefits.

1. Introduction

Reactive N and its transformations play an important role in biological and chemical processes, particularly in agricultural systems. Nitrogen cycles in agricultural ecosystems are influenced by fertilizer N inputs (Richter and Roelcke, 2000) and effective crop management plays an important role in minimizing N input losses occurring through gaseous and leaching loss (Spalding and Exner, 1993; Xing and Zhu, 2000). N balance of a cropping system is often evaluated by comparing various N inputs and outputs in soil – crop systems by either considering changes of soil mineral N (Sogbedji et al., 2000) or not (Sapek, 1997). The assessment of N budgets of agro-ecosystems has been helpful to increase the understanding of nutrient cycling, as an indicator of agronomical performance of the cropping systems, and to direct and derive crop management policies (de Vries et al., 2011).

Excessive N fertilization may result in low nitrogen-use efficiency (NUE) and in turn cause potential adverse effects on the environment. Estimates of NUE are affected by the complexities of the N cycle and the changes in the soil and crop environment. The factors which have been reported to have an influence on crop growth and NUE include: crop rotation (Baldock et al., 1981; Pierce and Rice, 1988), genotype (Johnson et al., 1973), tillage (Elliott et al., 1987; Huggins and Pan, 1993), methods and timing of N application (Morris and Paulsen, 1985), and available water (Campbell et al., 1993), etc. Cropping systems with well synchronized crop N demand and soil N supply have demonstrated improved performance of NUE and minimized N loss (Chen et al., 2005). However, in order to evaluate the cropping system for an optimized N fertilization technique with minimization of N loss, the resulting N losses need to be evaluated in relation to the N management practices.

Process - based models have been used extensively in agroecosystem research to help improve our understanding of soil N dynamics and cycling, influence of addition of N fertilizer and other crop

* Corresponding author.
E-mail address: Baishali.Dutta85@gmail.com (B. Dutta).

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management techniques (tillage practices, etc.) on NUE and yields of cropping systems (Chamberlain et al., 2011; Grant et al., 2016). Process - based models such as, STICS, DayCent, SWAT, DNDC, DSSAT, AquaCrop FAO, and EPIC models (Roloff et al., 1998; Ahmad et al., 2011; Kröbel et al., 2011; Mkhabela and Bullock, 2012; Sansoulet et al., 2014; Li et al., 2015; Grant et al., 2016) have been used in Canada to simulate N transformations in soil and N uptake by fieldcrops for refining N application rates and timing recommendations in order to increase NUE. One of the strengths of process-based models is that they simulate the interactions of soil-plant-atmospheric processes while accounting for the mass balance of nutrients and water. DNDC model has been effective in predicting N losses through trace gas emissions in agroecosystems (Li et al., 1992; Li, 2000; Giltrap et al., 2010) as well as other interdependent factors such as soil carbon and crop productivity (Smith et al., 2013). DayCent (Del Grosso et al., 2001; Parton et al., 1998) is a terrestrial biogeochemical model that was developed to simulate C, N, P and S dynamics for agricultural ecosystems. While both models benefit from having a well-defined mass balance of water, C and N, they have most commonly been tested for individual N components but not as often in an overall N budget approach.

CENTURY model was used to simulate long-term management practices for wheat (*Triticum aestivum* L.) to compare the accuracy of the model and determine the long-term impact of crop management on C and N stabilization in soil (Parton and Rasmussen, 1994). Recently, DayCENT model has been employed to simulate the effects of conventional tillage (CT) and no-till (NT) practices on the dynamics of soil organic carbon (SOC) for evaluating the effects of tillage on crop residues and heterotrophic respiration (Rh) dynamics over a long term (9 yr) cropping system in Southern Ontario, Canada (Chang et al., 2013). APSIM and DNDC were used to simulate nitrification, denitrification and nitrous oxide (N_2O) emissions from New Zealand soils following N input from either fertilizer or excreta deposition to evaluate the effect of environmental conditions on N transformations (Vogeler et al., 2013). Congreves et al. (2015) evaluated the Campbell, introductory carbon balance model (ICBM), and DayCent for the long-term productivity of soils, to quantify and predict SOC dynamics in response to crop management.

A comparative analysis of DayCent and DNDC models at the Swift Current long-term Old Rotation site for spring wheat yields, soil carbon change, and trace gas emissions indicated low predictability for ContW (P) and F–W (NP) systems in both models, which was attributed primarily to their underestimation of available N (Grant et al., 2016). Hence Grant et al. (2016) have recommended the need for the determination of a full N balance which would help identify the deficiencies in the estimated mass balance of N. Thus, testing these models against a uniquely comprehensive dataset such as that from the Old Rotation site, where many of the N components have been measured over the long-term, is especially beneficial for this purpose.

DNDC v.CAN model, the DNDC version developed for Canadian agroecosystems (Kröbel et al., 2011; Smith et al., 2013), and DayCent were evaluated in this study to simulate the impact of different cropping systems and N fertilizer rates on crop production and N dynamics at the long term Old Rotation experiment at Swift Current, Saskatchewan. The models were used to help interpret the observed data and to identify specific research that is needed to improve our understanding of N dynamics in soil in terms of: (1) the yield response to different N fertilizer rates; (2) nitrogen use efficiencies considering the entire N balance under different cropping frequencies; and (3) the N balance and pathways for N losses as related to the N application rate.

2. Materials and methods

2.1. Site description

The measurement data used for modeling in this study were obtained from the Old Rotation experiments which were conducted at Swift Current, Saskatchewan (lat. 50°17″N, long. 107°48″W) and was established in 1967 on a soil classified as Swinton loam to silt loam (Orthic Brown Chernozem) with a 3% sloping land (Lemke et al., 2012) and a soil pH of 6.5 (0–15 cm depth). The wilting point (at 4 MPa) at the site was reported to be 154 mm (0–120 cm depth) (Ritchie, 1981; Campbell et al., 1987; Cutforth et al., 1991). Further information on weather and soil characteristics are described by Kröbel et al. (2012). The site was previously cropped as a fallow-wheat rotation before the establishment of the 12 crop rotation-fertility treatments. These were established on 81 plots (10.54 m in size), using three replicates in a randomized complete block design. All phases of each rotation were present every year and each rotation was cycled on its assigned plot. A 10 year period (1975–1984) at the site was evaluated in this study for crop yield (kg ha^{-1}), grain N (%), aboveground biomass production (kg ha^{-1}), NUE and crop N dynamics for the following crop rotations:

- Fallow-wheat with NP fertilizer [F-W (NP)];
- Continuous wheat with NP fertilizer [ContW (NP)];
- Continuous wheat with P fertilizer only [ContW (P)].

The mean annual daily minimum and maximum temperatures, and precipitation for the period were − 2.1, 9.4 °C, and 1 mm, respectively. Fertilizer N was surface broadcast as 34-0-0 (ammonium nitrate) before seeding, based on amounts of soil NO_3-N (0–60 cm depth) and measured in individual plots in the previous fall according to the N rates recommended by the soil-testing laboratory of the University of Saskatchewan (Saskatchewan Agriculture, 1985). The 10 year duration for each rotation was further divided into two sub periods for analysis based on the differences in N rates (Table 1). The P fertilizer source of monoammonium phosphate also contains N (11-48-0) and hence approximately 5 kg N ha^{-1} was taken into account when calculating NUE. The management practices such as seedbed preparation, herbicide application, seeding, harvesting, and tillage operations applied at the site have been described previously (Campbell et al., 1983; Zentner and Campbell, 1988; Campbell et al., 1992).

2.1.1. Soil sampling and analysis

The soil N measurements were carried out using a Giddings soil corer at 30 cm increments to 300 cm depth from each plot with three replicates which were analyzed separately. A roller mill (<153 μm) was used to ground the soil samples before analysis for total N and SOC which were determined using an automated combustion technique (Carlo Erba, Milan, Italy) at 1000 °C. A reference soil obtained from the Canadian certified reference materials, supplied by Canada Centre for

Table 1
Nitrogen fertilizer application rates from the Old Rotation study (1975–84) at Swift Current, SK, Canada, for three cropping rotations.

N fertilizer rate (kg ha^{-1})[a]			
Year(s)	ContW(NP)	F–W (NP)	ContW(P)[b,c]
1975	33.3	5.0	5.0
1976	27.7	5.0	5.0
1977	55.0	5.0	5.0
1978	55.0	10.7	5.0
1979	39.0	10.7	5.0
1980	60.7	5.0	72.0[c]
1981	33.3	5.0	5.0
1982	27.7	5.0	39.0[c]
1983	20.0	8.7	5.0
1984	44.3	5.0	5.0
1975–79 (mean)	42.0	7.3	5.0
1980–84 (mean)	37.2	5.7	25.2

[a] Nitrogen fertilizer application based on soil NO_3–N test (Saskatchewan Soil Testing Laboratory, 1990).
[b] P fertilizer was monoammonium phosphate containing N (11-48-0), hence approximately 5 kg N ha^{-1} was applied with each application.
[c] ContW (P) received >5 kg N ha^{-1} N fertilizer unintentionally in 1980 and 1982.