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Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model

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ABSTRACT

Biogeochemical models are useful tools for integrating the effects of agricultural management on GHG emissions; however, their development is often hampered by the incomplete temporal and spatial representation of measurements. Adding to the problem is that a full complement of ancillary measurements necessary to understand and validate the soil processes responsible for GHG emissions is often not available. This study presents a rare case where continuous N_2O emissions, measured over seven years using a flux gradient technique, along with a robust set of ancillary measurements were used to assess the ability of the DNDC model for estimating N_2O emissions under varying crop-management regimes. The analysis revealed that the model estimated soil water content more precisely in the normal and wet years (ARE 3.4%) than during the dry years (ARE 11.5%). This was attributed to the model's inability to characterize episodic preferential flow through clay cracks. Soil mineral N across differing management regimes (ARE 2%) proved to be well estimated by DNDC. The model captured the relative differences in N_2O emissions between the annual (measured: 35.5 kg N_2O-N ha^{-1}, modeled: 30.1 kg N_2O-N ha^{-1}) and annual-perennial (measured: 26.6 kg N_2O-N ha^{-1}, modeled: 21.2 kg N_2O-N ha^{-1}) cropping systems over the 7 year period but overestimated emissions from alfalfa production and underestimated emissions after spring applied anhydrous ammonia. Model predictions compared well with the measured total N_2O emissions (ARE −11%) while Tier II comparison to measurements (ARE −75%) helped to illustrate the strengths of a mechanistic approach in characterizing the site specific drivers responsible for N_2O emissions. Overall this study demonstrated the benefits of having near continuous GHG flux measurements coupled with detailed ancillary measurements towards identifying soil process interactions responsible for regulating GHG emissions.

1. Introduction

The increase in agricultural N_2O emissions, which accounts for a major portion of the total anthropogenic N_2O emissions (Kroeze et al., 1999; Mosier and Kroeze, 2000), has been attributed primarily to increased reliance on fertilizer nitrogen (N) for crop production (Saggar, 2010; Scott et al., 1996; Snyder et al., 2009). The level of N use by crops depends on crop species, fertilizer type, and the timing and quantity of fertilizer application. Unrecovered N can be lost to the environment either through runoff, leaching or gaseous emissions (Brady and Weil, 2002).

Several management options have the potential to reduce N_2O emissions such as improved fertilizer placement and scheduling, soil N testing to optimize application rate, the use of N inhibitors, slow release fertilizers, catch and cover crops. In the IPCC 5th Assessment Report it was indicated that cropland management was one of the most cost-effective options to mitigate GHG (greenhouse gas) emissions in agriculture (Smith et al., 2014). Several authors (Goglio et al., 2012; Sieling and Kage, 2006) have suggested that environmental impacts at the field level should be assessed at the crop system scale. It has been acknowledged that changes in management practices to produce a given environmental effect may also produce unfavorable environmental impacts that counterbalance the benefit. Also, the effects of management on GHG emissions are strongly tied to climate and soil properties such as soil organic carbon (SOC) content, soil nitrogen content, and pH, thus there can be contrasting effects of

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management both temporally and spatially. Soil temperature and moisture have significant impacts on all processes (mineralization, nitrification, and denitrification) affecting N_2O emissions (Dalal et al., 2003; Frolking et al., 1998; Saggar, 2010; Snyder et al., 2009) and also strongly influence crop production.

The high variability of N_2O fluxes makes it difficult to quantify emissions across contrasting environments. Chambers, automated chambers and micrometeorological techniques provide crucial data on a site-basis for a specific period of time, however, models and tools are required to extrapolate these data to larger spatial and temporal scales. Micrometeorological techniques, which allow for continuous field scale monitoring of N_2O emissions (Denmead and Raupach, 1993) are of particular value for understanding soil–climate–plant processes required to develop and test models (Del Grosso et al., 2008).

As an alternative to direct measurements, process-based models enable the integration of the contributing biogeochemical processes and are increasingly used internationally to simulate N_2O emissions in agroecosystems (Jarecki et al., 2008; Kariyapperuma et al., 2011; Parton et al., 1988; Smith et al., 2002; Wolf et al., 2012). Dynamic process based models are mathematical models which describe the growth and development of a crop interacting with a soil–carbon system (Wallach et al., 2006). A major strength of process-based models is that they consider agriculture from a systems perspective including productivity, GHG emissions and soil carbon, all of which are inter-dependent. The models ensure that a mass balance of C, N and water is maintained.

The development of predictive models is limited both by the mathematical integration of complex processes and the lack of understanding of some processes. It is important to test models rigorously against comprehensive datasets and report findings regarding which processes work and which processes require improvement under various environments. Model testing and validation is of great importance to the scientific community to the extent that large scale projects such as the Agricultural Model Inter-comparison and Improvement Project (AgMIP; Rosenzweig et al., 2013) have been formed to link various communities who focus on improving agricultural models.

The DeNitrification DeComposition (DNDC) model is a widely used process-based model which simulates C and N dynamics and trace gas emissions for a wide range of management practices (Smith et al., 2013). The model was primarily designed and parameterized using measurements and cropping systems in the US (Li et al., 1992) which prompted many researchers to develop country-specific versions of the model to better enable the simulation of regional soils, climate events, crop cultivars and management practices (Brown et al., 2002; Giltrap et al., 2008; Kröbel et al., 2011; Werner et al., 2007). Over the last few years a Canadian regionalized version of the DNDC model has been developed in parallel with the standard DNDC model through close collaborations with the model author in order to improve model performance in cool weather conditions (Grant et al., 2015; Kröbel et al., 2011; Smith et al., 2013).

Because of the dependence of N_2O emissions on environmental factors, which are continuously changing with climatic conditions, vegetation types and farming systems, there is a need for continuous testing, improvement and validation of models as new measurements become available. Most DNDC validation studies for Canada focused on using chamber N_2O measurements (Grant et al., 2015; Smith et al., 2008, 2002) as continuous micrometeorological data were rarely available. The objectives of this study were: (i) to use continuous measurements to evaluate DNDC from a systems perspective considering soil water, temperature, N dynamics, and N_2O emission mechanisms, (ii) to evaluate the ability of the DNDC model to estimate the influence of management practices (tillage, annual vs. perennial crops, timing

Table 1
Agricultural management performed on the four plots (P1, P2, A1 and A2) during the experimental period (2006–2012).

Years	Crop	Tillage type	Planting date (day of year)	fertilizer type	Fertilizer ($kg\,N\,ha^{-1}$)	Fertilizer timing (day of year)	Harvest date (day of year)
P1 and P2 (annual–perennial system)							
2006	Corn[a]	RT	136	N-P-K-S/urea	109	136	279
2007	Faba bean[b]	RT	131				239
2008	Alfalfa[c]	RT	149				
2009	Alfalfa[c]	RT	197				187, 323
2010	Alfalfa[c]	RT					192, 239
2011	Alfalfa[c]	RT					210, 217
2012	Corn[a]	IT	124	N-P-K/urea	63	124	292
A1 (annual system)							
2006	Corn[a]	IT	136	N-P-K-S/urea	109	136	279
2007	Faba bean[b]	IT	131				239
2008	Spring Wheat[d]	IT	142	N-P-K	98	142	260
2009	Rapeseed[e]	IT	150	Urea	146	158	265
2010	Barley[f]	IT	142	Urea	98	146	
2011	Spring Wheat[d]	IT	161	Anhydrous NH_3	100/160	161/308	270
2012	Corn[a]	IT	124				292
A2 (annual system)							
2006	Corn[a]	IT	136	N-P-K-S/urea	109	136	279
2007	Faba bean[b]	IT	131				239
2008	Spring Wheat[d]	IT	142	N-P-K	98	142	260
2009	Rapeseed[e]	IT	150	Urea	146	158	265
2010	Barley[f]	IT	142	Urea/NH_3	98/100	146/288	
2011	Spring Wheat[d]	IT	161				270
2012	Corn[a]	IT	124	Anhydrous NH_3	160	124	292

[a] *Zea mays* L.
[b] *Vicia faba* var *minor* L.
[c] *Medicago sativa* L.
[d] *Triticum aestivum* L.
[e] *Brassica napus* L.
[f] *Hordeum vulgare* L.