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Comparing the performance of the STICS, DNDC, and DayCent models for predicting N uptake and biomass of spring wheat in Eastern Canada

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ABSTRACT

Modelling the production and N uptake of spring wheat (*Triticum aestivum* L.) according to climate and N fertilization in Eastern Canada is important for estimating efficient N application rates and evaluating the sustainability of agricultural practices. The objective of this paper was to examine the response of observed yield, biomass, and plant N to fertilization rates and climate variations and to compare the performance of the STICS (Simulateur mulTIdisciplinaire pour des Cultures Standard), DNDC (DeNitrification and DeComposition), and DayCent (daily version of CENTURY) models for predicting these outcomes. The results indicate that when rainfall was near normal and the recommended N application rates were applied, the three models had good predictions, especially STICS and DNDC (average relative error < 10%, root mean square error < 24%). Under lower N rates, STICS and DayCent were less effective for predicting biomass, whereas for rainfall excess, DNDC and DayCent overestimated plant N. For simulating plant N, the STICS model was more sensitive to the quantity and timing of water available to the crop. The models showed that mild rainfall deficit or excess early in the season had a negative impact on estimates of biomass and plant N as well as on yield and protein content, and the impact of the N application rate tended to disappear. When rainfall was near normal and close to measured evapotranspiration, the effect of N rates on biomass and plant N was accurately predicted.

1. Introduction

Modelling N transformations in soil and N uptake by crops is important for refining N application rates and timing recommendations in order to increase the N-use efficiency (NUE) of field crops. In the Canadian provinces of Ontario and Quebec (Mixedwood Plains Ecozone), a wide variety of agricultural activities are carried out, and the average annual growing season ranges, north to south, from 1600 to 3800 growing degree days (GDD) above 0 °C. The Mixedwood Plains Ecozone has relatively warm summers and cool winters and receives 720–1000 mm of precipitation annually, with more occurrences of dry spells in Ontario than in Quebec. This amount of rainfall is sufficient to allow rainfed cropping. According to Statistics Canada, Ontario and Quebec produced 340 kt of spring wheat (*Triticum aestivum* L.) in 2009. Spring wheat is the largest category of wheat grown in Canada, with 80% of wheat production (24.5 Mt per year), and the country is the world's third largest exporter of wheat (agri benchmark, 2011). Wheat production in Canada occurs primarily in the western Prairie region. The cultivars used in Eastern Canada are often issued from cultivars grown in Western Canada. Under future climate change, it is possible that Eastern Canada will experience average annual warming of 3 °C to 8 °C by the latter part of the 21st century and thus have fewer weeks of snow cover, potentially less soil moisture, and likely an increase in the frequency and severity of droughts (Intergovernmental Panel on Climate Change, 2007). Qian et al. (2010, 2012) found in an assessment of historical trends in Canada that there have already been significant trends in terms of an earlier last spring frost, a later first autumn frost, a longer growing season, and more crop heat units. Canada's climate will change and potentially become more variable, making it important to study the effect of a range

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of climatic conditions on crop growth to determine possible influences.

Nitrogen fertilization in spring wheat fields (total amount of about 70 kg N ha^{-1}) is usually applied prior to planting and incorporated into the soil (Centre de référence en agriculture et agroalimentaire du Québec, 2010; Ontario Ministry of Agriculture, Food and Rural Affairs, 2009). However, N applied prior to or at seeding can be subject to gaseous loss, leaching below the root zone, or immobilization before plant uptake, thus affecting availability for the plant and NUE. To increase the NUE of spring wheat, soil N and plant N uptake need to be quantified so that the recommended N rate based on soil texture, which takes into account the influence of mineralization rate, and on the average climatic conditions can be applied. Although N fertilization plays an important role in modulating crop biomass and N accumulation, also important are GDD, rainfall distribution, and rainfall amount. Under very dry or wet conditions, spring wheat yield may not be responsive to differing N fertilizer rates. The greater climate variability predicted to occur as a result of climate change is expected to curb crop yields (Adams et al., 1995; Bryant et al., 2000; Cabas et al., 2010). Temperature and moisture stresses are recognized as the dominant limiting factors for spring wheat yield in Canada (Campbell et al., 1997; Qian et al., 2009; Raddatz et al., 1994). Qian et al. (2010, 2012) found that the growing season in Canada is lengthening because of an earlier start and a later end. A positive trend in heat accumulation and a decreasing trend in the occurrence of low temperatures during the growing season have also been observed. Despite an upward trend in evaporative demand resulting from increasing ambient temperatures, that increase was offset by a small increase in precipitation such that the precipitation deficit during the growing season did not increase. Smith et al. (2013), in a study that incorporated results from free-air carbon dioxide enrichment experimentation into the DNDC model, including the effect of increased water-use efficiency under CO_2 fertilization, found that spring wheat, winter wheat, and maize production at several sites in Canada exhibited less water stress for three future scenario projections (2041–2070) from the Special Report on Emissions Scenarios. Campbell (1968) and Bootsma et al. (1992) found that the spring wheat growth stage from emergence to anthesis/soft dough was the most sensitive to soil moisture stress. Moreover, climate change is unfavourable to cereal yields in temperate climates because of heat stress during grain filling and drought during stem elongation (Brisson et al., 2010). The three experimental sites selected for the present study are located in an area that is relatively well suited for growing spring wheat. However, Ottawa tends to have more occurrences of heat stress and rainfall deficit than do St-Bruno-de-Montarville and St-Jean-sur-Richelieu, which are more susceptible to water excess in the spring.

The interaction of climate and N management causes important year-to-year variations in biomass and crop N requirements (Montemurro et al., 2006). The application of N fertilizer followed by sustained precipitation may result in the leaching of soil nitrates below the root zone as well as the development of anoxic soil conditions that affect crop germination and growth. In contrast, rainfall deficit results in reduced N uptake because of limited water movement to the root system, as well as in water shortage-induced physiological reductions in biomass accumulation and yield; in both cases, less N is required and higher amounts of N are left in the soil after crop harvest.

Using adapted crop models as research tools is essential for identifying opportunities to increase water- and nitrogen-use efficiencies for spring wheat and for studying the effect of climate variation on NUE and how it varies. In this study, crop biomass and plant N were evaluated according to rainfall and N application rates using soil–crop models. In Western Canada, where similar spring cultivars are grown, a few modelling studies have been carried out using the SWAT, DNDC, AquaCrop FAO, and EPIC models (Ahmad et al., 2011; Kröbel et al., 2011; Mkhabela and Bullock, 2012; Roloff et al., 1998). A spring wheat cultivar adapted to the Mixedwood Plains Ecozone of Eastern Canada (Jégo et al., 2010) was recently developed in the STICS (Simulateur mulTIdisciplinaire pour des Cultures Standard) soil–crop model (Brisson et al., 2003). That study is one of the few crop-modelling studies applied in Eastern Canada and the only one on spring wheat. The STICS model was selected for the present comparison because it takes into account the concept of the N dilution curve (Justes et al., 1994), which has not been extensively validated in North America. This model can be used to predict biomass, yield, N in plants, and soil N dynamics in response to daily climatic conditions and the impact of N application rates. The DNDC (DeNitrification and DeComposition) and DayCent (daily version of CENTURY) models were also added to the comparison because they have the capacity to predict N_2O emissions, a major challenge that must be overcome to increase the sustainability of crop production in Eastern Canada.

Although STICS can predict processes affecting the environment, such as N leaching and water budget, the model's version 6.9 cannot predict N_2O emissions. In Canada, the DNDC model (Li, 2000) has been adapted and used extensively to evaluate N_2O emissions from agricultural lands (e.g., Smith et al., 2004, 2008), whereas the CENTURY model (Parton et al., 1998) and its daily version, DayCent, have been used mostly to evaluate soil C sequestration (e.g., Smith et al., 2000, 2009, 2012) and the impact of past climate variations and future climate scenarios. However, the performance of these more soil-oriented models for predicting crop productivity in relation to abiotic conditions needs to be evaluated.

The objective of this study was to evaluate the performance of the STICS, DNDC, and DayCent models for simulating the components involved in the determination of the NUE of spring wheat in Eastern Canada. The study focused on the response of plant biomass and N uptake to N fertilization rates over several growing seasons and in several locations to capture the influence of climate variations.

The study's hypotheses were as follows: (1) variations in seasonal rainfall have a greater influence on potential biomass and yield than N application rates do; and (2) the models are able to predict year-to-year variations in biomass and crop N requirements owing to the interaction between climate and N management.

2. Materials and methods

A data set consisting of nine site-years distributed between 1993 and 2008 across three locations in the Mixedwood Plains Ecozone of Eastern Canada was used to calibrate and evaluate STICS, DNDC, and DayCent predictions of N uptake, shoot biomass, and grain yield for spring wheat in response to N application rates.

2.1. Experimental sites and management practices

The three locations were St-Bruno-de-Montarville, QC (referred to as St-Bruno; 45°33′ N, 73°21′ W, east of Montreal, 36 m a.s.l.), St-Jean-sur-Richelieu, QC (referred to as St-Jean; 45°13′ N, 73°17′ W in 2005, 45°26′ N, 73°10′ W in 2006, southeast of Montreal, 41 m a.s.l.), and Ottawa, ON (referred to as Ottawa; 45°18′ N, 75°46′ W, 71 m a.s.l.). The locations cover a wide range of soil textures. Clay content was highest in St-Bruno (48%), intermediate in Ottawa (31%), and lowest in St-Jean (20%). Over the growing season (May–August), the cumulative 30-year normals (i.e., 1971–2000) for GDD at 0 °C and for rainfall are similar for St-Bruno (2159 °C and 354 mm) and St-Jean (2164 °C and 366 mm) but are slightly warmer and drier for Ottawa (2234 °C and 349 mm).