



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.

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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 CO₂ 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 N₂O 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 N₂O emissions. In Canada, the DNDC model (Li, 2000) has been adapted and used extensively to evaluate N₂O 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).

Table 1A

Cultivars and management practices (AN = ammonium nitrate) used at the three experimental sites. Dates of application are followed by calendar days between parentheses.

Location	Cultivar	Field	Year	Type of fertilizer 1	Type of fertilizer 2	Rate 1 (kg ha ⁻¹)	Rate 2 (kg ha ⁻¹)	Total rate (kg ha ⁻¹)	Date of application 1	Date of application 2	Seeding date	Harvest date
St-Bruno	AC Pollet	41	1993	AN	AN	0	0	0	–	–		
						18	12	30				
						36	24	60				
						54	36	90	May 9 (129)	July 9 (190)	May 10 (130)	Aug. 17 (229)
						72	48	120				
						90	60	150				
						0	0	0	–	–		
						15	15	30				
						30	30	60				
						45	45	90	May 4 (124)	July 1 (182)	May 5 (125)	Aug. 19 (231)
						60	60	120				
						75	75	150				
St-Jean	AC Barrie	31	2005	AN	AN	0	0	0	–	–		
						10	20	30				
						20	40	60				
						30	60	90	May 13 (133)	June 29 (180)	May 4 (124)	Aug. 10 (222)
						40	80	120				
						50	100	150				
						30	–	30				
						30	30	60	May 1 (121)	June 22 (173)	May 11 (131)	Aug. 9 (221)
						30	60	90				
						30	90	120				
						30	–	30				
						30	30	60				
Ottawa	Hoffman	32	2006	AN	AN	30	60	90	May 10 (130)	July 3 (184)	May 10 (130)	Sept. 1 (244)
						30	90	120				
						–	–	–				
						0	–	0				
						41	–	41				
						68	–	68	Apr. 25 (115)	–	Apr. 25 (115)	Aug. 23 (235)
	AC Brio	14	2001	AN	–	88	–	88				
						78	–	78	May 8 (128)	–	May 9 (129)	Aug. 18 (230)
						0	–	0	–	–		
						77	–	77	May 7 (127)	–	May 8 (128)	Aug. 16 (228)
						76	–	76	May 8 (128)	–		
						0	–	0				
	AC Brio	14	2005	Urea	–	62	–	62	May 8 (128)	–	May 19 (139)	Sept. 4 (247)
						77	–	77				
						–	–	–				
						–	–	–				
						–	–	–				
						–	–	–				

Table 1B
Soil properties at the three experimental sites.

Location	Unit	St-Bruno			St-Jean		Ottawa			
Field	–		41		31	32	25		14	
Years	–	1993	1994	1995	2005	2006	2001	2003	2005	2007
Soil texture	–	Silty clay			Loam		Clay loam			
Organic N	%	0.30	0.30	0.30	0.20	0.18	0.20	0.20	0.20	0.20
Organic C	%	1.8	1.8	1.8	2.5	2.4	2.0	3.1	3.1	3.1
Clay content	%	48.0	48.0	48.0	20.0	20.0	31.4	31.3	31.3	31.3
Sand content	%	8	8	8	8	33	32	20	20	20
Field capacity	%	40.3	40.3	40.3	24.7	26.8	26.0	33.0	33.0	33.0
Wilting point	%	15.0	15.0	15.0	12.6	13.2	12.0	17.0	17.0	17.0
Bulk density	kg m ⁻³	1300	1300	1300	1400	1500	1300	1300	1300	1300
pH	–	7.3	7.3	7.3	6.8	6.4	6.6	6.8	6.8	6.8

2.1.1. St-Bruno

The effect of N fertilizer rate on spring wheat production was evaluated at the St-Bruno experimental farm belonging to CÉROM (Centre de recherche sur les grains) in 1993, 1994, and 1995 using a randomized block of four replicates with N application rates being the main factor. The N rates ranged from 0 to 150 kg N ha⁻¹ in increments of 30 kg N ha⁻¹ (i.e., 0N, 30N, 60N, 90N, 120N, and 150N). Granular ammonium nitrate was applied at seeding and at the boot stage (Table 1A). The fertilizer was broadcast by hand on the plot surface, with the application at seeding incorporated with a rotovator and the application at the boot stage left on the surface.

According to the Canadian System of Soil Classification (Soil Classification Working Group, 1998), the dominant soil texture at the St-Bruno site was silty clay (48% clay, 44% loam, 8% sand). Soil pH was 7.3, organic N content was about 0.3%, and bulk density was around 1300 kg m⁻³ (Table 1B). The previous crop was sorghum (*Sorghum bicolor* L.), which was planted on the site in 1990–1992. Spring wheat (cv. AC Pollet, for bread making) was seeded around May 10 at a density of 450 seed m⁻² (18-cm row spacing) and harvested by the end of August. Each plot was 6 by 5 m.

Weather data were collected primarily on site, and data from the St-Hubert airport, located 8 km from the experimental site, were used to fill data gaps.

2.1.2. St-Jean

For St-Jean, two different experimental sites 25 km apart were used, one in 2005 and the other in 2006. Four in-season N-rate treatment plots were randomized within four blocks during the development years (Table 1A). Each plot was 6 by 10 m, and row spacing was 0.15 m. All plots received 30 kg N ha⁻¹ broadcast at seeding, and the remaining N rate was applied to the plot surface at the boot stage, for a total of 30, 60, 90, and 120 kg N ha⁻¹.

The experimental results were published in Ziadi et al. (2010a,b) for the development of a simple plant-based diagnostic tool for N.

The soil texture was predominantly loamy with high pedodiversity, ranging from silty clay to sandy loam. For this study, it was decided to consider the dominant observed clay content (20%). Soil pH ranged from 6.4 to 6.8, organic N content ranged from 0.18% to 0.20%, and bulk density was about 1450 kg m⁻³ (Table 1B). The previous crop prior to the study was soybean (*Glycine max* L.). The wheat cultivars were AC Barrie (for bread making) in 2005 and Hoffman (for forage) in 2006. The planting and harvesting dates are reported in Table 1A. The wheat seeding density was 450 seed m⁻² in 2005 and 350 seed m⁻² in 2006.

Weather data were obtained from the weather station at the L'Acadie experimental farm, located 3 km from the two sites.

2.1.3. Ottawa

The experimental fields were located south of Ottawa on the Canadian Food Inspection Agency experimental farm. Data were collected in 2001, 2003, 2005, and 2007 from three different nearby

fields with similar soil properties. As indicated in Table 1B, the soil texture was predominantly clay loam, soil pH varied from 6.6 to 6.8, organic N content was about 0.20%, and bulk density averaged 1300 kg m⁻³. Each plot was at least 100 by 50 m, and row spacing was 0.15 m.

The cropping sequences of the Ottawa fields are summarized in Table 1A. Spring wheat (cv. AC Brio) was planted between April 26 and May 19, depending on the year, at a seeding density of 400 seed m⁻². The previous crops were corn in 2000, 2002, and 2006 and canola in 2004. Nitrogen fertilization was applied to the surface at rates ranging from 0 to 88 kg N ha⁻¹, with most of the applications close to the recommended N rates in Ontario (70–80 kg N ha⁻¹) (Ontario Ministry of Agriculture, Food and Rural Affairs, 2009).

Weather data were collected on site. Evapotranspiration was measured with flux towers installed in Ottawa fields using the eddy covariance technique (Pattey et al., 2006). Half-hourly latent heat fluxes were screened and aggregated to daily and seasonal evapotranspiration as described in Pattey et al. (2001).

2.2. Destructive biomass and plant N determination

Total shoot biomass was measured about 30, 45, 60, 75, 90, and 100 d after seeding. Plants in quadrats (0.20–0.40 m²) were harvested by hand and air-dried in a forced-air dryer for 48 h (60–80 °C). Sub-samples of shoot biomass were ground and passed through a 100-mesh sieve to determine total N content. At crop maturity, plants were harvested by hand in 1-m² areas. Shoot biomass was divided into grain biomass and vegetative biomass. As described by Isaac and Johnson (1976), a mixture of sulphuric and selenious acids was used to mineralize 0.1-g samples of dried and ground wheat. Total N in the crop tissue was determined by Kjeldahl digestion and measured by a colorimetric method with a Technicon auto-analyzer or with an automated continuous-flow injection analyzer using Method 13-107-06-2-D (QuickChem 8000; Lachat Instruments, Loveland, CO).

2.3. STICS, DNDC, and DayCent

An overview of the modelling approaches used to describe the major processes for determining crop growth and N uptake are presented in Table 2. The three models use daily climatic data, N inputs, and soil properties as forcing variables and include the following processes: biomass accumulation, grain yield formation, crop phenology, abiotic stresses, soil water transfers, evapotranspiration, soil C and N dynamics, and N uptake. In the STICS model, initial N measurements were input, whereas in the DayCent and DNDC models, linked simulations had been run for 10 years prior to the experiments to stabilize soil N and C.

Table 2Modelling approaches used to describe the major processes for determining crop growth and N uptake [$f(\cdot)$ indicates “as a function of”].

	STICS	DNDC	DayCent
Biomass accumulation ^a	RUE, $f(\text{ps})$	Emp–Dyn C/N	GDD or Emp
Yield formation ^b	$Y(\text{HI}(\text{Gn}), \text{B})$	$Y(\text{HI}_d, \text{B})$	$Y(\text{HI}_d, \text{B})$
Crop phenology ^c	$f(\text{T}, \text{DL}, \text{V})$	$f(\text{T}, \text{O}, \text{DL}, \text{V})$	$f(\text{T}, \text{O}, \text{V}, \text{DL}, \text{S})$
Stresses involved ^d	W, N, T	W, N, T	W, N, T
Water dynamics ^e	C	C	$f(\text{C}, \text{R})$
Evapotranspiration ^f	SW	T	PM
Soil C/N model ^g	N, P(3), B	N(8), P(8), B	N(6), P(6), B
N uptake ^h	DC	CNB	CNP

^a RUE, radiation-use efficiency as a function of phenological stage (ps); Emp, empirical biomass accumulation; Dyn C/N, dynamic C/N; GDD, growing degree day sub-model.^b Y, yield, HI, harvest index; Gn, number of grains; B, total (shoot) biomass; HI_d, harvest index with grain filling/dynamic C allocation affected by N and water stress.^c T, temperature; DL, photoperiod (day length); V, vernalization; O, other water/nutrient stress effects considered; S, senescence.^d W, water stress; N, nitrogen stress; T, temperature stress.^e C, cascade approach; R, Richards approach.^f SW, Shuttleworth–Wallace (resistive model); T, Thornthwaite; PM, Penman–Monteith.^g N(x), x number of N pools; P(x), x number of organic matter pools; B, microbial biomass pool.^h DC, critical N dilution curve; CNB, time-dependent upper and lower boundaries for adequate and deficient C/N; CNP, plant C/N ratio from biomass production (determined by model and already stressed).

2.3.1. STICS

The STICS model was developed to simulate the influence of environmental conditions on crop production and cropping systems. This model uses limited input parameters to describe soil and management practices. The main crop output variables are leaf area index (LAI), yield, shoot dry biomass, and plant N content. The soil profile is divided into horizontal layers, with specific water and mineral N contents. The main simulated processes are crop growth and development as well as water and N budgets. The plant's carbon metabolism drives crop growth with solar radiation intercepted by the canopy converted into shoot biomass. Crop development is driven by the accumulation of degree days. Water and N stresses are taken into account by constraining functions varying from 0 (full stress) to 1 (no stress) that reduce leaf growth and biomass accumulation under water- and nutrient-limiting conditions. The influence of water excess on crop growth is also taken into account in the model. The STICS model has been verified in a wide range of spring wheat studies (e.g., Casa et al., 2012; Guillaume et al., 2012; Jégo et al., 2010; Palosuo et al., 2011; Wallach et al., 2011).

2.3.1.1. Evapotranspiration. As an extension of the Penman–Monteith equation (Allen et al., 1998), the Shuttleworth–Wallace equation used in STICS considers dual sources, namely transpiration from vegetation and evaporation from underlying soil (Shuttleworth and Wallace, 1985). Moisture enters the atmosphere both through evaporation from the soil surface and through transpiration from leaves. The relative importance of evaporation and transpiration changes dynamically as the vegetation develops. Shuttleworth and Wallace (1985) proposed a resistive model, in which the interactions between soil and canopy fluxes are taken into account with controlling resistances associated with the plants and with the soil in which they are growing. The algorithm has proved to be an efficient tool for explaining the energy budget of canopies (Sene, 1994) and was adapted to STICS by Brisson et al. (1998).

2.3.1.2. Shoot biomass. In STICS, the daily production of shoot biomass is a function of constant radiation-use efficiencies (RUE) (Monteith, 1972) over three phenological stages (i.e., seedling growth RUE = 2.2 g MJ⁻¹, vegetative RUE = 4.25 g MJ⁻¹, and grain-filling RUE = 4.25 g MJ⁻¹), which are constrained by abiotic stressors known to affect photosynthesis and respiration, such as water and N deficiencies and sub-optimal temperature conditions.

2.3.1.3. Plant N status and calibration. The STICS model expresses plant N status (% N) at a given time as a function of shoot biomass

accumulation using the critical N curve (N_c ; %). The concept was first proposed by Lemaire and Salette (1984) for tall fescue (*Festuca arundinacea*) and has been successfully applied to winter wheat using measurements collected in Belgium and Sweden (Greenwood et al., 1990) and in France (Justes et al., 1994) as well as to spring wheat using data collected in Eastern Canada (Ziadi et al., 2010a). This last study demonstrated that the N_c was lower for spring wheat than for winter wheat.

The N_c declines as a function of shoot dry biomass accumulation (B_s ; Mg ha⁻¹). The curve is used as a diagnostic tool for N status. Justes et al. (1994) suggested that a crop has a maximum capacity to accumulate N in its shoots, which was defined by the maximum dilution curve ($N_{c,\max}$; %). In Eastern Canada, the N_c and $N_{c,\max}$ of spring wheat are defined as follows:

$$N_c = 3.85(B_s)^{-0.57}$$

$$N_{c,\max} = 4.48(B_s)^{-0.46}$$

To account for the dilution curves recently published by Ziadi et al. (2010a), an additional calibration of the cultivar parameters initially defined in Jégo et al. (2010) was carried out. The calibration was done in two steps, one using plant growth from a data set in which LAI measurement was complete, and a second using plant N uptake from a data set in which plant N measurement was complete. In Step 1, three parameters—Stlevamf (duration between emergence and maximum leaf growth), Stamflax (duration between maximum leaf growth and maximum LAI), and DurvieF (maximum lifespan of the green leaves)—were optimized with the STICS built-in simplex algorithm using LAI observed in St-Jean on five dates in 2005 in all N-rate plots. In Step 2, the maximum nitrate uptake rates for the high-affinity (Vmax1) and low-affinity (Vmax2) uptake systems of roots were optimized using N in plants measured in St-Bruno in 1993 in all N-rate plots.

2.3.2. DNDC

The DNDC model was originally developed to simulate N₂O emissions from agricultural soils but has been expanded to estimate crop biomass production, methane and ammonia emissions, and soil C and N dynamics. The model describes C and N transport and transformation driven by a series of soil environmental factors such as temperature, moisture, redox potential, pH, and substrate concentration gradients. The DNDC model was extensively verified with respect to organic C dynamics and N₂O emissions in agroecosystems (Cai et al., 2003; Jagadeesh Babu et al., 2005; Li et al., 1996, 2000, 2002; Smith et al., 2008, 2012). Recently, a new sub-model was developed for biomass and yield using spring wheat

data from western Canada and was included in DNDC (Kröbel et al., 2011).

2.3.2.1. Evapotranspiration. The DNDC model calculates potential evapotranspiration (PET) with the adapted Thornthwaite equation (Li et al., 1992), which includes a multiplier for wind speed. The estimated plant transpiration (T) is a function of the crop water requirement (g water g^{-1} shoot biomass), which depends on the estimated crop biomass and water uptake from the soil root layers. Potential evaporation is estimated as the difference between PET and T, and the final evaporation depends on the available soil moisture in the top 15 cm of the soil, as well as on the presence of crop residues.

2.3.2.2. Shoot biomass. In the DNDC model, crop growth is driven by GDD above 0 °C, and daily growth is derived from the potential daily biomass growth (kg C ha^{-1}) that can be constrained by abiotic stresses (water, frost, and heat) (Li et al., 1994). The present study used the improved empirical spring wheat growth sub-model developed by Kröbel et al. (2011). In the sub-model, algorithms were developed to (1) provide a growth curve based on wheat cultivars grown in western Canada, (2) include dynamic C/N ratios for the different plant organs (e.g., grain, stem, and root), (3) incorporate dynamic translocation of N from the plant to the grain during grain filling, and (4) employ a function describing root growth over time and depth.

2.3.2.3. Plant N status. In DNDC, dynamic biomass fractions of the organs and their current C/N ratios are calculated to determine daily crop N demand. Plant N uptake from the dissolved inorganic N pools in the soil is the key crop growth process that links climate and soil status (Li et al., 1994). Crop N uptake is a function of root biomass and N availability in the soil profile. Nitrogen accumulates in the plant over time as a function of the daily potential biomass growth and the corresponding plant C/N ratio (Kröbel et al., 2011). The accumulated N is converted into biomass using the plant C/N ratio, and any lack of N uptake therefore reduces crop biomass accumulation.

Calibration of the biomass and yield of the different organs was carried out using data from the Old Rotation long-term field experiment in Swift Current, SK (Kröbel et al., 2011), whereas temperature, degree days, and water requirements were identified based on literature values. The present study used averaged C/N ratios for straw, grains, and plants measured in St-Bruno in 1993, 1994, and 1995 as input parameters for the DNDC model for all the simulations.

2.3.3. DayCent

The DayCent model (Del Grosso et al., 2005; Parton et al., 1998) is a biogeochemical model used to estimate changes in soil organic matter and simulate N gas emissions, plant biomass, and nutrient dynamics in response to management events such as fire, grazing, cultivation, and fertilizer or organic matter additions, as well as climate variations. DayCent was derived from CENTURY (Parton and Rasmussen, 1994), a monthly time-step compartmental model used to estimate C sequestration potential. Both models have been developed and parameterized to simulate a wide range of agricultural crops. DayCent has been used extensively to simulate spring wheat production in Canada and the United States (Del Grosso et al., 2005, 2006, 2009; Smith et al., 2012; Stehfest et al., 2007). The present study used a recent version of DayCent that scales a number of weekly outputs to daily outputs (i.e., biomass and plant N).

2.3.3.1. Evapotranspiration. DayCent calculates evapotranspiration with the Penman–Monteith equation (Allen et al., 1998). Maximum potential transpiration and bare soil evaporation are

determined as a function of the extent of coverage of live leaf biomass (Parton et al., 1998). The model's most recent version (August 2011) now takes into account solar radiation outside the atmosphere and cloud cover based on temperature range. The effect of solar radiation on snow melt has also been added. A new routine has been added to calculate runoff, and runoff values are removed from water inputs (precipitation plus irrigation) before evapotranspiration occurs.

2.3.3.2. Plant biomass and N uptake. DayCent calculates net primary production as a function of nutrient availability, soil water and temperature, shading, and vegetation type (Metherell et al., 1993). Net primary production is allocated to the different biomass organs (i.e., leaf, stem, fruit, and root) based on the type of plant. A function of soil water content and mineral N availability determines the root-to-shoot ratio of net primary production allocation. Potential production is calculated as a function of solar insolation, an energy-to-biomass conversion factor, and temperature (using a crop-specific optimum temperature growth function) (Stehfest et al., 2007). The potential production is modulated by water and nutrient stresses. If the ratio between available water and PET drops below an upper threshold, potential production is linearly reduced to a lower threshold of available water to PET, below which no production is taking place. Water-limited production is further limited by the availability of N. Nutrient concentrations in the plant shoot biomass are regulated using upper and lower limits that are set independently for both shoots and roots. The rates differ in that shoot nutrient concentrations vary as a function of plant biomass, whereas root nutrient concentrations are regulated as a function of annual precipitation. The proportion of root biomass determines the rate of N uptake for plant growth.

In addition to heterotrophic respiration, DayCent now includes maintenance respiration for above- and below-ground plant fractions as a function of the mass of each plant fraction, soil and air temperature, and a maximum respiration parameter.

The present study simulated spring wheat using the phenologically based sub-model in DayCent that allows the model to be parameterized to discern when germination and harvest events occur. Options to include grain filling and dynamic C allocation as a function of soil water and nutrient availability were also employed. Nitrogen concentrations in shoot biomass and potential monthly shoot production were adjusted according to observations in the 1993 plots in St-Bruno.

2.3.4. Management of water and nitrogen excesses and shortages

2.3.4.1. Water excess. In both the DayCent and the DNDC cascade models, there are currently no functions for water excess affecting biomass. Excess water above field capacity is drained through the profile at the maximum rate of the saturated conductivity or allocated to runoff or deep water storage. In STICS, roots are affected by anoxic conditions, which limit crop growth. Root growth, leaf development, and RUE are affected in STICS by this stress, which is a function of the proportion of roots in saturated layers.

2.3.4.2. Water shortage. In DNDC, water shortage is initiated when soil water availability is no longer able to meet the potential crop water demand. The crop water demand is calculated as a function of the daily potential biomass growth and the crop water requirement. In DayCent, if the ratio between available water and PET drops below an upper threshold, potential production is linearly reduced to a lower threshold of available water to PET, below which no production is taking place. Additionally, for grain crops a crop-specific water-stress factor regulates the harvest index during grain filling. In STICS, a stress index ranging between 0 and 1 is used as a multiplier to reduce the several processes of the plant (e.g., emergence, LAI, root and fruit growth, transpiration, RUE, senescence, #

of grains). This index is a function of the available water content (water content above the wilting point) in the root zone.

2.3.4.3. Nitrogen excess. None of the models simulate the effect of N excess on the crop canopy itself. Excessive N application will lead to increased N leaching, runoff, and gaseous emissions, but there is no adverse effect on simulated biomass in any of these models.

2.3.4.4. Nitrogen shortage. In the version of DNDC used in this study, DNDC-CSW, nitrogen shortage was calculated as a ratio of the N available through plant uptake to the potential N demand. In DayCent, N demand is determined by trying to meet the C/N ratios of new biomass, and N stress is incurred when N availability in the profile to the depth where roots exist does not meet this demand. In STICS, a stress index similar to the water shortage index is applied. The N stress index is a function of the nitrogen nutrition index, which is a ratio between the N concentration in the plant and the critical N concentration.

2.4. Statistical criteria for model performance evaluation

Verification of the model results was conducted against all measurements excluding those used for calibration. The models were statistically evaluated by comparing N in plants and shoot dry biomass predictions for the various N application rates and sites during the growing season with the corresponding measurements (averages of four replicates). The criteria used to calibrate and evaluate the model shoot biomass and plant N predictions were the relative root mean square error (RMSE) and the average relative error (ARE) between model predictions and measurements. The RMSE indicates the error of model prediction by giving more weight to high errors.

The RMSE and ARE are defined mathematically as follows:

$$RMSE = \left[N^{-1} \times \sum_{i=1}^N (P_i - O_i)^2 \right]^{0.5}$$

$$ARE (\%) = \frac{\sum_{i=1}^N (P_i - O_i)}{N \times \bar{O}} \times 100$$

where P_i is the predicted value, O_i is the observed value, and N is the number of observed values.

Flénet et al. (2004) found that model shoot biomass predictions were acceptable for an RMSE of approximately 20%, whereas Corre-Hellou et al. (2009) reported barley predictions as satisfactory for a relative RMSE of 25–35%. The ARE is an indicator of the model prediction bias. Hu et al. (2006) reported biomass and plant N evaluation for corn and wheat as good when the ARE was less than 10% and considered predictions to be biased when the ARE was greater than 20%. Fang et al. (2008) found that N uptake predictions reached higher errors than biomass did, with ARE reaching 14% and 33%, respectively; the first was evaluated as acceptable whereas the second was evaluated as less accurate.

A series of multiple linear regression models were calculated to evaluate whether any residual effects of climate and N fertilization were still significant after crop model predictions had been accounted for, as suggested by White et al. (2007), using the following equation:

$$O = \beta_0 + \beta_1 P_{\text{model}} + \beta_2 R + \beta_3 F + \beta_4 RF + \beta_5 P_{\text{model}} R + \beta_6 P_{\text{model}} F + \varepsilon$$

where O is the observed variable (either N in plant or biomass), P_{model} is the corresponding predicted variable of a given model (i.e., STICS, DNDC, or DayCent), F is the N fertilization rate, R is the rainfall, β_0 – β_6 are the regression coefficients, and ε is the residual

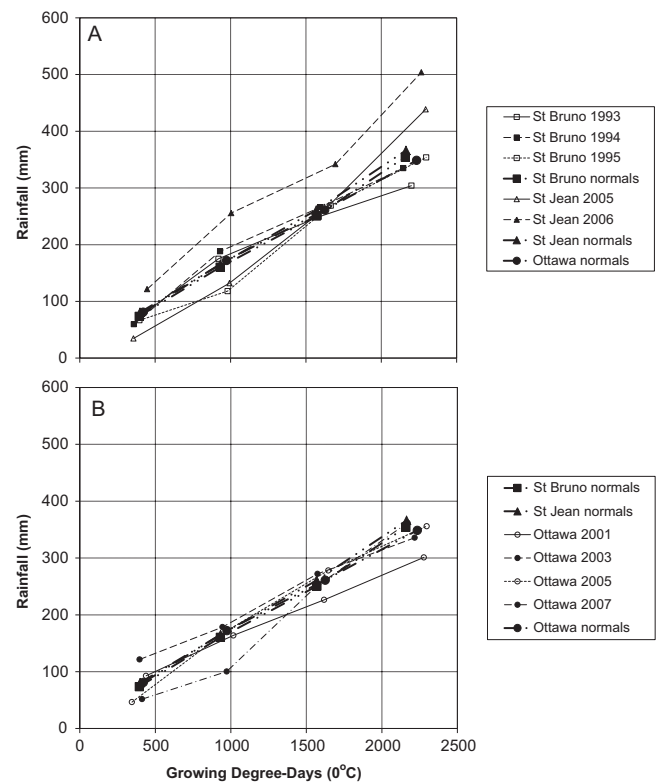


Fig. 1. Cumulative rainfall and growing degree days at 0 °C between May and August at the (A) St-Bruno and St-Jean and (B) Ottawa sites in comparison with the 30-year normals (1971–2000).

error term. All regressions were performed using the linear regression procedure (analysis of variance) of the StatPlus 2009 software package (AnalystSoft Inc., Vancouver, BC, Canada).

3. Results

3.1. Experimental results

The three sites had relatively similar cumulative rainfall amounts as a function of GDD (0 °C) over the period of May 1–August 31 (Fig. 1A and B), with a slightly drier trend towards the end of the season for the Ottawa site. The climatic conditions in St-Jean in 2006 were constantly well above normal for rainfall and GDD (Fig. 1A), whereas 2005 was drier than normal in May and June and had more rainfall afterwards. Most of the monthly observations in St-Bruno were near normal, with the exception of August 1993 and May and June 1995, which experienced rainfall deficits. For the Ottawa site, the climatic conditions in 2001, 2003, and 2005 were constantly near or above normal for rainfall and GDD over the growing season. In 2007, the first two months experienced 36% and 47% less precipitation than normal.

Pedoclimatic conditions were more likely to be suitable for wheat growth at the St-Bruno and Ottawa sites in 1993, 1994, 2001, 2003, and 2005 because of the higher clay contents (>31%) and field capacities (>26%) and thus greater soil water availability at those locations in comparison with St-Jean. Early-season rainfall deficits or excesses for other site-years should lead to less optimal wheat growth or N application efficiency, because of the anoxic conditions surrounding the root system.

The dynamics of shoot dry biomass accumulation in response to N rates are presented in Fig. 2 for the different site-years. The N dynamics in plants were similar to shoot dry biomass and are not illustrated. The cumulative shoot dry biomass ranged from

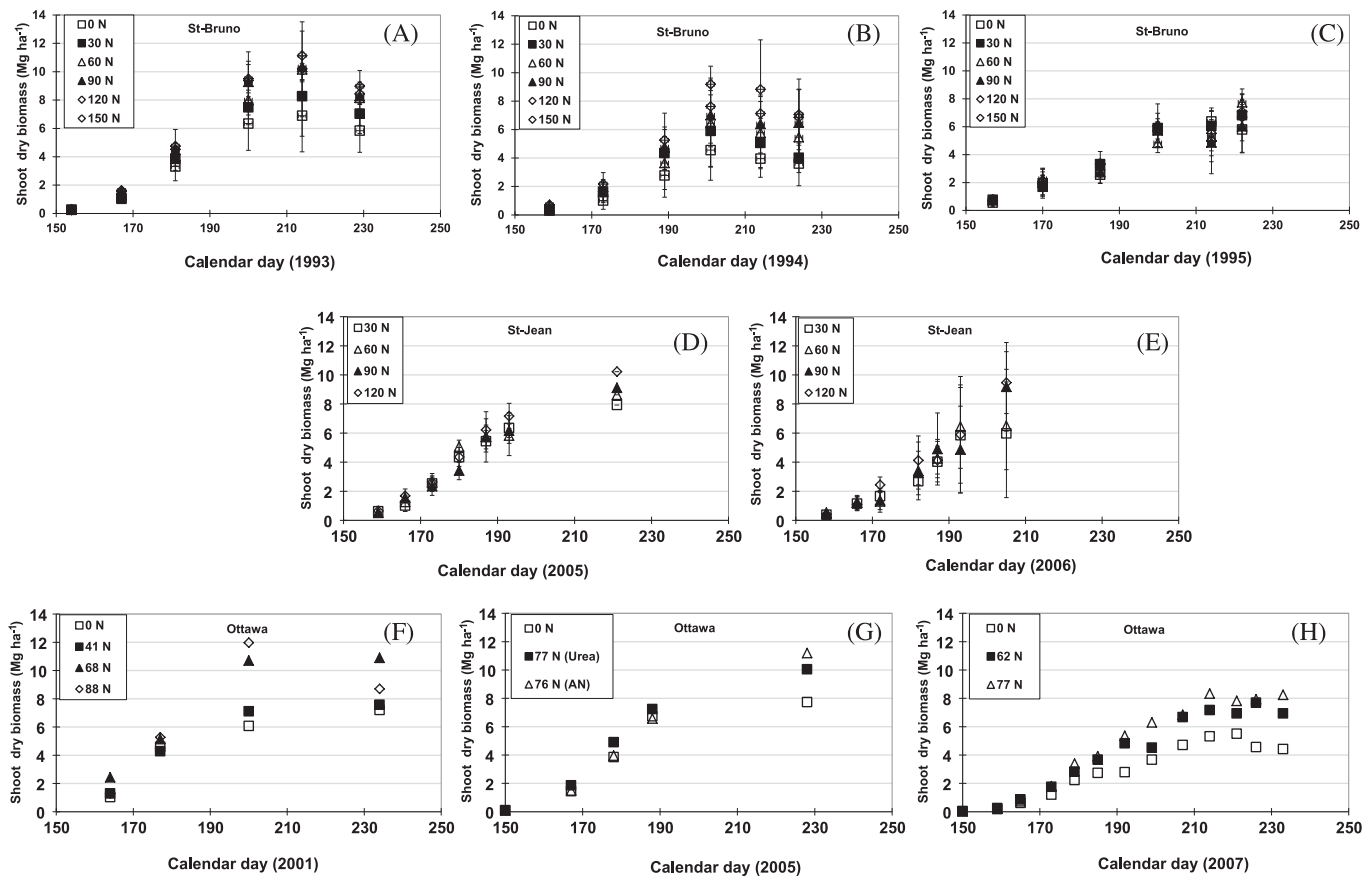


Fig. 2. Temporal dynamics of measured shoot dry biomass for various N application rates in St-Bruno (A) 1993, (B) 1994 and (C) 1995 (0N to 150N), St-Jean (D) 2005 and (E) 2006 (30N to 120N), and Ottawa (F) 2001, (G) 2005 and (H) 2007 (0N to 88N) (AN = ammonium nitrate).

4.5 Mg ha⁻¹ (0N) to 11.6 Mg ha⁻¹ (highest N rates), and the N in plants ranged from 53.5 to 152.7 kg N ha⁻¹. The data from Ottawa in 2003 are not illustrated, as only one N rate was used there.

The response of biomass accumulation and N in plants to N application rates varied according to the pedoclimatic conditions. When no rainfall deficit was observed early in the season, as was the case for St-Bruno in 1993 and 1994 and for Ottawa in 2001, 2003, and 2005, the cumulative shoot biomass increased between 34% and 51% above the response observed without any N application and similarly the N in plants increased between 47% and 63%. The relationship was nonlinear and became insensitive to any further fertilization changes between 60N and 90N. In 2001, the rainfall deficit in Ottawa occurred late in the growing season (August) and did not seem to influence the biomass accumulation in response to N fertilization before August (to Day 213).

The increases in shoot biomass accumulation induced by higher fertilization rates were limited by rainfall deficits or excesses observed during the early part of the season. Indeed, no response to increasing N rates could be detected in shoot biomass or N in plants early in the season in the data sets for St-Bruno in 1995, St-Jean in 2005 and 2006, or Ottawa in 2007 (higher N rates), whereas a limited response emerged towards the end of the season for near-normal rainfall.

Protein content in grain and dry yield tended to exhibit similar trends as shoot dry biomass and N in plants in St-Bruno, St-Jean, and Ottawa (Fig. 3). Protein content ranged from 12% (0N) to 18% (highest N rates), and dry yield varied from 1.6 to 3.9 Mg ha⁻¹. Yield increased with N application rates except for the data sets for St-Bruno in 1995, St-Jean in 2005 and 2006, and Ottawa in 2007 (higher N rates). Protein content exhibited the same pattern except

for the data set for St-Jean in 2005, when the highest N rates induced the highest protein content.

3.2. Model predictions

Shoot biomass predictions according to N rates were fair for STICS and DNDC and not as good for DayCent (Table 3) except for lower application rates, for which the STICS and DayCent predictions were also poor. These observations are confirmed by ARE values greater than 10% (>0.5 kg N ha⁻¹) for low N rates in comparison with much better ARE values for higher N rates. Biases were lowest with DNDC and highest with DayCent. The STICS and DNDC models did not show significant biases by rainfall amount early in the season, but biases increased for DayCent when water was in excess. In general, biomass predictions were not very good in response to water, with RMSE values greater than 20%.

For N in plants, the predictions by N rate ranged from fair to good at high N rates and dropped to fair to poor at lower N rates (RMSE > 20%, >15 kg N ha⁻¹ for 30N and 0N rates). Most of the predictions by rainfall amount were fair with STICS. DayCent and DNDC showed significant biases when early-season rainfall was in excess. When rainfall was near normal during the first two months, the three models did better in predicting N in plants. The dynamics of shoot biomass accumulation over the growing season were captured relatively well by the three models for the recommended N rates (Fig. 4).

Water budget predictions were established for near-normal rainfall for non-limiting (90N, 120N, and 150N) and limiting (0N, 30N, and 60N) N rates and for rainfall deficits early in the growing season for non-limiting and limiting N rates (Fig. 5). According to

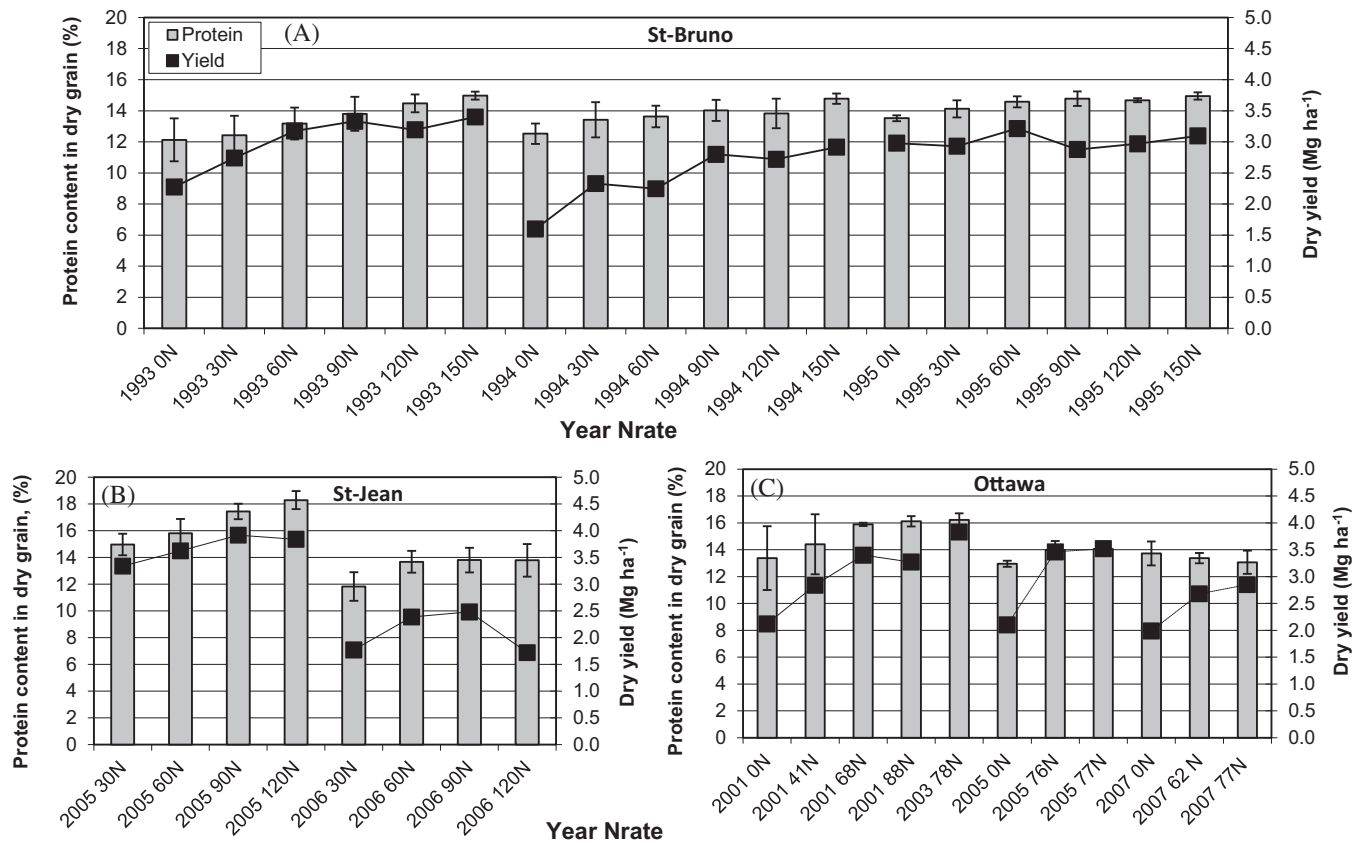


Fig. 3. Measured protein content in dry grain (bars; % dry grain mass) and measured dry yield (solid squares; Mg ha^{-1}) by year and N rate at the (A) St-Bruno, 1993, 1994 and 1995 (B) St-Jean 2005 and 2006, and (C) Ottawa sites 2001, 2003, 2005 and 2007. Solid lines and dotted lines illustrate even N-rate increases and uneven N-rate increases, respectively, over a season (Ottawa in 2005: 76N ammonium nitrate, 77N urea; Ottawa in 2007: 62N slurry + urea, 77N urea). The N rates ranged from 0 to 150 kg N ha^{-1} (0N to 150N).

Table 3

Statistical evaluation of the predicted shoot dry biomass and N in plants by the STICS, DNDC, and DayCent models at three different sites in Eastern Canada during the growing season (May–August in 1993–2007). Classification is done by site and N application rate. The average relative error (ARE) is an estimate of the bias of the model. The root mean square error (RMSE) indicates the error of prediction of the model by giving more weight to high errors. The N rates ranged from 0 to 150 kg N ha^{-1} (0N to 150N). Values are expressed quantitatively (in Mg ha^{-1} for shoot dry biomass and in kg ha^{-1} for N in plants), followed by percentages within parentheses.

	ARE			RMSE		
	STICS	DNDC	DayCent	STICS	DNDC	DayCent
By N rate						
Biomass 0N	0.5 (14.9)	0 (1.1)	0.6 (17.3)	1.2 (34.7)	1.3 (34.7)	1.4 (39.5)
Biomass 30N	0.5 (12.2)	0.1 (2.9)	0.5 (13.1)	1.1 (28.2)	0.9 (28.2)	1.4 (34.4)
Biomass 60N	0.2 (5.6)	0 (0.6)	0.2 (4.3)	0.9 (19.6)	1.0 (21.8)	1.6 (35.6)
Biomass 90N	0.2 (3.9)	0.1 (2.4)	0.2 (3.5)	1.1 (24.1)	1.1 (23.5)	1.6 (35.0)
Biomass 120N	0 (–0.5)	–0.3 (–5.7)	0.5 (9.8)	0.7 (16.0)	1.0 (21.7)	1.4 (30.5)
Biomass 150N	0.3 (6.2)	–0.1 (–1.8)	0.6 (12.4)	0.8 (15.1)	0.9 (18.0)	1.4 (26.8)
N in plants 0N	0.6 (1.2)	–5.5 (–2.9)	3.2 (6.1)	12.4 (23.8)	13.6 (26.0)	15.6 (29.8)
N in plants 30N	–2.2 (–3.5)	–2.2 (–3.6)	–1.4 (–2.2)	20.4 (33.2)	12.2 (19.9)	15.4 (25.1)
N in plants 60N	–1.1 (–1.6)	–2.0 (–2.9)	–4.2 (–6.2)	12.8 (18.8)	12.9 (19.1)	18.4 (27.2)
N in plants 90N	–3.6 (–4.9)	–4.1 (–5.5)	–7.1 (–9.5)	10.7 (14.4)	12.2 (16.4)	17.7 (23.7)
N in plants 120N	0.7 (0.9)	–3.2 (–4.2)	–2.1 (–2.7)	15.1 (19.7)	19.0 (24.9)	25.3 (33.1)
N in plants 150N	–0.4 (–0.4)	–5.2 (–6.0)	–10.1 (–11.6)	14.2 (16.3)	16.3 (18.7)	24.7 (28.4)
By early-season rainfall amount						
<i>Rainfall deficit</i>						
Biomass	0.2 (4.8)	0.3 (6.7)	0.2 (4)	0.9 (21.4)	1.0 (24.7)	1.3 (33.2)
N in plants	–13.7 (–20.6)	–5.1 (–7.7)	–13.5 (–20.4)	19.5 (29.4)	17.5 (26.4)	23.9 (36.1)
<i>Rainfall excess</i>						
Biomass	–0.3 (–7.7)	0.3 (9.2)	1.4 (39.9)	0.7 (19.2)	0.9 (24.3)	1.6 (33.2)
N in plants	7.8 (14.5)	17.8 (33.2)	22.5 (42)	16.2 (30.2)	22.6 (42.3)	26.3 (49.3)
<i>Near-normal rainfall</i>						
Biomass	0.5 (9.9)	–0.4 (–7.5)	0.2 (4.3)	1.2 (24.8)	1.2 (24.2)	1.8 (36.7)
N in plants	2.5 (3.4)	–3.2 (–4.4)	–0.1 (–0.2)	13.6 (18.4)	15.3 (20.7)	20.9 (28.3)

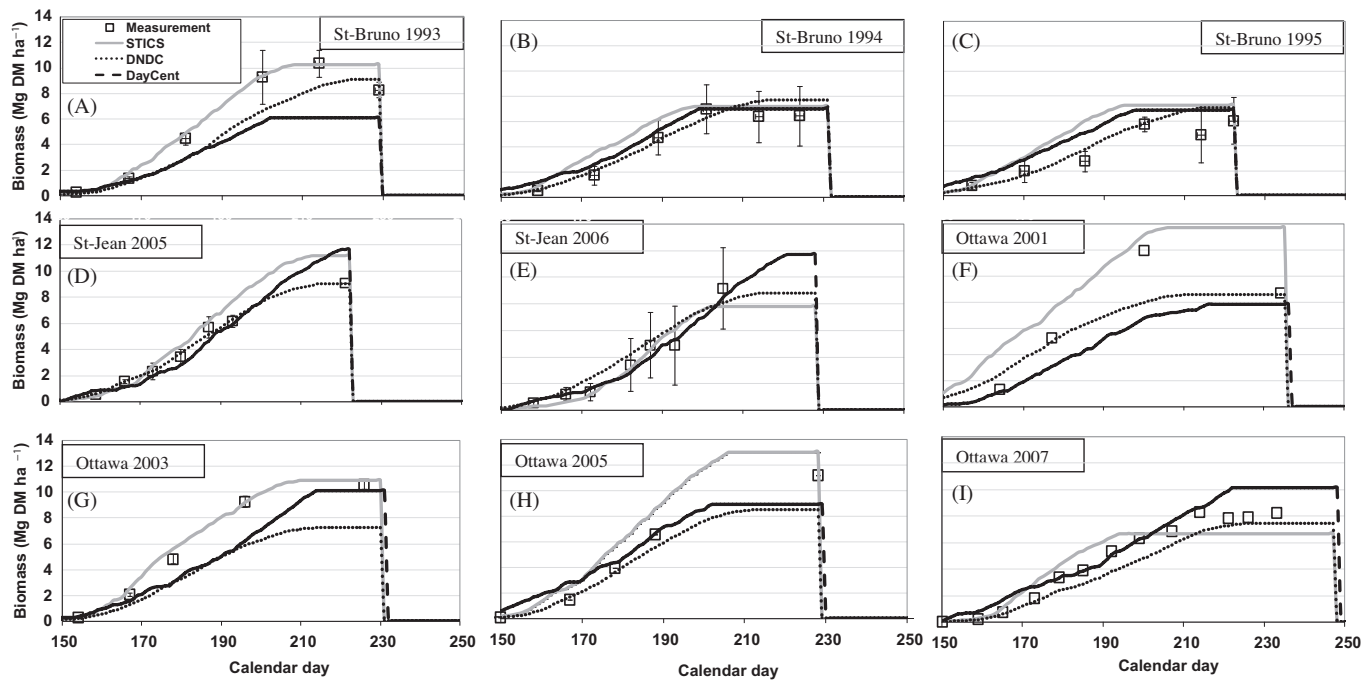


Fig. 4. Measured and predicted shoot dry biomass using the STICS, DNDC, and DayCent models at the St-Bruno site in (A) 1993, (B) 1994 and (C) 1995 (90N), at the St-Jean site in (D) 2005 and (E) 2006 (90N) and the Ottawa site ((F) 88N in 2001, (G) 78N in 2003, (H) 77N in 2005 and (I) 77N in 2007).

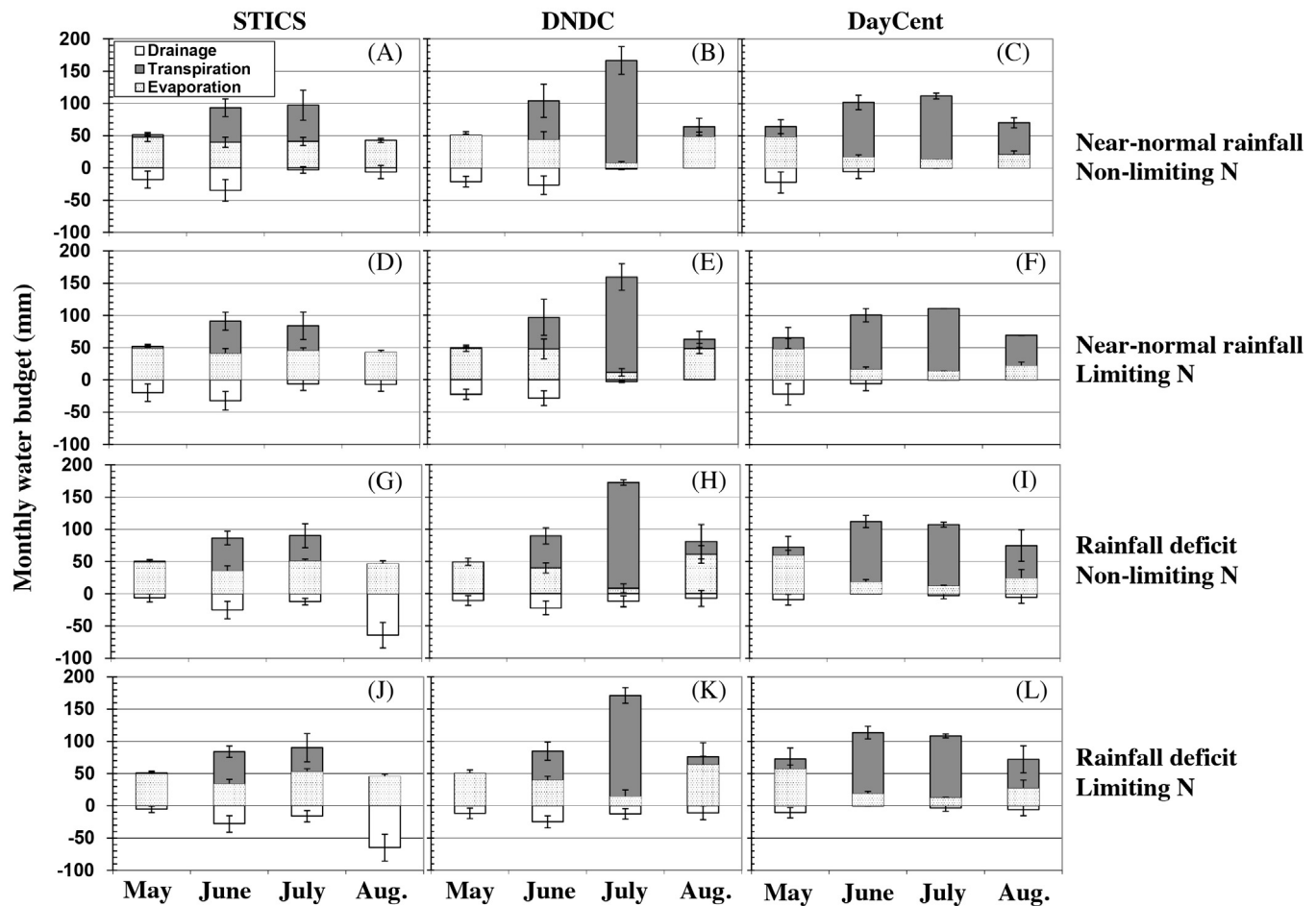


Fig. 5. Components of simulated water budget at the three experimental sites for the growing seasons during the period from 1993 to 2007. Monthly evaporation, transpiration (illustrated as positive terms), and drainage (illustrated as negative terms) were sorted according to near-normal rainfall (A, B, C, D, E and F) and rainfall deficit early in the season (G, H, I, J, K and L) and according to non-limiting (A, B, C, F, H and I) and sub-optimal (D, E, F, J, K and L) N rates for STICS (A, D, G and J), DNDC (B, E, H and K) and DayCent (C, F, I and L) predictions.

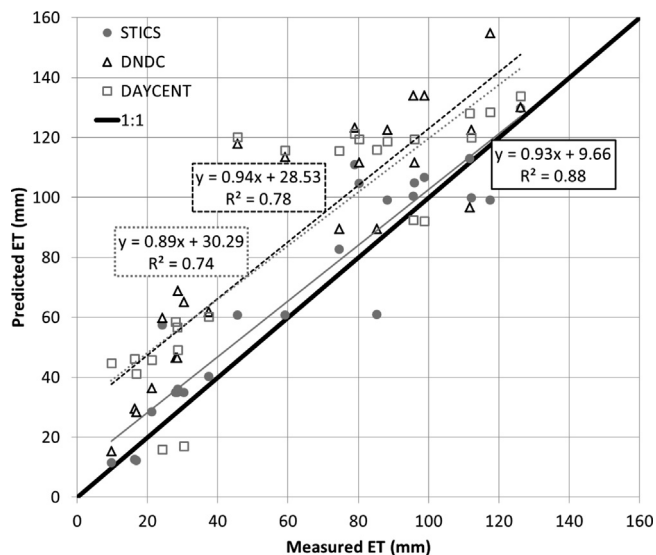


Fig. 6. Predicted evapotranspiration (ET) using the STICS (solid grey line), DNDC (dashed line), and DayCent (dotted line) models in comparison with measured ET using the eddy covariance technique. Data are plotted by month except in May (plotted from the seeding date to the end of the month) and August (plotted from the beginning of the month to the harvest date).

the range of evapotranspiration measured using eddy covariance in Ottawa early in the season (108–160 mm from seeding to the end of June), these rainfall deficits represented a mild stress for the plants (a water deficit of up to 30% relative to plant needs).

Evaporation predictions were relatively constant during the growing season, except for DNDC in July (strong reduction) and DayCent in May (much higher than in the remainder of the season), with no effect of either N rate or rainfall deficit. Soil evaporation was higher in STICS and DNDC (except in July) than in DayCent, in which the exclusive use of the Penman–Monteith equation seemed to lower the soil evaporation predictions.

Transpiration predictions were of about the same magnitude in June and July for STICS and were almost zero in August. Transpiration was the dominant term of the water budget for DayCent and DNDC, especially in June and July, when the canopy was fully developed. The DNDC predictions were two times higher in July than in June. Significant transpiration was predicted by DayCent in August. The results showed that there was no clear influence of early-season rainfall or N application rate on transpiration except in STICS, for which higher N rates seemed to be associated with higher transpiration in the absence of rainfall deficit. This was also the case for STICS predictions when rainfall was near normal for non-limiting N rates. As expected, drainage predictions were relatively small when the canopy was fully developed.

There was a systematic trend in the evapotranspiration predictions among the models, with DNDC predicting the highest values, followed by DayCent and then STICS, which predicted values closest to the eddy flux measurements in Ottawa (Fig. 6). Transpiration was simulated using the Shuttleworth–Wallace equation (Shuttleworth and Wallace, 1985) in STICS, the Penman–Monteith equation (Allen et al., 1998) in DayCent, and the Thornthwaite equation (Li et al., 1992) in DNDC. The Thornthwaite model is temperature-based with no explicit indication of the water supply, whereas the Penman–Monteith and Shuttleworth–Wallace equations require additional data, namely solar radiation, air humidity, and wind speed. The literature shows that the Thornthwaite method did not perform well (Amatya et al., 1995; Fisher et al., 2011) in comparison with models combining energy and atmospheric drivers (i.e., wind speed and air humidity) such as the Penman–Monteith or Shuttleworth–Wallace methods. Moreover,

the Penman–Monteith model is a one-canopy layer model (i.e., a big-leaf model) that is designed to be used with dense crops, whereas the Shuttleworth–Wallace model is a two-layer model that considers soil evaporation and vegetation transpiration, as a logical extension of the Penman–Monteith model to be used with sparse crops (Stannard, 1993). Indeed, the Penman–Monteith model is dependent on a bulk surface resistance that is difficult to define and was derived for horizontally homogeneous vegetation, so that method could fail to provide good predictions of transpiration rate over sparse canopies, as is the case at the beginning of the growing season. With STICS, the lowest transpiration rates were generally predicted for the growing seasons with the lowest precipitation, but this was not the case for DNDC and DayCent. The evapotranspiration measurements in Ottawa showed the same trend (data not shown), as did the water use derived from the soil moisture profile in the semi-arid Prairies (Campbell et al., 2005). The DNDC model was recently modified to use the Penman–Monteith equation, a change that has dramatically improved evapotranspiration predictions. DayCent estimates could be further improved with additional climate drivers.

Similar to water budget predictions, N budget predictions were established according to rainfall deficit and N limitation (Fig. 7). Nitrogen budget predictions indicated that losses were minimal in term of gaseous losses and leaching (Fig. 7). However, these predictions were made with all N species confounded and did not look at the potential impact on the environment (e.g., nitrous oxide emissions). Available N was similar to crop N uptake, and these two components were quite high in June and decreased a great deal in July to reach almost negligible levels in August. In comparison with STICS and DNDC, DayCent simulated less available N and plant N uptake in June but simulated the opposite situation in July. Early-season rainfall deficit had an impact on simulated plant N with STICS, whereas the effect was not as clear with DayCent and DNDC. Higher N application rates generated higher plant N predictions in STICS and DNDC. As expected, plant N was higher in June than in July for all the models. For early-season rainfall that was near normal, predictions of available N were similar for all the models.

The water budget deficit was attributed to water storage. The STICS and DayCent models simulated similar water storage, whereas DNDC exhibited a higher default attributed to water available for the plant.

Available N was comparable to crop N uptake, and these two components simulated with STICS and DNDC were quite high in June and lower in July, whereas crop N uptake simulated with DayCent was only slightly higher in June than in July. The trends of STICS and DNDC (and to a lesser extent DayCent) are supported by the study by Blankenau et al. (2002) reporting larger wheat N uptake at tillering in June than during stem elongation in July. Early-season rainfall deficit had an impact on simulated plant N with STICS, whereas the effect was not as clear with DayCent and DNDC. This impact was confirmed by the studies by Karam et al. (2009) and Kibe et al. (2006), who also demonstrated that the response of production to N supply is strongly influenced by environmental conditions, especially the quantity and timing of water available to the crop. The present study observed not only the influence of application rates but also the co-influence of water and N application: N rates had an impact when water was not limited or in excess. These results were in agreement with several studies. Indeed, in the semi-arid Prairies, Campbell et al. (2005) studied the long-term influence of N fertilizers on crop production, N uptake, and water use in hard red spring wheat and found that the straw N concentration of wheat grown on stubble during the period from 1985 to 2002 was increased by fertilizer N. Moreover, a three-year study by Mooleki et al. (2010) to determine the effect of N form, timing, and rate on the N uptake of spring wheat at four sites representing

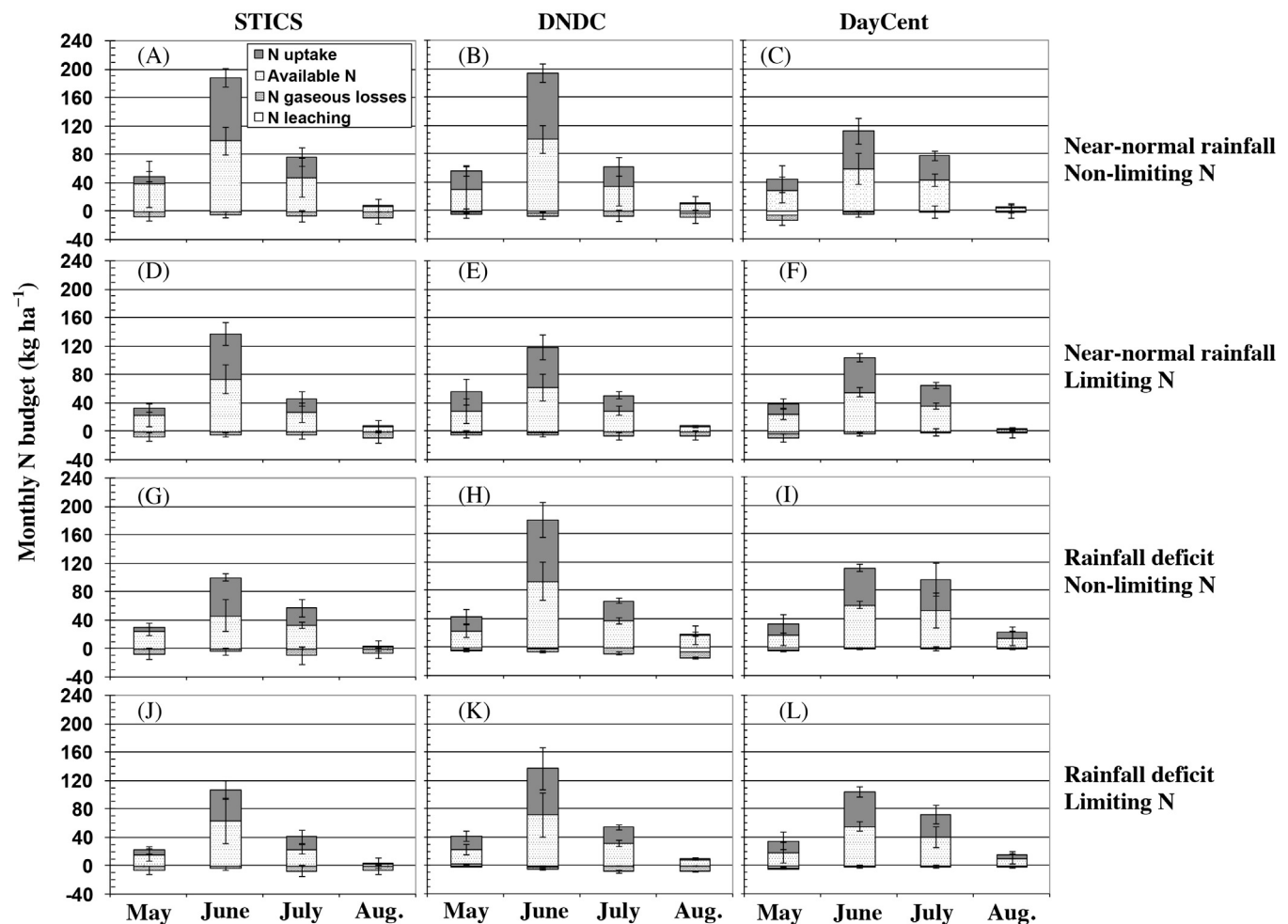


Fig. 7. Components of the N budget at the three experimental sites for the growing seasons during the period from 1993 to 2007. Average soil N content, plant N uptake (cumulative plant N uptake over the month, illustrated as positive terms), leached N ($\text{NO}_3 + \text{NH}_4$), and N gaseous losses ($\text{N}_2 + \text{N}_2\text{O} + \text{NH}_3$, illustrated as negative terms) were sorted according to near-normal rainfall (A, B, C, D, E and F) and rainfall deficit early in the season (G, H, I, J, K and L) and according to non-limiting (A, B, C, F, H and I) and sub-optimal (D, E, F, J, K and L) N rates for STICS (A, D, G and J), DNDC (B, E, H and K) and DayCent (C, F, I and L) predictions.

different agro-ecological zones in Saskatchewan, Canada, found that N rate had the most dominant effect on agronomic variables.

The residual error terms (Table 4(i)), which represented the variability not accounted for by the model predictions in the series of linear regressions, were less than 8.2% for plant N (according to the *F*-test) for all three models, whereas for shoot dry biomass, the residual error terms were 3.9% for STICS, 4.9% for DNDC, and 9.5% for DayCent. The residual error terms were small, a fact that indicates that the majority of the observed variability was explained by the model predictions in this study. By accounting for the other independent variables (Table 4(ii)), the decrease of the error was marginal, which means that the contribution of independent variables in the explanation of variability was negligible (less than 0.5% for STICS, less than 1.4% for DNDC and less than 2.3% for DayCent).

Regarding plant N, environmental factors did not seem to exhibit a significant effect, whereas a significant interaction was obtained between the model predictions and the N rate (Table 4).

Regarding biomass, the STICS model explained the majority of the variation, although there was still a significant interaction between prediction and rainfall. The DNDC model, associated with all environmental variables, explained the variability of the observed values, especially at 10% significance. DayCent itself and in interaction with N rate, explained the main observation variability.

4. Discussion

4.1. Experimental results

Previously, several groups of researchers carried out field studies on wheat in Eastern Canada. Tran and Tremblay (2000) showed that grain yield, grain protein concentration, and straw N content increased significantly with N application rates. Ziadi et al. (2008, 2010a,b) showed that N nutrition index and leaf N concentrations increased with increasing N rates. Cabas et al. (2010) estimated that climate variability had a major impact on average yield, especially from emergence to anthesis/soft dough, the growth stage that was the most sensitive to soil moisture stress. The present experimental results clearly showed the interaction of both early-season rainfall and N application rates with grain yield, grain protein concentration, plant N, and shoot biomass of spring wheat.

Rainfall deficit and excess during the first two months of the growing season seemed to have a greater effect than N application rates on spring wheat production. These results are in agreement with those of Gajri et al. (1993), Hussain and Al-Jaloud (1995), and Wang et al. (2010), who demonstrated that, under normal irrigation, grain yield in wheat increases with increasing N rates. Under soil moisture deficit, however, water stress reduces wheat yield more than N deficit does. Indeed, water shortage can drastically reduce photosynthesis through stomatal closure because of

Table 4

Significance levels (*10%, **5%, and ***2%) and residues of the linear regression models between plant N [biomass] observations and (i) model prediction (P_{model}) only, and (ii) model predictions, rainfall and N rate (fertilization).

	Plant N			Biomass		
	STICS	DNDC	DayCent	STICS	DNDC	DayCent
Intercept		**		*	*	*
P_{model}	***	***	***	***	***	***
Rainfall					*	*
Fertilization					*	
Rainfall \times Fertilization						
$P_{\text{model}} \times$ Fertilization	**	***	***		*	***
$P_{\text{model}} \times$ Rainfall	*	***	**	**	*	*
% of residues						
(i) P_{model} only	6.0	6.7	8.2	3.9	4.9	9.5
(ii) All	5.5	5.3	5.3	3.7	4.1	7.9

the effect on cell turgidity. Photosynthesis mechanisms shut down, leaves start to wilt, and growth slows to a halt when cell expansion is stopped.

When soil water content is in excess, huge reductions in emergence, growth, and yield of wheat are observed. Zheng et al. (2009) reported a significant decrease in photosynthetic rates 7–12 d after anthesis. Malik et al. (2002) demonstrated that even short periods (as little as 3 d) of waterlogged conditions had considerable effects on the growth of wheat plants: the seminal root system stopped growing, the number of tillers was lower, the final leaf lengths were shorter, and leaf N concentration decreased severely. Li et al. (2012) showed in wheat that waterlogging within two weeks immediately after anthesis caused higher yield losses (15–17%) compared with later waterlogging (7–8%). This finding explains the observed absence of an N rate response in the present study. Waterlogging depletes oxygen, leading to reduced root respiration and nutrient assimilation. Saturated soil conditions change the soil's redox potential, promoting N loss and the production of ions that are toxic under certain soil conditions. These factors combine to hamper plant growth and cause significant yield losses.

Tavakkoli and Oweis (2004), Kibe et al. (2006), and Karam et al. (2009) also reported that the response of yield to N supply is strongly influenced by environmental conditions, especially the quantity and timing of water available to the wheat canopy. Their findings are in agreement with the present study's observations that early-season water deficit and excess had a greater effect on grain yield, grain protein concentration, plant N, and biomass of spring wheat than late-season water availability did.

In the semi-arid Canadian Prairies, where rainfall deficit is chronic unlike in the Mixedwood Plains, spring wheat yield is mainly a function of available water, the timeliness of water availability, and to a lesser extent, available N (Campbell et al., 2005). Water use in the Prairies accounts for about 65% of the variability in wheat yield, and soil test N and fertilizer N account for about 13% each (Campbell et al., 1997, 2005).

4.2. Model predictions

Even though the models used in this study had different purposes—STICS was originally a soil–crop model, DNDC was developed to predict nitrous oxide emissions in agroecosystems, and DayCent was created to estimate changes in soil organic matter—the study originally hypothesized that they would be able to simulate biomass and N in plants with suitable RMSE and ARE values. The results (Table 3) clearly suggest that DNDC provided good biomass and plant N predictions for any N rate and early-season rainfall deficit conditions ($|\text{ARE}| < 8\%$), whereas STICS and DayCent were slightly less effective for predicting biomass under lower N rates, although those models performed better for N in plants ($|\text{ARE}| < 7\%$). However, a previous study reported

considerable variability in crop yield and grain protein in response to lower N rates in Canada (Walley et al., 2001). Under rainfall excess, DayCent and DNDC were less effective (ARE and $\text{RMSE} > 33\%$ for plant N), as those models do not currently have functions for water excess affecting production. Although some issues remained, the three models performed better for predicting biomass when early-season rainfall was near normal, even if the RMSE were quite large ($|\text{ARE}| < 10\%$, $\text{RMSE} < 25\%$ for STICS and DNDC, $\text{RMSE} < 37\%$ for DayCent).

During the past decade, DNDC was further developed to successfully simulate NO and N₂O emissions in forests ($\text{ARE} < 13\%$ obtained by Li et al., 2000; Stange et al., 2000). By comparing simulated and observed daily gross primary productivity fluxes for grassland, Kang et al. (2011) showed that DNDC did a good job of capturing the seasonal gross primary productivity variations ($\text{RMSE} = 1\%$, $\text{ARE} = 4\%$). Recently, Kröbel et al. (2011) adapted the model to spring wheat, introducing dynamic C/N ratios for the different plant organs, and showed that DNDC performed well for simulating spring wheat biomass ($\text{ARE} = 6\%$) in Canada. The results obtained in the present study are in agreement with the performance reported by those researchers. In the present study, DNDC showed a slight bias in simulating N in plants when early-season rainfall was in excess.

Other researchers found that DayCent predicted the biomass of fertilized humid grass with an ARE of -23% (Abdalla et al., 2010). However, the model performed poorly in the absence of N application, with a relative deviation of -57% from the measured data. A comparison between the simulated and measured data suggests that the DayCent model's response to N fertilizer needs to be improved. This need was confirmed by the present study, which showed that lower N application rates resulted in poorer statistics for biomass and plant N. While DayCent's crop parameterization does allow for the C:N boundaries to be set for each of the biomass fractions, there is a need to balance these requirements with soil N in the simulated profile. At the three investigated locations, results indicated that DayCent had difficulties in simulating adequate amounts of soil N to allow for the parameterization of a narrower upper limit on plant C:N which in turn would have improved the model's plant N response to fertilizer. This study suggests that further validation of the simulated N budget in low N systems is required for DayCent in order to quantify any missing N inputs. For bioenergy crops, Adler et al. (2007) and Sendich et al. (2008) concluded that DayCent was able to accurately simulate biomass, yield, and N uptake in various pedoclimatic situations for corn, soybean, alfalfa, hybrid poplar, reed canary grass, and switch grass. DayCent was parameterized and calibrated by Stehfest et al. (2007) to simulate global yield levels for wheat. Simulation results show that the DayCent model was able to reproduce the major effects of climate, soil, and management on crop production. Nevertheless, the average simulated crop yields by country agree moderately

well with agricultural statistics (efficiency of about 0.66, ARE not shown). Recently, Grant et al. (2013) evaluated the DayCent model for its ability to capture the inter-annual variation in spring wheat yields due to climate at three long-term experimental sites on the Canadian prairies. The model predicted yields well for continuous wheat rotation fertilized with N and P ($|ARE| \leq 10\%$) but had greater difficulty in estimating yields for the unfertilized N continuous wheat rotation ($|ARE| \leq 22\%$). Those researchers concluded that the underestimation of spring soil $\text{NO}_3\text{-N}$ contributed to the poor performance of the model under the unfertilized N rotation and that the individual components of the mass balance of N need further validation. So far, no experimental verification has been published to evaluate the performance of DayCent for predicting spring wheat biomass and plant N.

Guillaume et al. (2012) conducted an agronomic analysis to evaluate the capacity of the STICS soil–crop model to respond to varying fertilization strategies. The capacity of STICS to predict grain yield (RMSE = 19%) and grain N concentration (RMSE = 15%) over a large range of growing conditions was satisfactory for each tested strategy. Their RMSE values for grain yield are comparable to the RMSE of 23% obtained by Meinke et al. (1998) and the RMSE values reported by Brisson et al. (2002) for wheat and maize crops (15–20%). Jégo et al. (2010) evaluated whether a new regionally adapted spring wheat cultivar in the Mixedwood Plains could be used to predict biomass and yield for recommended N rates using STICS. The adapted cultivar provided good estimates of biomass and yield (RMSE \approx 10–20%). In their study, the critical N dilution curve implemented in the model was for winter wheat (Justes et al., 1994) rather than for spring wheat (Ziadi et al., 2010a). The statistics (ARE and RMSE) for biomass and plant N in the present study were similar to those already published. They were the lowest for plant N in comparison with the other two models: it seems that the concept of critical and maximum dilution curves implemented in STICS for spring wheat was more adapted to simulating N in plants, especially when water was in excess. This concept was also successfully applied in other well-known crop models (CERES, DAISY, and CROPSYST) (Jeuffroy et al., 2002). Moreover, STICS takes into account the influence of water excess on crop growth, whereas DayCent and DNDC do not currently have a mechanism to characterize this effect. The addition of this mechanism should be considered for both of these models.

5. Conclusion

Under rainfall deficit or excess, between emergence and maximum leaf growth (May and June), it was found that biomass, protein content, yield, and N in plants did not respond to N fertilization. Under near-normal climatic conditions, predicted biomass, yield, protein content, and N in plants varied according to the N rate applied in the field. These results support the present study's hypothesis that variations in early-season rainfall have a greater influence on potential biomass and N in plants than N application rates do. The results clearly suggest that STICS and DNDC provided good biomass and plant N predictions for all sites, whereas the results with DayCent were not as good, even if they were satisfactory. Shoot biomass predictions were fair for STICS and DNDC and weaker for DayCent, with the exception of the 0 and 30 kg N ha⁻¹ rates, under which both STICS and DayCent had poor predictions. The dynamic C/N ratios for the different plant organs implemented in DNDC performed well for the entire range of N application rates. The STICS model performed better for predicting N in plants when early-season rainfall was in excess, whereas the DNDC model performed better when there was a shortage of rainfall. All three models provided good predictions for average plant N when rainfall was near normal, but the DayCent model had more scattered

results. The concept of critical and maximum dilution curves implemented in STICS along with the new dynamic plant fractioning and C/N ratios employed in DNDC produced reasonably accurate results for simulating N in plants. The STICS model estimates of evapotranspiration were closest to the eddy flux measurements. The water budget showed that STICS predicted a lower proportion of transpiration than the other two models did. The N budget indicated that the STICS-simulated response of production to N supply is influenced by environmental conditions, especially the quantity and timing of water available to the crop, whereas that was clearly not the case for DayCent and DNDC.

This study could be extended to help quantify the uncertainties associated with crop modelling, as a contribution to the international Agricultural Model Intercomparison and Improvement Project (AgMIP <http://www.agmip.org/>; Rosenzweig et al., 2013). An inter-model comparison of this type would be advantageous for confirming the effect of early-season rainfall on spring wheat growth and production (yield and grain quality) in various agricultural regions, as Asseng et al. (2013) showed in a wheat model comparison study. Finally, the present study demonstrated that the boundary between crop-oriented models (such as STICS) and environmental models (such as DNDC and DAYCENT) was not so tight.

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