



# Simulating alfalfa regrowth and biomass in eastern Canada using the CSM-CROPGRO-perennial forage model

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## ABSTRACT

Alfalfa (*Medicago sativa* L.) is the predominant forage legume species in Canada and is considered a prioritized option for sustainable cropping under climate change. Crop growth models provide an opportunity to explore the potential impacts of climate change on alfalfa and for evaluating potential adaptation options. For this study, six experimental datasets in eastern Canada were used to parameterize the newly adapted CSM-CROPGRO-Perennial Forage Model (CSM-CROPGRO-PFM) in simulating alfalfa regrowth and to identify areas for further model improvement needed for climate change assessments in the northern agricultural regions of North America. Estimated air temperatures under snow cover were used successfully to drive the CSM-CROPGRO-PFM model for simulating alfalfa regrowth in eastern Canada. The simulated values of aboveground biomass across all sites and years were acceptable with a root mean square error (RMSE) of 936 kg dry matter (DM) ha<sup>-1</sup> and a normalized RMSE of 24%. A sensitivity analysis of the model revealed that with no change in the number of harvests per year, the simulated annual herbage yield (harvestable biomass) declined with increasing temperature, increased with elevated atmospheric CO<sub>2</sub> concentration, and changed little with increased precipitation. However, the increase in the number of harvests made possible by warmer temperatures may increase the simulated annual herbage yield. Although most alfalfa physiological processes were successfully simulated, some additional model functions may be required to further improve the simulation of alfalfa regrowth for climate change studies conducted in Canada. These functions include quantifying plant density decline and its relationship with biomass in post-seeding years, estimating temperatures surrounding alfalfa crowns during the overwintering period, and simulating herbage nutritive attributes.

## 1. Introduction

Alfalfa is widely grown in temperate regions where temperature is one of the major factors regulating crop growth. It is the predominant perennial legume species for forage production in Canada because of its high yield and nutritive value. There are about 4 million ha of alfalfa and alfalfa-based mixtures grown across Canada (Statistics Canada, 2018). Alfalfa is considered a sustainable crop because of its ability for biological fixation of atmospheric N<sub>2</sub>, which minimizes the need for industrial N fertilizers (Crews and Peoples, 2004). In addition, the high fraction of belowground biomass helps to sequester substantial soil organic carbon (SOC), highlighting alfalfa's potential towards mitigating global warming (Robertson et al., 2000). Both cultivars and harvest management significantly affect the yield, nutritive value, and

persistence of alfalfa under the current climatic conditions in eastern Canada. Climate change is expected to impact the management of alfalfa and affect its yield potential (Bélanger et al., 2002; Thivierge et al., 2016), but few tools exist to explore the potential impact of climate change on alfalfa by taking into account both the growing season and the overwintering conditions.

Crop growth models, including cultivar and environmental interactions in association with crop management, provide unique opportunities to systematically analyze the response of perennial alfalfa under climate change and are useful to explore adaptation options. They have been successfully used to explore annual crop growth performance through ensemble modelling approaches (Asseng et al., 2013; Bassu et al., 2014; Li et al., 2015). However, only a few of these crop models have been developed or adapted for modelling alfalfa since

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1975, as reviewed by Malik et al. (2018), and most of those models have, more or less, deficiencies in simulating specific characteristics of alfalfa. The process-based crop model CSM-CROPGRO has been modified to simulate perennial forage grasses (Rymph, 2004) by adding perennating storage organs and establishing a set of rules for storing C and N reserves in those organs and their use to drive regrowth despite a leaf area index (LAI) of zero. Recently, the CSM-CROPGRO model for perennial forage (PFM) was adapted to simulate alfalfa in Spain (Malik et al., 2018). The CSM-CROPGRO model was originally developed for soybean and accounted for cultivar interactions with environment and management, and simulated the characteristics of legumes such as symbiotic  $N_2$  fixation (Hoogenboom et al., 1992; Boote et al., 1998). However, the CSM-CROPGRO-PFM model for alfalfa has not yet been tested in northern latitudes where significant sub-freezing temperatures and snow cover occur during the winter.

The objectives of this study were 1) to parameterize the CSM-CROPGRO-PFM model for simulating alfalfa regrowth using experimental data in eastern Canada, 2) to analyze the model's sensitivity to changes in environmental conditions, and 3) to identify areas for further model improvement in simulating alfalfa with CSM-CROPGRO-PFM to facilitate its use for climate change studies in the northern agricultural regions of North America.

## 2. Materials and methods

### 2.1. Field experimental data

Crop measurements from field experiments conducted with alfalfa at six sites across eastern Canada were used to parameterize the CSM-CROPGRO-PFM model. These sites are spatially distributed across the region by a distance of 400 km from the South to the North and 1000 km from the East to the West (Fig. 1), and include various types of soils and climate conditions (Table 1). Across all sites, the number of days with minimum temperatures below  $-20^\circ\text{C}$  range from 10 to 69, and snow typically remains on the ground for at least three months (Table 1). The northernmost site (Normandin) has the least frost-free days (78 days) and the lowest cumulative growing degree days (GDD;  $1387^\circ\text{C-d}$  with a base temperature of  $5^\circ\text{C}$ ).

Alfalfa was seeded at the recommended rate of  $12\text{ kg ha}^{-1}$  at Truro

and Nappan in Nova Scotia in the spring of 1992, and at Fredericton in New Brunswick in the spring of 1994 in a study on alfalfa harvest management. The plot size varied with sites and ranged from  $7$  to  $9\text{ m}^2$  with four replications of the experimental treatments at each site. The cultivars Apica and Oneida VR were used and they are rated as having very good and good winter hardiness, respectively (Bélanger et al., 1999). No nitrogen fertilizer was applied over the duration of the experiment. Alfalfa was harvested once in the seeding year and twice in the subsequent years with intervals of around  $450^\circ\text{C-d}$  (calculated with a base temperature of  $5^\circ\text{C}$ ) between 1 May and the first harvest and  $500^\circ\text{C-d}$  between the first and second harvests. These harvest intervals improved the yield and nutritive values of herbage and allowed alfalfa to restore sufficient reserves for regrowth in the next spring (Bélanger et al., 1992). The experiment was terminated at Nappan after the second post-seeding year due to a plant density of less than  $30\text{ plants m}^{-2}$ . The weather data were collected near the experimental sites within a distance of two kilometers. Details of the experimental design and crop management can be found in Bélanger et al. (1999).

At Normandin, the alfalfa cultivar Apica was seeded along with 26 other cultivars in the spring of 1994 and 1995. The two seeding years are referred to as 1994–1996 and 1995–1997 (Table 1). The seeding rate was  $15\text{ kg ha}^{-1}$  with a plot size of  $9\text{ m}^2$  and a row spacing of  $15\text{ cm}$ . The experiment was designed as a randomized complete block with three replications. Nitrogen fertilizer was applied at  $40\text{ kg N ha}^{-1}$  at seeding, and  $15\text{ kg N ha}^{-1}$  in the spring of the first post-seeding year. Alfalfa was harvested twice in the post-seeding years when it reached the early flowering stage of development. The weather data were recorded near the experimental site. Additional descriptions of crop management and measurement methods are given in Tremblay et al. (2000).

The alfalfa cultivar Apica was seeded along with other cultivars on a loam soil at Lévis in Quebec in the spring of 2008. Nitrogen fertilizer was applied at  $20\text{ kg N ha}^{-1}$  at seeding and no N fertilizer was applied in the subsequent growing periods. The seeding rate was  $12\text{ kg ha}^{-1}$  and the plot size was  $9\text{ m}^2$ . The experiment was designed as a randomized complete block with four replications. Alfalfa was harvested once in the seeding year, three times in the subsequent two post-seeding years, and once in the fourth year. In post-seeding years, the first and second harvests were taken at the early flowering stage of development while

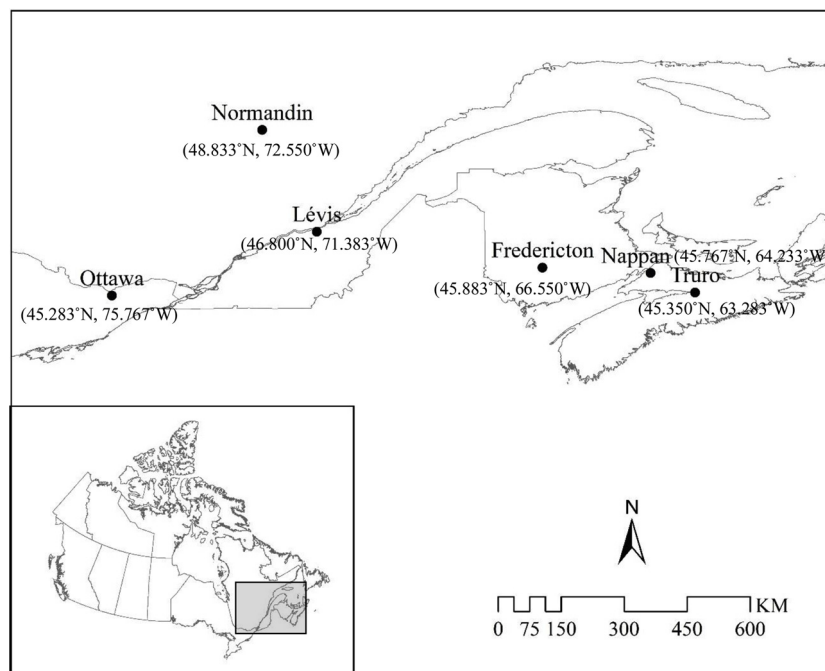


Fig. 1. Locations of the experimental sites in eastern Canada.

**Table 1**  
Summary information for alfalfa field experiments conducted at six sites in eastern Canada.

Site	Years	Cultivar	Soil property <sup>1</sup>			Climate Normals (1981–2010) <sup>3</sup>						No. of measurements		
			FC (m <sup>3</sup> m <sup>-3</sup> )	WP (m <sup>3</sup> m <sup>-3</sup> )	BD (Mg m <sup>-3</sup> )	SOC (g kg <sup>-1</sup> )	Prec. (mm) <sup>2</sup>	GDD (°C-d) <sup>2</sup>	Frost free days	Days with snow ≥ 1 cm	Days with T <sub>min</sub> ≤ -20 °C	AGB <sup>2</sup> at harvests <sup>4</sup>	AGB between harvests <sup>5</sup>	N at harvests <sup>4</sup>
Truro	1992–1995	Apica Oneida VR	0.210	0.105	1.5	21.6	1183	1725	125	89 <sup>3</sup>	10	12	n/a	n/a
Nappan	1992–1994	Apica Oneida VR	0.210	0.105	1.5	21.6	1155	1762	120	99 <sup>3</sup>	12	8	n/a	n/a
Fredericton	1994–1996	Apica Oneida VR	0.284	0.108	1.4	26.4	1095	1804	140	110	20	8	n/a	n/a
Normandin	1994–1996	Apica	0.375	0.166	1.3	46.0	989	1387	78	161	69	4	n/a	n/a
	1995–1997	Apica	0.375	0.166	1.3	46.0						4	n/a	n/a
Lévis	2008–2011	Apica	0.409	0.264	1.3	18.0	1190	1733	145	141	31	8	n/a	8
Ottawa	2014–2016	n/a	0.290	0.130	1.4	31.0	920	2182	158	115	17	7	44	n/a

<sup>1</sup> Soil property refers to top soil layer (0–30 cm). FC – Field capacity, WP – Wilting point, BD – Bulk density, SOC – Soil organic carbon.  
<sup>2</sup> Prec. – precipitation, GDD – growing degree days based on base temperature of 5 °C. AGB – aboveground biomass.  
<sup>3</sup> Climate Normals (1981–2010) are from Environment and Climate Change Canada (<http://climate.weather.gc.ca>). Days with snow on the ground at Truro and Nappan were not available in 1981–2010 Climate Normals; data from the 1971–2000 Climate Normals are presented.  
<sup>4</sup> Measurements of aboveground biomass and N concentration at recommended harvest times.  
<sup>5</sup> Measurements of aboveground biomass with sequential sampling between recommended harvest times.

the third harvest was taken approximately 500 °C-d after the second harvest. The N concentration of the harvestable herbage was measured using an automated continuous flow injection analyzer. The details of crop management and measurements are described in Bélanger et al. (2014).

At the Ottawa site, alfalfa was seeded on a sandy loam soil in Field 13 of the Canadian Food Inspection Agency (CFIA) farm in the spring of 2014. The previous crop was spring wheat. The cultivar was unidentified and no N fertilizer was applied. Alfalfa was harvested twice in the seeding year (16 July and 1 September) and thrice in the following two post-seeding years (21 June, 27 July, and 30 August in 2015; 17 June, 21 July, and 29 August in 2016). The experiment was terminated in 2016. During alfalfa primary growth and regrowth, sequential short-term measurements of harvested herbage mass were conducted 3 to 7 times between harvests. The weather data were recorded on site and obtained from a weather station within a distance of 10 km when onsite data were missing. At this site, snow depth and soil temperature at a soil depth of 5 cm were recorded.

To measure herbage mass, alfalfa plants were mechanically harvested at the soil surface at the Ottawa site and at a 5-cm height at the other sites, as described by Bélanger et al. (2014). The stubble mass after each harvest was used in the model as input data; however stubble dry weights were not measured in these experiments. According to the reported data on stubble height versus herbage yield of alfalfa (Yolcu et al., 2006; Shen et al., 2013; Meyer and Norby, 2018), the residual stubble mass after each harvest with a stubble height at 5 cm was estimated to be 350 kg DM ha<sup>-1</sup>. Therefore, aboveground biomass (here after referred as biomass) was calculated by summing harvestable herbage mass (here after referred as herbage) and residual stubble mass. For consistency in simulations, a stubble height of 5 cm and a stubble biomass of 350 kg DM ha<sup>-1</sup> with 20% leaves were used for all sites in model input files and herbage and biomass after each harvest were calculated accordingly.

## 2.2. Crop model

The CSM-CROPGRO model and its adaptation CSM-CROPGRO-PFM were developed as a generic approach for modelling crops with one set of common source codes to predict the growth of a number of different crops (Boote et al., 1998; Jones et al., 2003). The model template provides for species, ecotype, and cultivar traits to be defined in the external data files for simulations of specific crops. The CSM-CROPGRO model has a daily time step for biomass gain, but it computes canopy photosynthesis at an hourly time step using leaf-level photosynthesis parameters and hedge-row light interception calculations. In the CSM-CROPGRO model, the growth rate is regulated mainly by temperature, solar radiation, and photoperiod, and includes constraints of water and N stresses. The temperature growth factors use an average daily value that is computed using hourly temperatures. Hourly temperatures are calculated using a sine curve for temperatures during daylight hours and an exponential decay curve for decreasing temperatures from sunset to the minimum temperature. Water stress is calculated with potential and actual evapotranspiration with the latter potentially limited by soil water uptake. The potential evapotranspiration is calculated with the Priestley-Taylor equation (Priestley and Taylor, 1972). The actual evapotranspiration is calculated using the LAI, a model-computed energy extinction coefficient, and root water uptake as a function of root length density and soil water content in respective soil layers (Boote et al., 2008). Nitrogen supplies may come from soil N, N mobilized from plant tissues, and N assimilated through symbiotic N<sub>2</sub> fixation. Under N deficiency, assimilates are directed to nodule growth and N<sub>2</sub> fixation (see discussion on modifying temperature sensitivities and nodule death rate for Canadian data and Fig. 5 in Malik et al., 2018). Photosynthesis of sunlit and shaded leaves is computed hourly using the asymptotic exponential response equation, where quantum efficiency and light saturated photosynthesis rate vary depending on

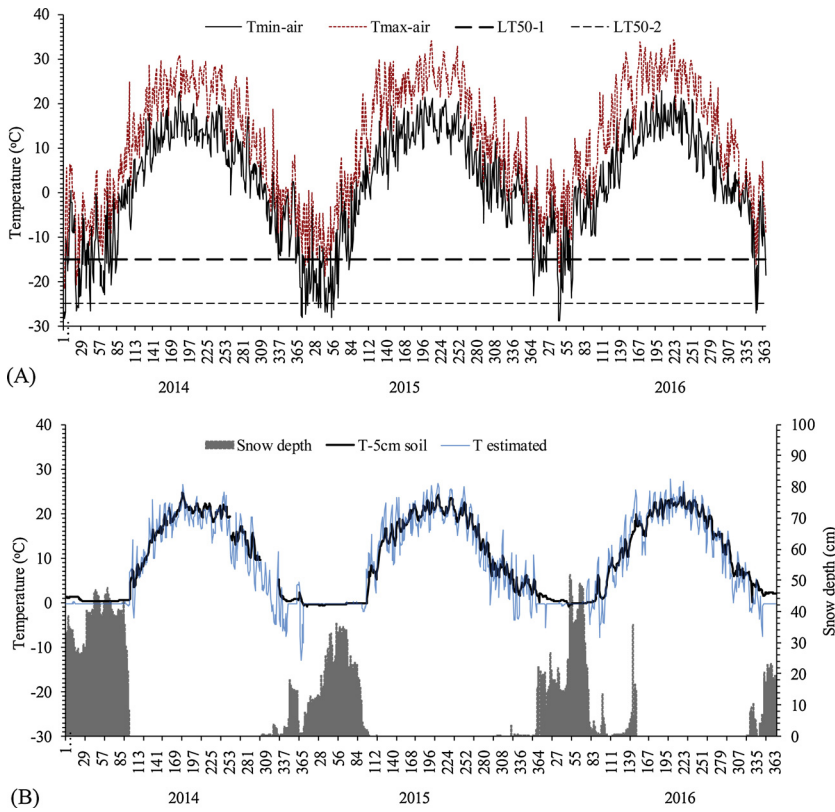
CO<sub>2</sub> concentration and temperature (Boote and Pickering, 1994). Thus, CO<sub>2</sub> concentration can affect both photosynthesis and evapotranspiration (Pickering et al., 1995). Doubling of ambient CO<sub>2</sub> concentration may increase the photosynthetic rate by about 30% and reduce the potential evapotranspiration rate by about 5%. New codes and functions were added to adapt the CSM-CROPGRO model to simulate the perennial grass species bahiagrass (*Paspalum notatum* Flüggé) for the regrowth in consecutive growing seasons. A storage organ and rules for the storing and use of reserves for regrowth were added along with overwintering features like dormancy (Rymph, 2004). The original perennial forage model CSM-CROPGRO-PFM has been adapted to simulate Marandu palisade grass (*Brachiaria brizantha*) (Pedreira et al., 2011; Pequeno et al., 2014), bermudagrass (*Cynodon* spp.) (Pequeno et al., 2018) and, recently, to simulate alfalfa (Malik et al., 2018). The model is generic in the sense that there is one set of FORTRAN code for all these perennial forage species, but the parameterization of the different species is specified in an extensive species genetic parameter file.

In simulating alfalfa, the dormancy and enhanced allocation to stored reserves are triggered by a short photoperiod. With a shortening of the day length in the fall, the partitioning of assimilates to storage organs, such as the taproots in alfalfa, increases while the partitioning to shoots decreases. For alfalfa, the taproot represents the vegetative storage organ in the model structure, although for other forages, the storage organ could be rhizomes or stem bases. The vegetative storage organ acts as a sink in the fall and a source of N and carbohydrate for regrowth in the spring. Freezing is controlled by two temperatures: one for leaves at a temperature of -2 °C below which all leaf tissues drop off and one for the whole plant at a temperature of -25 °C below which the plant including storage organ completely stop growth and start to die, and the simulation is terminated. In the northern regions, winter air temperatures below -25 °C may occur often, which would stop model simulation of alfalfa (Fig. 2A). The snow cover in winter can provide a relatively mild environment near the soil surface, and the plants are thus often protected from freezing damage in Canada (Bélanger et al., 2002).

The CSM model simulates snow accumulation and melting. Snow is accumulated and water available for infiltration is reduced to zero if the daily maximum temperature is below 1 °C, otherwise snowmelt occurs and the water available for infiltration is increased (Porter et al., 2010). Soil temperature is computed from air temperature, solar radiation and a deep soil temperature boundary condition. The deep soil temperature boundary condition is calculated by a function that uses day of year, and the average long-term annual air temperature and the range of monthly mean temperatures from the coldest to the warmest months. A simple approach is also included to calculate the impact of solar radiation and albedo on the soil surface temperature. Soil temperature is used to modify plant processes (emergence) and soil organic matter decomposition. However, the mild environment under snow cover is not considered and the aboveground plant and the storage organ are exposed to air temperature in the model. In reality, model code improvements are needed to properly simulate storage organ survival as a function of soil temperature, not just air temperature, for which the thermal insulating effects of snow and residue cover should be considered. To allow the CSM-CROPGRO-PFM model to simulate perennial alfalfa at our experimental sites, where minimum air temperature below -25 °C often occur, we replaced air temperatures with estimated temperatures surrounding the crown zone under the snow layer for periods with a snowpack. The temperatures estimated under snow were calculated using the methodology evaluated by Jégo et al. (2014) for Canadian conditions.

## 2.3. Model parameterization

In the CSM-CROPGRO-PFM model in DSSAT, species file parameters apply to all cultivars of a given crop. Since DSSAT v4.7 was released, species parameters of the CSM-CROPGRO-PFM model for alfalfa have



**Fig. 2.** (A) Measured daily maximum air temperature (Tmax-air), minimum air temperature (Tmin-air), and two levels of cold tolerance [LT50-1, lethal freezing temperature at which 50% of the plants are killed (Bélanger et al., 2002); LT50-2, lethal freezing temperature used in the CSM-CROPGRO-PFM model]. (B) Measured daily mean temperatures at a 5-cm soil depth (T-5 cm soil) and estimated daily mean temperatures at the soil surface (T estimated) considering snow insulation along with snow depth at the experimental field at Ottawa.

been modified based on unpublished data on fall dormancy types, biomass partitioning and leaf expansion at locations in Arizona and Montana. These modified species parameters were used to determine if the additional parameterization was appropriate for the Canadian sites and they continued to work well for all sites. The modified species parameters from DSSAT v4.7 were applied and illustrated in this study. The parameters in cultivar and ecotype files of the model were calibrated for the two cultivars Apica and Oneida VR used in our field experiments.

The cultivars Apica and Oneida VR were parameterized by comparing simulated crop attributes to the measured values across five sites except for Ottawa. Because the cultivar at the Ottawa site was unidentified, we used the cultivar Apica to simulate alfalfa growth and then compared the simulated with the measured biomass. As alfalfa plants were harvested before or at flowering, parameters related to the reproductive phase were not considered, thus the calibration mainly focused on parameters of photosynthesis and regrowth processes. The calibrations were manually conducted by tuning the parameters to minimize the difference between simulated and measured biomass values. Parameters for the cultivars Apica and Oneida VR were modified slightly from the default values in the CSM-CROPGRO-PFM model for alfalfa (Hoogenboom et al., 2017; Malik et al., 2018).

The simulated (Y) and measured (X) biomass were graphically compared. A paired *t*-test [ $P(t)$ ] was applied to the simulated and measured values. The root mean square error (RMSE) and the normalized RMSE (nRMSE) were calculated using Eqs. 1 and 2, where *n* is the number of observations:

$$RMSE = \left( \frac{\sum (Y_i - X_i)^2}{n} \right)^{0.5} \quad (1)$$

$$nRMSE = \frac{RMSE}{\bar{X}} \times 100 \quad (2)$$

Model simulation efficiency (EF), Mean Error (ME), the relative Mean Error (rME), and index of agreement (*d*) between the simulated

and measured values were calculated using Eqs. 3–6 as in Beaudoin et al. (2008) and Yang et al. (2014).

$$EF = 1 - \frac{\sum (Y_i - X_i)^2}{\sum (X_i - \bar{X})^2} \quad (3)$$

$$d = 1 - \frac{\sum (Y_i - X_i)^2}{\sum (|Y_i - \bar{X}| + |X_i - \bar{Y}|)^2} \quad (4)$$

$$ME = \frac{1}{n} \sum_{i=1}^n (Y_i - X_i) \quad (5)$$

$$rME = \frac{ME}{\bar{X}} \times 100 \quad (6)$$

An optimal model is assumed to reproduce experimental data with *P* (*t*) greater than 0.05, EF and *d* close to 1.0, and RMSE and ME close to 0.

To illustrate and test the regrowth mechanisms of the model, we also graphed the simulated temporal variations of biomass, taproot biomass, and non-structural carbohydrate concentration in the taproot along with the rate of non-structural carbohydrate moving to the storage organ (influx) and mobilizing from the storage organ (outflux).

#### 2.4. Sensitivity analysis

Ten scenarios were employed to analyze the sensitivity of the model to changes in the environmental conditions related to climate change at four sites: Ottawa, Lévis, Fredericton, and Normandin (Table 2). The baseline weather data (1981–2010), including daily temperature, precipitation, and solar radiation, were obtained from the climate data archive of Environment and Climate Change Canada (<http://climate.weather.gc.ca>). Missing solar radiation data were estimated from daily temperatures and precipitation using the modified method of De Jong and Stewart (De Jong and Stewart, 1993; Qian et al., 2019). The calibrated model with the cultivar Apica was driven by weather data under each scenario. The scenarios were established by changing each individual environmental factor from the baseline weather data (Table 2).



**Table 2**

Scenarios for model sensitivity analysis of alfalfa herbage production using weather data from 1981 to 2010 at four sites in eastern Canada.

Scenario	Factors	Abbreviation	Average number of harvests per year			
			Ottawa	Fredericton	Normandin	Lévis
1	Baseline, [CO <sub>2</sub> ] = 380 ppm	B	3.7	2.2	1.2	2.0
2	B + 1 °C	T1	4.1	2.6	1.7	2.3
3	B + 2 °C	T2	4.3	3.0	2.0	2.9
4	B + 10% precipitation	P10	3.7	2.2	1.2	2.0
5	B + 20% precipitation	P20	3.7	2.2	1.2	2.0
6	B + 70 ppm of [CO <sub>2</sub> ]	C70	3.7	2.2	1.2	2.0
7	B + 140 ppm of [CO <sub>2</sub> ]	C140	3.7	2.2	1.2	2.0
8	B + 2 °C + 70 ppm of [CO <sub>2</sub> ]	T2C70	4.3	3.0	2.0	2.9
9	B + 2 °C + 140 ppm of [CO <sub>2</sub> ]	T2C140	4.3	3.0	2.0	2.9
10	B + 2 °C, no additional harvest <sup>1</sup>	T2Bh	3.7	2.2	1.2	2.0

<sup>1</sup> The number of harvests was the same as that in the baseline although with an increased temperature of 2 °C.

This sensitivity analysis only illustrates how the outputs of the model respond to the changes to the inputs of the model. We selected factors related to future climate changes but the changes do not represent the future climate conditions. The changed environmental factors include increasing temperature by 1 and 2 °C, precipitation by 10 and 20%, and CO<sub>2</sub> concentration by 70 and 140 ppm from 380 ppm. These values are based on the environmental changes from the 1950s to the 2000s, during which the atmospheric CO<sub>2</sub> concentration increased by about 70 ppm, temperature increased by about 1–2 °C, and precipitation increased by about 10–20% across Canada (Environment and Climate Change Canada, 2019a, 2019b). The weather data in each scenario were used to estimate snow depth and the temperature under snow using the method proposed by Jégo et al. (2014). The harvest dates were determined by GDD, i.e. 450 °C-d ( $T_b = 5$  °C) for the first harvest and an interval of 520 °C-d for the following harvests with at least 500 °C-d left for reserve accumulation after the last harvest based on field experimental observations (Bootsma and Suzuki, 1985; Bélanger et al., 1999). To test for a warmer environment while keeping the number of harvests compared to the baseline, the number of harvests in the baseline were applied in the scenario B + 2 °C with no additional harvest (Table 2). Alfalfa was planted in the spring and the crop was terminated in the fifth year. Each year was set as seeding year to include all possible 5-year cycles during 1981–2010. No fertilizer N was applied and the soil from each of the experimental sites were used for these simulations. The response of biomass to plant density was analyzed by setting the plant density at 150, 200, 300, and 400 plants m<sup>-2</sup> at seeding under the baseline conditions. Herbage mass were harvested at a 5-cm stubble height assuming 350 kg DM ha<sup>-1</sup> of residual stubble mass after each harvest. Changes of annual herbage DM yield in post-seeding years were compared among the different scenarios.

### 3. Results and discussion

#### 3.1. Subfreezing temperatures during winter

Subfreezing temperatures are the most significant risk factor for alfalfa winter survival in Canada (Bélanger et al., 2006). The CSM-CROPGRO-PFM model for alfalfa takes into account that risk factor by simulating winterkill when the minimum air temperature drops below -25 °C (Hoogenboom et al., 2017; Malik et al., 2018). Research conducted in Canada, however, has shown that the maximum cold tolerance of alfalfa, expressed by LT<sub>50</sub> or the air temperature at which 50% of the plants are killed, is -15 °C when crowns were exposed (Bélanger et al., 2002). Daily minimum air temperatures below -15 °C often occur during winters in Canada (e.g. 30 days per year at Ottawa and 50 days per year at Lévis for the 1981–2010 period). Daily minimum air temperatures below -25 °C also occur (e.g. 2 days per year at Ottawa and 10 days per year at Lévis). Examples are shown for Ottawa with daily maximum and minimum air temperatures observed in three

experimental years from 2014 to 2016 (Fig. 2A). The daily minimum air temperatures during the winter can be even lower at Lévis and Normandin, two sites that are located north of Ottawa. Because the air temperature often drops below -15 °C in Canada, and temperature in the top layer (2.5–5 cm in depth) of exposed soil is close to air temperature (Campbell et al., 1981; Dwyer et al., 1990), the winter survival of alfalfa is highly dependent on the insulating effects provided by snow cover. Considering the importance of this mechanism, the temperature under snow cover was estimated in an effort to appropriately simulate overwintering conditions for alfalfa as experienced in the field experiments. The estimated soil surface temperature, often under snow cover, was compared with measured soil temperature at a 5-cm depth (Fig. 2B) as there was no temperature measurement at the soil surface. It is expected that the soil surface temperature changes day by day with higher amplitudes than the soil temperature when there is no snow cover. While under snow cover, a good agreement can be seen between the estimated temperature at the soil surface and the measured soil temperature at a depth of 5 cm. No measured and estimated temperatures dropped below -15 °C during the three years of the experiment. If air temperatures were input to drive the model, the simulation usually terminated in a winter before the input ending date. Alternately, the simulation succeeded when the estimated temperatures under snow cover were used. Therefore, appropriate algorithms for estimating the soil-crown temperature under snow cover need to be integrated in the crop models for simulating perennial and other overwintering crops in northern regions with subfreezing temperatures during winter.

#### 3.2. Model parameterization

Since the release of the alfalfa model (Malik et al., 2018) in DSSAT V4.7, additional modifications of the species parameters of the model (Table 3) were made by K. J. Boote based on unpublished data on fall dormancy types 3, 6, and 10 at locations in Arizona and Montana. Therefore, it was decided to accept the model parameterizations resulting from those sites and sites in Spain, and to determine whether additional parameterization was appropriate for the Canadian sites that continued to work well for all sites. Based on the data, minor changes had been made in the temperature parameterization of C<sub>3</sub> photosynthesis. The base temperature for instantaneous leaf rate (XLMAXT) was increased from 0.2 to 1.5 °C but  $T_{opt}$  was unchanged at 33.0 °C. The minimum night temperature effect on next day's photosynthesis (FNPGL) was increased slightly from -5.1 and 8.2 °C (prior) to -4.0 and 9.0 °C (this is an asymptotic function with zero rate at the lowest value and no effect at the highest value). These changes also worked well for Canadian data. The specific leaf area (SLA) function for newly formed leaves was modified slightly to reduce the SLAMIN value from 250 to 240 cm<sup>2</sup> g<sup>-1</sup> DM, along with the SLAVAR of 240 cm<sup>2</sup> g<sup>-1</sup> DM. The SLA of new leaf expansion response to temperature (SLATM) was made more sensitive to cool temperature; the old function of 0.50 at 7 °C

**Table 3**

Species parameter names, definitions, initial values and modified values for partitioning during perennating phase, temperature effects on specific leaf area, height, photosynthesis, nodule growth rate, and N-fixation, and photoperiod effects on partitioning to taproot.

Name	Definition	V4.7 values	Modified values
XLFEET	Leaf number or vegetative stage at which the partitioning is defined	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0
YSTEET	Dry matter partitioning to stem among all tissues as a function of vegetative stage (fraction)	0.17, 0.17, 0.17, 0.21, 0.25, 0.32, 0.37, 0.37	0.19, 0.19, 0.20, 0.24, 0.30, 0.36, 0.41, 0.41
SLAMIN	SLAMIN is the (thickest) leaves under high light ( $\text{cm}^2 \text{g}^{-1} \text{DM}$ )	250	240
FNPGL (1-2)	Relative effect of minimum night temperature on next day's leaf light-saturated photosynthesis rate. Quadratic shape, first value defines base (0.0) and second defines maximum (1.0) ( $^{\circ}\text{C}$ )	-5.1, 8.2	-4.0, 9.0
XLMAXT(2-3)	Relative rate of photosynthetic electron-transport in response to temperature, linear from base (0.0) to maximum (1.0) ( $^{\circ}\text{C}$ )	0.2, 33.0	1.5, 33.0
SLATM(2-4)	Relative temperature effect on specific leaf area of newly formed leaves, $^{\circ}\text{C}$ vs. fraction reduction (x, y pair)	0.0, 0.35	0.0, 0.20
HWTEM(2-5)	Relative temperature effect on internode elongation (height), $^{\circ}\text{C}$ vs. fraction reduction (x, y pair)	7.0, 0.50	7.0, 0.30
		22.5, 1.00	22.5, 1.00
		0.0, 0.45	0.0, 0.35
		0.0, 0.45	0.0, 0.35
		18.0, 1.00	18.0, 1.00
FNNGT(4)	Relative temperature effect on nodule growth rate, $^{\circ}\text{C}$ vs. fraction (x, y pair)	60.0, 1.00	60.0, 1.00
		-1, 0.0	-3, 0.0
		19, 1.0	17, 1.0
		30, 1.0	30, 1.0
		44, 0.0	44, 0.0
FNEXT(4)	Relative temperature effect on specific nitrogenase activity, $^{\circ}\text{C}$ vs. fraction (x, y pair)	-1, 0.0	-3, 0.0
		15, 1.0	14, 1.0
		30, 1.0	30, 1.0
		44, 0.0	44, 0.0
		0.02	0.011
NDTHMX	Relative rate of nodule death	11.1, 12.2	9.8, 14.2
FNPTD (2-3)	Daylength effect on partitioning to storage-taproot (h)	8.5, 12.5, 0.63	9.9, 13.9, 0.43
FNPMD(1-3)	Daylength effect on mobilization from taproot to regrowth (h)		

**Table 4**

Cultivar and ecotype parameters and their definitions for alfalfa along with their calibrated values in CSM-CROPGRO-PFM for the cultivars Apica and Oneida VR.

Parameter	Definition	Apica	Oneida VR
LFMAX	Maximum leaf photosynthetic rate ( $\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$ )	1.34	1.32
SLAVR	Specific leaf area under standard growth conditions ( $\text{cm}^2 \text{g}^{-1} \text{DM}$ )	240	240
RDRMT	Relative dormancy sensitivity to day length for partitioning (0-1)	0.421	0.500
RDRMM	Relative dormancy sensitivity to day length for mobilization (0-1)	0.95	0.95

ramping up to 1.0 at 22.5  $^{\circ}\text{C}$  was reduced to 0.30 at 7  $^{\circ}\text{C}$  ramping up to 1.0 at 22.5  $^{\circ}\text{C}$ . Similarly, the temperature function affecting internode elongation (HWTEM) was made more sensitive to cool temperature, the old function 0.45 at 0  $^{\circ}\text{C}$  ramping up to 1.0 at 18  $^{\circ}\text{C}$  was reduced to 0.35 at 0  $^{\circ}\text{C}$  ramping up to 1.0 at 18  $^{\circ}\text{C}$ . These changes to SLAMIN, SLAVAR, and temperature functions (Table 3) worked well for Canadian cultivars. The Canadian data, however, lacked SLA and LAI measurements and could not be tested for those functions. Based on the Arizona and Montana data where the proportions of leaves and stems were available, the instantaneous daily partitioning to stems was increased by 0.03 to 0.05 fraction units over successive main-stem node numbers (V-stage).

Based on the Canadian data, the temperature parameterization of nodule growth and N-fixation rate in the species file was modified because the model computed N stress too frequently, thus reducing early season productivity. The temperature look-up function for nodule growth (Table 3; FNNGT) was made less sensitive to cool temperatures and was changed from -a 1 to 19  $^{\circ}\text{C}$  linear function to a -3 to 17  $^{\circ}\text{C}$  linear function. The function for N-fixation specific activity (FNEXT) was changed from a -1 to 15  $^{\circ}\text{C}$  linear function to a -3 to 14  $^{\circ}\text{C}$  linear function. In addition, the nodules died almost completely over the long winter season and, therefore, the rate of nodule death (NDTHMX) was reduced from 0.02 to 0.011 per day.

The daylength sensitivities for partitioning to storage (dormancy type) and for mobilization for regrowth were modified based on data from Arizona, Montana, Spain, and Canada (Table 3). The FNPTD values were set to a 9.8 to 14.2 h quadratic function compared to the

original values of 11.1 and 12.2 h. Because of the wide range of daylength environments, the lower critical short day for maximum partitioning to taproot and the higher upper threshold for minimum partitioning to taproot was needed to increase the range of model sensitivity to daylength for partitioning to storage. The FNPMD values for mobilization for regrowth were similarly modified for the same reason from 8.5 and 12.5 h to 9.9 and 13.9 h, the first value represents slowest mobilization and the second value represents the most rapid mobilization for regrowth. It is possible that the daylength sensitivities may need to be specific to fall dormancy (FD) classes (ecotypes) which would require a future code change. However, the strength of those daylength sensitivities is set by the ecotype parameters, RDRMT for partitioning dormancy and RDRMM for mobilization for regrowth (Table 4). A small value of RDRMT (close to 0) defines a cultivar with less shift in C partitioning to the taproots with shortening daylength and, therefore, less dormant in the fall, while a RDRMT closer to 1 defines a more dormant cultivar with a greater shift in C partitioning. The RDRMT values for strength of the daylength effect on partitioning were based on FD classes 3, 4, 6, and 10 with a corresponding range from 0.500, 0.421, 0.320, to 0.140. Thus, the RDRMT of Oneida VR and Apica were set at 0.500 and 0.421, respectively. The parameter RDRMM is the relative sensitivity of ecotype to daylength for decreased mobilization of C and N from taproots toward regrowth. The strength of the RDRMM parameter was increased from 0.850 to 0.950 for Oneida VR and Apica based on giving slightly better predictions, but the parameter is less important than RDRMT. Apica and Oneida VR had similar calibrated parameter values for RDRMM but they differed for

RDRMT. The calibrated higher parameter value of RDRMT (0.500) for Oneida VR suggests that it is more dormant than Apica (RDRMT of 0.421), which agrees with the dormancy ratings of 3 for Oneida VR and 4 for Apica for the two cultivars (Michaud et al., 1983; Viands et al., 1990; Lamb et al., 2006). Dormancy scores range from 1 to 11, with 1 being the most dormant and 11 being the least dormant (experience with the model so far only ranges from FD 3 to 10). Although more dormant cultivars are expected to have better winter hardiness, the cultivars Apica and Oneida VR were rated as having very good and good winter hardiness in Atlantic Canada, respectively (Bélanger et al., 1999).

The modifications to the temperature sensitivities of photosynthesis were relatively minor, but were changed to reduce photosynthetic rate and productivity under cool temperature. The light-saturated leaf photosynthesis rate (LFMAX) was designed to be a function of fall dormancy, ranging from 1.32 (FD3) to 1.46 (FD10), to mimic Canadian, Montana, and Arizona FD classes. As a result, Oneida VR (FD3) and Apica (FD4) were set at LFMAX of 1.32 and 1.34  $\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$ . The LFMAX values of 1.32 and 1.34  $\text{CO}_2 \text{m}^{-2} \text{s}^{-1}$  for Oneida VR and Apica are in the range of the measured values for alfalfa (1.32  $\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$ ) in Teixeira et al. (2008) and consistent with the LFMAX of 1.4  $\text{mg CO}_2 \text{m}^{-2} \text{s}^{-1}$  in Malik et al. (2018). The unnamed cultivar at the Ottawa site was assigned all values similar to Apica. To confirm that the calibrated values were reasonable for canopy carbon assimilation, we calculated the radiation use efficiency for shoot biomass (RUEshoot) for the cultivar Apica over all of the experimental sites and years. The canopy absorbed PAR (Photosynthetically Active Radiation) was calculated using the simulated LAI and a radiation extinction coefficient of 0.81 from Teixeira et al. (2007). The results showed that the range of RUEshoot from 0.63 to 1.8  $\text{g MJ}^{-1} \text{PAR}$  with an average of 1.31  $\text{g MJ}^{-1} \text{PAR}$  was within the reported values from 0.58 to 2.18  $\text{g MJ}^{-1} \text{PAR}$  for alfalfa (Brown et al., 2006; Teixeira et al., 2008).

### 3.3. Simulated vs. measured alfalfa attributes

The measured biomass of the first harvest was higher than that of the second harvest for all post-seeding years; this variation in biomass was simulated by the model with measured values close to the simulated values for Lévis (Fig. 3A). The simulated biomass matched well the sequentially measured biomass during the primary growth and regrowth at Ottawa (Fig. 3B). The simulations confirmed that the cultivar used at the Ottawa site could be very similar to cultivar Apica. The

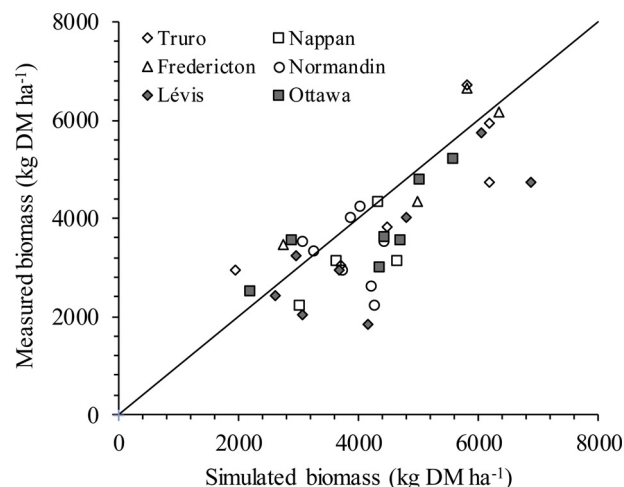


Fig. 4. Measured versus simulated aboveground biomass (sum of herbage harvest and residual stubble mass of 350  $\text{kg DM ha}^{-1}$ ) at each harvest at six sites. The slanted solid line is the 1:1 line between measures and simulated values.

model successfully simulated the temporal growth patterns of alfalfa biomass between harvests with *nRMSE* of 26%, and *d* and *EF* close to 1 in the Ottawa experiment.

The biomass at each harvest across all sites and years were scattered around a 1:1 line (Fig. 4). The model simulated the biomass well at Fredericton with a *nRMSE* of 12%, and *d* and *EF* greater than 0.78 (Table 5). The biomass simulation was also good at Ottawa and Truro with a *nRMSE* less than 23%. The high *nRMSE* at Lévis mainly came from the considerable overestimation for the second harvest in 2009 (Fig. 3A). It is not clear what factors caused the low measured aboveground biomass for the second harvest compared to the third harvest in 2009. The negative values of *EF* at Nappan and Normandin indicated that the model did not perform very well at those two sites. At Nappan in the second post-seeding year (1994), the plant density was 22  $\text{plants m}^{-2}$ , which was much less than 83  $\text{plants m}^{-2}$  in the preceding year (Bélanger et al., 1999). The reduction in plant density has a limited impact on DM yield unless the plant density decreases below 40  $\text{plants m}^{-2}$  (Bélanger et al., 1992). In contrast, the plant densities at Truro and Fredericton were higher than 40  $\text{plants m}^{-2}$  throughout the study, and

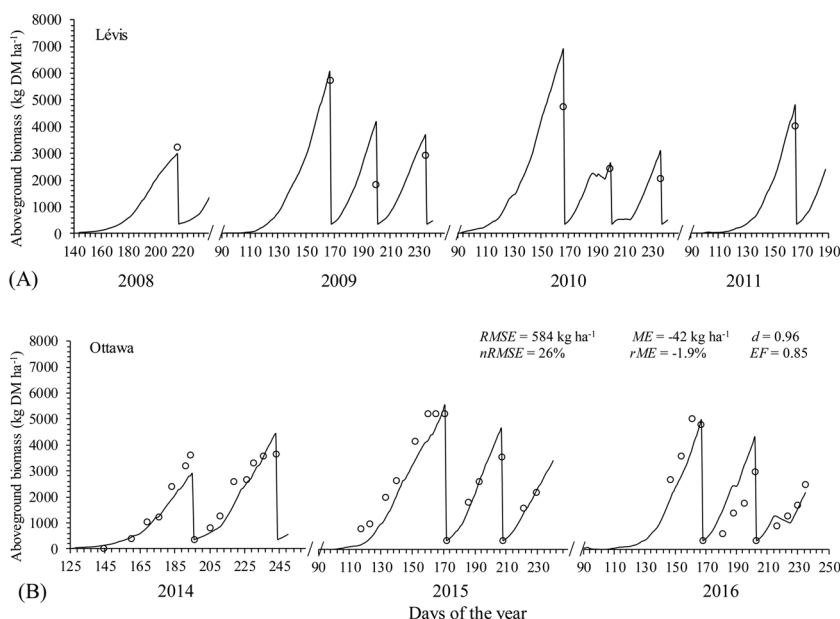
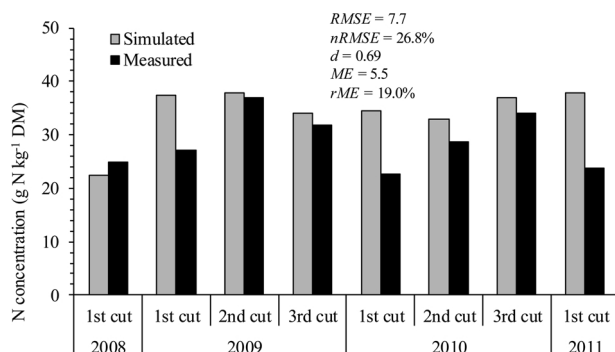


Fig. 3. Simulated (lines) and measured (symbols) temporal dynamics of aboveground biomass (sum of herbage mass and residual stubble mass of 350  $\text{kg DM ha}^{-1}$ ) at Lévis (A) and Ottawa (B) with the cultivar Apica. --- refers to the omitted days. *RMSE*, root mean square error between simulated and measured values; *nRMSE*, normalized *RMSE*; *d*, index of agreement; *ME*, mean error; *rME*, relative *ME*; *EF*, model efficiency coefficient.





**Fig. 5.** Simulated and measured herbage N concentrations for the alfalfa cultivar Apica at each harvest at Lévis. *RMSE*, root mean square error between simulated and measured values; *nRMSE*, normalized *RMSE*; *d*, index of agreement; *ME*, mean error; *rME*, relative *ME*.

the simulations were better at these two sites than at Nappan. The plant density was not measured at Normandin but we can speculate that it might have decreased to less than 40 plants m<sup>-2</sup> in the second post-seeding year (1997), a site where the biomass was overestimated by 52%. To confirm this speculation for the simulation at Normandin, excluding the data for 1997 improved the simulation evaluation statistics with a *nRMSE* of 20.8%. The plant density of alfalfa declines over time, primarily because of harsh winter conditions and winterkill in Canada (Bélanger et al., 1999; Castonguay et al., 2006). The density decline due to subfreezing temperature stresses and the plant density-biomass relationship is not simulated in the current version of the model. Our results suggest that adding this component could improve the ability of the model to simulate alfalfa DM yield. He et al. (2019), who included revised empirical growth and regrowth functions and winterkill algorithms mimicking planting density for alfalfa in the DNDC model, found that *EF* increased from -0.35 to 0.90 at Normandin (1996–1997). However, the DNDC model does not explicitly simulate carbohydrate storage and the empirical growth functions may not be applicable for other cultivars/climatic regions outside their study area.

The CSM-CROPGRO-PFM model for alfalfa performed well when assessed across all sites and years with *d* = 0.86 and *EF* = 0.48 (Table 5). The *RMSE* of 936 kg DM ha<sup>-1</sup> and the *nRMSE* of 24% were comparable to the evaluation results for a previous study conducted in Spain (Malik et al., 2018). This good performance was consistent for all three post-seeding years with *nRMSE* around 20–30% and *d* close to 1 (Table 6). The CSM-CROPGRO-PFM model performed slightly better in the simulation of alfalfa biomass than the Integrated Farm System Model (IFSM) in the same region with the experimental data in this study (Jégo et al., 2015), as indicated by a lower *nRMSE* (24% versus 30%) with a close *EF* (0.48 versus 0.51).

Simulated and measured shoot N concentrations were compared for

the site at Lévis (Fig. 5). The variation of N concentrations among harvests and years ranged from 22.7 to 34.1 g N kg<sup>-1</sup> DM in the measured data, which were reproduced in the simulations with a range from 22.5 to 37.8 g N kg<sup>-1</sup> DM. The standard deviations for measurements (5.15 g N kg<sup>-1</sup> DM) and simulations (5.1 g N kg<sup>-1</sup> DM) were also close. The *RMSE* (7.7 g N kg<sup>-1</sup> DM) was smaller than the value (10 g N kg<sup>-1</sup> DM) reported by Malik et al. (2018), while a *nRMSE* of 26.8% indicates an acceptable simulation of N concentration.

### 3.4. Regrowth depending on reserves

The regrowth of perennial crop depends on stored non-structural carbohydrates (CH<sub>2</sub>O) and N, the residual leaf area, and active meristems to form new leaves in the spring or after herbage removal (Richards, 1993). Jing et al. (2012) described this regrowth pattern as reserve-dependent growth and successfully quantified non-structural carbohydrate accumulation and remobilization to simulate the regrowth of perennial grasses in Canada. A similar approach of regrowth using reserves has been adapted for alfalfa in the CSM-CROPGRO-PFM model (Malik et al., 2018). Simulated variations of non-structural carbohydrate accumulation in the taproots and mobilization from the taproots during regrowth in spring and after herbage removals are shown in Fig. 6. After a harvest, the concentration of CH<sub>2</sub>O in the taproots decreases (Fig. 6A) as they are mobilized out to newly growing organs. Once a plant has sufficient new leaves for maximum photosynthesis, it begins to store carbohydrates back in the storage organs (Smith and Jewiss, 1966; Smith, 1974). The estimated outflux from the taproots, expressed in kg ha<sup>-1</sup> d<sup>-1</sup>, can be seen in Fig. 6B for three regrowth patterns for two post-seeding years (2015 and 2016) at the Ottawa site.

The simulation of reserve-dependent regrowth in the CSM-CROPGRO-PFM model is essential for perennial crops like alfalfa to study the impact of climate change. Environmental factors (e.g. temperature) and management practices such as harvest timing and frequency may change the flux of non-structural CH<sub>2</sub>O between photosynthetic and storage organs (Rymph, 2004). For example, insufficient CH<sub>2</sub>O reserves due to a very late harvest in fall may lead to a poor alfalfa regrowth the next spring because the CH<sub>2</sub>O reserves may be exhausted during winter for maintenance respiration (Dhont et al., 2002). In a study of the potential impact of climate change on timothy (*Phleum pratense* L.), the main forage grass species in eastern Canada, Jing et al. (2014) attributed the poor spring regrowth at some of the sites to a reduced accumulation/storage of carbohydrates due to an additional harvest taken in the previous year. The well-matched simulated biomass to measured values in temporal regrowth patterns (Fig. 3), especially with the sequential sampling during each regrowth at the Ottawa site, confirms that the regrowth simulation was successful. The projected warmer climatic conditions in eastern Canada are expected to result in additional harvests (Thivierge et al., 2016) and

**Table 5**

Model evaluation statistics for the simulation of aboveground alfalfa biomass (kg DM ha<sup>-1</sup>, sum of herbage mass and residual stubble mass of 350 kg DM ha<sup>-1</sup>), at each harvest for six sites and across all sites in eastern Canada.

Site	No.	$X_{obs}$	$SD_{Xobs}$	$X_{sim}$	$SD_{Xsim}$	$P(t)^1$	<i>RMSE</i>	<i>nRMSE</i> (%)	<i>d</i>	<i>EF</i>	<i>ME</i>	<i>rME</i> (%)
Fredericton	8	5016	1348	4934	1432	0.45	595	11.9	0.94	0.78	-82	-1.6
Truro	12	4386	1510	4676	1591	0.33	978	22.3	0.88	0.54	290	6.6
Nappan	8	3170	740	3841	638	0.04	825	26.0	0.75	-0.42	671	21.2
Normandin	8	3325	680	3857	483	0.05	1011	30.4	0.52	-1.53	532	16.0
Lévis	8	3388	1369	4287	1536	0.12	1244	36.7	0.81	0.06	900	26.6
Ottawa	7	3776	949	4168	1196	0.26	791	20.9	0.86	0.19	392	10.4
All sites	51	3887	1306	4326	1265	0.04	936	24.1	0.86	0.48	439	11.3

No., number of measured/simulated data pairs;  $X_{obs}$ , mean of measured values;  $X_{sim}$ , mean of simulated values; *SD*, standard deviation;  $P(t)$ , *p*-value from the paired *t* test; *RMSE*, root mean square error between simulated and measured values; *nRMSE*, normalized *RMSE*; *d*, index of agreement; *EF*, model efficiency coefficient; *ME*, mean error; *rME*, relative *ME*.

<sup>1</sup> Difference in the means of measured and simulated values is considered statistically significant when the *P*-value is smaller than 0.05.

**Table 6**

Model evaluation statistics for the simulation of aboveground biomass ( $\text{kg DM ha}^{-1}$ , sum of herbage mass and residual stubble mass of  $350 \text{ kg DM ha}^{-1}$ ) for each post-seeding year across all sites in eastern Canada.

Post-seeding year	No.	$X_{\text{obs}}$	$SD_{X_{\text{obs}}}$	$X_{\text{sim}}$	$SD_{X_{\text{sim}}}$	$P(t)^1$	RMSE	nRMSE (%)	d	EF	ME	rME (%)
First	21	4204	1404	4393	1021	0.31	834	19.8	0.87	0.63	189	4.5
Second	22	3595	1360	4242	1509	0.07	1023	28.5	0.87	0.41	647	18.0
Third	8	3683	950	4502	1323	0.09	1019	27.7	0.79	-0.31	820	22.3

No., number of measured/simulated data pairs;  $X_{\text{obs}}$ , mean of measured values;  $X_{\text{sim}}$ , mean of simulated values;  $SD$ , standard deviation;  $P(t)$ ,  $p$ -value from the paired  $t$  test;  $RMSE$ , root mean square error between simulated and measured values;  $nRMSE$ , normalized  $RMSE$ ;  $d$ , index of agreement;  $EF$ , model efficiency coefficient;  $ME$ , mean error;  $rME$ , relative  $ME$ .

<sup>1</sup> Difference in the means of measured and simulated values is considered statistically significant when the  $P$ -value is smaller than 0.05.

may result in an increased incidence of winter damages. Thus, alfalfa production under a future climate needs to be assessed using modelling approaches in order to systematically quantify the effects of environmental factors, management practices, and cultivars on the entire production life-cycle.

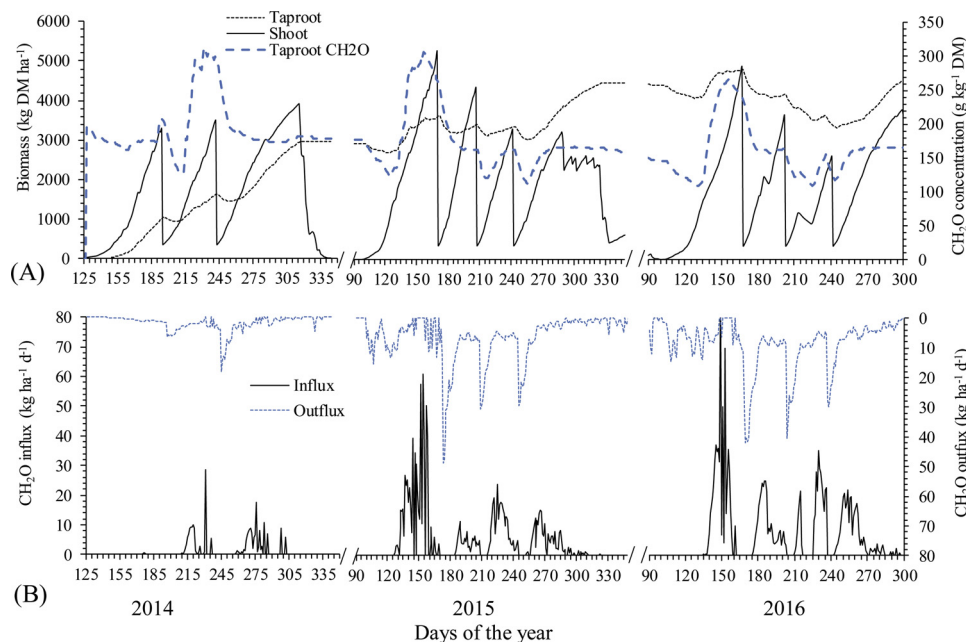
### 3.5. Sensitivity analysis

The number of harvests per year varied with sites and years with three to four harvests at Ottawa, two to three harvests at Fredericton and Lévis, and one to two harvests at Normandin under baseline climate conditions. The number of harvests per year increased with an increase in air temperature of 1 or 2 °C above the baseline (Table 2, scenarios T1 and T2).

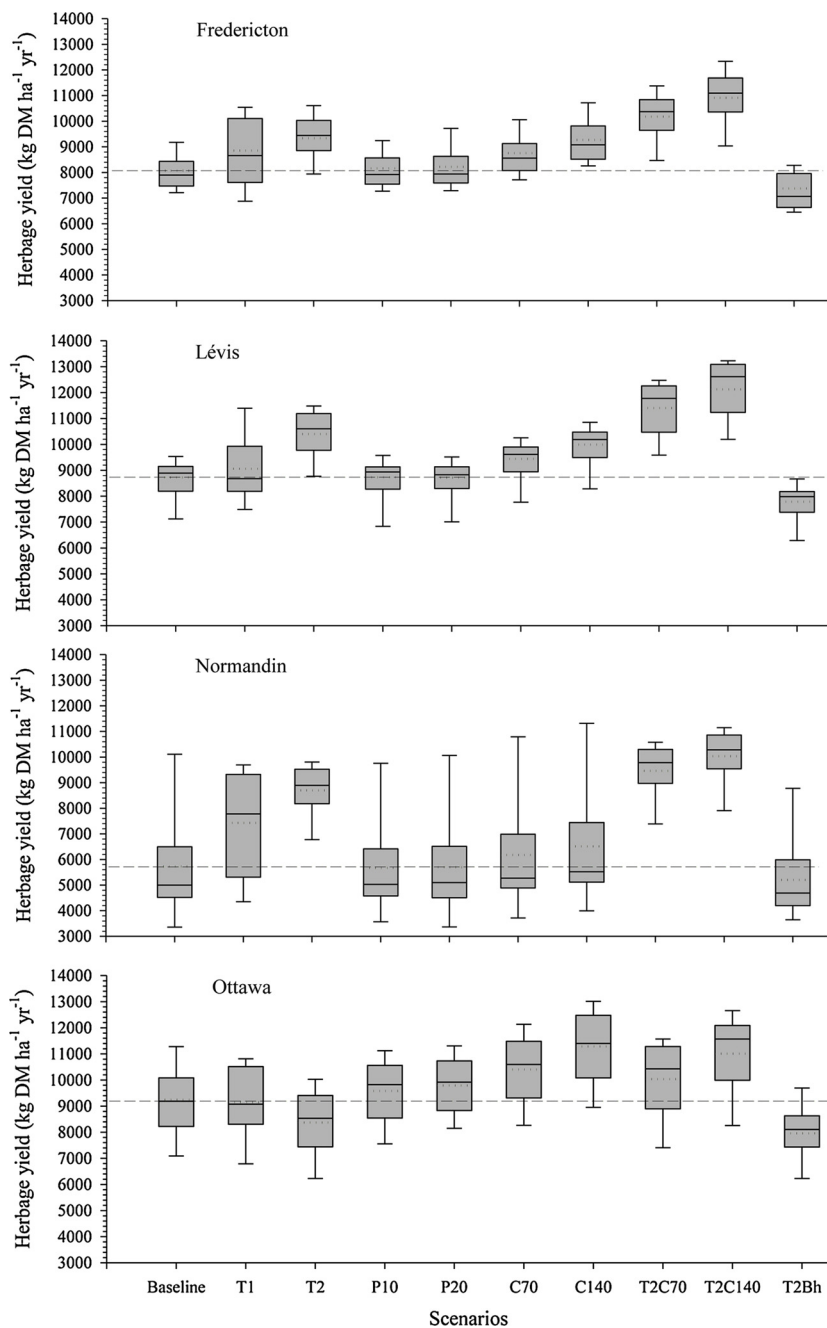
Under increased temperatures, these additional harvests resulted in increased annual herbage DM yield at Fredericton, Lévis, and Normandin but in a decrease at Ottawa (Fig. 7). With no change in the number of harvests (scenario T2Bh), increasing temperatures by 2 °C reduced annual herbage DM yield at all sites compared to the simulated annual herbage yield with the baseline scenario (B). On average, all harvest intervals were reduced by one day with a 1 °C increase above the baseline. At Ottawa, the benefit from the increase in the number of harvests was not greater than the decrease in herbage DM yield due to the increased temperatures. Ottawa has warmer climate conditions (Table 1) with about four harvests annually compared with one or two harvests for the other sites with cool weather conditions (Table 2).

Therefore, the length of the growth periods between harvests are reduced more at Ottawa than at the other sites, and may be reduced by up to ten days with a 2 °C increase above the baseline temperature. Additionally, leaf assimilation will decrease at temperatures above 33.0 °C in the model simulation processes (Hoogenboom et al., 2017). There were, on average, eight days per year with a maximum temperature above 33 °C between 1981 to 2010 at Ottawa but only 1.4 days at Fredericton and less than one day at Lévis and Normandin. As a result, the increase in temperature may lead to more heat stress at Ottawa than at the other sites, contributing to much more herbage yield reduction at Ottawa. Furthermore, the increasing drought stress with increased temperature led to the reduction of herbage DM yield at Ottawa. From the simulations, the number of days per year with a daily water stress (daily value > 0.1) was 12.2 at Ottawa, 4.7 at Fredericton, 1.8 at Lévis, and no drought stress at Normandin under the baseline conditions. The number of days with a drought stress (daily value > 0.1) increased with an increase in temperature, with an increment of 3.8 days at Ottawa, 2.9 days at Fredericton, 1.7 days at Lévis, and 0.3 days at Normandin under a 2 °C increase above the baseline.

Compared with the baseline, the simulated annual herbage yield increased by 3.6% and 6% with an increase in precipitations of 10% and 20% for Ottawa, while the response to the increase in precipitation was much smaller (< 2%) for the other three sites (Fig. 7). The marginal herbage yield increases showed much less sensitivity of the model to precipitation increases in eastern Canada where the precipitation is generally sufficient. The model simulated higher herbage yield under



**Fig. 6.** Simulated temporal changes of aboveground and taproot biomass, and taproot carbohydrate ( $\text{CH}_2\text{O}$ ) concentration (A) associated with  $\text{CH}_2\text{O}$  added to the taproot (influx) and mobilized from the taproot (outflux) (B) in simulations over three years (2014–2016) at the Ottawa site. –//– refers to the omitted days.



**Fig. 7.** Simulated annual herbage DM yield under independently modified environmental factors from 1981 to 2010 (baseline). The boundary of the box closest to zero indicates the 25th percentile, the solid line within the box marks the median, the short dotted line marks the mean, the boundary of the box farthest from zero indicates the 75th percentile, whiskers above and below the box indicate the 90th and 10th percentiles. The dashed horizontal lines indicate the average herbage yield under the baseline. Scenarios: T1 — plus 1 °C only in temperatures over baseline; P10 — plus 10% of precipitation; C70 — plus 70 ppm in CO<sub>2</sub> concentration; T2C70, combining T and C scenarios; T2Bh, T2 with the same harvest times as in baseline; and details in Table 5.

increased CO<sub>2</sub> concentrations of 450 ppm and 520 ppm than under 380 ppm for all sites. The relative increases of herbage yield were similar among sites with an increase of 9% for a CO<sub>2</sub> concentration of 450 ppm and about 16% for a 520 ppm on average across sites.

We also tested the model response to the combined effects of increased temperature and CO<sub>2</sub> concentration. Historic weather data showed that increasing temperature has been attributed to an increase in CO<sub>2</sub> and other greenhouse gas emissions (IPCC, 2013). How alfalfa can benefit from climate change depends on the balance between both the adverse and beneficial effects on herbage mass from the increasing CO<sub>2</sub> concentration and temperatures. The simulation results showed that alfalfa production would increase with a 2 °C warming combined with increased CO<sub>2</sub> concentrations to 450 ppm and 520 ppm across sites (Fig. 7). Similar results were reported for an alfalfa-timothy mixture in eastern Canada in a study with the Integrated Farm System Model (Thivierge et al., 2016). The herbage yield increase was apparently less at Ottawa than at the other three sites due to the herbage yield

reduction under increased temperatures as previously discussed. All these scenarios with individual and combined factors, including subsequent changes in the number of harvests following increasing temperatures, showed that the model accounts for all these factors and their interactions, and the response sensitivities to these factors varied among sites.

### 3.6. Potential areas for further improvements

The plant density of alfalfa declines over time and can reach values below 30 plants m<sup>-2</sup> after a few years in eastern Canada, primarily because of harsh winter conditions and winterkill (Bélanger et al., 1999; Castonguay et al., 2006). In our modelling of alfalfa with CSM-CROPGRO-PFM, the relationship between plant density and biomass production was not simulated and, thus, the mortality of alfalfa due to stressful environments and its effect on herbage yield was not quantified. In the original adaptation of the CSM-CROPGRO model for

perennial grass species, plant density was not considered in post-seeding years because the regrowth of most of those perennial grasses occurs from axillary buds or new growing points in the nodes of stolons. The spreading of stolons during the growing season allows the grass plants to occupy bare land areas with new plants and tillers, maintaining the stand density (Rymph, 2004). The alfalfa regrowth, however, is principally from buds on the crown on the top of the taproots and, thus, alfalfa cannot spread from new plants or tillers (Smith et al., 1989; Probst and Smith, 2008). The maximum density of taproots is determined at seeding and the plant density declines over time due to environmental stresses and competition. Overseeding could be an option to recover plant density but the autotoxicity of alfalfa reduces the development of seeds in existing stands (Jennings and Nelson, 2002). Recently, the declining biomass due to reduced plant density by winterkill was mimicked in the newly adapted DNDC model for alfalfa in Canada, and the simulations of biomass were improved (He et al., 2019). Further improvements of the CSM-CROPGRO-PFM model should include the ability to take into account changes in plant density due to overwintering conditions and their impact on herbage yield.

The feature of externally simulating temperatures near the crowns of alfalfa plants under snow cover using the method of Jégo et al. (2014) as was done in this study should be added to the CSM-CROPGRO-PFM model, as scientists in many other regions of the world would benefit from having this module to overcome the issues of freeze-kill of alfalfa and other overwintering crops. The module should also have the ability to include snowfall as input in weather files or estimated snowfall based on temperature and precipitation along with the ability of simulating the melting and extension of snow cover over time.

Crude protein concentration, one of herbage nutritive attributes, is simulated in the CSM-CROPGRO-PFM model (Malik et al., 2018). Other nutritive attributes such as dry matter digestibility, are important to dairy animals (Tremblay et al., 2002) but they are not simulated. Increasing temperature reduces dry matter digestibility of alfalfa (Sanz-Sáez et al., 2012). The nutritive attributes of alfalfa may be reduced by climate change and elevated CO<sub>2</sub> concentration, and necessary adaptations may mitigate their negative impact (Thivierge et al., 2016). Additional nutritive attributes of alfalfa such as neutral detergent fibre (NDF) and in vitro digestibility of NDF (dNDF) that have been simulated in other forage crop models (Jing et al., 2014; Thivierge et al., 2016) may need to be computed in the CSM-CROPGRO-PFM model for alfalfa. Plans for improving the CSM-CROPGRO-PFM model to simulate the nutritive value for its forage species are currently being considered.

#### 4. Conclusions

The use of an external model for estimating temperatures around alfalfa crowns under snow greatly improved the simulation of alfalfa regrowth using the CSM-CROPGRO-PFM model under the overwintering conditions in eastern Canada. Most of the alfalfa physiological processes (e.g. regrowth by reserve mobilization and restoration, dormancy, and N fixation) are simulated by the model. The model evaluation results were acceptable in simulating herbage DM yield and N concentration in eastern Canada. The alfalfa model proved to be sensitive to the individual and combined environmental conditions of increased temperature and CO<sub>2</sub> concentration, and less sensitive to precipitation changes in eastern Canada as a result of already sufficient precipitation.

For Canada and other regions with subfreezing temperatures during winter, where cold temperatures can strongly impact alfalfa production, improvements are suggested before the alfalfa model can be used in climate change impact assessments including the simulation of 1) reduced plant density due to lethal sub-freezing temperatures; 2) the relationship between plant density and canopy biomass; 3) herbage nutritive value; 4) temperatures at alfalfa crown in winter when a snow cover is present; and 5) additional harvest options to a given date, such as following a given stage of alfalfa development.

#### Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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