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Predicted Yield and Nutritive Value of an Alfalfa–Timothy Mixture under Climate Change and Elevated Atmospheric Carbon Dioxide

Marie-Noëlle Thivierge, Guillaume Jégo,* Gilles Bélanger, Annick Bertrand, Gaëtan F. Tremblay, C. Alan Rotz, and Budong Qian

ABSTRACT

Climate change studies have often focused on individual forage species although legume-grass mixtures are predominant on dairy farms in northern areas of North America. We assessed the effect of (i) future climate conditions (temperature and precipitation) and elevated atmospheric CO_2 concentration ([CO_2]), separately and together, on yield of alfalfa (*Medicago sativa* L.) and timothy (*Phleum pratense* L.), grown alone or in mixture, and (ii) an adaptation strategy (timing and number of harvests) on future yield and nutritive value of an alfalfa–timothy mixture. Forage dry matter (DM) yield and nutritive value for two contrasting climate areas in eastern Canada were simulated with the Integrated Farm System Model over two future periods (2020–2049 and 2050–2079) using three climate models and two representative concentration pathways (RCP 4.5 and 8.5) of greenhouse gas emissions. Under projected future climate and without adaptation, annual forage yield of both species and the mixture increased in the colder area and decreased in the warmer area. In both areas, first-cut yield increased due to faster growing degree-day accumulation, while regrowth yield decreased due to greater water and temperature stresses. Under elevated [CO_2], annual yield and the alfalfa percentage in the mixture increased. When combining climate change and elevated [CO_2], yield increased, except with the more drastic scenario (RCP 8.5, 2050–2079) in the warmer area, and forage nutritive value was reduced. With adaptation, the mixture yield was increased from 5 to 35%, while nutritive value was generally maintained under all future scenarios, mostly because of additional cuts.

Core Ideas

- In eastern Canada, colder areas will benefit the most from climate change.
- In future climate, water and temperature stresses will reduce forage summer regrowth.
- Elevated CO_2 will result in a higher yield increase in alfalfa than in timothy.
- When adapting harvest timing and number, annual forage mixture yield will increase.
- When adapting harvest timing and number, forage nutritive value will be maintained.

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Changes in forage yield and nutritive value due to climate change and elevated atmospheric [CO_2] are likely to affect the agronomic, economic, and environmental performance of dairy farms. A better understanding of these changes will allow dairy farmers to develop and implement adaptation strategies (Antle et al., 2004; Prato et al., 2010).

Crop growth will be affected by changes in temperature, precipitation, and atmospheric [CO_2], as well as by their interactions (Hatfield et al., 2011). Growth chamber experiments (Bertrand et al., 2007a, 2007b; Kettunen et al., 2007; Baslam et al., 2014) and modeling studies (Hunt et al., 1991; Parton et al., 1995; Riedo et al., 1999) have shown that many forage and pasture crops, mostly cool-season forage species with a C3 photosynthetic pathway, will benefit from elevated atmospheric [CO_2], either because of increased photosynthesis or because of decreased soil moisture depletion due to stomatal closure (Morgan et al., 2004b). Elevated [CO_2] has also been shown to stimulate biological N fixation, hence favoring legume species (Zanetti et al., 1996; Hebeisen et al., 1997; Lazzarotto et al., 2010).

Assessing the effects of future climate conditions (elevated temperature and precipitation changes) on forage crop production is difficult because they depend on the current climatic conditions at a given location, the species-specific critical temperature range for growth and photosynthesis, and soil resources (Hunt et al., 1991; Riedo et al., 1999; Hatfield et al., 2011; Lee et al., 2013). In growth chamber experiments, increased temperature reduced DM yield of timothy (Bertrand et al., 2008; Piva et al., 2013). For alfalfa, yield was either enhanced by a temperature increase alone (Aranjuelo et al., 2007) or by a temperature increase combined with elevated [CO_2] (Aranjuelo et al., 2006; Sanz-Sáez et al., 2012). Many forage species are drought sensitive, including timothy (Bertrand et al., 2008) and alfalfa (Aranjuelo et al., 2006, 2007), and are expected to be affected by future changes in precipitation. Variation in

M.-N. Thivierge, G. Jégo, G. Bélanger, A. Bertrand, and G.F. Tremblay, Quebec Research and Development Centre, Agriculture and Agri-Food Canada, 2560 Hochelaga Boulevard, Québec, QC, Canada, G1V 2J3; C.A. Rotz, Pasture Systems and Watershed Management Research Unit, USDA, 3702 Curtin Road, University Park, PA 16802; B. Qian, Ottawa Research and Development Center, Agriculture and Agri-Food Canada, 960 Carling Ave., Ottawa, ON, Canada, K1A 0C6. *Corresponding author (guillaume.jego@agr.gc.ca).

Abbreviations: CP, crude protein; DF, distant future; DM, dry matter; DOY, day of the year; GCM, global climate model; GDD, growing degree-days; GHG, greenhouse gas; IFSM, Integrated Farm System Model; LDM, liquid dairy cattle manure; NF, near future; NDF, neutral detergent fiber; QE, Quebec East; QSW, Quebec Southwest; RCM, regional climate model; RCP, representative concentration pathway; TDN, total digestible nutrients; TSI, temperature stress index; WSI, water stress index.

precipitation could even be the primary factor affecting alfalfa yield across the United States under future climate scenarios, more than atmospheric [CO_2] or temperature changes (Izaurralde et al., 2011). Elevated temperature and changes in precipitation might offset the positive crop response to elevated [CO_2] (Morgan et al., 2004b; Hatfield et al., 2011; Izaurralde et al., 2011; Lee et al., 2013; Piva et al., 2013).

Forage nutritive value is also likely to be affected by climate change and elevated [CO_2]. Increased temperature was shown to reduce forage or pasture nutritive value (Thorvaldsson, 1992; Wan et al., 2005; Thorvaldsson et al., 2007; Lee et al., 2013), and specifically to reduce the in vitro neutral detergent fiber (NDF) digestibility in timothy (Bertrand et al., 2008; Jing et al., 2013b) and in vitro dry matter digestibility in alfalfa (Sanz-Sáez et al., 2012). Elevated atmospheric [CO_2] has been found to decrease the crude protein (CP) concentration of several species (Milchunas et al., 2005; Soussana and Lüscher 2007; Sanz-Sáez et al., 2012; Baslam et al., 2014; Irigoyen et al., 2014; Dumont et al., 2015), including alfalfa (Bertrand et al., 2007b), and to reduce the digestibility of grasses (Morgan et al., 2004a) but not that of alfalfa (Irigoyen et al., 2014).

Climate change is expected to affect the forage harvest schedule in Canada (Jing et al., 2013b, 2014). Forage growth is expected to begin earlier in the season, and the increase in daily temperature might reduce the number of days between forage cuts, allowing for an increase in the number of cuts (Ruget et al., 2012). Recent research on timothy has shown that an additional forage cut in eastern Canada would result in increased annual forage DM yield with a minimal effect on forage nutritive value (Jing et al., 2014). Therefore, modifying the forage harvest schedule, with the possibility of adding cuts, could be an important climate change adaptation strategy for dairy and beef farms.

Crop responses to climate change are expected to differ among species (Hatfield et al., 2011; Mäkinen et al., 2015). For example, N-fixing species have been shown to be more responsive to elevated atmospheric [CO_2] than non-fixing species (Zanetti et al., 1996; Hebeisen et al., 1997; Lazzarotto et al., 2010). In Canada, timothy and alfalfa are commonly grown together in a mixture, generally producing greater DM yields than when they are grown in monocultures (Bélanger et al., 2014). Because of its many specific characteristics, notably enhanced N fixation by the legume component (Nyfeler et al., 2011), a legume-grass forage mixture can be expected to behave differently than pure stands of the individual species under climate change. Many recent studies have used crop models to evaluate the potential effect of climate change on perennial forage crops (Thomson et al., 2005; Prato et al., 2010; Ruget et al., 2012; Höglind et al., 2013; Jing et al., 2013a; Prato and Qiu, 2014). Few studies, however, have considered the effect of climate change on legume-grass forage mixtures (Riedo et al., 1999; Lazzarotto et al., 2010), and none have been conducted in northern areas of North America.

Models that simulate all major farm components are needed in order to assess the agronomic, economic, and environmental performance of dairy farms. Such models have been developed for areas with oceanic or maritime climates (Wastney et al., 2002; Schils et al., 2007; Chardon et al., 2012). The Integrated Farm System Model (IFSM) (Rotz et al., 2014) is the only process-based model adapted to the continental climate of the northern areas of North America. This farm-scale model, developed for dairy, beef, and cash crop farms in the northeastern United States, allows the simulation of forage mixture yield and nutritive value as a process part of the whole-farm system. Jégo et al. (2015) showed that IFSM can be used under current climate conditions in northern regions of North America, like eastern Canada, to simulate the yield and nutritive value of timothy and alfalfa, grown alone or in a mixture.

The long-term objective of this project was to assess the agronomic, economic, and environmental performance of dairy farms under future climate change scenarios using IFSM for simulations of virtual dairy farms representing two climatically contrasting areas in eastern Canada. The specific objectives of this study were (i) to assess the effect of future climate conditions (temperature and precipitation) and elevated atmospheric [CO_2], separately or together, on the yield of alfalfa and timothy, grown alone or in a mixture; and (ii) to assess the effect of a climate change adaptation (modified harvest schedule including additional cuts) on yield and nutritive value of an alfalfa–timothy mixture.

MATERIALS AND METHODS

Climate Scenarios and Weather Data

Forage yield and nutritive value were simulated using IFSM version 4.2 (Rotz et al., 2014) for two agricultural areas in the province of Quebec (Canada): the southwestern area (Quebec Southwest, QSW) and the eastern area (Quebec East, QE) (Fig. 1). These areas, which are approximately 500 km apart, were chosen because of their importance in dairy production and their contrasting climate. Daily weather data (minimum and maximum air temperatures, precipitation, and solar radiation) for the 1971 to 2000 period (reference period) were retrieved from the nearest existing weather stations, in Saint-Hubert (45°31′ N, 73°25′ W) for the QSW area and in Mont-Joli (48°36′ N, 68°13′ W) for the QE area.

The effect of climate change on forage yield and nutritive value was studied by comparing IFSM predictions using synthetic climate data representative of the reference period (1971–2000) with that of the 2020 to 2049 (near future, NF) and 2050 to 2079 (distant future, DF) periods. For each of these two future periods, two scenarios of greenhouse gas (GHG) concentrations were applied: the representative concentration pathway (RCP) 4.5 (reduced rate of emissions) and RCP 8.5 (emissions continue to increase at current rate) (IPCC, 2014). Hereafter, the four future scenarios will be identified as NF4.5 and NF8.5 (near future with RCP 4.5 and RCP 8.5, respectively), and DF4.5 and DF8.5 (distant future with RCP 4.5 and RCP 8.5, respectively). As defined in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014), RCPs are expressed as approximate total radiative forcing in year 2100 relative to 1750: +4.5 W m^{-2} for RCP 4.5 and +8.5 W m^{-2} for RCP 8.5. On the basis of simulations with integrated assessment models, each RCP defines the prescribed annual emissions and concentration of GHGs that lead to its respective radiative forcing in 2100. The atmospheric [CO_2] for the reference and future periods under RCP 4.5 and RCP 8.5 were retrieved from the RCP Database version 2.0.5 (Meinshausen et al., 2009) and averaged for each 30-yr period: 346 µmol mol^{-1} for the reference period, 447 and 469 µmol mol^{-1} for scenarios NF4.5 and NF8.5, respectively, and 514 and 639 µmol mol^{-1} for scenarios DF4.5 and DF8.5, respectively.

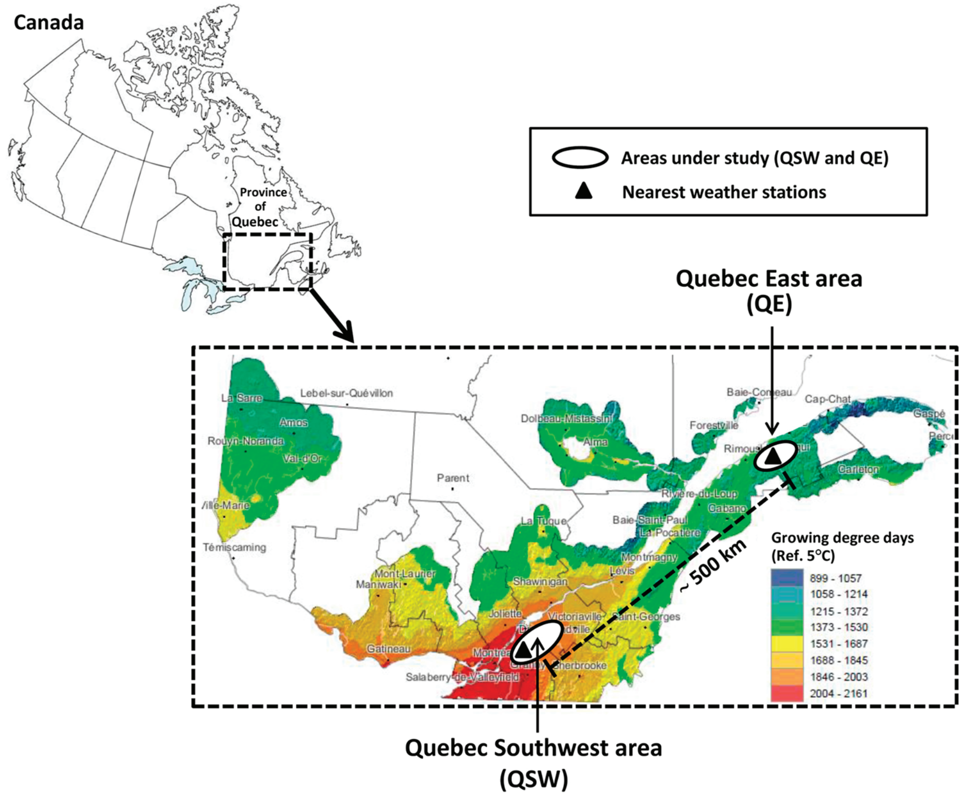

Fig. 1. Map of the studied areas (Quebec Southwest, QSW; and Quebec East, QE) in the province of Quebec, Canada, and location of the nearest weather stations (Atlas Agroclimatique du Québec, 2012).

Climate models are the primary tools used to project future climate change driven by radiative forcing scenarios associated with GHG emissions. The resulting projections are used in climate change impact studies. In this study, three climate models were selected, based on their availability and our previous experience: (i) the second-generation Canadian Centre for Climate Modelling and Analysis Earth System Model (CanESM2) (Arora et al., 2011); (ii) a newly developed Canadian Regional Climate Model (CanRCM4) (Qian et al., 2015b; Scinocca et al., 2015); and (iii) the Hadley Centre Global Environment Model version 2 (HadGEM2) (Johns et al., 2006; Martin et al., 2006; Ringer et al., 2006). CanRCM4 is a regional climate model (RCM), while CanESM2 and HadGEM2 are global climate models (GCM).

To assess the effect of future climate scenarios on forage crops with acceptable estimates of climate risks, a 300-yr series of synthetic weather data was generated for each scenario (Jing et al., 2014) using the stochastic weather generator AAFC-WG (Hayhoe, 2000; Qian et al., 2004). As proposed by Qian et al. (2011) and Jing et al. (2013a), statistical tests were first performed to verify that the 300-yr series of synthetic data correctly represented the 30-yr weather data observed for the reference period (1971–2000) at the weather stations in QSW and QE. The weather generator was then used to generate a 300-yr series of synthetic data for future periods and RCPs by perturbing the weather generator parameters based on the simulated changes in climate parameters from the climate models (CanESM2, CanRCM4, and HadGEM2). Details on how future daily scenarios were generated by perturbing the weather generator parameters based on GCM/RCM-simulated climate change can be found in Qian et al. (2005, 2010, 2015a). The 300-yr series of synthetic weather data were then used to run the IFSM model.

Integrated Farm System Model

The IFSM simulates all major farm components on a process level (Rotz et al., 2014). The farm components include crop growth, harvest and storage, animal feeding, and manure storage and handling. Interactions between components are taken into account. Farm characteristics and daily weather data for a particular location are supplied to the program as input information.

In the present study, output variables retrieved or calculated from IFSM included the date of growth onset; DM yield (Mg ha^{-1}); percentage of alfalfa in the forage mixture (%); concentrations of NDF (g kg^{-1} DM), total digestible nutrients (TDN, g kg^{-1} DM), and CP (g kg^{-1} DM); and temperature (TSI, 0–1.0) and water (WSI, 0–1.0) stress indices. Annual NDF, TDN, and CP concentrations were calculated in proportion to the DM yield for each cut with weighted averages. Standard deviation over the 300 simulated years was determined for forage annual DM yield and annual NDF, TDN, and CP concentrations. As in Rotz et al. (2014), TDN was predicted from forage NDF concentration:

$$\text{TDN} = [2.863 - 2.62\ (\text{NDF})] + (0.12/2.45)$$

The TSI and WSI, varying between 0 and 1.0, were simulated on a daily basis for the entire growing season (April–October). The TSI was calculated by linear interpolation of a triangular function in which no stress (TSI = 1.0) occurs at the optimum photosynthesis temperature [20°C for alfalfa (Jégo et al., 2015) and 13.5°C for timothy (Bonesmo and Bélanger, 2002)], and in which maximum stress (TSI = 0) occurs below the minimum photosynthesis temperature (5°C for alfalfa and 0°C for timothy) or above the maximum photosynthesis temperature (35°C for both species). The WSI (1.0 = no water stress) was calculated as the ratio of plant available water to critical soil moisture concentration. The amount of water available to plants was calculated with IFSM, taking into account precipitation, evapotranspiration, and water flow to lower soil layers (Rotz et al., 2014). The critical soil moisture concentration (Rotz et al., 2014) was set to half the soil available water-holding capacity (Table 1), giving 45 and 32 mm of water in QSW and QE, respectively, in the 1-m-deep root zone.

The crop growth parameters used in IFSM were previously calibrated and evaluated by Jégo et al. (2015) for alfalfa and timothy with daily average optimum photosynthesis temperatures of 20.0 and 13.5 °C, minimum photosynthesis temperatures of 5 and 0°C, base photosynthetic rates of 25.0 and 17.1 mmol CO_2 m^{-2} s^{-1}, and radiation use efficiencies of 4.0 and 5.0 g DM MJ^{-1} of global radiation, respectively. Only the specific leaf area (leaf area/leaf dry mass ratio) of alfalfa was adjusted from 20 to 26 m^2 kg^{-1} leaf DM based on the findings of Bourgeois et al. (1990), while the specific leaf area of timothy was kept at 30 m^2 kg^{-1} leaf DM.

Virtual Dairy Farms

Virtual dairy farms representative of each area (QSW and QE) were created in IFSM, using characteristics (Table 1) determined from available statistics for dairy farms in these areas in collaboration with a panel of experts in dairy systems and forage crops. The virtual farm representative of the QSW area has 87 lactating cows and grows mostly silage and grain corn (*Zea mays* L.), with small areas of soybean [*Glycine max* (L.) Merrill] and forage crops. The virtual farm representative of the QE area has 72 cows and grows mostly forage crops, with small areas of silage corn and barley (*Hordeum vulgare* L.). In the present simulations with IFSM, all crops were rain fed. All liquid dairy cattle manure (LDM, 8–10% DM) from each virtual farm was partitioned among crop species in order to meet P requirements according to local recommendations (CRAAQ, 2010). Nutrients were applied to forage crops using LDM and purchased mineral fertilizers, in keeping with optimal nutrient conditions (Table 1). The LDM was broadcast in spring, except as otherwise specified (Table 1). For each simulated year, IFSM determines the initial soil N concentration in proportion to the amount of excess N remaining in the soil the previous year.

In the reference period, and in the future climate scenarios without an adaptation strategy, forage crops were harvested three times annually in QSW, and twice in QE. In IFSM, the authorized start of the growing season was set to Day 60 (1 March) for both areas, and from this date, forage can begin to grow immediately after the spring thaw. Accordingly, the simulated dates of the onset of forage growth for the reference period were 5 April in QSW and 5 May in QE (Table 2). Soils chosen as most representative of the two areas were a St. Jude sandy loam (gleyed humo-ferric podzol/mixed, frigid Haplorthod) in QSW and a St. André sandy loam (orthic humo-ferric podzol/mixed, frigid Haplorthod) in QE. Characteristics of the top soil layer (0–15 cm) (Table 1) were obtained from the Canadian Soil Information Service (CanSIS, 2015).

Forage Harvest Dates

Dates on which each forage harvest could begin for the reference period were based on conservative recommended practices and were determined by considering a minimum accumulation of approximately 450°C-d (growing degree-days, GDD, above

Table 1. Characteristics of the virtual dairy farms representative of the Quebec Southwest and Quebec East areas.

Basic farm characteristics	Unit	Quebec Southwest (QSW)	Quebec East (QE)
		Crops	
Total area	ha	142	139
Area of perennial forage species	ha	27.4	93.0
Stand life of forage species	yr	4	4
Number of annual forage harvests	Number yr^{-1}	3	2
Minimum forage NDF concentration at harvest (1st, 2nd, and 3rd cut)	g kg^{-1} DM	500–400–400 (timothy and mixture) 350–350–350 (pure alfalfa)	500–400 (timothy and mixture) 350–350 (pure alfalfa)
Fertilization of perennial forage species			
Nutrients from liquid dairy manure	kg $N–P_2O_5–K_2O$ ha^{-1}	102–34–82	112–34–75
Nutrients from mineral fertilizer	kg $N–P_2O_5–K_2O$ ha^{-1}	100–0–14 (pure timothy) 0–0–14 (mixture and alfalfa)	75–0–21(pure timothy) 0–0–21 (mixture and alfalfa)
Splitting of nutrient application	percent applied in spring and after subsequent cuts	40–30–30 (pure timothy) 100–0–0 (mixture and alfalfa)	70–30 (pure timothy) 100–0 (mixture and alfalfa)
		Animal production	
Number of lactating dairy cows	Number	87	72
Milk production target	L milk cow^{-1} yr^{-1}	8444	7776
		Soil characteristics	
Soil type		St. Jude	St. André
Predominant soil texture in IFSM (surface layer)		Medium sandy loam	Medium sandy loam
Silt–Clay–Sand concentration	g kg^{-1}	350–120–530	290–120–590
Organic carbon concentration	g kg^{-1}	18	22
Available water holding capacity†	mm	90	64
Moist soil bulk density	g cm^{-3}	1.35	1.35

† Difference between water concentration at field capacity and at permanent wilting point, and expressed in mm of water available in soil at a 1-m depth.

5°C) before the first cut, 520°C-d between following cuts, and 500°C-d after the last cut (Bootsma, 1984; Bootsma and Suzuki, 1985; Bélanger et al., 1999). Harvests were allowed to begin on these prescribed dates (Table 2), provided that specific criteria were met, including a minimum DM yield of 400 kg ha^{-1}, a species-specific minimum NDF concentration (Table 1), and little or no rain on the day of mowing (Rotz et al., 2014). Since IFSM is a whole-farm model, it takes into account a number of farm operations competing for machinery, labor, and time. For example, the completion of corn planting takes priority over the first forage cut. This can delay or extend the forage harvest period, but represents realistic on-farm situations.

Simulations of future climate scenarios without adaptation were run, assuming an identical number of annual forage harvests as in the reference period, and identical dates on which harvests were allowed to begin. Simulations for future scenarios were also run with the implementation of an adaptation strategy consisting of earlier harvest dates based on GDD accumulation (same criteria as for the reference period: 450°C-d before the first cut, 520°C-d between following cuts, and 500°C-d after the last cut) and additional cuts in order to take advantage of the longer growing season. In these scenarios with adaptation, the timing of the first cut was 10 to 19 d earlier than in the reference period in QSW, and 11 to 24 d earlier in QE, depending on the future scenario (Table 2). Dates of the second cut were 12 to 24 d earlier in QSW and 18 to 35 d earlier in QE. In QSW, the third cut was 17 to 33 d earlier than in the reference period. One additional cut (fourth cut in QSW, third cut in QE) was added to scenarios NF4.5, NF8.5, and DF4.5. As well, two additional cuts (fourth and fifth cuts in QSW, third and fourth cuts in QE) were added to scenario DF8.5. Except for the harvest schedule and the number of harvests per year, none of the other farm parameters were modified for the adaptation strategy compared to the situation without adaptation.

Table 2. Predicted harvest schedule of an alfalfa-timothy mixture with/without an adaptation strategy in two contrasting areas (Quebec Southwest and Quebec East) for the near (2020–2049) and distant (2050–2079) future periods under representative concentration pathways (RCP) 4.5 and 8.5, simulated with the climate model CanESM2.†

Harvest schedule	Reference period		RCP 4.5, near future		RCP 4.5, distant future		RCP 8.5, near future		RCP 8.5, distant future	
					Quebec Southwest (QSW)					
					Without adaptation strategy (unchanged harvest dates)					
	Dates (DOY‡)	GDD§	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD
Beginning of growth	5 Apr. (95)	0	23 Mar. (82)	0	19 Mar. (78)	0	24 Mar. (83)	0	18 Mar. (77)	0
Cut 1	9 June (160)	458	9 June (160)	592	9 June (160)	654	9 June (160)	591	9 June (160)	747
Cut 2	15 July (196)	516	15 July (196)	594	15 July (196)	646	15 July (196)	612	15 July (196)	724
Cut 3	18 Aug. (230)	519	18 Aug. (230)	595	18 Aug. (230)	640	18 Aug. (230)	602	18 Aug. (230)	716
Remaining GDD		728		909		986		933		1118
					With adaptation strategy (modified harvest dates and additional cuts)					
	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD
Beginning of growth	5 Apr. (95)	0	23 Mar. (82)	0	19 Mar. (78)	0	24 Mar. (83)	0	18 Mar. (77)	0
Cut 1	9 June (160)	458	30 May (150)	458	25 May (145)	447	30 May (150)	456	21 May (141)	450
Cut 2	15 July (196)	516	3 July (184)	513	28 June (179)	526	3 July (184)	525	21 June (172)	519
Cut 3	18 Aug. (230)	519	1 Aug. (213)	523	25 July (206)	524	31 July (212)	516	16 July (197)	524
Cut 4	·	·	2 Sept. (245)	517	23 Aug. (235)	527	1 Sept. (244)	523	9 Aug. (221)	514
Cut 5	·	·	·	·	·	·	·	·	6 Sept. (249)	526
Remaining GDD		728		680		901		717		772
					Quebec East (QE)					
					Without adaptation strategy (unchanged harvest dates)					
	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD
Beginning of growth	5 May (125)	0	26 Apr. (116)	0	13 Apr. (103)	0	24 Apr. (114)	0	9 Apr. (99)	0
Cut 1	3 July (184)	457	3 July (184)	606	3 July (184)	712	3 July (184)	620	3 July (184)	836
Cut 2	14 Aug. (226)	519	14 Aug. (226)	637	14 Aug. (226)	696	14 Aug. (226)	647	14 Aug. (226)	789
Remaining GDD	·	618		754		833		786		959
					With adaptation strategy (modified harvest dates and additional cuts)					
	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD	Dates (DOY)	GDD
Beginning of growth	5 May (125)	0	26 Apr. (116)	0	13 Apr. (103)	0	24 Apr. (114)	0	9 Apr. (99)	0
Cut 1	3 July (184)	457	22 June (173)	455	15 June (166)	448	21 June (172)	451	9 June (160)	449
Cut 2	14 Aug. (226)	519	27 July (208)	519	18 July (199)	517	25 July (206)	516	10 July (191)	518
Cut 3	·	·	3 Sept. (246)	526	19 Aug. (231)	517	31 Aug. (243)	525	6 Aug. (218)	514
Cut 4	·	·	·	·	·	·	·	·	7 Sept. (250)	517
Remaining GDD		618		497		759		561		586

† CanESM2, Canadian Centre for Climate Modelling and Analysis Earth System Model (Arora et al., 2011).

‡ DOY, day of the year.

§ Growing degree-days (GDD, °C-day) were calculated on a 5°C basis from the beginning of growth to the first cut, for each interval between cuts, and from the last cut to 31 December.

Simulation 1: Separate and Combined Effect of Changes in Climate and [CO_2] (Objective 1)

Simulation 1 (Table 3) was run with (i) only climate condition changes (temperature and precipitation) with 346 μmol mol^{-1} of atmospheric [CO_2] for all scenarios; (ii) only elevated [CO_2] with climate conditions from the reference period for all scenarios; and (iii) changes in climate conditions (temperature and precipitation) and elevated [CO_2]. To distinguish the effect attributable solely to timothy or to alfalfa in the forage mixture, and to learn about the synergistic effect from the combination of these two species, simulation 1 was run with (i) pure alfalfa, (ii) pure timothy, and (iii) a mixture of alfalfa and timothy (50:50). The DM yield, change in the percentage of alfalfa in the forage mixture, TSI, and WSI were predicted. This simulation was performed only with the CanESM2 climate model, without adaptation (Table 3).

Simulation 2: Effect of an Adaptation Strategy on Forage Mixture (Objective 2)

Simulation 2 (Table 3) was run for the alfalfa–timothy forage mixture only, and under the combined effect of climate and [CO_2] changes with three climate models (CanESM2, CanRCM4, and HadGEM2), in order to assess the effects of an adaptation strategy on forage DM yield, nutritive value (NDF, TDN, and CP concentrations), and the percentage of alfalfa in the mixture.

RESULTS AND DISCUSSION

Climate Conditions

For the reference period, average GDD accumulations (base 5°C) during the growing season (1 April–31 October) were 2008°C-d in QSW and 1393°C-d in QE, with respective average growing season temperatures of 14.0 and 10.7°C. For the near (2020–2049) and distant future (2050–2079) periods, average monthly temperature (Fig. 2a, 2b) and cumulative GDD during the growing season increased for all future scenarios in both areas compared to those in the reference period (1971–2000). This is in line with previous results from Jing et al. (2013b) and Qian et al. (2013), who predicted an increase in cumulative GDD for overwintering crops across Canada for the future period 2040 to 2069. As expected, increases in temperature (Fig. 2a, 2b) and cumulative GDD for the growing season, averaged across the two agricultural areas, were greater in the distant future (+4.3°C and +821°C-d) than in the near future (+2.3°C and +432°C-d). Differences in temperature and cumulative GDD between RCP 8.5 and RCP 4.5 were greater in the distant future (+1.6°C and +325°C-d) than in the near future (+0.2°C and +39°C-d). Over the entire year, the largest differences in air temperature between future climate scenarios and the reference period were found in December and January, as also observed by Jing et al. (2013b) across Canada. For scenario DF8.5, the corresponding differences ranged from +6.3 to +8.2°C, depending on the climate model (data not shown). In general, the smallest differences in temperature and cumulative GDD relative to the reference period were found with the NF4.5 scenario, and the largest differences were found with the DF8.5 scenario.

For the reference period, average cumulative precipitation during the growing season was 625 mm in QSW and 552 mm in QE. With future scenarios, cumulative precipitation increased slightly, but the difference relative to the reference period never exceeded +81 mm in QSW or +96 mm in QE for the entire growing season (1 April–31 October; Fig. 2c, 2d). For the future period 2040 to 2069, Jing et al. (2013b) and Qian et al. (2013) predicted an average precipitation increase of 64 mm in eastern Canada during the growing season for overwintering crops. Despite this generalized modest increase in future cumulative precipitation, variability was observed in precipitation distribution over time, and a decrease in precipitation was projected for some months with certain models, particularly in September and October in QSW (Fig. 2c), and in August and September in QE (Fig. 2d). This decrease in precipitation for specific months was also predicted across Canada by Jing et al. (2013b), specifically for August and September.

Even with an annual increase in precipitation in the future, the expected increase in evapotranspiration during summer months in Canada (Jing et al., 2013b; Qian et al., 2013) could lead to water

Table 3. Main parameters of simulations 1 (separate and combined effects of climate and atmospheric [CO_2] changes) and 2 (adaptation strategy with modified harvest dates and additional cuts) in IFSM for the reference period (1971–2000) and for the near (2020–2049) and distant future (2050–2079), with the representative concentration pathways (RCP) 4.5 and 8.5.

Simulation parameters		Simulation 1	Simulation 2
Forage crops	Pure alfalfa	×	
	Alfalfa–timothy mixture	×	×
	Pure timothy	×	
Climate parameters	Climate†	×	
	CO_2 concentration	×	
	Climate† + CO_2 concentration	×	×
Climate models	CanESM2	×	×
	CanRCM4		×
	HadGEM2		×
Adaptation strategy	Without	×	×
	With		×
Output variables	DM yield	×	×
	Percentage of alfalfa in the mixture	×	×
	Temperature stress index (TSI)	×	
	Water stress index (WSI)	×	
	Nutritive value		×
Resulting figures and tables		Fig. 3 and Fig. 4	Tables 4, 5, 6

† Climate changes include temperature and precipitation changes.

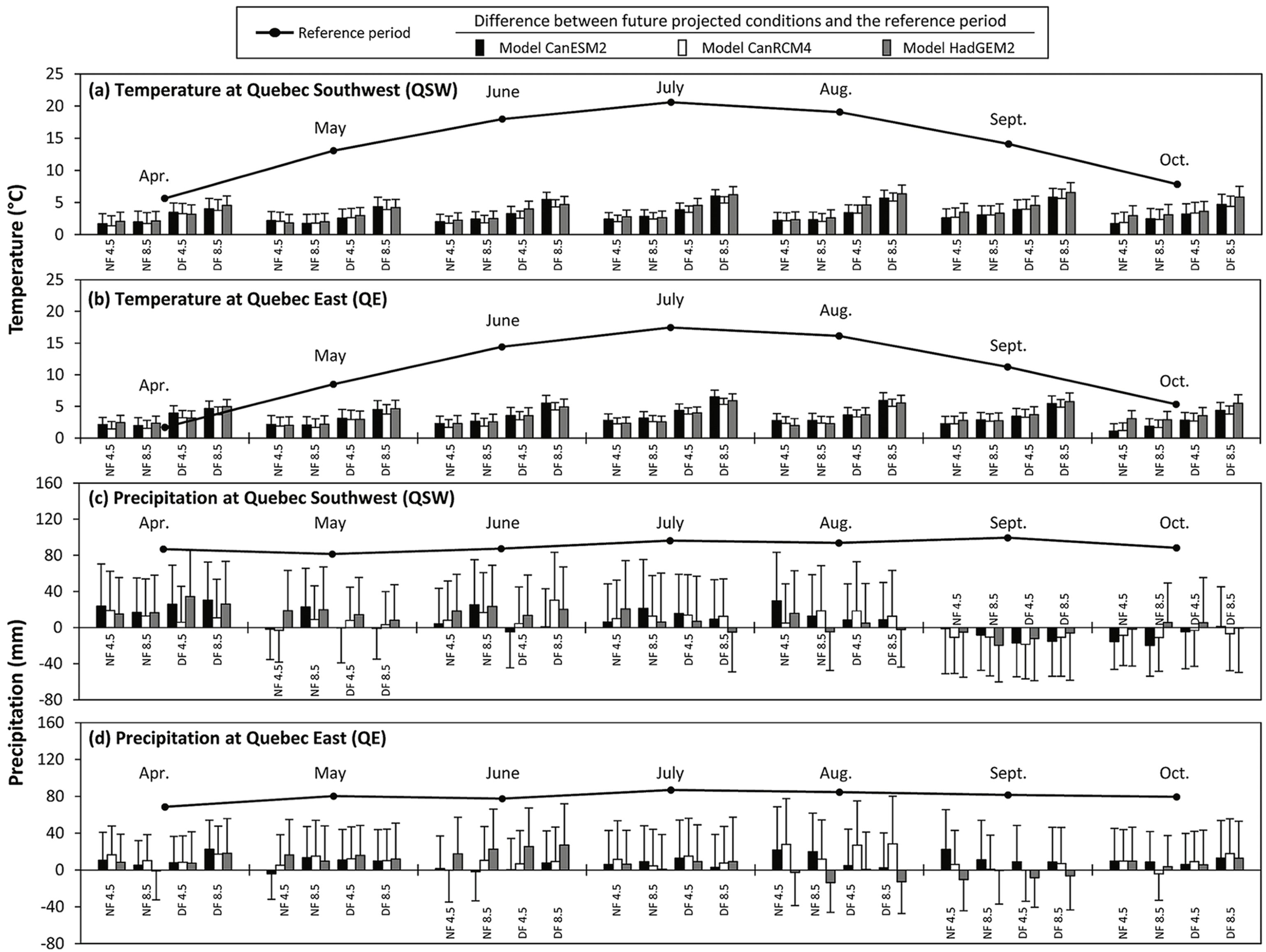

Fig. 2. (curve, a and b) Monthly average air temperature and (curve, c and d) monthly precipitation in two contrasting climate areas in eastern Canada (a and c, Quebec Southwest, QSW; and b and d, Quebec East, QE) during the reference period (1971–2000), and differences (bars) in (a and b) monthly average air temperature and (c and d) monthly precipitation between projected future climate conditions and reference period conditions in the two areas. Projected climate conditions were obtained from several climate models (CanESM2, Canadian Centre for Climate Modelling and Analysis Earth System Model [Arora et al., 2011]; CanRCM4, Canadian Regional Climate Model [Qian et al., 2015b; Scinocca et al., 2015]; HadGEM2, Hadley Centre Global Environment Model [Johns et al., 2006; Martin et al., 2006; Ringer et al., 2006]) for GHG emission scenarios (RCP 4.5 and 8.5) covering near (NF; 2020–2049) and distant (DF; 2050–2079) future periods. Scenarios and reference period conditions are based on data averaged over 300 simulated years. The vertical line on each bar represents the standard deviation of the mean.

stress and reduced forage growth. Similarly, in the northeastern United States, the soil water deficit during summer is predicted to increase by the year 2050 even with little change in the amount of annual precipitation (Hayhoe et al., 2007). Moreover, there is a great deal of uncertainty among climate models and emission scenarios, along with considerable interannual and regional variability, associated with precipitation-related predictions (Hayhoe et al., 2007; Qian et al., 2013).

Simulation 1: Separate and Combined Effect of Changes in Climate and [CO_2]

As reported in previous studies (Hatfield et al., 2011; Izaurralde et al., 2011), predicted changes in forage DM yield varied depending on whether they were caused by change in climate conditions (temperature and precipitation) alone, by elevated atmospheric [CO_2] alone, or by a combination of these factors.

Changes in Climate Conditions (Temperature and Precipitation)

Under future scenarios, in both areas and for both species, the DM yield of the first cut generally increased, while that of subsequent cuts decreased (Fig. 3a, 3b). The marked increase in first-cut yield, which was similar in both areas, can be explained mainly by the greater accumulation of GDD before the first cut in future scenarios without an adaptation strategy: 747°C-d in QSW and 836°C-d in QE in scenario DF8.5, compared to 458°C-d in both areas for the reference period (Table 2). Along with higher temperatures, future scenarios are characterized by an earlier spring thaw and earlier onset of forage growth. In the present study, the first day of crop growth in scenario DF8.5 was 18 and 26 d prior to that of the reference period in QSW and QE, respectively (Table 2). This is in accordance with previous simulations across Canada that predicted that the growth of overwintering crops would begin 13 d earlier (Qian et al., 2013), and specifically that the growth of timothy would begin 21 d earlier (Jing et al., 2013b) for the future period 2040 to 2069.

The decrease in second- and third-cut yield was much larger in QSW than in QE (−1.6 vs. −0.3 Mg ha^{-1}, averaged across future scenarios), a finding that can be attributed mainly to the more acute water and temperature stresses in QSW, as will be discussed later. Growth chamber studies showed that higher timothy yields were obtained with lower daytime temperatures of 17 to 22°C than with higher daytime temperatures of 25 to 27°C (Bertrand et al., 2008; Piva et al., 2013). In the present study, average temperatures in QSW in July and August were 21 and 19°C in the reference period but reached 27 and 25°C in scenario DF8.5, which is higher than the optimum temperature for timothy growth. In contrast, in QE, average temperatures in July and August were 18 and 16°C in the reference period but reached 24 and 22°C in scenario DF8.5. In the case of alfalfa, it is known that summer temperatures as low as 28°C, along with drought, drastically inhibit biological N_2 fixation (Aranjuelo et al., 2007). Therefore, it is likely that forage summer regrowth will be higher in the colder area (QE).

Consequently, in the warmer area (QSW) and across the four future scenarios, annual average DM yield decreased by 11% for pure alfalfa and the alfalfa–timothy mixture, and by 21% for pure timothy, compared to the reference period (Fig. 3a). Particularly significant reductions in annual DM yield were observed in scenario DF8.5, with predicted annual DM yield decreases of 29, 28, and 40% relative to the reference period for pure alfalfa, alfalfa–timothy mixture, and pure timothy, respectively. The DM yield reductions for second and third cuts under future scenarios could not be offset by the increase in the first-cut yield. However, in the colder area (QE), climate change caused an average increase of 7% in the DM yield of pure alfalfa, pure timothy, and alfalfa–timothy mixture across three of the four scenarios (NF4.5, NF8.5, and DF4.5; Fig. 3b). The small decrease in second-cut DM yield could be easily offset by the increase in the first-cut yield. In scenario DF8.5, however, the annual DM yield decreased by 6 to 10% (Fig. 3b). The percentage of alfalfa in the mixture, averaged across all future scenarios, decreased by five percentage points in QSW and increased by three percentage points in QE (Fig. 3a, 3b).

Previous studies have shown that rising temperatures may have a positive or negative effect on yield, depending on the current climatic conditions at a given location, the species-specific critical temperature range for growth and photosynthesis, and soil resources (Hunt et al., 1991; Riedo et al., 1999; Hatfield et al., 2011; Lee et al., 2013). This conclusion is supported by the results of the present simulations, in which rising temperatures along with small changes in precipitation caused reductions in annual forage DM yields of pure timothy, pure alfalfa, and alfalfa–timothy mixture in the warmer area (QSW), compared to increases in the colder area (QE), except in the more drastic scenario, DF8.5 (Fig. 3a, 3b).

Changes in Carbon Dioxide Concentration

The effect of elevated atmospheric [CO_2] alone on forage DM yield was similar in the two areas (Fig. 3c, 3d). When averaged across future scenarios and compared to the reference period, annual DM yield increased moderately in pure alfalfa and in the alfalfa–timothy mixture (+16%), and increased slightly in pure timothy (+4%). Elevated [CO_2] had the most pronounced effect on annual DM yield under scenario DF8.5 (+22% for pure alfalfa and timothy–alfalfa mixture; +7% for pure timothy). The positive effect of increased [CO_2] on legume crops, which has been demonstrated in experiments and modeling studies, appears to be due to the favorable effect of elevated atmospheric [CO_2] on biological N_2 fixation, although the exact mechanism is not clearly understood (Zanetti et al., 1996; Lazzarotto et al., 2010). Moreover, N_2-fixing species have been found to show a greater positive response than non-fixing species to increased atmospheric [CO_2], possibly because N_2-fixing species are able to meet the higher N requirements associated with elevated [CO_2] (Lee et al., 2003). Growth chamber studies have produced divergent results concerning the effect of elevated [CO_2] on timothy yield. Piva et al. (2013) did not observe any response in timothy to an increase in atmospheric [CO_2] from 400 to 600 μmol mol^{-1}, while Kettunen et al. (2007) noted a small increase in timothy yield (+8 to +14%) when the [CO_2] went from 360 to 720 μmol mol^{-1}. Hence, the present results seem reasonable, with a predicted DM yield increase for timothy ranging among the scenarios from +2 to +8% for the two areas. In studies on the growth of forage grasses under future climate conditions, Höglind et al. (2013) with the LINGRA model and Jing et al. (2013b) with the CATIMO model did not consider the effect of elevated atmospheric [CO_2] on timothy because of the lack of evidence of an effect on this grass species. In IFSM, however, elevated atmospheric [CO_2] has a linear fertilization

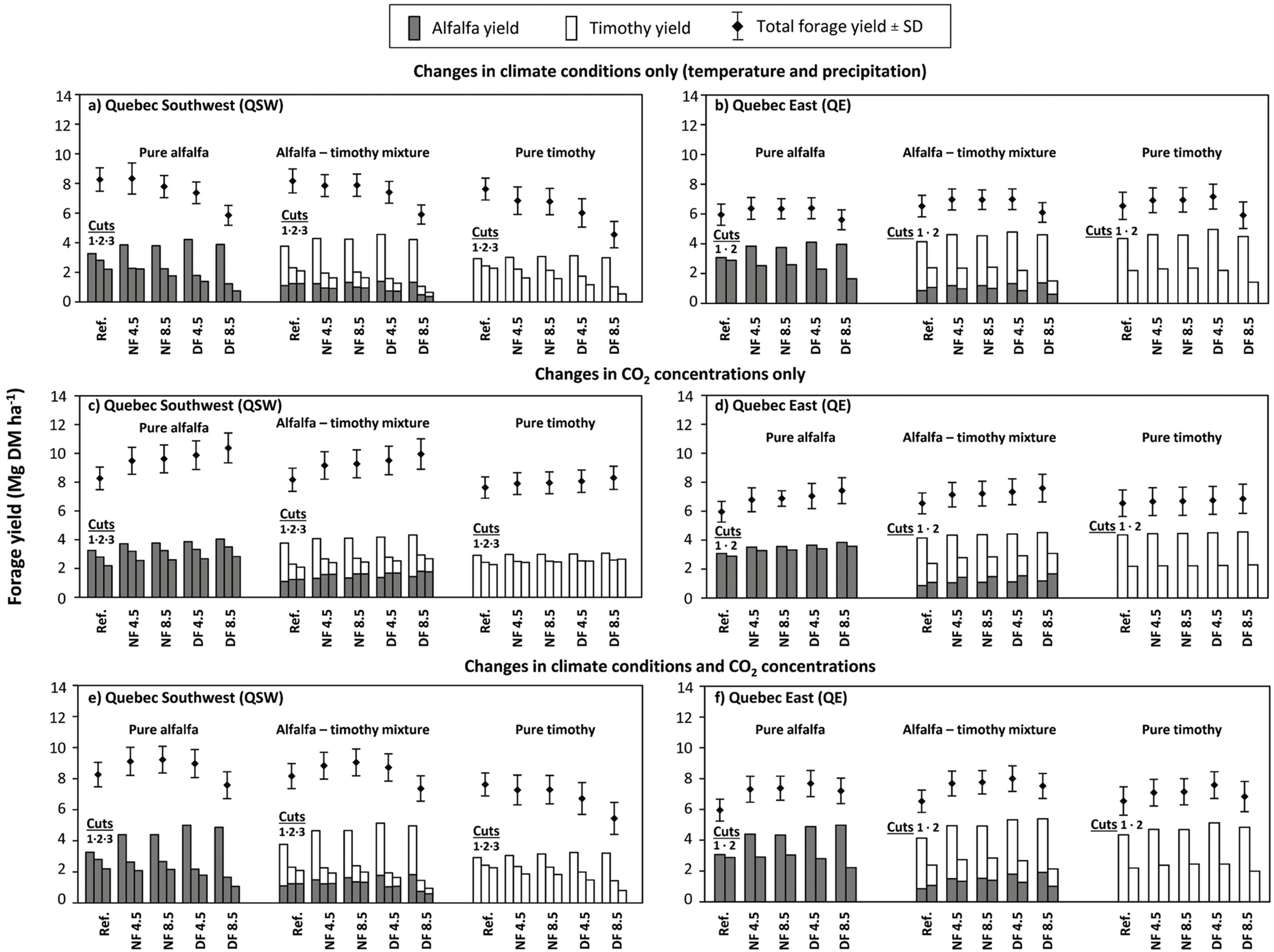

Fig. 3 Predicted DM yields (average of 300 simulated years) of forage crops (pure alfalfa, alfalfa–timothy mixture, and pure timothy) at the first, second, and third cuts (bars) and for the entire season (dots) without any adaptation strategy, for the reference period (ref., 1971–2000) and for near (NF) and distant future (DF) scenarios (RCP 4.5 and 8.5), with the climate model CanESM2 (Canadian Centre for Climate Modelling and Analysis Earth System Model; Arora et al., 2011), and (a, b) under the influence of climate change alone (i.e., temperature and precipitation) with a constant atmospheric CO_2 concentration of 346 μmol mol^{-1}, (c, d) under CO_2 concentration changes only (same climate conditions than the reference period), and (e, f) under climate and CO_2 concentration changes in the two areas studied ([a, c, e] Quebec Southwest, QSW; and [b, d, f] Quebec East, QE).

effect on grass yield (Rotz et al., 2014). This explains the modest but positive response obtained for timothy in the present study.

When averaged across future scenarios, elevated [CO_2] also resulted in an increased percentage of alfalfa in the mixture (+7 percentage points), irrespective of the climate area. This can be explained by the aforementioned greater yield increase for alfalfa than for timothy under elevated [CO_2]. In field-grown legume-grass forage mixtures, the legume delivers N to the grass, enabling the latter to meet the higher N demand that accompanies greater C assimilation under elevated [CO_2]. The increased N demand reduces mineral N availability in the soil, which in turn stimulates biological N_2 fixation by the legume (Zanetti et al., 1996). Hence, the competitive ability of the legume is increased by the presence of non-symbiotic plants under elevated [CO_2] (Zanetti et al., 1996; Hebeisen et al., 1997). This ties in with the conclusion of Soussana and Lüscher (2007) that elevated atmospheric [CO_2] affected the botanical composition of temperate grasslands and induced a decline in the relative proportion of grasses.

Combined Changes in Climate Conditions and Carbon Dioxide Concentration

The combination of climate change and elevated [CO_2] was expected to increase crop growth since, in addition to having a fertilization effect, increased [CO_2] induces the partial closure of stomata in C3 species, which decreases transpiration rate and improves water use efficiency under conditions of temperature and water stresses (Morgan et al., 2004b; Hatfield et al., 2011). As with climate change alone, the combination of climate change and elevated atmospheric [CO_2] affected DM yield differently in QSW and QE (Fig. 3e, 3f). In QE, climate change and elevated [CO_2] taken together increased annual DM yield in all future scenarios. This was expected, since climate change and elevated [CO_2] individually were found to have positive effects in this area. As for increased [CO_2] alone, the effect was greater for pure alfalfa and alfalfa–timothy mixture (+21% on average) than for pure timothy (+9%; Fig. 3f), and the annual percentage of alfalfa in the mixture increased (+9 percentage points, averaged across future scenarios). In QSW, the warmer area, the annual DM yield of pure alfalfa and alfalfa–timothy mixture increased in scenarios NF4.5, NF8.5, and DF4.5 (+9% on average), but decreased in scenario DF8.5 (–9% on average) compared to the reference period (Fig. 3e). Under the more drastic scenario, DF8.5, the markedly unfavorable temperature effect (Fig. 3a) probably more than counterbalanced the modest but favorable effect of elevated [CO_2] (Fig. 3c). Hatfield et al. (2011) pointed out that higher temperature can negate the positive effect of increased [CO_2] on plant growth. In QSW, only timothy yield did not have a positive response to combined changes in climate and [CO_2]; the annual timothy DM yield was lower in scenarios NF4.5, NF8.5, and DF4.5 than in the reference period (–7% on average), and much lower in scenario DF8.5 (–29%; Fig. 3e). Piva et al. (2013) observed that the combined effect of elevated temperature and [CO_2] had little effect on timothy yield. The temperature difference they investigated (+3°C) corresponded to the near future scenario (+2.3°C) used in the present study, for which we likewise found no effect on timothy yield (–2 to +3%). In all future scenarios in both areas, the first-cut yield increased while the yields of second and third cuts did not change or decreased (Fig. 3e, 3f). Similar projections were obtained for timothy in eastern Canada (Jing et al., 2013b) and for forage crops in France (Ruget et al., 2012).

Temperature and Water Stresses

In IFSM, the growth of perennial grasses and legumes depends on the gross photosynthetic rate, which is constrained by the most limiting of four stress factors: ambient temperature, soil water availability, soil N availability, and stored carbohydrate concentration in the plant (Rotz et al., 2014). Climate change is likely to affect directly the first two factors: temperature and water availability. Lower forage DM yields were observed for the second and third cuts under future scenarios only when temperature and precipitation changes were part of the simulation (Fig. 3a, 3b, 3e, 3f), and never when only atmospheric [CO_2] changed (Fig. 3c, 3d). Therefore, temperature or water stress appears to be implicated in this lower forage DM yield.

The extent of the growth reduction due to temperature stress is known to vary among plant species (Lee et al., 2013). In the reference period, the TSI for alfalfa increased during the growing season (temperature stress decreased) until the beginning of July in both areas, then plateaued slightly above 0.80, and decreased until the end of the growing season (Fig. 4a, 4b). Therefore, the temperature of the reference period was suitable (TSI close to 1.0) for alfalfa growth during most of the growing season in both areas. The TSI never rose above 0.86 because its maximum value is 1.0, a value that can only be reached given an optimum photosynthesis daily temperature of 20°C for alfalfa and 13.5°C for timothy. Since the present results were averaged over 300 yr, it was unlikely for the optimum temperature to be reached on the same date every year. As temperature increases in future scenarios, crops in the warmer area will become more exposed to temperature stress than in the colder area. In QSW, the TSI increased at an earlier point in the growing season and decreased at a later point in the season in all future scenarios relative to the reference period. For most of the summer, however, the TSI was lower under future scenarios than in the reference period, indicating that alfalfa was subjected to higher temperature stress (Fig. 4a). The TSI reached its lowest point (maximum stress) in mid-July under scenario DF8.5, with a value of 0.55. In QE, an area with colder temperatures, TSI also increased earlier in the growing season and decreased later in the season, in all future scenarios. However, only scenario DF8.5 induced a decrease in the TSI during the warmer part of the growing season, with its lowest point being 0.68 in mid-July (Fig. 4b). For all other scenarios, the TSI plateaued from the end of June to the end of August, with values ranging from 0.79 to 0.84. Consequently, in QSW, temperature stress in the summer would limit alfalfa growth in all future scenarios, whereas in QE, a colder area, only the most drastic scenario (DF8.5) would limit alfalfa growth.

The growth of timothy, which has a lower optimum photosynthesis temperature than alfalfa, was already limited by temperature stress in the reference period. The TSI began to decrease in June in QSW and in July in QE, and did not return to a peak level until the beginning of September in both areas (Fig. 4c, 4d). The decline in the TSI in the reference period was much smaller in QE (Fig. 4d) than in QSW (Fig. 4c). With all future climate scenarios in both areas, the TSI increased at an earlier point in the growing season, but decreased soon afterward at a lower level than in the reference period. At its lowest point (maximum stress), in mid-July under scenario DF8.5, the TSI for timothy reached 0.37 in

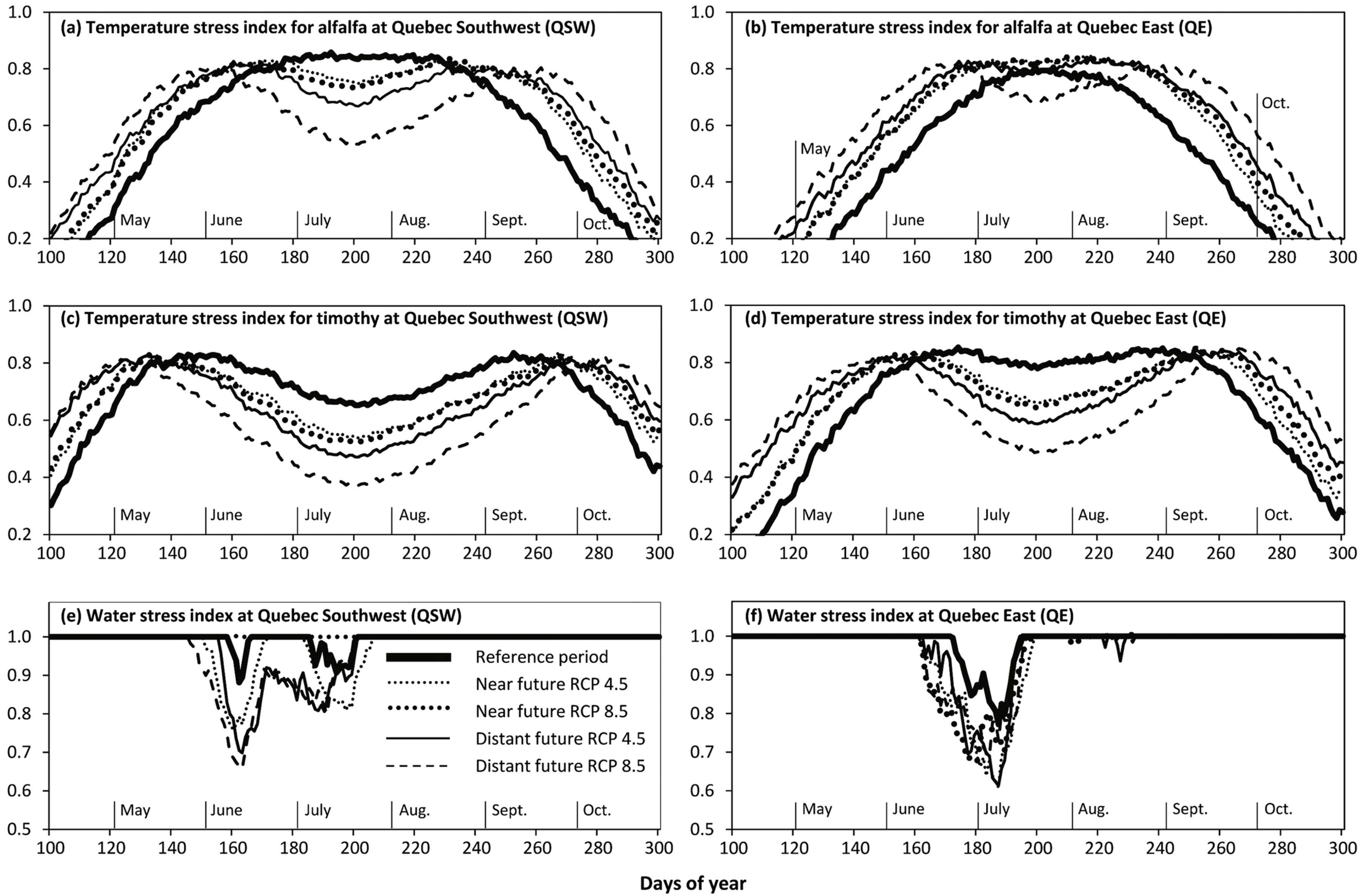

Fig. 4 (a, b) Temperature stress index for pure alfalfa and (c, d) pure timothy, and water stress index for an alfalfa-timothy mixture (e, f), averaged over 300 simulated years, in Quebec Southwest (QSW, a, c, e) and Quebec East (QE, b, d, f) areas between day of the year 100 (10 April) and day of the year 300 (27 October), for the reference period (1971–2000) and for two near (2020–2049) and two distant (2050–2079) future scenarios (RCP 4.5 and 8.5), with climate model CanESM2 (Canadian Centre for Climate Modelling and Analysis Earth System Model; Arora et al., 2011), and under the influence of climate and CO_2 changes, without any adaptation strategy.

QSW (Fig. 4c) and 0.49 in QE (Fig. 4d). Since timothy growth was already affected by temperature stress in the reference period, it will be limited to a greater extent under the climatic conditions expected in the near and distant future. Nevertheless, for both crop species in both areas, temperature stress was less acute in spring under the future climate scenarios. This helps to explain why the first cut had a higher yield in future scenarios than in the reference period. Jing et al. (2013b) reported similar TSI values during spring growth (until the first cut) under future scenarios relative to a reference period.

Water stress is related to temperature stress because the latter increases evapotranspiration. Growth reduction will depend on the severity and duration of water stress (Lee et al., 2013). However, as reported by Hayhoe et al. (2007), even a small period of few weeks of water stress at a critical growth stage can induce a significant loss of plant productivity. In the reference period, the WSI dropped below 1.0 for short periods around mid-June and mid-July in QSW (Fig. 4e) and between the end of June and mid-July in QE (Fig. 4f), but it never went below 0.88 in QSW or 0.77 in QE. Under future scenarios, the duration of the period with a WSI value below 1.0 increased, and the WSI dropped to lower values than in the reference period. In QSW, water stress was more acute under the distant future scenarios than the near future scenarios, and the lowest WSI value (0.66) was observed in scenario DF8.5 (Fig. 4e). In QE, there was no clear evidence that water stress was greater in any given future scenario (Fig. 4f). Jing et al. (2013b) demonstrated that water stress largely explained the decrease in second-cut timothy yield in the coldest agricultural area of eastern Canada. The alfalfa yield across the United States was found to be affected more by precipitation decreases than by atmospheric [CO_2] or temperature changes (Izaurralde et al., 2011). Our results show that forage water stress during summer regrowth is more acute in future scenarios than in the reference period (except for scenario NF8.5 in QSW). Since previous studies have shown that timothy (Bertrand et al., 2008) and, to a lesser extent alfalfa (Aranjuelo et al., 2006, 2007), are sensitive to drought, increased water stress during forage regrowth may help to explain the lower level of regrowth observed in summer. This conclusion only applies to sandy loam soils, which are representative of the two studied areas. A reduction in winter snow cover under future climate change scenarios, which has been predicted in the northeastern United States (Hayhoe et al., 2007) and eastern Canada (Bélanger et al., 2002), could reduce the replenishing of soil water reserves over winter and in turn increase water stress during the growing season (Ruget et al., 2012). This aspect was not taken into account in our simulations with IFSM.

In QSW, scenario NF8.5 was the only future scenario that did not show increased water stress. As shown in Fig. 2, this scenario generated more precipitation than the reference period, and even more precipitation than scenario DF8.5 for the months of June and July. This amount of precipitation may have offset losses due to evapotranspiration. Our results do not allow us to identify the separate effects of temperature and precipitation on yield, since they were not examined individually.

Switching to more drought-tolerant crop species (Prato et al., 2010) or to forage species better adapted to increased water stress and higher temperature (Jing et al., 2013b) is an option that can be considered for the future. This is particularly true for timothy, known for its poor tolerance to dry conditions and high temperatures. Selecting and developing timothy cultivars with improved tolerance to drought and heat is another option that can be used to mitigate the effects of climate change (Jing et al., 2013b, 2014).

Aside from temperature stress during summer, the expected temperature increase in winter under future climate conditions in eastern Canada will likely affect winter survival of perennial crops (Bélanger et al., 2002). Winter survival can be compromised by unsuitable conditions for winter hardening during the fall, inadequate snow cover during the winter, and/or ice encasement of plants and anoxia damage caused by the formation of an ice layer at the soil surface (Bélanger et al., 2002, 2006; Castonguay et al., 2006). Unlike timothy, which is a winter-hardy species (Rapacz et al., 2014), alfalfa is sensitive to harsh winter conditions (Bélanger et al., 2006; Castonguay et al., 2006). Furthermore, it has been demonstrated that elevated atmospheric [CO_2], as predicted in future scenarios, reduces alfalfa freezing tolerance (Bertrand et al., 2007a). Although winter survival of forage crops was not taken into account in our simulations with IFSM, as is the case with most models for temperate grasslands (Rapacz et al., 2014), this aspect should be considered in future studies on forage performance under climate change in northern areas of North America.

Along with abiotic stresses, there is evidence that stress induced in plants by weeds, pests, and diseases will be exacerbated in the future (Hatfield et al., 2011). Alfalfa is particularly vulnerable to pest and disease pressure (Annicchiarico et al., 2015). These effects of climate change were not taken into account in the present study, but warrant further investigation.

Simulation 2: Effect of an Adaptation Strategy on Forage Mixture

The objective of adaptation strategies is to improve cropping system resilience to the stress induced by climate change (Hatfield et al., 2011; Izaurralde et al., 2011), and even to take advantage of it (Lee et al., 2013; Jing et al., 2014). In the case of forage crops, this means taking advantage of the longer growing season to compensate for the losses in summer yield and nutritive value (second and third cuts) predicted in future scenarios. The average frost-free period for overwintering crops across Canada is projected to increase by 23 d, while heat accumulation is projected to increase by 516 GDD (base 5°C) by the period 2040 to 2069, since growth will begin earlier and the first fall frost will be delayed (Qian et al., 2013). For timothy in eastern Canada, Jing et al. (2014) concluded that increased cumulative GDD in the future may allow an additional forage cut. We therefore used a modified harvest schedule as an adaptation strategy, an approach also used elsewhere (Ruget et al., 2012; Prato and Qiu, 2014).

Forage Mixture Yield

With the adaptation strategy, the interval between growth onset and the first cut did not increase in future scenarios compared to the reference period (66 d in QSW and 60 d in QE). However, the interval between first and second cuts in the distant future was reduced by up to 5 d in QSW and 11 d in QE, and the interval between second and third cuts was reduced by up to 9 d in QSW (Table 2). Jing et al. (2013b) in their study of 10 sites across Canada with the CATIMO model also concluded that the interval between first and second cuts would be reduced from 52 to 47 d due to the expected increase in ambient temperatures.

Table 4. Predicted forage dry matter (DM) yields of an alfalfa–timothy mixture for cuts (C) 1, 2, 3, 4, and 5, for the reference period (1971–2000) and for two representative concentration pathways (RCP 4.5 and 8.5) in a near (2020–2049) and distant future (2050–2079), with three climate models (CanESM2, CanRCM4, and HadGEM2†), without and with modifying harvest scheduling as an adaptation strategy.‡ Data are averages over 300 simulated years.

Adaptation	Period	RCP	Model	C1	C2	C3	C4	C5	Annual	SD§
				Mg ha^{-1}						
	1971–2000	–	Ref. period	3.77	2.30	2.09			8.17	0.81
Without adaptation	Near future	4.5	CanESM2	4.65	2.26	1.93			8.83	0.87
			CanRCM4	4.54	2.39	2.09			9.02	0.93
			HadGEM2	4.80	2.46	2.00			9.26	0.83
		8.5	CanESM2	4.66	2.40	1.99			9.04	0.86
			CanRCM4	4.69	2.50	2.16			9.35	0.89
			HadGEM2	4.77	2.51	1.96			9.24	0.88
	Distant future	4.5	CanESM2	5.13	1.94	1.64			8.72	0.88
			CanRCM4	5.18	2.28	1.79			9.25	0.88
			HadGEM2	5.10	2.04	1.36			8.50	0.90
		8.5	CanESM2	4.96	1.45	0.95			7.36	0.82
			CanRCM4	5.06	2.09	1.36			8.51	0.91
			HadGEM2	5.50	1.84	0.91			8.25	0.98
With adaptation	Near future	4.5	CanESM2	3.96	2.06	1.56	1.79		9.37	0.92
			CanRCM4	3.81	2.11	1.74	1.83		9.49	0.95
			HadGEM2	4.01	2.26	1.62	1.83		9.72	0.89
		8.5	CanESM2	3.85	2.26	1.51	1.86		9.47	0.93
			CanRCM4	3.89	2.25	1.66	1.96		9.76	0.96
			HadGEM2	4.01	2.24	1.63	1.73		9.61	0.99
	Distant future	4.5	CanESM2	4.06	2.01	1.20	1.41		8.67	0.90
			CanRCM4	4.01	2.17	1.43	1.48		9.10	0.89
			HadGEM2	3.94	2.13	1.21	1.16		8.43	0.92
		8.5	CanESM2	3.76	1.84	0.83	0.61	1.01	8.05	0.82
			CanRCM4	3.72	2.01	1.26	0.84	1.09	8.92	0.88
			HadGEM2	4.05	2.22	0.97	0.57	0.88	8.69	0.94
				Mg ha^{-1}						
	1971–2000	–	Ref. period	4.14	2.39				6.53	0.72
Without adaptation	Near future	4.5	CanESM2	4.94	2.73				7.67	0.81
			CanRCM4	4.84	2.91				7.75	0.83
			HadGEM2	4.92	3.07				7.99	0.83
		8.5	CanESM2	4.92	2.84				7.76	0.76
			CanRCM4	4.91	2.95				7.86	0.87
			HadGEM2	4.97	3.05				8.02	0.83
	Distant future	4.5	CanESM2	5.34	2.66				7.99	0.83
			CanRCM4	5.32	2.93				8.25	0.87
			HadGEM2	5.30	3.03				8.32	0.83
		8.5	CanESM2	5.38	2.13				7.52	0.81
			CanRCM4	5.49	2.70				8.19	0.87
			HadGEM2	5.77	2.55				8.33	0.86
With adaptation	Near future	4.5	CanESM2	4.15	2.05	2.33			8.53	0.88
			CanRCM4	4.01	2.11	2.50			8.61	0.86
			HadGEM2	4.09	2.33	2.42			8.84	0.86
		8.5	CanESM2	4.07	2.01	2.33			8.41	0.84
			CanRCM4	3.96	2.12	2.39			8.47	0.90
			HadGEM2	4.01	2.30	2.28			8.58	0.91
	Distant future	4.5	CanESM2	4.17	1.86	1.88			7.91	0.86
			CanRCM4	4.00	1.98	2.06			8.04	0.89
			HadGEM2	3.93	2.24	2.04			8.20	0.86
		8.5	CanESM2	4.12	1.71	1.05	1.59		8.47	0.86
			CanRCM4	3.81	1.88	1.34	1.77		8.81	0.85
			HadGEM2	4.14	1.98	1.25	1.56		8.93	0.88

† CanESM2, Canadian Centre for Climate Modelling and Analysis Earth System Model (Arora et al., 2011); CanRCM4, Canadian Regional Climate Model (Qian et al., 2015b; Scinocca et al., 2015); HadGEM2, Hadley Centre Global Environment Model (Johns et al., 2006; Martin et al., 2006; Ringer et al., 2006).

‡ The effects of cutting strategy on plant persistence and stand decline are not considered.

§ SD, standard deviation among DM yields over the 300 simulated years.

Future climate scenarios with an adaptation strategy resulted in increases in annual DM yields that ranged from +5 to +18% in QSW and from +23 to +34% in QE (averaged across climate models; Table 4) relative to the reference period. In QSW, the predicted annual DM yield increase was greater in the near future (+1.40 Mg ha^{-1} on average) than in the distant future (+0.47 Mg ha^{-1} on average). Therefore, under the more extreme scenario (RCP8.5) in the distant future, the adaptation strategy resulted in approximately the same yield as in the reference period, and therefore prevented the yield decrease expected without adaptation. In QE, the predicted DM yield increase was substantial irrespective of the future period or scenario (+1.52 to +2.21 Mg ha^{-1}; Table 4). It can be concluded that, under the more extreme scenario (RCP8.5) in the distant future, the colder area (QE) would benefit more from climate change than the warmer area (QSW). In the cold climate of northern Europe (Iceland, Scandinavia, and Baltic countries), Höglind et al. (2013) predicted an increase in forage DM yield for timothy under future elevated temperatures for the period 2046 to 2065 with an adaptation of harvest dates. Also, Jing et al. (2014) predicted that a colder area in the province of Quebec benefited more from the addition of a third cut for timothy than a warmer area (Normandin, +2.7 Mg DM ha^{-1} vs. Montreal, +2.0 Mg DM ha^{-1}).

The DM yield of the first cut in future scenarios with adaptation was similar to that in the reference period in both areas (–0.13 to +0.23 Mg DM ha^{-1}; Table 4). This contrasts with the findings of Höglind et al. (2013) and Jing et al. (2014), who reported decreases in the first-cut yield for timothy with an adapted harvest schedule and additional cuts. Grass models used by Höglind et al. (2013) and Jing et al. (2014) consider grass growth as part of a cycle in which leaf area development early in the spring regrowth uses organic reserves accumulated the previous fall. Jing et al. (2014) concluded that taking an additional cut at the end of the growing season, when less than 3000°C-d (GDD base 0°C) has accumulated, reduces the yield of the first cut the following year. This effect of an additional fall cut was not taken into account in our simulations. However, as a precaution, the last forage harvest date in every scenario was scheduled so as to preserve a minimum of 500°C-d (base 5°C) until the first fall frost, thus ensuring sufficient organic reserves in the fall every year (Bootsma and Suzuki, 1985).

In future scenarios with adaptation, a decrease in DM yield was projected for the third cut in QSW (–0.5 Mg ha^{-1}) and the second cut in QE (–0.3 Mg ha^{-1}) compared to the reference period. This was similar to the decreases (–0.1 and –0.6 Mg DM ha^{-1}) projected by Jing et al. (2013b) for two areas in eastern Canada. The greater annual DM yield was therefore the result of additional cuts, which is consistent with the results reported by Höglind et al. (2013) and Jing et al. (2014) for pure timothy.

When averaged across future scenarios, the percentage of alfalfa in the mixture increased by four percentage points over the growing season in QSW and by eight percentage points in QE in relation to the reference period (Table 5). The percentage of alfalfa did not change much for the first and second cuts,

Table 5. Predicted percentage of alfalfa in the alfalfa–timothy mixture (50:50 at seeding), for cuts (C) 1, 2, 3, 4, and 5, for the reference period (1971–2000) and for two representative concentration pathways (RCP 4.5 and 8.5) in a near (2020–2049) and distant future (2050–2079) without and with modifying harvest scheduling as an adaptation. Data are averages over 300 simulated years and three climate models (CanESM2, CanRCM4, and HadGEM2†).

Adaptation	Period	RCP	C1	C2	C3	C4	C5	Annual‡
			Quebec Southwest (QSW) area					
			%					
	1971–2000	–	29	53	59			44
Without adaptation	Near future	4.5	32	53	65			46
		8.5	35	56	67			48
	Distant future	4.5	35	53	65			46
		8.5	37	51	63			45
With adaptation	Near future	4.5	26	54	65	73		48
		8.5	28	55	66	74		49
	Distant future	4.5	25	54	67	76		47
		8.5	25	50	62	71	78	47
			Quebec East (QE) area					
			%					
	1971–2000	–	20	44				29
Without adaptation	Near future	4.5	30	48				37
		8.5	31	48				38
	Distant future	4.5	33	47				39
		8.5	35	47				41
With adaptation	Near future	4.5	22	45	56			38
		8.5	23	45	56			38
	Distant future	4.5	21	43	53			36
		8.5	19	40	50	57		37

† CanESM2, Canadian Centre for Climate Modelling and Analysis Earth System Model (Arora et al., 2011); CanRCM4, Canadian Regional Climate Model (Qian et al., 2015b; Scinocca et al., 2015); HadGEM2, Hadley Centre Global Environment Model (Johns et al., 2006; Martin et al., 2006; Ringer et al., 2006).

‡ The annual percentage of alfalfa in the alfalfa–timothy mixture was calculated as the ratio of the sum of alfalfa dry matter (DM) yield from all cuts over the growing season to the sum of total DM yield (alfalfa and timothy) over the same period, multiplied by 100.

Table 6. Predicted concentrations of neutral detergent fiber (NDF), total digestible nutrients (TDN), and crude protein (CP) of an alfalfa–timothy mixture for cuts (C) 1, 2, 3, 4, and 5, for the reference period (1971–2000) and for two representative concentration pathways (RCP 4.5 and 8.5) in a near (2020–2049) and distant future (2050–2079), without and with modifying harvest scheduling as an adaptation strategy. Data are averages over 300 simulated years and three climate models (CanESM2, CanRCM4, and HadGEM2†).

			NDF							TDN							CP						
Adaptation	Period	RCP	C1	C2	C3	C4	C5	Annual‡	SD§	C1	C2	C3	C4	C5	Annual‡	SD§	C1	C2	C3	C4	C5	Annual‡	SD§
Quebec Southwest (QSW) area																							
			g kg^{-1} DM																				
	1971–2000	–	473	397	395			429	18	762	784	789			776	13	186	232	240			213	8
Without adaptation	Near future	4.5	497	411	401			452	19	733	763	775			751	14	182	242	241			211	9
		8.5	505	436	419			462	20	727	744	758			740	15	195	228	246			214	13
	Distant future	4.5	504	419	401			465	21	722	750	766			737	17	184	253	243			210	9
		8.5	513	433	408			482	24	705	734	753			718	20	189	270	256			212	11
With adaptation	Near future	4.5	499	399	394	387		435	10	738	776	774	794		765	10	181	237	243	233		214	7
		8.5	498	402	393	386		436	16	737	774	774	793		764	11	184	238	242	232		215	8
	Distant future	4.5	496	405	397	385		442	18	739	765	764	784		757	12	180	240	248	229		210	8
		8.5	462	427	415	385	373	428	17	769	746	747	770	793	766	12	180	244	262	240	225	214	9
Quebec East (QE) area																							
			g kg^{-1} DM																				
	1971–2000	–	523	397				473	15	731	799				758	13	173	227				193	9
Without adaptation	Near future	4.5	542	411				494	17	695	777				725	16	180	229				198	9
		8.5	544	409				494	17	693	776				724	16	182	227				199	9
	Distant future	4.5	554	418				507	19	675	763				705	18	185	233				201	10
		8.5	566	422				524	21	653	749				681	21	192	255				209	10
With adaptation	Near future	4.5	518	395	392			448	12	725	785	802			764	11	175	232	234			207	6
		8.5	519	393	390			447	13	725	784	801			763	11	176	231	234			207	7
	Distant future	4.5	516	399	391			451	13	729	775	788			757	11	172	237	235			205	7
		8.5	501	415	385	381		437	16	741	757	776	801		764	12	169	246	248	238		213	7

† CanESM2, Canadian Centre for Climate Modelling and Analysis Earth System Model (Arora et al., 2011); CanRCM4, Canadian Regional Climate Model (Qian et al., 2015b; Scinocca et al., 2015); HadGEM2, Hadley Centre Global Environment Model (Johns et al., 2006; Martin et al., 2006; Ringer et al., 2006).

‡ Annual NDF, TDN, and CP concentrations were calculated proportionally to each cut contribution to annual DM yield.

§ SD, standard deviation over the 300 simulated years.

but increased for the third cut in QSW. For additional cuts, it reached high values of 71 to 78% in QSW and 53 to 57% in QE (Table 5). In addition to being more responsive to elevated [CO_2] than grasses, legume species are less prone to photosynthetic acclimation, a phenomenon that reduces the plant response to elevated atmospheric [CO_2] by inhibiting photosynthetic capacity after long-term exposure (a few weeks to months) (Irigoyen et al., 2014). Indeed, the ability of legume species to increase the C sink through symbiotic associations with bacteria or arbuscular mycorrhizal fungi prevents this phenomenon, provided that no growth-limiting factors (e.g., insufficient N or P supply) are present (Irigoyen et al., 2014). Although elevated temperature and [CO_2] might favor alfalfa in the mixture, the risk of winter damage to alfalfa is expected to increase with rising temperatures (Bélanger et al., 2002). Future changes in fall and winter conditions may have a negative effect on crop hardening and survival of winter sensitive species (Bélanger et al., 2002; Höglind et al., 2013). This was not addressed in the present study.

The use of multiple climate models makes it possible to quantify the uncertainty due to climate predictions (Höglind et al., 2013). In the present study, differences in annual forage DM yield were observed among the three climate models (CanESM2, CanRCM4, and HadGEM2) for a given scenario (Table 4). With adaptation, these differences [(highest value – lowest value) / lowest value × 100] ranged from 2.0% (8.58 Mg DM ha^{-1} with HadGEM2 vs. 8.41 Mg DM ha^{-1} with CanESM2) in scenario NF8.5 in QE to 10.8% (8.92 Mg DM ha^{-1} with CanRCM4 vs. 8.05 Mg DM ha^{-1} with CanESM2) in scenario DF8.5 in QSW. Specifically for the first cut, differences among climate models averaged 5.3% and never exceeded 9.0% (scenario DF8.5 in QSW), which is in the same range than similarly calculated values reported by Jing et al. (2013b) and Höglind et al. (2013) for first cut DM yield in timothy (5.5–10%). Uncertainties related to IFSM predictions were also low and in the same range as those reported for climate models. Jégo et al. (2015) compared measured yield of an alfalfa–timothy mixture over 2 yr with simulated yield from IFSM, and found that the latter was underestimated by only 6%. The IFSM was also accurate in predicting each forage cut of the mixture within the growing season.

Forage Mixture Nutritive Value

Without the adaptation strategy, the annual NDF concentration of the alfalfa–timothy mixture was greater under all future scenarios (+34 g kg^{-1} DM, averaged across future scenarios and areas) than in the reference period (Table 6), particularly in scenario DF8.5 (+52 g kg^{-1} DM, averaged across areas). This increase under all future scenarios was mainly attributable to increases in the first and second cuts in QSW and in the first cut in QE. This was expected since higher temperatures and GDD accumulation under future scenarios will likely cause forage crops to reach a more advanced phenological stage at harvest (Izaurralde et al., 2011) and, hence, a greater NDF concentration.

With adaptation, the additional cuts in both areas under all future scenarios had lower NDF concentrations (373–392 g kg^{-1} DM among areas and scenarios) than the first cut (Table 6). In QE, this contributed to a marked decrease in forage annual NDF concentration (–25 to –36 g kg^{-1} DM; Table 6) in all future scenarios compared to the reference period. In QSW, however, the annual NDF concentration of the alfalfa-timothy mixture increased modestly under scenarios NF4.5, NF8.5, and DF4.5 (+6 to +13 g kg^{-1} DM; Table 6) compared to the reference period, but remained unchanged under scenario DF8.5. In scenarios NF4.5, NF8.5, and DF4.5, the NDF concentration of the first cut was much higher than in the reference period (+23 to +26 g kg^{-1} DM). The earlier harvest date for the first cut in most future scenarios (NF4.5, NF8.5, and DF4.5) was insufficient to counterbalance the faster growth and development of the alfalfa–timothy mixture under higher temperatures, and therefore its high NDF concentration. Nonetheless, this increase in NDF concentration was smaller than for simulations without adaptation. Recent results from a meta-analysis of the effects of climate change on the nutritive value of pure forage stands showed that elevated [CO_2] and temperature will not affect forage structural carbohydrate concentrations (NDF, acid detergent fiber, and acid detergent lignin) or DM digestibility, provided that farmers harvest their crops earlier under climate change (Dumont et al., 2015).

The concentration of total digestible nutrients (TDN) provides an estimate of forage energy density and is used in the calculation of the net energy for lactation (Harlan et al., 1991; NRC, 2001). Without adaptation, the TDN concentration of the alfalfa–timothy mixture was less for all cuts under all future scenarios than in the reference period (Table 6), and the lowest values were reached under scenario DF8.5. This is in accordance with the aforementioned results for NDF concentration because the TDN concentration usually decreases with increasing NDF concentration. With adaptation, forage TDN concentrations for the first two cuts in QSW and QE were greater than without adaptation, but were still lower than in the reference period in most scenarios. Even though TDN concentrations for additional cuts were greater than those for the previous cuts, the resulting annual TDN (weighted average between cuts) was slightly reduced in QSW (–10 to –19 g kg^{-1} DM) and similar in QE (–1 to +6 g kg^{-1} DM) compared to the reference period.

Annual CP concentration did not change under all future scenarios in QSW, with or without adaptation (–3 to +2 g kg^{-1} DM; Table 6). The well-documented decrease in grass protein concentration due to elevated atmospheric [CO_2] (Milchunas et al., 2005; Soussana and Lüscher 2007; Irigoyen et al., 2014; Dumont et al., 2015) and elevated temperature (Wan et al., 2005) was probably offset by the increased percentage of alfalfa in the mixture in the present study. The beneficial effect of high legume abundance in this context has been described in a literature review (Soussana and Lüscher, 2007) and a recent meta-analysis (Dumont et al., 2015). In QE, however, annual CP concentration increased slightly in future scenarios; the increase was greater with the adaptation strategy than without it (+15 vs. +8 g kg^{-1} DM), and the largest increase was found in scenario DF8.5 with adaptation (+20 g kg^{-1} DM compared to the reference period). A lower decrease in grass CP concentration relative to that in QSW and a greater increase in the percentage of alfalfa probably explain this increase in annual CP concentration under future scenarios.

CONCLUSIONS

Our simulations with the IFSM indicated that, under future climate conditions characterized by rising temperature and a slight increase in precipitation and without adaptation, annual forage yield of alfalfa and timothy will slightly increase in the colder area

(QE) but decrease in the warmer area (QSW). In both areas, first-cut yield will increase because of increased GDD accumulation, while summer regrowth yield will be negatively affected by increasing water and temperature stresses, especially in the warmer area (QSW). Regional-level studies are therefore needed to examine the effect of climate change on forage crops in the northern areas of North America. Under elevated atmospheric [CO_2], alfalfa will respond more positively than timothy, resulting in an increased percentage of alfalfa in the alfalfa–timothy mixture. Under the combination of climate change and elevated [CO_2], forage yield will increase in most scenarios except in the more drastic scenario (DF8.5) in QSW, and nutritive value will be reduced in all scenarios. With the implementation of an adaptation strategy consisting of a modified harvest schedule including additional forage cuts, yield will be increased under all future scenarios, and forage nutritive value will be maintained, mostly because of additional cuts.

Only the alfalfa–timothy mixture was considered in this study, but other forage mixtures could be considered in future work and might be more suitable to future climate conditions in eastern Canada. Finally, the next step will be to validate the environmental and economic outputs under current climate conditions to ultimately simulate the overall performance of dairy farms in eastern Canada under future climate scenarios.

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