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Projected impact of future climate conditions on the agronomic and environmental performance of Canadian dairy farms

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ABSTRACT

Climate change is expected to increase agricultural productivity in Canada and in other northern countries but this increase will likely affect the environmental performance of dairy farms, one of the most important agricultural sectors in Canada. The objective of this study was to project the impact of climate change on the agronomic and environmental performance of a virtual dairy farm in each of three climatically contrasting areas of Canada through near future (2020–2049) and distant future (2050–2079) periods, using the Integrated Farm System Model (IFSM) and three climate models (CanESM2, CanRCM4, and HadGEM2). Under future climate conditions and relative to a reference period (1971–2000), projected yields of perennial forages and warm-season crops increased, whereas those of small-grain cereals decreased slightly. Projected ammonia emissions increased on virtual farms of the three areas and in all future scenarios (+ 18% to + 54%). Methane emissions from manure storage increased (+ 26% to + 120%), whereas those from enteric fermentation and field manure application decreased. Projected farm N_2O emissions changed only slightly relative to the reference period. Fossil fuel CO_2 emissions related to field operations increased slightly, due to a larger number of forage cuts per year in future scenarios, but CO_2 emissions related to grain drying decreased substantially. Projected losses of P increased on virtual farms of the three areas. The projected reactive N footprint of dairy farms in future scenarios varied more (− 15% to + 46%) relative to the reference period than the C footprint (− 5% to + 9%). Although greenhouse gas mitigation should be a priority for dairy farms under future climate conditions, it should not overshadow the need for strategies to reduce reactive N losses.

1. Introduction

Dairying in Canada and elsewhere is known to have significant environmental impacts. Total greenhouse gas (GHG) emissions from Canadian milk production, based on annual milk production of 81.8 million hL in 2015 (Canadian Dairy Information Centre, 2015), can be estimated at 8.4 Mt CO_2 equivalent (CO_2eq) (Quantis Canada et al., 2012). Nevertheless, the environmental impact of dairy farms is not limited to GHG emissions, as the dairy sector also generates NH_3 emissions (Sheppard et al., 2011b) and contributes to water pollution through nitrate and P losses (Paul and Zebarth, 1997; Simard et al., 1995), as has been demonstrated in Canadian studies.

Although a number of recent studies proposed mitigation measures for reducing the environmental impact of Canadian dairy farms (Hawkins et al., 2015; Chai et al., 2016; Jayasundara et al., 2016), little research has sought to project how climate change will affect the environmental performance of Canadian dairy farms in the future. Based on projections derived for many northern regions in the world (Tatsumi

Abbreviations: CAB, Central Alberta; CanESM2, Canadian Centre for Climate Modelling and Analysis Earth System Model; CanRCM4, Canadian Regional Climate Model; CHU, crop heat unit; CO_2eq, CO_2 equivalent units; DF, distant future; DM, dry matter; FPCM, fat- and protein-corrected milk; GDD, growing degree day; GHG, greenhouse gas; HadGEM2, Hadley Centre Global Environment Model version 2; IFSM, Integrated Farm System Model; NF, near future; QE, Quebec East; QSW, Quebec Southwest; RCP, representative concentration pathway; TAN, total ammoniacal nitrogen

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et al., 2011), climate change can be expected to have a positive impact on crop productivity in Canada given the expected increased CO_2 concentration, warmer temperature, and longer growing season (Qian et al., 2016a, 2016b; Smith et al., 2013; Wang et al., 2012). However, Canadian studies using simulation models have projected an increase in N_2O emissions from crop production systems as a consequence of higher N rates required to support expected greater crop yield (Smith et al., 2013), as well as an increase in annual NO_3 losses from an agricultural watershed due to expected increase in precipitation (Dayyani et al., 2012). Climate change can reasonably be expected to affect other environmental emissions as well, since it is known, for example, that higher temperatures increase NH_3 and CH_4 emissions from manure (Sheppard et al., 2011b; Jayasundara et al., 2016) and that an increase in precipitation intensity leads to higher P losses (Messing et al., 2015). A better understanding of the overall agronomic and environmental effects of changes in temperature, precipitation, and atmospheric CO_2 concentrations on dairy farming through modelling would enable the identification of the best suited mitigation measures and adaptation strategies for sustainable production in the future (Rotz et al., 2016).

A dairy farm is a complex system, and comprehensive whole-farm simulations are required to describe the internal cycling of nutrients on the farm and the nutrient exchange that occurs between the farm and its environment (Schils et al., 2007). Several farm-scale models have been developed in recent years, such as DairyWise in the Netherlands (Schils et al., 2007), WFM (Whole-Farm Model) in New Zealand (Beukes et al., 2008; Wastney et al., 2002), GAMEDE (Global Activity Model for Evaluating the sustainability of Dairy Enterprises) in France (Vayssières et al., 2009a, 2009b), and the Integrated Farm System Model (IFSM) in the United States (Rotz et al., 2015). The IFSM is the only process-based farm-scale model that has been developed to represent dairy, beef, and cash-crop farms in the temperate regions of the northern United States and southern Canada. The model provides an assessment of the economic and environmental sustainability of dairy farms (Rotz et al., 2014). The model's components include crops and soils, harvest and storage, animal feeding, manure storage and handling, and economic analysis (Rotz et al., 2015). Jégo et al. (2015) previously showed that IFSM can be used to simulate the current yield and nutritive value of perennial forage crops and annual crops in eastern Canada. Thivierge et al. (2016) used IFSM to simulate the future yield and nutritive value of an alfalfa (*Medicago sativa* L.) and timothy (*Phleum pratense* L.) mixture in eastern Canada. Environmental losses simulated by IFSM (e.g. NH_3 and GHG emissions; N and P losses to water) have been compared with reports in the literature and with farm measurements and have been found to be in the realistic range (Chianese et al., 2009a, 2009b, 2008; Rotz et al., 2014, 2011).

The objective of this study was to examine the projected impact of climate conditions in the near (2020–2049) and distant (2050–2079) future on the agronomic and environmental performance of one virtual dairy farm in each of three climatically contrasting areas of Canada, by using IFSM with three climate models and under two representative concentration pathways (RCP 4.5 and 8.5). The main hypotheses were that under future climate conditions, (1) yield would increase for most crops except for small-grain cereals, (2) emissions of N_2O, CH_4, and NH_3 in the atmosphere as well as losses of N and P in water through runoff and leaching would increase, and (3) N and C footprints would increase, particularly in the distant future.

2. Materials and methods

2.1. Climate scenarios and weather data

A virtual dairy farm was created for each of three climatically contrasting agricultural areas in Canada: Central Alberta (CAB) in the Prairies Ecozone, Quebec Southwest (QSW) in the Mixedwood Plains Ecozone, and Quebec East (QE) in the Atlantic Maritime Ecozone (Fig. 1). For each virtual farm, daily minimum and maximum air temperatures, precipitation, and solar radiation were retrieved from the nearest weather stations for the 1971–2000 reference period (Fig. 1).

The impact of climate change on dairy farms was studied by comparing IFSM predictions derived from synthetic climate data representative of the reference period (1971–2000) with predictions derived from synthetic climate data for the near future (NF; 2020–2049) and the distant future (DF; 2050–2079). For both of these future periods, two radiative forcing scenarios of atmospheric GHG concentration were applied: representative concentration pathways (RCP) 4.5 and 8.5. In RCP 4.5, GHG emissions increase only slightly until around 2040 and decline thereafter, while in RCP 8.5, GHG emissions keep increasing over time (IPCC, 2014). Both RCP 4.5 and 8.5 lead to an increase in atmospheric CO_2 concentration in the future, but to a greater extent in RCP 8.5. The four future scenarios investigated in the present study are identified hereafter 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). Atmospheric CO_2 concentrations averaged 346 μmole mol^{-1} for the reference period; 447 and 469 μmole mol^{-1} for scenarios NF4.5 and NF8.5, respectively; and 514 and 639 μmole mol^{-1} for scenarios DF4.5 and DF8.5 (RCP Database version 2.0.5; Meinshausen et al., 2009).

Climate scenarios used in this study were developed based on climate change simulations by three climate models: (1) the second-generation Canadian Centre for Climate Modelling and Analysis Earth System Model (CanESM2) (Arora et al., 2011) and (2) the Hadley Centre Global Environment Model version 2 (HadGEM2) (Johns et al., 2006; Martin et al., 2006; Ringer et al., 2006), which are global climate models, and (3) a newly developed Canadian Regional Climate Model (CanRCM4) (Scinocca et al., 2015; Qian et al., 2016b). To obtain acceptable estimates of climate risks, series of 300-yr synthetic weather data each representing a 30-yr period were generated for each of these models and RCPs, as well as for the reference period, using the stochastic weather generator AAFC-WG (Hayhoe, 2000; Qian et al., 2016b, 2004). The 300-yr synthetic weather data were then used to run the IFSM model.

All three climate models used in the present study account for the greater likelihood of occurrence of extreme events in the future as determined by the dynamical processes in the models, but regional climate models like CanRCM4 are often more reliable than global climate models when it comes to simulating extremes at the regional scale. Changes in the likelihood of occurrence of extreme events are accounted for in the climate scenarios we used in this study since the stochastic weather generator AAFC-WG is able to reproduce historical climate extremes and to project changes in the future (Qian et al., 2008; Qian et al., 2010). Finally, because IFSM uses daily climate data as an input, it can account for some extreme events (e.g. very high temperatures, drought or soil water saturation). However, other extreme weather events such as hail or wind gusts are beyond the scope of this model.

2.2. Projected climate conditions

Table 1 describes the projected climate characteristics of the three virtual farms (CAB, QSW, and QE), derived from averaging the results from the three climate models. The average daily growing degree-days (GDD) or crop heat units (CHU) were calculated as follows:

$$\text{Average daily GDDs} = T_{mean} - 5.0 \text{ (if } T_{mean} < 5.0, \text{GDDs}=0.0)$$

$$\text{Average daily CHUs} = [1.8(T_{min} - 4.4) + 3.33(T_{max} - 10) - 0.084(T_{max} - 10)^2]/2$$

where T_{mean} is the average daily temperature in degrees Celsius, T_{min} is the daily minimum temperature set at 4.4 °C if < 4.4 °C, and T_{max} is the daily maximum temperature set at 10 °C if < 10 °C, as per Brown and