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Assessing the effects of climate change on crop production and GHG emissions in Canada

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ABSTRACT

Regions in northern latitudes are likely to be strongly affected by climate change with shifts in weather that may be conducive to increased agricultural productivity. In this study the DNDC model was used to assess the effect of climate change on crop production and GHG emissions at long-term experimental sites in Canada. Crop production in the model was parameterized using measured data, and then simulations were performed using historical weather (1961–1990) and future IPCC SRES climate scenarios (2040–2069). The DNDC model predicted that for western Canada under the SRES scenarios and no change in cultivar, yields of spring wheat would increase by 37% and winter wheat by 70%. Corn responded favorably to an increase in heat units at the eastern site with a 60% increase in yields. At all locations, yields were projected to increase further when new cultivars with higher GDD requirements were assumed. These increases were notable considering that the estimated soil water deficit indices indicated that there could be less water available for crop growth in the future. However, when accounting for increased water use efficiency under elevated CO_2, DNDC predicted less crop water stress. Nitrous oxide emissions per ton of wheat were projected to increase across most of western Canada by about 60% on average for the A1b and A2 SRES scenarios and by about 30% for the B1 scenario. Nitrous oxide emissions per unit area were predicted to increase under corn production at the eastern location but to remain stable per ton of grain. Model results indicated that climate change in Canada will favor increased crop production but this may be accompanied by an increase in net GHG emissions for small grain production.

1. Introduction

On a global scale there are many indications that climate change is occurring (Tebaldi et al., 2006; Oreskes, 2004) and that this change will continue and could result in major shifts in biomes by the turn of the century (Bergengren et al., 2011). Staudinger et al. (2012) hypothesized that biomes can be tied to climate thresholds whereby a small change can result in a shift. Effects of climate change on regional ecology are predicted to be major in North America's Great Plains and Great Lakes areas (Bergengren et al., 2011), areas which account for a large proportion of North American agricultural production. Changes in climate will affect biodiversity, soil fauna and microbial activity and could greatly influence the type and productivity of cropping systems in these regions. Increased temperature and water stress, and more extreme weather events over the next 50 years could decrease crop productivity in many regions of the world; however, in cooler regions such as in Canada the effect of climate change on production could be beneficial (Qian et al., 2013, 2012, 2011, 2010b). In a review focussing on the implications of climate change for crop yields, Parry (2007) concluded that crop yields have the potential to increase at mid and high-mid latitudes but may generally decrease in the tropics and subtropics.

There is currently a general trend of increased crop production in Canada. For example, yields of grain corn in eastern Canada and spring wheat in western Canada have increased by 64% and 57%, respectively, since 1980 (Statistics Canada, 2010). The yield increase can be attributed to improved cultivars, improved management and changes in climate. Based on favorable temperature-based climate indices, it is expected that yields will continue to increase, however, there may be negative consequences that will impact agricultural production through the introduction of new diseases and pests and more frequent extreme climate events (Rosenzweig et al., 2001).

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Process-based models have been developed which examine the effects of climate, soil properties and agricultural management on crop productivity and several of these have been employed to estimate the effect that climate change may have on biomass production and sustainability (Pan et al., 2013; Abdalla et al., 2011; Wang et al., 2011; Smith et al., 2009a,b; Li, 2007; Berntsen et al., 2006; Olesen, 2005). The CLIMCROP model was used to evaluate the influence of climate change on productivity in Danish Agricultural systems (Olesen, 2005), and it predicted that the yields of winter wheat and spring barley would increase by 13% and 17% under the HCGG scenario by 2050 and potato and grass production would increase by 9% and 12%. A study by Smith et al. (2009a), using the Century model, indicated that even when crop yields increased in eastern Canada, soil carbon was often lost due to greater rates of decomposition. Pan et al. (2013) used the DAYCENT model to evaluate the vulnerability of agricultural soils to SOC loss under three climate scenarios (SRES-A1b, SRES-A2 and SRES-B1) for two GCM's (Canadian Centre for Climate Modeling and Analysis Model [CaGCM] and Météo-France Centre National Recherches Météorologiques [FrGCM]) on a corn–soybean rotation in the Midwestern United States. Results suggested that under all climate scenarios SOC would decline slightly by the mid-21st century even though NPP would increase by 22% and 14% under both the CaGCM and FrGCM scenarios respectively. The increase in NPP was offset by an increase in soil respiration, which led to a slight loss in SOC. A study by Smith et al. (2009b) where the DNDC model was used to estimate the effect of climate change on net GHG emissions at 10 locations around the world also found that SOC was generally lost under climate change and there were greater rates of loss in cooler climatic zones. In this study the DNDC model did not include the effect of CO_2 fertilization on increased water and N use efficiency nor the effect of temperature stress during anthesis, factors which could strongly influence crop production and C inputs. Wang et al. (2011) using the DSSAT model, predicted that wheat yields in southern Saskatchewan in the 2040–2069 time period would increase by 41–74% relative to the 1961–1990 historical period. The effect of heat shock during anthesis was also not included in this model; thus yield increases may have been overestimated.

Although several modeling studies have examined the effect of climate change on specific components of agricultural cropping systems, there has been little effort to estimate the effect from an ecosystem perspective including both crop growth and environmental sustainability. Also, it is important that models be updated using the latest experimental data and that they respond well to water, nutrient and temperature stresses. It is our hypothesis that trends in increased temperature-based indices in Canada when coupled with increases in water and nitrogen use efficiency of crops under higher CO_2 fertilization could result in a general positive feedback on crop production with the opportunity to shift to cultivars or crop species that favor more temperate climates The objectives of this study are to: (i) update the DNDC model with new information describing the effect of climate on crop growth, (ii) estimate temperature and water based climate indices as an indicator of changes in climate that may affect crop growth (iii) use the improved DNDC model to assess the effect of climate change on crop production, soil carbon change and N_2O emissions at several locations in Canada, and (iv) identify cropping systems that perform well under projected climate conditions.

2. Methodology

2.1. DNDC model

The DNDC model (DNDC (i.e., DeNitrification–DeComposition) by Li (2000) is a well-known mathematical model used to simulate carbon and nitrogen biochemistry for agricultural systems over a wide range of agricultural management, soil and climatic conditions. It is able to estimate crop growth, soil temperature and moisture regimes, C&N dynamics, and trace gas emissions, reporting at a daily time scale. DNDC has been parameterized and tested for its ability to predict soil temperature, soil water content, soil N content, and N_2O emissions at experimental sites in eastern and western Canada (Smith et al., 2002, 2008). It has been used to estimate the inter-annual variations in N_2O emissions at a national level (Smith et al., 2004) and effect of residue removal on soil organic matter (Smith et al., 2012). A tool, based on this model, was developed for predicting effects of agricultural management on GHG emissions (Smith et al., 2010). The model was also used to predict the effect that climate may have on GHG emissions at various locations around the world (Smith et al., 2009b). More recently, an empirical crop growth model was developed to improve estimates of crop biomass in Canada (Kröbel et al., 2011).

2.1.1. Improvement of the DNDC model to simulate effects of climate

Initial investigations using the DNDC model to simulate crop productivity in our current study indicated that the temperature stress applied to crop growth in non-optimal temperature ranges was smaller than in published literature (i.e., Weikai and Hunt, 1999), particularly for temperatures significantly above the optimum. As a result we incorporated a formulation whereby estimated crop production is based on cardinal temperatures (Weikai and Hunt, 1999):

$$\frac{r}{R_{\max}} = \left(\frac{T_{\max} - T}{T_{\max} - T_{opt}}\right)\left(\frac{T}{T_{opt}}\right)^{T_{opt}/T_{\max} - T_{opt}}$$

where r is the daily rate of growth (or development) at any temperature (T), $R_{\max}$ is the maximum rate of growth or development at the optimum temperature T_{opt}, and $T_{\max}$ is the maximum temperature that growth can occur.

A number of studies have indicated that high maximum temperature during anthesis could result in lower kernel number and lower harvest index (McCaig, 1997; Ferris et al., 1998). The effect of grain exposure to high temperature during anthesis was incorporated into DNDC when temperature was greater than 22 °C for winter wheat, 28 °C for spring wheat and 38 °C for corn. Timing of anthesis was assumed to occur between 0.5 and 0.6 of the modelled Plant Growth Index (PGI; the fraction of achieved crop growth as a function of GDD) which is just before grain filling. Thus, depending on climate, the timing that anthesis occurs is automatically adjusted by the model. Adapting results by Ferris et al. (1998), winter wheat and spring wheat harvest indices were reduced by 1.43% for every degree above 22 °C and 28 °C, respectively. For corn an approximation was taken from Carberry et al. (1989), who parameterized the CERES model for temperature effects on maize yield during anthesis. Yield was reduced when air temperature was above 38 °C as follows; 1-(AirTemp−38.0) × 0.019. Further, an effect of cold winter temperatures on winter wheat survival was added to the model, whereby the crop potential biomass was reduced by 10% per day when crown temperatures dropped below −24 °C (Fowler, 1992).

In the calculation of evapotranspiration, albedo during the cropping season was adjusted to an average of 0.195, based on MODIS data (Davidson and Wang, 2005) for crops grown in Canada. The data indicated that albedo was relatively constant over the growing season and was generally higher than the previous DNDC estimate. The Penman–Monteith routine in DNDC was ported to Microsoft Excel® for testing and it was found that PET (potential evapotranspiration) estimates improved in comparison to Canadian ecodistrict averages (Agriculture and Agri-food Canada, 2008)