Living With It: Adapting Crop-Production Systems to Emerging Climate Change

DONALD SMITH
McGill University
Montreal, Quebec

This paper presents an overview of challenges facing agriculture as a result of developing climate change and discusses adaptations the agricultural sector will need to make to meet these challenges. It provides a summary of:

- potential climate changes that could affect crop-production activities,
- characteristics that make a crop better able to adapt to climate change, and
- changes to crop production that are likely to occur in response to climate change.

EXPECTED CHANGES IN CLIMATE

Global climate change is well-documented and generally accepted (IPCC, 2007). Atmospheric carbon dioxide (CO_2) levels, strongly linked to climate dynamics, have been steadily increasing since the onset of the industrial revolution. This increase is widely regarded as a major etiological agent of increasing atmospheric temperatures based on the heat-trapping capacity of CO_2, the "greenhouse" effect. Releases and atmospheric concentrations of other, more-powerful greenhouse gases (GHGs), such as methane (CH_4) and nitrous oxide (N_2O), have also been rising, contributing to ozone depletion and increasing temperatures (IPCC, 2001).

Climate change will cause increasing average atmospheric temperatures and evaporation of surface water (Zhang *et al.*, 2000); increased incidence and periods of drought (Kerr, 2003); and an increase in incidence of other extreme weather events (Rosenzweig *et al.*, 2001; Kerr, 2003). Each of these emergent and interacting factors poses significant challenges to our current agricultural systems' infrastructure and management practices, threatening our national and global food supplies.

Global temperatures are expected to increase by 1.5 to 4.5°C over the next 100 years (Vaughan *et al.*, 2001). Canada, at its high latitudes, has already experienced more climate change over the last 100 years than have most countries (IPCC, 2001; IPCC, 2007).

The mean annual temperature within Canada has increased 0.5 to 1.5°C during the last century (Zhang *et al.*, 2000) and is expected to increase by 3 to 5°C over this century (IPCC, 2007), with increases on the order of 8°C at the most northerly regions, reflecting a general trend for high latitude areas to show greater temperature increases than more-equatorial areas. In addition, night temperatures have been shown to be increasing at greater rates than daytime temperatures (Easterling *et al.*, 1997) and winter temperatures are increasing more than summer. Although some areas are expected to have greater precipitation, others will generally become drier (Kerr, 2003) due to reduced precipitation, increased evaporation resulting from increasing temperature and extended periods with unfrozen water in northern areas. Simulation models predict an increase in evaporation of 2 to 3% for each 1°C increase in atmospheric temperature (Lockwood, 1999). However, this effect may be moderated by increased cloud cover (Ohmura and Wild, 2002). In general, precipitation is predicted to increase at higher latitudes, but decrease by about 20% in most subtropical areas (IPCC 2007). Mendelsohn (2000) indicated that global precipitation may rise by 7% with a global temperature rise of 2°C by 2100.

Observational data and output of twenty-three global-climate models indicate that, by the end of 21st century, growing-season temperatures will exceed the most extreme seasonal temperatures recorded from 1900 to 2006 for tropical and subtropical areas (Battisti and Naylor, 2009). Anthropogenic warming of the Indian Ocean disrupts onshore moisture transport, reduces rainfall and creates drought for countries dependent on rain-fed agriculture. Current tendencies could result in a 50% increase in undernourished people by 2030 (Funk *et al.*, 2008).

Increasing temperatures are also responsible for rapid shrinking of glaciers, which are vital sources of river water used for irrigation of large agricultural areas. In Canada, the Peyto glacier in Alberta, which supplies river water used to irrigate neighboring prairie crops, has lost over 70% of its mass during the last few decades (Demouth and Pietroniro, 2003).

Melting of glaciers and polar ice will also result in increased sea level, threatening to submerge coastal areas, some of which are highly populated and maintain very productive agricultural land, with Bangladesh being the best example. A number of island nations will be at extreme risk. Sea levels are predicted to rise on the order of 50 to 100 cm by 2100 (Gregory and Oerlemans, 1998; IPCC, 2007), the effects of which will be exacerbated by more-frequent, larger coastal storms.

Climate change is expected to increase the incidence of extreme weather events (IPCC, 2001; Rosenzweig *et al.*, 2001; IPCC, 2007), such as drought, heat waves, and heavy precipitation and floods, making crop production more unpredictable and difficult. Wind speeds are also expected to increase due to an increased heat flux from the equator to the poles, resulting from increased temperature, increasing the potential for wind erosion of agricultural soils. Increased temperatures and intensive rains will accelerate the breakdown of soil organic matter, increasing nutrient leaching and soil erosion (Smith and Almaraz, 2004; Lotze-Campen and Schellnhuber, 2009).

Much of the climate change currently being recorded is attributable to the continuous increase in GHG emissions, most notably CO_2. This increase in atmospheric CO_2 concentration will have direct and indirect effects on crop plants, not all of them negative; CO_2 is often a limiting resource in plant canopies, and it is expected that an increase in CO_2 will generally increase plant productivity and water-use efficiency by reducing stomatal aperture and/or number per unit leaf area (Drake *et al.*, 1997; IPCC, 2007).

Crop Plants and Climate Change

Studies of climate-change impacts on crops have been largely confined to simulation models (Challinor *et al.*, 2009), and there is a need for empirical data regarding the relationship between climate trends and yield variability of major crops.

Climate change is already affecting many organisms (Jensen, 2003), impacting photosynthesis, water use and movement through the landscape, and distributions of crop and pest species. Temperature and CO_2 increases are expected to boost plant productivity and yields of crops like wheat, rice and soybean (Lobell and Asner, 2003), though this is not seen with small-grain cereals, important components of Canada's agricultural industry, which show accelerated development and decreased yields in response to increased temperature (Batts *et al.*, 1997). In high-latitude areas, the growing season is roughly defined by the time between the last killing frost in the spring and the first in the fall; these frost events invariably occur at night. Greater increases in nighttime than daytime temperatures are expected to lengthen the growing seasons more rapidly than average daily temperatures. This will result in an ability to produce crops and crop varieties requiring more thermal-time for maturity. Climate warming will also allow production of new temperature-sensitive crops, such as fruit and nut trees in more northern locations than currently, for example in southern Quebec and Ontario (Bélanger *et al.*, 2000). However, higher nighttime temperatures will also increase the rate of consumption of photosynthates through respiration, potentially offsetting some of the increases due to longer growing seasons (Smith and Almaraz, 2004). Warming of 1 to 2°C at low latitudes is likely to produce a negative responses for crop growth and yield and small beneficial response at higher latitudes (Easterling *et al.*, 2007).

Drier conditions will result in greater drought stress for crop plants (IPCC, 2001, 2007). Plants will likely respond by reducing stomatal aperture and/or number of stomata per unit area of leaf, decreasing water loss through decreased evapotranspiration; however, this will also decrease photosynthetic rates (Flexas and Medrano, 2002). Potential losses of photosynthesis from reduced stomatal opening may be offset by increases in atmospheric CO_2 levels. This will, however, also increase average leaf temperature as a result of reduced evaporative cooling from the leaf surface. Increased CO_2 levels have been shown to increase root-C dry weight, and plant responses have been observed to involve increases in the size of root systems, facilitating water acquisition and retention (Kimball *et al.*, 2002).

Yields of most agricultural crops increase under elevated CO_2 concentrations; productivity increases are in the range 15 to 25% for C_3 crops (wheat, rice, soybean) and 5 to 10% for C_4 crops (maize, sorghum, sugar cane) (IPCC, 2007; Lotze-Campen and Schellnhuber, 2009). The former will likely benefit through increased productivity as photorespiration losses are reduced, whereas the latter are not expected to show such benefits, at least not as substantially. However, C_4 plants may receive a competitive advantage under warmer, drier conditions, as they generally have higher water-use efficiencies, making them more adapted to these conditions. Climate change will, therefore, affect competitive interactions between C_3 and C_4 plants and, by extension, crop-weed interactions (Kimball *et al.*, 2002; Lotze-Campen and Schellnhuber, 2009). Which photosynthetic type benefits more will depend on the interaction between water and CO_2 availability, and so will be site-specific.

Although increased atmospheric CO_2 has the potential to increase plant photosynthetic activity, the nutritional quality may be negatively impacted by shifting carbon:nitrogen ratios, leading to reduced protein levels and increased amounts of starch (Conroy *et al.*, 1994; Jablonski *et al.*, 2002) limiting potential benefits from increases in plant productivity.

Nitrogen fixation has been observed to increase with rising CO_2 (Iñaki De Luis et al., 2002) and may increase under drier soil conditions due to improved water-use efficiency under elevated CO_2 levels (Yu *et al.*, 2002).

Increased productivity of crop plants due to increased CO_2 levels may force corresponding increases in fertilizer demand, in order to achieve higher yield potentials. However, nitrogen-use efficiency is reportedly higher under elevated CO_2 levels (Prior *et al.*, 1998), potentially mitigating increases in fertilizer demand. Application of plant-growth-promoting rhizobacteria (biofertilizers) and understanding signaling between bacteria and crop plants may also lead to improved plant productivity and, as a result, increase soil-C storage and reducing potential; some of these signals also have the potential to increase legume nitrogen fixation, reducing nitrogen-fertilizer applications in the long term and, therefore, reducing nitrous-oxide emissions (Mabood *et al.*, 2006).

Enhancement of plant growth in response to increased atmospheric CO_2 levels will also improve plants' capacity to respond to pests and pathogens by providing additional resources to mount defense mechanisms (Street-Perrott *et al.*, 1997; Smith and Almaraz, 2004; Lotze-Campen and Schellnhuber, 2009).

The northerly migration of pest and weed species in response to warmer conditions at higher latitudes has already been documented (Walther *et al.*, 2002; Ziska and Runion, 2007) and poses serious challenges to growers unfamiliar with their management. Insect pests may also increase their numbers of generations produced *per annum*, thereby increasing insect densities and associated predation of crops. Temperature rise and elevated CO_2 concentration could increase plant damage from pests in future decades, although only a few quantitative analyses exist to date (Easterling *et al.*, 2007; Ziska and Runion, 2007). Weeds show a larger range of responses to elevated CO_2 than crops due to their greater genetic diversity (Ziska and Runion, 2007). Furthermore, increased wind speeds will facilitate the dispersal of disease spores.

Soil-C stores are expected to decline as increased temperatures promote microbial activity and the breakdown of organic matter (Anderson, 1991; Smith and Almaraz, 2004; Lotze-Campen and Schellnhuber, 2009). This phenomenon is expected to be most pronounced in arctic and sub-arctic regions where organic matter remains in soils for long periods of time due to temperature-limited microbial activity. However, increased allocation of C to plant-root systems in response to increased CO_2 levels may offset these losses (Suter *et al.*, 2002). The increase in root mass may also benefit mycorrhizal fungi and increase the production of glomalin, a glycoprotein produced by endomycorrhizae that contributes to soil aggregation, thus mitigating soil erosion resulting from higher wind speeds and drier soil conditions (Rillig *et al.*, 1999).

Timing of heat stress is critical for crop development. For example, high-temperature stress during grain filling of chickpea, canola and mustard resulted in greater losses of yield than during the flowering stage (Gan *et al.*, 2004; Wang *et al.*, 2006). In Mediterranian rain-fed regions, chickpea grain yields were 50 to 80% greater with early planting (late autumn, early to mid-winter) because of a longer vegetative period, extended flowering and maturing phases and better environmental conditions (Lopez-Bellido *et al.*, 2008).

A Canadian study (Almaraz *et al.*, 2009) showed that sorghum could do well in Canada under climate-changed conditions. Sorghum is known to produce an extensive root system early in its development and to close its stomata quickly when faced with increasing water deficit. A study in Uzbekistan (Bourgault, Madraootoo and Smith, unpublished data) showed that mung bean is considerably better at handling water deficit than common bean due to its higher root:shoot ratio and restriction of water loss through stomatal control. Together, these studies suggest that larger root development, for better soil-water access, and stomatal restriction of water loss are two important elements of crop adaptation to drier conditions.

An evaluation of drought stress on dry-bean cultivars in the United States demonstrated reductions in yield and seed weight of 60% and 14%, respectively, with a 4-day increase in growing season (Singh, 2007).

Production-System Adaptations to Increasing Atmospheric Temperatures

Crop development and total agricultural production depend directly on climatic factors, such as temperature and precipitation, and will, therefore, be directly affected by climate change (Salinger, 2005; Lotze-Campen and Schellnhuber, 2009). How emerging climate changes will impact agricultural production is difficult to predict and remains uncertain (Lobell *et al.*, 2008; Challinor *et al.*, 2009).

Rising atmospheric temperatures will have both direct and indirect consequences for crop plants. Greater heat stress will likely be experienced more often by temperate-adapted species, potentially reducing their photosynthetic efficiency and increasing their susceptibility to pests, disease, and competition from weedy species (Garrett *et al.*, 2006). This will probably result in a need for more-frequent pesticide applications, more-careful pest monitoring, and development of pest-resistant crops.

Climate-change conditions will affect crop yields and may require changes in the types of crops produced in a given area. Increased spring and winter temperatures will increase the length of the growing season in Canada, increasing agricultural production with the introduction of new varieties and species of crop plants that demand longer periods for maturation than are currently grown. Warmer autumn conditions in Quebec are already leading to a longer growing season (Almaraz *et al.*, 2008) and simulation models predict an increase of 30 to 45 days in growing-season length by the end of the 21st century in the main agricultural regions of Ontario and Quebec (Bootsma *et al.*, 2004). In contrast, in the United States, corn and soybean yields decreased in response to increased growing-season temperature, with an observed reduction of 17% for each degree Celsius increase in average temperature (Lobell and Asner, 2003).

Northern nations, such as Canada, are expected to have the most drastic changes as higher latitudes see greater temperature increases relative to equatorial regions (IPCC, 2001). For example, over the past three decades, Quebec's Monteregie region has seen a general trend of increasing temperature, with the greatest change in the growing season occurring at the end of the season (September) where a mean increase of 2.8°C has occurred, whereas precipitation levels have shown no significant change over the same time period. An increase in average corn yields of 118 kg ha^{-1} $year^{-1}$ was observed between 1973 to 2005, and was explained, in part, by the increased September temperatures (Almaraz *et al.*, 2008).

Earlier springs may allow earlier planting of low-temperature-sensitive crops, early maturing and harvest, and possibility of double-cropping practices, which could greatly increase total productivity in parts of the northern hemisphere (Lotze-Campen and Schellnhuber, 2009). Lengthening of the growing season may also bring grain-corn production to areas of the United Kingdom where it is currently too cool (Kenny, 1993).

The productivity of C_3 plants is expected to increase in response to increasing CO_2 and this will mitigate energy losses associated with photorespiration (Kimball *et al.*, 2002). Increasing temperatures are likely to reduce stomatal aperture and duration of stomatal opening, a response to increasing leaf evapotranspiration through cuticular water losses. This is expected to increase the water-use efficiency of C_3 plants, which may make them more adapted to agricultural areas that experience decreased water availability through increased temperature, reduced rainfall, and/or reduced glacial runoff.

Warmer conditions on the Canadian prairies may allow production of winter wheat in areas where this was not previously possible. At higher latitudes, yields of winter wheat are generally higher than those of spring wheat. In part, this may be because they resume growth almost as soon as the snow cover has gone, enabling exploitation of soil moisture resulting from snow melt. One must wait until the soils become sufficiently dry to seed spring crops. The earlier development of winter cereals may also allow them to escape potentially hot and dry mid-summer conditions of a climate-changed world.

Traditional breeding programs should focus on selecting and optimizing heat-tolerant genotypes to replace current varieties. Molecular-genetics research will also play an important role in identifying specific genes associated with stress tolerance (Goswami, 2006; Lotze-Campen and Schellnhuber, 2009). Several specific targets for genetics-based adaptation of crop plants to emergent climate change include (Smith and Almaraz, 2004):

- increasing length and rate of development of plant-root systems;
- increased ability for osmotic adjustment in response to dry conditions;
- quicker stomatal closure at the onset of moisture stress;
- stronger responses to abscisic acid (ABA), which mediates many responses to drought;

- increasing water-use efficiency; and
- reduced cuticular and stomatal transpiration.

Identification of genes associated with these characteristics may lead to the development of genetically engineered cultivars much better adapted to emergent climate change.

Some tillage systems need improvement; for example, lower spring soil temperatures associated with no-till currently limit early crop development in much of the St. Lawrence Lowlands of Quebec (McRae *et al.*, 2000). No-till systems will become more feasible as conditions warm, allowing more sequestration of C in soil, better retention of water in soil, increased crop response to nitrogen fertilizers leading to reduced fertilizer application, and decreased soil erosion (Smith and Almaraz, 2004; Almaraz et al., 2009; Lotze-Campen and Schellnhuber, 2009).

Average precipitation levels have increased by 5 to 35% over the past three decades in Canada (Zhang *et al.*, 2000). However, net evaporative demand is also increasing and in some areas the increased evaporation will outstrip increased rainfall, leading to drier conditions. Nevertheless, in general, the outlook for Canada, with regard to climate change, is much better than for most of the world.

In temperate regions where conditions become hotter and drier, production of C_4 crop plants could be expanded as a way to adapt. C_4 plants are naturally more suited to these conditions than C_3 species (Ainsworth and Long, 2005) making them more tailored to emerging climate trends.

Indirect impact on crop plants will involve ecosystem changes as species composition is altered, both through emigration to the north and immigration from the south. Also, migrating populations of invasive and endemic species will need to be managed.

Need for cultivars with high pest and disease resistance will increase as new pests and pathogens migrate northward into Canadian agricultural areas. Genetic engineering of crop plants may be of assistance. Monitoring of pests currently existent just south of the border, and quarantine measures, should also be undertaken.

Adaptation strategies to climate change include:

- altering varieties with increased resistance or tolerance to heat and drought stress and altering the timing of planting or location of crops;
- adjusting fertilizer rates; and
- use of technologies for water preservation and integrated pest management.

Adaptations are efficient if costs of implementation are less than the resulting benefits (Mendelsohn, 2000; Howden et al., 2007; Lotze-Campen and Schellnhuber, 2009).

There is evidence that past climate shifts have caused social disruptions (Hodell *et al.*, 2001) including human migrations. In North America, there will be a northward migration of crop production (Smith and Almaraz, 2004). For instance, the Palliser triangle may became too dry for annual crop production, whereas more northerly areas of the Canadian prairies will become warm enough for crop production (Faculty of Agricultural and Food Sciences University of Manitoba, 1994; Smith and Almaraz, 2004). A northward movement of agricultural activities will require the development of rail infrastructure in the

Canadian north. At the same time, as conditions warm, it may become more feasible to ship larger amounts of grain from the port of Churchill (Smith and Almaraz, 2004). Current public policies promote the production of established crops in given areas. We need new, more flexible policies that allow the introduction of new crops and cropping practices that are better adapted to a climate-changed world (Smith and Almaraz, 2004).

Dynamic adaptation policies are necessary. Areas where adaptation policies have to be further developed are water management and distribution, optimization of land resources, carbon credits, management in agriculture including implementation of new technologies and changing of agricultural practices, government programs supporting carbon credits and trading and promotion of sustainable agricultural systems.

Studies of cropping systems indicate potential benefits from management adaptation under warming conditions and increased rainfall. For example, potential benefits for wheat have been estimated at about 18% in temperate and tropical wheat-growing systems and 10% for rice and maize (Howden *et al.*, 2007). Research advances in agriculture and forecast modeling of crop adaptation to climate change will enhance the capacity of food producers to manage the risk, by using the new adaptation strategies; however, this is an area that needs more research effort, which should be started soon.

REFERENCES

Ainsworth EA Long SP (2005) What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytologist 165 351–371.

Almaraz JJ *et al.* (2008) Climate change, weather variability and corn yield at a higher latitude locale: Southwestern Quebec. Climatic Change 88 187–197.

Almaraz JJ *et al.* (2009) Performance of agricultural systems under contrasting growing season conditions in South-western Quebec. Journal of Agronomy and Crop Science (in press).

Anderson JM (1991) The effects of climate change on decomposition processes in grassland and coniferous forests. Ecological Applications 1 326–347.

Battisti DS Naylor RL (2009) Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323 240–244.

Batts GR *et al.* (1997) Effects of CO_2 and temperature on growth and yield of crops of winter wheat over four seasons. European Journal of Agronomy 7 43–52.

Bélanger G *et al.* (2002) Climate change and winter survival of perennial forage crops in Eastern Canada. Agronomy Journal 94 1120–1130.

Bootsma A *et al.* (2004) Potential impacts of climate change on agroclimatic indices in southern regions of Ontario and Quebec. Technical Bulletin ICORC 03-284.

Challinor A *et al.* (2009) Crops and climate change: Progress, trends, and challenges in simulating impacts and informing adaptation. Journal of Experimental Botany 60 2775–2789.

Conroy J *et al.* (1994) Influence of rising atmospheric CO_2 concentrations and temperature on growth, yield and grain quality of cereal crops. Journal of Functional Plant Biology 21 741–758.

Demouth M Pietroniro A (2003) The Impact of Climate Change on the Glaciers of the Canadian Rocky Mountain Eastern Slopes and Implications for Water Resource-Related Adapatation in the Canadian Prairies. Ottawa: Geological Survey of Canada, Natural Resources Canada, Earth Science Sector.

Drake BG *et al.* (1997) More efficient plants: a consequence of rising atmospheric CO_2? Annual Review of Plant Physiology and Plant Molecular Biology 48 609–639.

Easterling D *et al.* (1997) Maximum and minimum temperature trends for the globe. Science 277 364–367.

Easterling W *et al.* (2007) Food, fibre and forest products. In: Climate Change 2007: Impacts, Adaptation and Vulnerability (M. Parry *et al.* Eds.) pp. 273–313. Cambridge, UK: Cambridge University Press.

Faculty of Agricultural and Food Sciences University of Manitoba (1994) Sustainability of Canada's Agri-Food System—A Prairie Perspective. Winnipeg: International Institute for Sustainable Development.

Flexas J Medrano H (2002) Drought-inhibition of photosynthesis in C3 plants: Stomatal and non-stomatal limitations revisited. Annals of Botany 89 183–189.

Funk C *et al.* (2008) Warming of the Indian Ocean threatens eastern and Southern African food security but could be mitigated by agricultural development. Proceedings of the National Academy of Sciences of the United States of America 105 11081–11086.

Gan Y *et al.* (2004) Canola and mustard response to short periods of temperature and water stress at different developmental stages. Canadian Journal of Plant Science 84 697–704.

Garrett KA *et al.* (2006) Climate change effects on plant disease: Genomes to ecosystems. Annual Review of Phytopathology 44 489–509.

Goswami H (2006) Climate change and crop breeding objectives in the twenty first century. Current Science 90 1053–1054.

Gregory JM Oerlemans J (1998) Simulated future sea-level rise due to glacier melt based on regionally and seasonally resolved temperature changes. Nature 391 474–476.

Hodell DA *et al.* (2001) Solar forcing of drought frequency in the Maya lowlands. Science 292 1367–1370.

Howden SM *et al.* (2007) Adapting agriculture to climate change. Proceedings of the National Academy of Sciences 104 19691–19696.

Iñaki De Luis *et al.* (2002) Low vapour pressure deficit reduces the beneficial effect of elevated CO_2 on growth of N_2-fixing alfalfa plants. Physiologia Plantarum 116 497–502.

IPCC (2001) Climate Change 2001:The Scientific Basis. Cambridge, UK: Cambridge University Press.

IPCC (2007) Climate Change Impacts, Adaptation and Vulnerability. Cambridge, UK: Cambridge University Press.

Jablonski LM *et al.* (2002) Plant reproduction under elevated CO_2 conditions: A meta-analysis of reports on 79 crop and wild species. New Phytologist 156 9–26.

Jensen MN (2003) Climate change: consensus on ecological impacts remains elusive. Science 299 38.

Kenny GJ (1993) The effects of climate change on land suitability of grain maize, winter wheat and cauliflower in Europe. European Journal of Agronomy 2 325–338.

Kerr RA (2003) Climate change: a perfect ocean for four years of globe-girdling drought. Science 299 636.

Kimball B *et al.* (2002) Responses of agricultural crops to free-air CO_2 enrichment. Advances in Agronomy 77 293–368.

Lobell DB Asner GP (2003) Climate and management contributions to recent trends in US agricultural yields. Science 299 1032.

Lobell DB *et al.* (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319 607–610.

Lockwood JG (1999) Is potential evapotranspiration and its relationship with actual evapotranspiration sensitive to elevated atmospheric CO_2 levels? Climatic Change 41 193–212.

Lopez-Bellido F *et al.* (2008) Effect of planting date on winter kabuli chickpea growth and yield under rainfed Mediterranuian conditions. Agronomy Journal 100 957–964.

Lotze-Campen H Schellnhuber H-J (2009) Climate impacts and adaptation options in agriculture: what we know and what we don't know. Journal für Verbraucherschutz und Lebensmittelsicherheit 4 145–150.

Mabood F *et al.* (2006) Exploiting inter-organismal chemical communication for improved inoculants. Canadian Journal of Plant Science 86 951–966.

McRae T *et al.* (2000) Environmental Sustainability Of Canadian Agriculture: Report of the Agri Environmental Indicator Project. Ottawa: Agriculture and Agri-Food Canada.

Mendelsohn R (2000) Efficient adaptation to climate change. Climatic Change 45 583–600.

Ohmura A Wild M (2002) Climate change: Is the hydrological cycle accelerating? Science 298 1345–1346.

Prior SA *et al.* (1998) Effects of carbon dioxide enrichment on cotton nutrient dynamics. Journal of Plant Nutrition 21 1407–1426.

Rillig MC *et al.* (1999) Rise in carbon dioxide changes soil structure. Nature 400 628–628.

Rosenzweig C *et al.* (2001) Climate change and extreme weather events; implications for food production, plant diseases, and pests. Global Change and Human Health 2 90–104.

Salinger M (2005) Climate variability and change: past, present and future – an overview. Climatic Change 70 9–29.

Singh SP (2007) Drought resistance in the race durango dry bean landraces and cultivars. Agronomy Journal 99 1219–1225.

Smith DL Almaraz JJ (2004) Climate change and crop production: contributions, impacts, and adaptations. Canadian Journal of Plant Pathology 26 253–266.

Street-Perrott FA *et al.* (1997) Impact of lower atmospheric carbon dioxide on tropical mountain ecosystems. Science 278 1422–1426.

Suter D *et al.* (2002) Elevated CO_2 increases carbon allocation to the roots of Lolium perenne under free-air CO_2 enrichment but not in a controlled environment. New Phytologist 154 65–75.

Vaughan DG *et al.* (2001) Climate change: Devil in the detail. Science 293 1777–1779.

Walther G-R *et al.* (2002) Ecological responses to recent climate change. Nature 416 389–395.

Wang J *et al.* (2006) Response of chickpea yield to high temperature stress during reproductive development. Crop Science 46 2171–2178.

Yu M *et al.* (2002) Simulating interactive effects of symbiotic nitrogen fixation, carbon dioxide elevation, and climatic change on legume growth. Journal of Environmental Quality 31 634–641.

Zhang X *et al.* (2000) Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38 395–429.

Ziska L Runion G (2007) Future weed, pest, and disease problems for plants. In: Agroecosystems in a Changing Climate (Newton P *et al.* Eds.) pp. 261–290. Boca Raton: CRC.

DONALD SMITH received his PhD from the University of Guelph in 1984 and then held a postdoctoral fellowship at Agriculture Canada. Since 1985 he has served on the faculty of the Plant Science Department at McGill University, working largely in production and physiology of crop plants. Areas of research include nitrogen metabolism, nitrogen fixation, root-zone temperature stress and nodule development, methods for injection of metabolites into developing plants, barley production, use of plant-growth regulators, intercropping, the dynamics of inter-plant competition, plant-microbe signaling, plants and climate change and biofuel crops. He is particularly interested in physiological responses of crop plants to increasing atmospheric CO_2 levels and to climate change.

Work on nitrogen fixation has been a consistent theme, beginning with an undergraduate research project on cyanobacteria in 1974. Current work includes signaling between symbiotic partners during establishment of the legume-rhizobia symbiosis. This research activity has resulted in over 250 publications, five patents issued and three others applied for, and a spin-off company (Bios Agriculture, Inc.). Dr. Smith leads the National Sciences and Engineering Research Council-funded ($1.2 million/year) Green Crop Network on crops and climate change, including work on biofuels, and he heads the McGill Network for Innovation in Biofuels and Bioproducts.