The Impact of Agriculture on Climate Change

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In considering the role of agriculture with respect to climate change, it is important to consider the impact of agricultural practices on the microclimate. For example, the type of vegetation, method of tillage, amount of land cover, type of windbreak and type of irrigation system are all factors that influence the microclimate and macroclimate either directly or indirectly, whether by changing transpiration, particles in the air (dust, soot), precipitation, wind, *etc*. These changes can alter the global climate if the energy budget at the Earth's surface is significantly changed. The main source of energy at the Earth's surface is the incoming solar radiation. However, as can be seen in Fig. 1, there is a whole series of forcing agents that have the potential to affect the radiation budget and the Earth's temperature. Some forcing agents, such as greenhouse gases (GHGs), cause warming whereas others, such as increased reflectivity of the surface (albedo) and aerosols, mainly cause cooling.

Globally, agriculture accounts for 13% of the radiative forcing related to GHGs; in Canada and the United States it accounts for 6% to 8%. The GHG emissions in Canada and the United States are mainly in the form of methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2007). Agricultural sources such as animal husbandry, manure management and agricultural soils account for about 52% of global methane (CH_4) and 84% of global nitrous oxide (N_2O) emissions (Smith *et al.*, 2008). In the past, deforestation and intensive agriculture (*e.g.*, cultivating grasslands) have contributed significantly to the increase in atmospheric carbon dioxide (CO_2). For example, until the 1970s, more CO_2 had been released into the atmosphere from agricultural activities than from fossil-fuel burning (Lal *et al.*, 1998).

Agricultural activities can influence climate through land-use change, which can modify the albedo of the Earth's surface. The albedo (α) in an agricultural context depends on a variety of factors including crop type (*e.g.*, cereals, forages, broadleaf crops, shrubs, bare soil), crop phenology (seedlings to mature plants), management practice (tilled, fallow, fertilized), surface condition (wet or dry), time of day (solar elevation) and time of year (growing season or snow cover). Any combination of factors that result in an increased albedo means that less solar energy is absorbed by the Earth's surface. Compared to the

globally averaged albedo of about 0.3 for the Earth's surface (Bender *et al.*, 2006), land covers with higher albedo (such as deserts, snow and ice, α = 0.35 to 0.90) tend to lower the air temperature, whereas land covers with lower albedo (such as oceans, grasslands and forests, α = 0.05 to 0.20) tend to increase air temperature. Based on the global annual average incoming shortwave radiation of about 341 Wm^{-2} (Trenberth *et al.*, 2009), a decrease of 0.005 in global albedo would modify the shortwave radiation forcing by about 1.7 Wm^{-2} and cause an increase in the global air temperature by about 0.9°C (Cess, 1976).

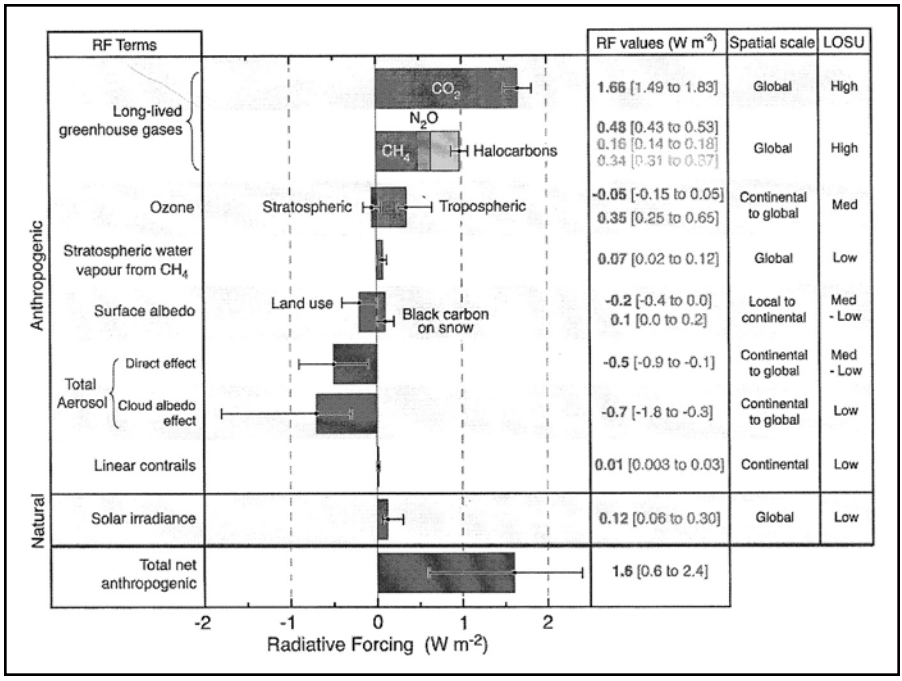

Figure 1. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic CO_2, CH_4, N_2O and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU) (IPCC, (2007).

Agriculture also impacts other radiative and non-radiative forcing agents that can have either a direct or an indirect effect on the climate (IPCC, 2007). As can be seen in Fig. 1, aerosols that are abundant in the environment as dust particles (from bare soil and plant residues) or as anthropogenic residues of combustion (from crop burning) can have a significant cooling effect. They have a direct effect on the radiation budget by scattering and absorbing short-wave and long-wave radiation. They also have an indirect radiative effect by influencing cloud formation, which may then lead to changes in the incoming solar radiation. An example of non-radiative forcing is a change in the hydrological

cycle due to different soil and crop conditions. This can modify the surface fluxes of heat and moisture, thereby changing the lower boundary conditions of the atmosphere, and influencing weather and climate (Pielke *et al.*, 1998).

Agriculture plays a relatively important role with respect to climate change, primarily because rapid changes in land use result in concomitant changes in the environment (Goldewijk, 2004). For example, the global area of cropland increased from 265 Mha in 1700 to 1,471 Mha in 1990 while the area used for grazing livestock increased from 524 Mha to 3,451 Mha. My objective is to examine the magnitude of the past, present and future impacts of agriculture on climate change and to discuss the possible tradeoffs between biogeochemical and biogeophysical forcing agents associated with management practices to minimize any negative impact of climate change.

Impact of agriculture on past climate

Anomalies in the concentration patterns of CO_2 and CH_4 during the last 8,000 years have helped demonstrate the role of the development of agriculture on climate change. Ruddiman (2003) reported an anomalous increase of about 40 ppmv in CO_2 during that period, which he hypothesized was related to forest clearing for the development of agriculture in Europe and China, which began 8,000 years ago. He also attributed an upward deviation of up to 250 ppbv in CH_4, observed during the last 5,000 years, to the adoption of paddy rice farming in Asia. He estimated that the increase in the atmospheric concentration of these gases increased global air temperature by about 0.8°C. He also suggested that several CO_2 oscillations of about 10 ppmv in the last 1,000 years were likely due to farm abandonment in western Eurasia due to bubonic plague, resulting in forest regrowth.

On an annual basis, early agricultural systems contributed little to the GHG build up in the atmosphere because of the small populations; however, small contributions integrated over long periods of time can become significant. For instance, land clearance for agriculture is estimated to have been a major source of CO_2. Between 8,000 years and 200 years ago, CO_2 emissions from land clearance were estimated to be about 0.04 Gt C yr^{-1}, for a total of about 310 Gt C. Since the industrial revolution in 1800, CO_2 emission from land clearance has averaged 0.8 Gt C yr^{-1} for a total of about 160 Gt C. Therefore, the small annual CO_2 emissions prior to the industrial revolution contributed about two times more CO_2 than the post-industrial revolution emissions (Ruddiman, 2003).

Using results from computer simulations, Betts *et al.* (2007) demonstrated that historical deforestation of predominantly northern temperate regions, with their snow cover during winter, probably did not contribute to global warming, if the effect on temperature due to the increase in albedo from land use change is taken into account. They showed that, by 1950, the global mean radiative forcing decreased by 0.18 Wm^{-2} as natural land cover was converted to agriculture and that winter and spring temperatures in northern temperate regions are probably 1 to 2°C cooler as compared to the temperature they would have been if land clearance had not occurred. They also estimated a decrease in radiative forcing from 1950 to 1990 of –0.06 Wm^{-2}, which may be associated with the Green Revolution in Asia.

Impact of agriculture on present climate

In the past 20 years, about 75% of the CO_2 emissions have been attributed to fossil-fuel burning and the remainder to land-use change (IPCC, 2001). The major impacts of agricultural land-use change are occurring in tropical rainforest regions such as Brazil, Congo, and Indonesia where native rainforests are being cleared for cultivation and pasture. Tropical deforestation, which now exceeds 13 Mha per year (World Resource Institute, 2000), is a substantial source of CO_2. It also causes a moderate increase in albedo, which causes cooling of the air; however, this cooling is more than offset by a warming of the air through a reduction in evapotranspiration and through CO_2 emissions associated with deforestation.

Through agricultural activities (*e.g.*, land clearing, cultivation of annual crops, irrigation, grazing of domesticated animals), humans are extensively altering the local, national and global land-cover characteristics, including physiological and physical characteristics. It is generally accepted that the expansion of agriculture into natural ecosystems has had a significant climate impact. Lobell *et al.* (2006) used the National Center for Atmospheric Research (NCAR) general circulation model to demonstrate that a reduction in tillage can have a significant cooling effect by increasing the albedo. The NCAR model predicted that increases in soil albedo by reduced tillage have a potential global cooling effect of 0.2°C. This value is comparable to the biogeochemical cooling from the expected global soil carbon sequestration potential. Boucher *et al.* (2004) examined the human influence of irrigation on atmospheric water vapor and climate. They estimated a global mean radiative forcing in the range of 0.03 to 0.1 Wm^{-2} due to the increase in water vapor in the atmosphere, but a cooling of up to 0.8°C over irrigated areas.

Summer fallowing, which is the practice of leaving land unplanted for a whole year to conserve soil moisture and control weeds in semiarid environments such as the Northern Great Plains, is now much less prevalent in Western Canada and the United States than it was prior to 1975. The area of land left fallow in Canada increased from 8.7 Mha in 1951 to 11.4 in 1975, however with alternatives to summer fallowing, such as snow trapping, irrigation, mechanical or chemical weed control and cultivars that make more efficient use of water, a reduction to 5.4 Mha had occurred by 2001. Associated with this change, for the period between June 15 and July 15, Gameda *et al.* (2007) reported an increase of about 2°C between 1951 and 1975 in the mean air temperature of all soil zones in the prairies, where summer fallowing was practiced, then a decrease of about 2°C for the period between 1976 to 2001 (Fig. 2a, b). They also reported an increase in precipitation of about 20 mm from 1976 to 2001. This is because the flux of heat is less over cropped land than over bare soil, whereas evapotranspiration is greater over cropped land as compared to bare soil, which adds moisture to the atmosphere. Therefore, conversion of land from summer fallow to crops decreases air temperature and increases the water content of the air, potentially resulting in greater precipitation. Several authors have documented that regional evapotranspiration by agricultural crops is an important source of moisture for growing-season rainfall (Brubaker *et al.*, 1993; Trenberth, 1999). Summer fallowing tends to enhance decomposition of crop residues as the result of greater soil temperature and soil moisture as compared to cropped soils. Therefore, soils that are frequently under

summer fallow have C contents that are several tons per hectare less than those that are cropped continuously.

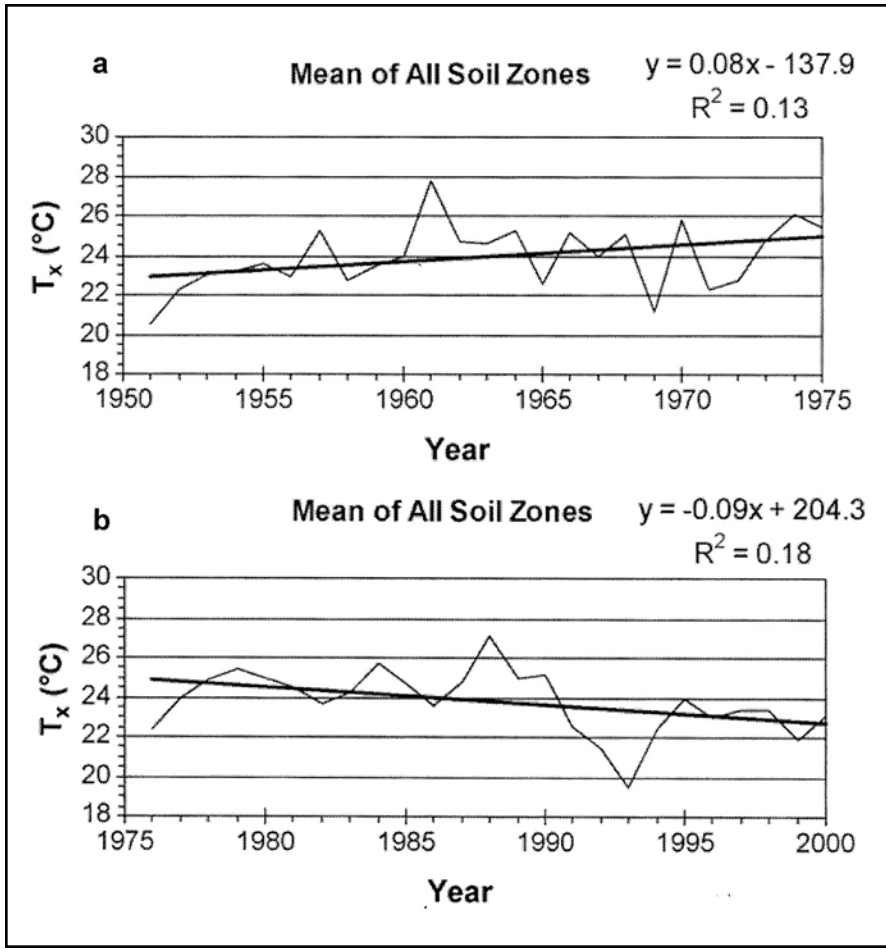

Figure 2. Trends in mean daily maximum temperature for the period June 15 to July 15, between a) 1951 and 1975 when area under summer fallow increased, and b) 1976 and 2001 when the area under summer fallow declined on the Canadian prairies (Gameda *et al.*, 2007).

By converting summer fallow to wheat in western Canada, carbon can be sequestered in soils at a rate of about 100 kg C ha^{-1} yr^{-1} (Campbell *et al.*, 2005). The biogeophysical effect of reducing summer fallow complements the effect of increasing C sequestration.

The biogeochemical and biogeophysical impacts of GHG-mitigation strategies on climate are not always complementary. For instance in Canada, afforestation and reforestation of marginal agricultural lands have been suggested as strategies to mitigate climate

change by sequestering C in forests. However, planting trees, particularly conifers, on agricultural land in northern regions may result in more radiation being absorbed and thus increase temperature, thereby negating the beneficial impact of C sequestration. That is, the biogeophysical effect of land-use change is likely more significant than the biogeochemical effect in terms of climate change. To illustrate this point, consider the conversion of 1 ha of wheat to coniferous forest, which would result in the sequestration of approximately 60 t of C over a 50-year period, which is equivalent to a global radiative forcing of –0.20 nWm^{-2} (Betts, 2000). However, the negative radiative forcing of this hectare of land is completely offset by the biogeophysical forcing of –14 Wm^{-2} (AK Betts *et al.*, 2007), which is equivalent to 0.27 nWm^{-2} on a global scale, resulting in a net positive forcing of 0.07 nWm^{-2}. This example demonstrates that GHG-mitigation practices, such as reforestation of agricultural lands need to account for both the biogeochemical and biogeophysical forcings.

There has been substantial progress in agriculture in recent years in reducing GHG-emission intensities, that is, emissions per unit of product. For example over the last 20 years, a significant reduction in GHG-emission intensities has been reported for the major livestock industries in Canada (Dyer *et al.*, 2008; Vergé *et al.*, 2008, 2009). The improvements in GHG-emission intensities have been realized because of a combination of improved animal breeding, reduction in tillage intensity and a reduction in synthetic fertilizer use as the result of increased feeding of leguminous crops. Combined, these factors have increased milk-production efficiency by 35%, beef-production efficiency by 37% and pork-production efficiency by 23%. Despite the improvements in GHG emission per unit of product, because of the increasing demand for food over this time period, animal production has increased substantially and total GHG emissions have continued to increase, hence this progress has not helped agriculture reduce its impact on the environment.

Potential impact of agriculture on future climate

There are approximately 1.4 billion hectares of farmland in the world today (FAO, 2003). Currently, the potential for further expansion of agricultural lands is limited because most of the good-quality arable land is already under cultivation. There is some limited potential to expand agricultural lands in humid tropical regions (FAO, 2003), but these areas have major limitations due to steep slope, stoniness, soil depth and poor natural fertility. With increasing population, agricultural lands are likely to come under increasing pressure. Emerging carbon-credit markets and biofuel incentives may encourage producers to intensify agricultural practices to enhance productivity. Some expansion is then likely to occur onto marginal land. This is likely to lead to land degradation and, in some instances, desertification. Land degradation has already taken place in many regions of the world because of dramatic changes in agricultural practices during the last several decades (Sivakumar, 2007). The obvious impact of land degradation is an increase in surface temperature and a decrease in latent heat flux, but actual changes are much more complex. The impacts affect regional atmospheric circulation far beyond the region involved (Werth and Avissar, 2002).

In agriculture, the main option for mitigating climate change is still considered to be the sequestration of C in soils. Agricultural management practices such as reduced tillage, converting cropland to forage crops, permanent cover crops, fall-seeded crops, better crop cultivars, more efficient use of nutrients, optimized irrigation, reduced summer fallow, more chemical fallow and leaving tall stubble standing to reduce evaporation and trap snow have all been identified as beneficial for increasing C sequestration and/or reducing GHG emissions. It is estimated that, globally, agricultural soils could be a potential sink of 30 to 60 Pg C over the next century (Lal, 2003). This is the case because soil-C stocks have been considerably depleted by farming. In Canada, it has been estimated that agricultural soils have lost about 1,000 Tg C since cultivation began (Smith *et al.*, 2000). The potential then exists to sequester in agricultural soils some of the CO_2 released by fossil-fuel combustion (Boehm *et al.*, 2004), however, even this potential is threatened by climate change. Using the Century Model (Parton *et al.*, 1993), Smith *et al.* (2009) predicted that by 2100, agricultural soils would lose between 62 and 164 Tg C, depending on the climate scenario. Because of the lack of permanence of soil C sink, there is a need to search for lower risk options to store CO_2.

We need to examine all reasonable strategies for climate-change mitigation in order to predict future climate. Many examples have been mentioned in the literature, but few have been fully studied (Table 1). For example, the production of biomass for biofuel production is frequently presented as a promising option to reduce net GHG emissions (Farrell *et al.*, 2006).

Table 1. The impact of various agricultural practices on climate change.

Agricultural practice	Biogeophysical effect	Biochemical effect	Net effect
Reduced tillage	–[a]	−−	−−
Reforestation	+++	−−	+
Deforestation	−−	+	−
Plant forage crops	−	−−	−−
Irrigation	−	−+	−
Biochar	+	−−	−
Leaf albedo bioengineering	−	−	−−
Biofuel	−	−+	−
Reduced meat consumption	+	−−	−
Reduced fallow	−	−−	−−−
Plant fall crops	−	−	−−
Leave long stubble for snow trapping	−	−	−−

[a] + indicates warming; – indicates cooling

The application of biomass-derived black C (biochar) to soil has been proposed as a novel approach to establish a significant long-term sink in terrestrial ecosystems (Lehmann, 2007). Others have proposed that tackling regional climate change using a "bio-geoengi-

neering" approach, using crop cultivars specifically chosen to maximize solar reflectivity, could result in a summertime cooling of more than 1°C throughout central North America and mid-latitude Eurasia (Ridgewell *et al.*, 2009). Stehfest *et al.* (2009) have reported that changing human diet, specifically less consumption of meat, could significantly impact climate change by reducing methane emissions. Feddema *et al.* (2005) demonstrated the importance of including land-cover change in forcing scenarios for future climate studies. For example, they estimated that reforestation in western Russia would lead to warming. One of our challenges for the future is to improve the information in Table 1 and make the information quantitative rather than qualitative.

Discussion and Concluding Remarks

There seems to be little doubt that climate change is occurring. The impact of agriculture on climate change is not fully understood, but it is clear that the human role within the climate system is considerably more than the increase in GHG concentration (Pielke Sr. *et al.*, 2007). Because agroecosystems are intensively managed, as farming practices evolve the role of agriculture will undoubtedly change. We have shown several examples of the diversity of human climate forcing. Agricultural practices can influence climate through a modification of the surface energy budget (the biogeophysical effects), as well as through GHG emissions (the biogeochemical effects). Many programs have been initiated to mitigate GHG emissions and, so far, considerable progress has been reported in reducing the GHG-emission intensities from agricultural sources, but because of increasing food demand and increasing energy requirements, the total GHG emissions from agriculture keep increasing. Biofuels hold some promise for reducing our dependency on oil and gas, however, at this point, it is still not clear if the net GHG saving gained by replacing a fossil fuel with biofuel options such as corn ethanol, soybean biodiesel or simply crop-residue-generated biofuel will appreciably reduce GHG emissions. So far, mitigation measures have been biased towards minimizing the biogeochemical effects, but there is growing awareness that the biogeophysical effects may also be important and should be considered in designing policy intended to mitigate climate change. Linking carbon storage in agroecosystems with other climate-forcing agents is the most reasonable approach for developing policies that maximize the impact of agroecosystems in climate policy. Better information on the various types of forcing is particularly important to help decisions that people, governments and industries of the world will have to make to minimize the impact and the consequences of climate change.

References

Bender FA-M *et al.* (2006) 22 views of the global albedo - comparison between 20 GCMs and two satellites. Tellus 58A 320–330.

Betts AK *et al.* (2007) Impact of agriculture, forest and cloud feedback on the surface energy budget in BOREAS. Agricultural and Forest Meteorology 142 156–169.

Betts RA (2000) Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408 187–190.

Betts RA *et al.* (2007) Biogeophysical effects of land use on climate: Model simulations of radiative forcing and large-scale temperature change Agricultural and Forest. Meteorology 142 216–233.
Boehm MM *et al.* (2004) Sink potential of Canadian agricultural soils. Climatic Change 65 297–314.
Boucher O *et al.* (2004) Direct human influence of irrigation on atmospheric water vapour and climate. Climate Dynamics 22 597–603.
Brubaker KL *et al.* (1993) Estimation of continental precipitation recycling. Journal of Climate 6 1077–1089.
Campbell CA *et al.* (2005) Carbon storage in soils of the North American Great Plains: Effect of cropping frequency. Agronomy Journal 97 349–363.
Cess RD (1976) Climate change: An appraisal of atmospheric feedback mechanisms employing zonal climatology. Journal of Atmospheric Sciences 33 1831–1843.
Dyer JA *et al.* (2008) Long-term trends in the greenhouse gas emissions from the Canadian dairy industry. Canadian Journal of Animal Science. 88 629–639.
FAO (2003) World agriculture: Towards 2015/2030. An FAO perspective. London: Earthscan Publication Ltd.
Farrell AE *et al.* (2006) Ethanol can contribute to energy and environmental goals. Science 311 506–508.
Feddema JJ *et al.* (2005) The importance of land-cover change in simulating future climates. Science 310 1674–1678.
Gameda S et al. (2007) Climatic trends associated with summerfallow in the Canadian Prairies. Agriculture and Forest Meteriorology 142 170–185.
Goldewijk KK (2004) Footprints from the past: Blueprint for the future? In: Ecosystems and Land Use Change (DeFries R *et al.* Eds.) pp. 203–215. Washington, DC: American Geophysical Union.
IPCC (2001) Climate change 2001, The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change Cambridge, UK and New York, USA: Cambridge University Press.
IPCC (2007) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge, UK and New York, USA: Cambridge University Press.
Lal R *et al.* (1998) The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Boca Raton: CRC Press.
Lal R (2003) Global potential of soil carbon sequestration to mitigate the greenhouse effect. Critical Reviews in Plant Sciences 22 151–184.
Lehmann J (2007) A handful of carbon. Nature 447 143–144.
Lobell DB *et al.* (2006) Biogeophysical impacts of cropland management changes on climate. Geophysical Research Letters 33 L06708.
Parton WJ *et al.* (1993) Observations and modeling or biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochemical Cycles 7 785–809.

Pielke Sr. RA *et al.* (1998) Interactions between the atmosphere and the terrestrial ecosystem: Influence on weather and climate. Global Change Biology 4 461–475.
Pielke Sr. RA *et al.* (2007) A new paradigm for assessing the role of agriculture in the climate system and in climate change. Agricultural and Forest Meteorology 142 234–254.
Ridgewell A *et al.* (2009) Tackling regional climate change by leaf albedo bio-geoengineering. Current Biology 19 146–150.
Ruddiman WF (2003) The anthropogenic greenhouse era began thousands of years ago. Climatic Change 61 261–293.
Sivakumar MVK (2007) Interactions between climate and desertification. Agricultural and Forest Meteorology 142 143–155.
Smith P *et al.* (2008) Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society, B 363 789–813.
Smith WN *et al.* (2000) The net flux of carbon from agricultural soils in Canada, 1970-2010. Global Change Biology 6 557–568.
Smith WN *et al.* (2009) Potential impact of climate change on carbon in agricultural soils in Canada 2000-2099. Climatic Change 93 319–333.
Stehfest E *et al.* (2009) Climate benefits of changing diet Climatic Change In press DOI 10.1007/s10584-008-9534-6.
Trenberth KE (1999) Atmospheric moisture recycling: role of advection and local evaporation. Journal of Climate 12 1368–1381.
Trenberth KE *et al.* (2009) Earth's global energy budget. Bulletin of the American Meteorological Society 90 311–323.
Vergé X PC *et al.* (2008) Greenhouse gas emissions from the Canadian beef industry. Agricultural Systems 98 126–134.
Vergé XPC *et al.* (2009) Greenhouse gas emissions from the Canadian pork industry. Livestock Science 121 92–101.
Werth D and Avissar R (2002) The local and global effects of Amazon deforestation. Journal of Geophysical Research 107 8087.
World Resource Institute (2000) A guide to World resources, 2000-2001. People and Ecosystems: The Fraying Web of Life. New York: Oxford University Press.

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Dr. Desjardins is acknowledged worldwide for having developed original techniques to measure carbon dioxide and various trace gases using tower and aircraft-based systems. He has been the principal investigator in many NASA-funded large-scale experiments designed to improve the understanding of biosphere-atmosphere interactions. He leads a research program on quantifying and reducing greenhouse-gas emissions, ammonia and particulate matter from agricultural sources.

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