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Some perspectives on agricultural GHG mitigation and adaptation strategies with respect to the impact of climate change/variability in vulnerable areas

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Abstract—It is generally agreed that agricultural activities contribute to greenhouse gas (GHG) build up in the atmosphere which influences climate change and climate variability. Worldwide agriculture is responsible for about 13 percent of the total anthropogenic emissions. The scientific community has placed considerable efforts on developing ways to mitigate this effect through improvements in agricultural management practices. Improved management practices such as precision farming, implementation of less intensive tillage, changes in crop rotation, improved feed quality for better digestibility, improved manure handling, better water management of rice paddies, and biofuel/bioheat production are commonly employed as a means to mitigate GHG emissions. Even with all these mitigation measures, climate change is likely to have a wide range of effects on agricultural systems and we must adapt to these changes to ensure that agricultural production is not only maintained but is increased to support a growing world population. In some areas shifts in crop zones are expected, whereby cool season crops may be replaced by warm season crops and new cropping zones may open up for production. Most adaptation scenarios are likely to influence GHG emissions. Production of bioenergy crops, particularly lignocellulosic crops can, in some cases, provide a means to both mitigate net CO_2 emissions and adapt to a changing climate and world energy needs. There are numerous potential mitigation strategies to reduce GHG emissions from agriculture, but their effectiveness depends on climate, soil, and economic conditions which vary across regions. Process-based models can potentially act as a useful tool for examining the influence that climate change may have on mitigation and adaptation efforts. However, there are gaps in knowledge regarding processes that govern GHG emissions and much uncertainty regarding future trends in climate. In this paper the DeNitrification-DeComposition (DNDC) model was used to investigate the influence that a changing climate might have on GHG emissions in agricultural systems. Results indicate that N_2O emissions will be highly variable across different landscapes, and that net CO_2 emissions will generally increase, particularly in cooler regions. In regions with an average annual temperature of less than 10 °C, enhanced soil carbon decomposition due to increased temperatures is expected to cause a loss of approximately 70 kg CO_2 ha^{-1} y^{-1} by 2100.

Key-words: greenhouse gas, mitigation, adaptation, climate change, model

1. *Introduction*

Mitigating greenhouse gas (GHG) emissions and adapting to climate change will give rise to economic and environmental constraints. The agricultural sector is responsible for approximately 10 –13% of total global anthropogenic emissions of GHGs (5.1 to 6.1 Gt CO_2-eq y^{-1} in 2005), and most of these emissions are in the form of CH_4 and N_2O (*Carter et al*., 2007). Agricultural CH_4 and N_2O emissions have increased by nearly 17% from 1990 to 2005. Although net CO_2 exchange from agriculture soils is approximately at equilibrium, substantial mitigation potential exists in sequestering atmospheric CO_2.

The mitigation of GHG in agricultural systems is undoubtedly not the primary concern for farmers. Increased production costs and a need to maintain or re-establish sustainable agricultural systems are the driving forces for the agricultural sector. However, if concentration of GHGs continue to increase, the vulnerability of agriculture to changes in climate will be significant. Due to economic constraints, farmers in developing nations are considerably more vulnerable to climate change than those in developed countries. Implementation of long-term mitigation measures should help to minimize the impacts of climate change and reduce this vulnerability. There is an extensive range of potential agricultural mitigation measures for most regions, but the full potential to reduce GHG emissions will only be realized if economic and policy incentives are given. Due to the inevitability of climate change, adaptation of agricultural systems is also required to maintain or increase production.

There are some difficulties in assessing the potential impacts of future climate change on mitigation and adaptation strategies for agriculture. Empirical data cannot always be extrapolated to forecast future changes in GHG emissions from agriculture as the impacts of climate change are often dynamic. The use of process-based models, that have been verified against measurements, present a means of quantifying changes in GHG emissions from agricultural systems under future climate change scenarios. In this paper we will review the status of agricultural mitigation strategies that can potentially reduce GHG emissions under a changing climate. We will also review how adaptation measures can influence GHG emissions. Additionally, we will demonstrate how process based model can be used to predict changes in GHG emissions from agriculture under future climate.

2. *Mitigation of agricultural GHG emissions through improved management practices*

Numerous mitigation measures have been proposed to reduce GHG emissions from agricultural systems (*Smith et al*., 2008a). Typically, the most promising practices are those that sequester carbon. *Smith et al.* (2007a) estimated that 90% of the total potential comes from sink enhancement. Mitigation measures that are particularly effective at reducing one GHG may, however, increase emissions of another thus it becomes important to quantify the emissions of CO_2, CH_4, and N_2O, simultaneously. In certain cases a change in albedo may also be an important factor in determining total radiative forcing of a management practice (*Janzen et al*., 2008).

It is also important that mitigation measures be of long duration. Some practices may sequester soil carbon for a few years before reaching a new equilibrium with no further storage of carbon. Additionally, any sequestered soil carbon is vulnerable to being lost by either a change in practice or by a change in climate. Soil carbon may also be depleted in the future due to enhanced organic matter decomposition under a warming climate (*Smith et al.*, 2008b). Adaptation measures to minimize climate change impacts on crop production using improved water, soil, and disease management may also hamper mitigation efforts and fuel further changes in climate. Therefore, it is important to quantify the impact of adaptation measures. The impacts of land management, crop management, and livestock management on GHG emissions are discussed below.

2.1. Land management

Changes in land management can reduce GHG emissions by enhancing the removal of CO_2 and to a smaller extent CH_4 from the atmosphere. N_2O emissions can also be highly influenced by changes in water and nutrient management. Land management practices that impact GHG emissions include changes in tillage, nutrient, and water management, as well as the management of organic soils and degraded land (*Table 1*).

Reduction in the frequency of tillage is a widely accepted means to reduce carbon loss from soils. Advances in farm machinery and weed control methods have made this a viable strategy in many areas. Reduced tillage results in less water loss, less soil erosion, and a lower rate of organic matter decomposition. Soil disturbance through tillage aerates the soil and mixes residues into the profile providing substrates for enhanced decomposition of organic matter. The benefit of a reduction in tillage depends largely on climate and soil type. It is usually more beneficial in dryer soils which are not susceptible to water logging and disease. A reduction in the frequency of tillage can also affect N_2O emissions. Globally, the effects are not consistent, but in some areas a pattern can be discerned. For instance, in the semiarid regions of western Canada N_2O emissions are generally reduced (*Helgason et al*., 2005), whereas in the humid east emissions often increase.

After years of intensive agriculture many soils have become less productive and thus fertilizer N use has been increased to compensate. Improved cultivars and management have also led to a higher fertilizer N requirement. Unfortunately, a large fraction of fertilizer N that is applied to crops remains unused or leaches out of the field and is subject to being transformed and emitted as N_2O. Improving N use efficiency by crops can yield both environmental and economic benefits. Frequent soil N testing is likely the most straightforward technique to improve nutrient management, although the cost of testing sometime limits its application. Applying the appropriate amount of nitrogen maximizes crop production and decreases N_2O formation. The use of slow release fertilizers, coated fertilizers, and nitrogen inhibitors has the potential to reduce N_2O production. Broadcast application of fertilizer often results in excess fertilizer application. Alternative fertilizer application techniques such as banding, precision, and deep placement can help alleviate over fertilization issues.

Table 1. Land management practices that reduce greenhouse gas emissions

Mitigation category	**Practice**	**Impact on GHG emissions**			**Correlation of mitigation to adaptation**
		CO_2	**CH_4**	**N_2O**	
Land management					
Tillage manage-ment	Reduction in tillage	↓↑		↓↑	Positive: Reduced tillage also helps maintain soil water and reduces soil erosion
	No tillage	↓↑		↓↑	
	Zone tillage	↓↑		↓↑	
Nutrient manage-ment	Slow release fertilizers or nitrogen	↓		↓	Positive: Efficient N management means less energy use and cost per unit of food production
	inhibitors	↓		↓	
	Improved N scheduling to minimize loss	↓		↓	
	Reduce leaching and volatile losses	↓		↓	
	Placement of N (banding)	↓↑	↓	↓	
	Timing of organic residue additions				
Water manage-ment	More efficient irrigation (Trickle, subsurface)	↓		↓↑	Positive: Practices which conserve water often reduce GHG emissions and help maintain crop production as an adaptive measure
	Drainage in humid areas	↓		↓	
	Keeping soil cropped to rice dry in off season	↓↑	↓	↓	
	Deficit irrigation	↓↑		↓	
	Mulching with crop residue during fallowing	↓		↓↑	
	Draining wetland rice during the growing season (one to several times)	↓↑	↓	↓↑	
Mana-ging organic soils and degraded land	Avoid drainage of wetlands	↓	↑	↓↑	Positive: Reclamation of degraded land can create a sustainable source of food production
	Maintain shallower water table in org.	↓		↓↑	
	soils	↓		↓↑	
	Re-vegetation of organic soils	↓		↓↑	
	Improve fertility of degraded soils	↓		↓↑	
	Apply organic substrates to degraded soils	↓		↓↑	
	Retain crop residues and conserve water				

Although water management is not considered to be one of the more prominent mitigation options in agriculture, the potential benefits of acting as both a mitigation practice as well as an adaptation option are attractive. Mitigation of GHGs through water management is most applicable in regions where irrigation and drainage management is prevalent. Globally, irrigated rice production accounts for nearly 75% of all rice produced. Continuous flooding of rice paddies has been discussed as a potential mitigation measure that reduces the N_2O emissions in comparison to fields that use mid-season drainage management (*Zheng et al.*, 2000). Considering that nearly 80% of the land area currently dedicated to rice production in China uses midseason drainage (*Li et al.*, 2002), the potential for mitigation of N_2O emissions is significant. Note that low denitrification rates occur either when soils are saturated or at low in water content. If continuous flooding is not an option, then techniques that reduce the frequency and magnitude of irrigation events could also decrease the production of N_2O emissions, i.e., deficit irrigation, trickle, and subsurface (*Doerge et al.*, 1991). The use of crop residues as mulch can limit both evaporation losses as well as improve soil quality through the incorporation of organic matter along with reducing the impact of soil erosion (*Dahiya et al.*, 2007; *Bilbro* and *Fryrear*, 1994).

Increasing demand for food production from agriculture has caused farmers to reclaim organic soils and degraded land. Serious obstacles exist, however, before these areas are suitable for agriculture. Organic soils tend to be acidic and inherently have low fertility. The topsoil is typically very shallow and susceptible to erosion. The application of manure and the burning of crop residues are not always sufficient to keep degraded soils viable for continuous agriculture, so alternative nutrient additions are sometimes unavoidable. The application of phosphorus (P) can usually overcome the fertility constraints inherent in these types of soils but not without introducing a high cost to farmers. The opportunity to sequester soil carbon and increase the area of productive agricultural land should not be ignored. However, due to the inherently high cost of reclaiming these infertile soils, governments may need to provide incentives.

2.2. Crop management

Crop management includes practices that enhance removals of CO_2 from the atmosphere by improving crop selection, using rotations that include high input crops, changing to permanent cover or trees, reducing bare fallow, retaining crop residues, and avoiding biomass burning (*Table 2*). These practices stand to promote carbon sequestration by absorbing more CO_2 from the atmosphere and increasing carbon inputs in the soil.

Crop management can also contribute to reduce N_2O and CH_4 emissions through reduction of fertilizer inputs, using rice cultivars with low exudation rates, organic agriculture, and adjusting timing of planting, harvesting, and fertilizer additions.

Another way to mitigate GHG emissions is to replace fossil fuels with biofuels. Currently much effort is focused on bioenergy production using wheat and maize. It is debatable whether or not biofuel production using existing mainstream crop cultivars mitigates GHG emissions. There is also a major concern that biofuel production will displace agricultural land that would otherwise be used for food production. This is particularly a concern for third world countries where inexpensive food sources are necessary. However, much research is going into new forms of biofuel production using crop residues, lignocellulosic crops, or grasses and shrubs which can, in some cases, be grown on marginal or abandoned land. *Smith et al*. (2008a) predicted that biofuel production could reduce GHG emissions by over 600 Mt CO_2 -eq y^{-1} at a market price of USD/20/t CO_2-eq.

Table 2. Crop management practices that reduce greenhouse gas emissions

Mitigation category	**Practice**	**Impact on GHG emissions**			**Correlation of mitigation to adaptation**
		CO_2	**CH_4**	**N_2O**	
Crop management					
Residue management	Retain crop residues	↓		↓↑	Positive: Crop residues are retained to reduce evaporation/water loss
	Avoid burning	↓		↓↑	
Change in land cover	Reduction in fallowing	↓		↓↑	Negative: Farmers may be required to increase fallow to store water in dryer conditions
	Cropland to Permanent grass/trees	↓		↓	
	More forage in rotations	↓		↓	
	Grassed waterways/field margins/ shelterbelts	↓↑		↓↑	Negative: Increased demand for food production may require more intensive agriculture
Improved crops/crop management	Improved varieties to enhance production	↓		↓↑	Positive: Increased crop production usually enhances soil carbon inputs
	Rice cultivars with low exudation rate	↓↑	↓	↓↑	
	Reduced fertilizer/pesticide inputs	↓↑		↓↑	
	Organic agriculture	↓↑		↓↑	
	Use catch or cover crops	↓		↓	
	Adjust fertilizer rate to crop needs	↓		↑	
Bioenergy	Biofuels from common crop cultivars	↓↑		↓↑	Positive: Biofuel production is an adaptation measure to meet global energy demands
	Biofuels from crop residues	↓		↓↑	
	Biofuels from Lignocellulosic crops	↓		↓↑	
	Bioheat from grasses and shrubs	↓		↓	Positive or negative: In some cases Biofuel crops may replace existing crops that become no longer suitable for production but in other cases they displace land that is needed for mainstream production

2.3. *Livestock and manure management*

Approximately 16% of the global atmospheric CH_4 emissions originate from livestock. The two main sources are enteric fermentation (83%) and manure management (17%) (*FAO*, 2007). It is well documented that the GHG emissions associated with livestock production are substantially higher than for crop production. Mean values of approximately 0.3 kg CO_2-eq per kg of soybean and

0.4 kg CO_2-eq per kg of corn have recently been calculated for these two crops in Canada. The GHG emission per kg of meat is substantially larger. The high emissions from livestock provide opportunities for reducing GHG emissions (*Table 3*). Emission intensities have been reduced in countries that have moved towards intensive production. For example, in Canada *Vergé et al*. (2008) reported a reduction of 5.9 kg CO_2-eq per kg of live weight for beef from 1981 to 2006. Gains in animal productivity as well as changes in animal management practices have contributed to this reduction in GHG emission intensity. Anaerobic digesters can also be used as an energy source thereby displacing emissions from fossil fuels. Other manure handling techniques such as more frequent applications to the field and mechanically separated solids, and handling manure in solid form can also reduce GHG emissions.

Table 3. Livestock and manure management practices that reduce greenhouse gas emissions

Mitigation category	**Practice**	**Impact on GHG emissions**			**Correlation of mitigation to adaptation**
		CO_2	**CH_4**	**N_2O**	
Livestock and manure management					
Grazing management	Grazing intensity and timing	↓↑	↓↑	↓↑	Positive: Improved grazing systems increase productivity
	Fertilizer or organic amendments	↓		↓↑	
	Irrigation (energy requirement)	↓↑		↑	
	Nutrient management	↓		↓	
	Reduce frequency of fires	↓	↓	↓↑	
	Species introduction	↓		↓↑	
Livestock management	Feeding more concentrates		↓	↓	Positive: More efficient feeding can enhance productivity Negative: In some areas breeds of livestock will need to be more resilient to heat and water stress. The dietary needs may be restricted by these requirements
	Adding more oilseeds to diet		↓	↓	
	Special agents and dietary additives		↓		
	Long-term management and improved breeding		↓	↓	
	Reduce confinement	↓	↓		
Manure and biosolid management	Anaerobic digestion to retrieve CH4 as an energy source		↓	↓↑	Positive: There are technologies which capture energy from manures
	Handling manure in solid form		↓	↓	
	More efficient use as nutrient source	↓		↓	
	Cooling of manure in lagoons or tanks, use of solid covers, mechanically separated solids, capturing emitted CH4		↓	↓↑	

3. *Agricultural adaptation to limited water resources*

Based on current climate model assumptions, it is predicted that there will be major shifts in global precipitation patterns and evaporation losses (*UNEP*, 1997; *Carter et al.*, 2007). Since many regions are already water stressed, any further declines in water resources would have an immediate impact on agroecosystems. Farmers would be forced to adopt water management techniques to ensure that agricultural productivity is minimally impacted. *Debaeke* and *Aboudare* (2004) identified six practices that farmers in dry land areas will need to employ to cope with future water limitations. These are: (1) increasing stored soil water at sowing to increase water availability, (2) increasing soil water extraction by crop by maximizing root extraction, (3) reducing the magnitude of soil evaporation and drainage, (4) optimizing the seasonal water use pattern during the growing season, (5) increasing crop tolerance to water stress, and (6) irrigating crops at the most-sensitive growth stages. These practices aim to improve water use efficiency by crops.

In soils that have low organic matter contents, the addition of farmyard manure or use of bio-fertilizers can help improve the soil structure and water holding capacity of these soils. Alternate deep tillage techniques can also increase soil water at sowing by encouraging water infiltration and by promoting deep root development. The deep tillage breaks up the sub soil which is often not ideal for root development. Stubble-mulch and minimum-tillage techniques can increase infiltration and lower evaporation. Evaporation of water was found to be reduced by 34 –50% by leaving crop residues on the surface (*Sauer et al*., 1996). The supply of water through irrigation at critical growth phases, deficit irrigation, would ensure that farmers can maintain productivity even when water resources are limited. Deficit irrigation can be accomplished by reducing the irrigation depth, refilling only part of the root zone, reducing the irrigation frequency, and various furrow wetting techniques (*Ali* and *Tualukder,* 2008).

Most of the water management practices mentioned are pertinent for dry land farming systems, but water management will also be important for rice production in many of the more humid regions. China and India produces much of their rice on irrigated lowlands which have relatively high water requirements. Irrigation water could be saved without yield loss by applying alternate wetting and drying or flush irrigation to rice systems, but in some cases this may increase N_2O emissions.

4. Modeling mitigation strategies to reduce GHG emissions

Future trends in climate will change the rate of GHG emissions from agroecosystems and will influence the effectiveness of mitigation strategies. We need to develop tools for estimating emissions under a changing climate. Due to limited data and the extreme number of variables in agricultural systems, it is difficult to extrapolate measured data to predict changes. In some cases, particularly for certain adaptation measures, no GHG emissions data are available.

The use of process-based models as prediction tools offers many advantages as they can simulate the highly diverse soils, farm management, and climatic conditions found in agroecosystems. They can simultaneously provide the interactions between all the GHG emissions and predict emissions over space and time. However, the biggest issue in using process-based models in various situations is that many of the processes observed are not fully understood. Therefore, process-based models require continuous development and verification to increase the confidence in the results.

Several researchers have used models to estimate GHG emission factors for different soils, crops, and climates (*Smith et al*., 2001; *Desjardins et al*., 2004; *Grant et al*., 2004), but few have attempted to estimate the effect of climate change on these factors. Changes in climate are accompanied by many possible changes in agricultural management, whereby the length of the crop growing season may change, crop cultivars may change, it may no longer be viable to grow certain crops, different rates of fertilizer will need to be applied, irrigation or drainage may be required, and pest management strategies may need to change. The effect of climate on our agroecosystems in the future is highly uncertain, partly because our ability to predict climate change is uncertain. *Smith et al*., (2008b) using the Century model found that climate change had little effect on no-till C sequestration factors, but had some influence on permanent cover factors. Both the SRES B2 and IS92a climate scenarios resulted in greater loss of soil C towards the end of the century. *Smith et al*., (2007b) estimated ranges of emission factors for changes in agricultural management. The estimates were derived from empirical data and process-based models such as Daycent (*Del Grosso et al*., 2001) and DNDC (*Li*, 2000). Based on these factors they estimated approximately 6000 Mg CO_2-eq y^{-1} as the global mitigation potential by 2030 and an economic potential of 1500–1600, 2500–2700, and 4000–4300 Mt CO_2-eq y^{-1} at carbon prices of 20, 50, and 100 USD/t CO_2-eq. No doubt there is much uncertainty involved in this process, but it is important to quantify the various mitigation options.

Adaptation methods and sometimes even mitigation measures may change with time as the climate becomes warmer, more arid, or more variable. For this review paper we also carried out a short study to serve as an example of how models may be applied to assess the effects of climate change on GHG emissions in some areas around the world. Ten locations were chosen across contrasting climatic zones, soils, and crops (*Table 4*). The purpose of this exercise was to gain a better understanding of how a changing climate might affect GHG emissions and not to fully characterize any given area.

Simulations were performed in a manner similar to that by Smith et al., 2008b. To generate future climate, 20 years of historical weather data (1970–1999) from a station at each of the 10 locations was used. A historical year was randomly selected from this 20-year period for each of the 100 years from 2000–2100. Thus each year from 2000 to 2100 had the same distribution and frequency of weather events as historical data. Seasonal changes in precipitation and temperature over time were applied based on estimates from the IPCC report on Climate Change: Impacts, Adaptation and Vulnerability (*Carter et. al*., 2007). In this report AOCM predictions of seasonal changes in mean temperature and precipitation for the A2 emission scenario were estimated and averaged from 15 recent AOCM simulations to the end of the 21st century for 32 regions. We used the average of these ranges to indicate changes in temperature and precipitation for the ten chosen locations and applied the change in temperature and precipitation linearly over the time period from 2000 to 2100. Simulations were carried out both with and without CO_2 fertilization. A nonlinear rate of CO_2 fertilization was assumed based on the A2 scenario. Generalized agricultural management, including fertilizer application rates and scheduling, planting, and harvest dates, and tillage scheduling were used for each location. We created a few new crop profiles by adjusting optimum grain and total biomass and degree days to maturity such that the DNDC model could better match biomass production.

Table 4. Estimated change in yield from 2090–2100 in comparison to baseline yields from 1970–1999 using the DNDC model for the A2 climate change scenario

Location	**Crop type**	**Average annual precipitation (cm)**	**Average annual temperature (°C)**	**Change in precipitation (%)**	**Change in temperature (°C)**	**Change in yield (CO_2 fertilization) (%)**	**Change in yield (no CO_2 fertilization) (%)**
Australia	WF	29	17	–4.6	3.2	–6	–15
Canada	W	39	6	3.6	4.0	6	–4
Canada	W	47	2	18.1	5.2	–1	–7
India*	R/W	66	23	4.8	3.5	17	–3
China*	W/M	68	14	11.5	4.1	24	1
Germany	W	81	8	–19.1	3.9	–3	–19
Africa	M	92	28	1.3	3.4	–24	–25
Canada	M	99	6	5.5	4.3	21	–5
Brazil	M	121	27	–4.0	3.8	9	–3
China	R/R	146	17	11.5	4.1	–6	–13

W – wheat, F – fallow, R – rice, M – maize
/ denotes two crops in same year
***** denotes irrigated systems

Crop yields were simulated under the A2 climate change scenario both with and without CO_2 fertilization. The resulting change in yield over the last 10 years from 2090–2100 in comparison to baseline yields from 1970–1999 is shown in *Table 4*. The average overall yield across the ten locations showed no change under the climate scenario when CO_2 fertilization was included, however, yield declined in simulations with no increase in CO_2 fertilization. Considering that recent research indicates some crops may reduce their rate of respiration and slow growth under higher temperatures (*Gill et al.*, 2002), we may not expect them to respond to increased CO_2 fertilization. Note that for the site in Mali, Africa a small increase in temperature resulted in a sizable decline in yield. This is because production at this location is already seriously hampered by poor soil quality, and the DNDC model indicates that any more stress could result in detrimental effects on crop yield.

Nitrous oxide emissions were extremely variable at several locations. Fertilizer rate was not adjusted to account for changes in growth which could result in over- or under-fertilization. At a subhumid location in Canada over-fertilization was not an issue. These results demonstrate the potential tradeoff that can occur between N_2O and CO_2 emissions (*Fig. 1*). At this location CO_2 flux from soils is increased due to enhanced decomposition of organic matter under higher temperatures. The denitrification process, on the other hand, is limited as soil-water availability declines and as a result less N_2O emissions occur. Some climate change studies have only looked at the effect of a changing temperature on GHG emissions but it is also of importance to examine the effects of a changing water regime. In semiarid and subhumid locations adaptation efforts will be required to maintain crop yields. Such measures might include selecting crops with improved water use efficiency, or a change in irrigation, or residue management. These changes should decrease soil carbon loss but will have variable effects on N_2O emissions.

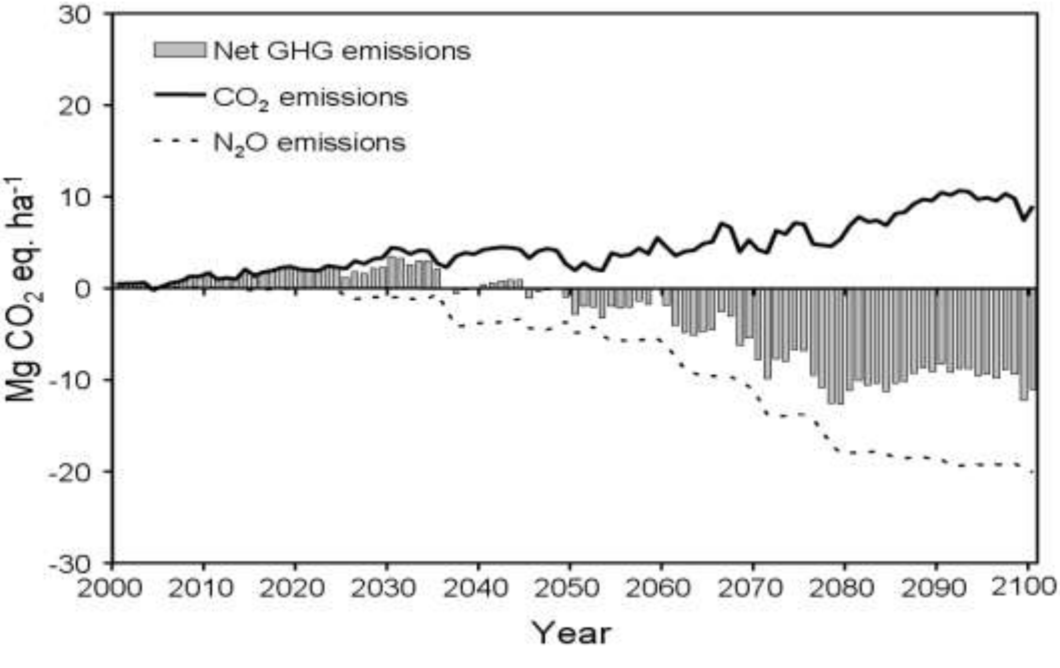

Fig. 1. Estimated influence of climate change on CO_2/N_2O emissions from a wheat crop in subhumid Canada, 2000 –2100.

An increase in temperature through climate change can result in enhanced soil organic matter decomposition and loss of soil carbon, which may offset some of the mitigative efforts. The results using the DNDC model indicate that soil carbon will be lost in cooler climatic zones but may be gained slightly in warmer regions (*Fig. 2*). In tropical regions soil carbon is often already in a degraded state, thus further increases in temperature have little effect. Furthermore, an increase in average annual temperature from 2 to 7 degrees will have more of an effect on decomposition than an increase from 28 to 33 degrees, largely because there are more frost free days, and the soil thaws much earlier in the spring.

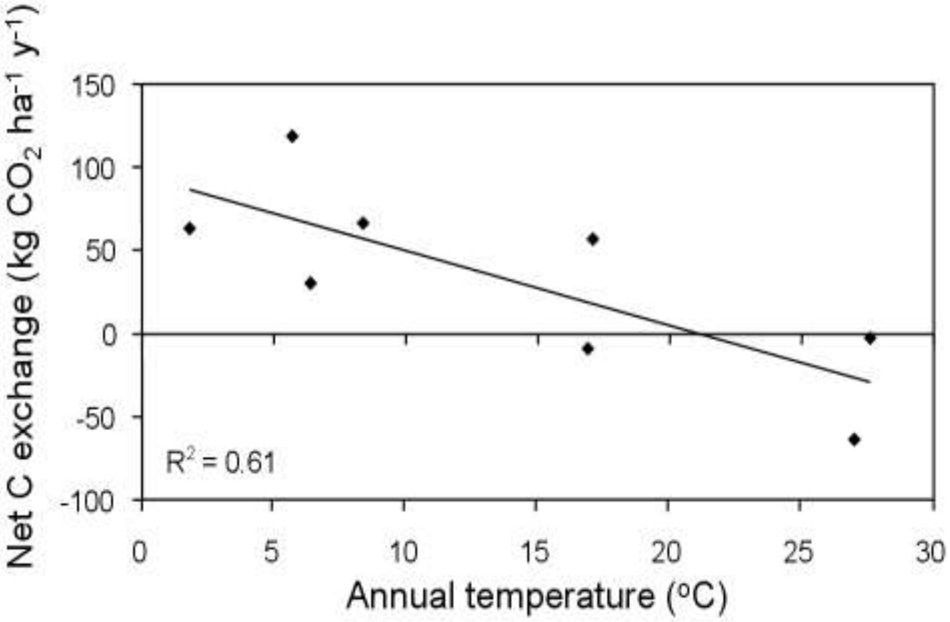

Fig. 2. Estimated effect of climate change by 2100 on CO_2 exchange from agricultural systems for a wide range of annual temperatures (see Table 4 for information on country selected).

5. *Conclusions*

Greenhouse gas emissions from most agricultural systems could be reduced, however, the extent to which reduction will occur is limited by policy, economics, and a need for more food production. Gaps in knowledge regarding the potential of various mitigation measures limit our ability to make recommendations. Policy and economic incentives will be needed to promote mitigation of GHG from agricultural sources. Reducing agricultural production that requires a large amount of energy input per unit of food (e.g., meat and milk) could substantially reduce GHG emissions. Biofuel production can be a viable adaptation and mitigation measure, but practices such as residue removal or growth of crops on marginal land should be promoted to avoid competition with mainstream agriculture. It is essential to assess long-term consequences of mitigation and adaptation strategies, determine how these actions are affected by climate, and develop strategies to combat climate change. Integration of mitigation and adaptation frameworks into sustainable development planning is required, especially in developing countries. It is imperative for countries to take a proactive and collaborative role in planning national and regional programs on mitigation and adaptation to climate variability and climate change.

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