CHAPTER 10

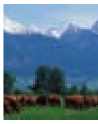
Agricultural and Grazing Lands

Lead Authors: Richard T. Conant, Colo. State Univ.; Keith Paustian, Colo. State Univ.

Contributing Authors: Felipe García-Oliva, UNAM; H. Henry Janzen, Agriculture and Agri-Food Canada; Victor J. Jaramillo, UNAM; Donald E. Johnson, Colo. State Univ. (deceased); Suren N. Kulshreshtha, Univ. Saskatchewan

KEY FINDINGS

- Agricultural and grazing lands (cropland, pasture, rangeland, shrublands, and arid lands) occupy 789 million hectares (1.95 billion acres), which is 47% of the land area of North America, and contain 78.5 ± 19.5[1] billion tons of organic carbon (17% of North American terrestrial carbon) in the soil alone.
- The emissions and uptake and storage of carbon on agricultural lands are mainly determined by two conditions: management and changes in the environment. The effects of converting forest and grassland to agricultural lands and of agricultural management (e.g., cultivation, conservation tillage) are reasonably well known and have been responsible for historic losses of carbon in Canada and the United States (and for current losses in Mexico); the effects of climate change or of elevated concentrations of atmospheric carbon dioxide are uncertain.
- Conservation-oriented management of agricultural lands (e.g., use of conservation tillage, improved cropping and grazing systems, reduced bare fallow, set-asides of fragile lands, and restoration of degraded soils) can significantly increase soil carbon stocks.
- Agricultural and grazing lands in the United States and Canada are currently near neutral with respect to their soil carbon balance, but agricultural and grazing lands in Mexico are likely losing carbon due to land-use change. Although agricultural soils are estimated to currently uptake about 19-20 million tons of carbon per year, the cultivation of organic soils releases approximately 6-12 million tons of carbon per year. On-farm fossil-fuel use (around 31 million tons of carbon per year), agricultural liming (1.2 million tons of carbon per year), and manufacture of agricultural inputs including fertilizer (approximately 6 million tons of carbon per year) yields a net source from the agricultural sector of about 25-30 million tons of carbon per year.
- As much as 120 million tons of carbon per year may be accumulating through woody encroachment of arid and semi-arid lands of North America; this value is highly uncertain. Woody encroachment is generally accompanied by decreased forage production, and ongoing efforts to reestablish forage species are likely to reverse carbon accumulation by vegetation.
- Projections of future trends in agricultural land area and soil carbon stocks are unavailable or highly uncertain because of uncertainty in future land-use change and agricultural management practice.
- Annualized prices of $15/metric ton carbon dioxide, could yield mitigation amounts of 46 million tons of carbon per year captured in agricultural soils and 14.5 million tons of carbon per year from reductions in fossil-fuel use. At lower prices of $5/metric ton carbon dioxide, the corresponding values would be 34 million tons of carbon per year and 9 million tons of carbon per year, respectively.
- Policies designed to suppress emissions of one greenhouse gas need to consider complex interactions to ensure that *net* emissions of total greenhouse gases are reduced. For example, increased use of fertilizer or irrigation may increase crop residues and carbon uptake and storage, but may stimulate emissions of methane or nitrous oxide.



---

[1] The uncertainty in this value is given as one standard error of the mean.

- Many of the practices that lead to carbon capture and storage or to reduced carbon dioxide and methane emissions from agricultural lands not only increase production efficiencies, but lead to environmental co-benefits, for example, improved soil fertility, reduced erosion, and pesticide immobilization.
- An expanded network of intensive research sites would allow us to better understand the effects of management on carbon cycling and storage in agricultural systems. An extensive national-level network of soil monitoring sites in which changes in carbon stocks are directly measured would allow us to reduce the uncertainty in the inventory of agricultural and grazing land carbon. Better information about the spatial extent of woody encroachment, the amount and growth of woody vegetation, and variation in impacts on soil carbon stocks would help reduce the large uncertainty of the carbon impacts of woody encroachment.

BOX 10.1: Nitrous Oxide Emissions From Agricultural and Grazing Lands

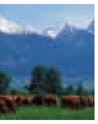
Nitrous oxide (N_2O) is the most potent greenhouse gas in terms of global warming potential, with a radiative forcing 296 times that of CO_2 (IPCC, 2001). Agricultural activities that add mineral or organic nitrogen (fertilization, plant N_2 fixation, manure additions, *etc.*) augment naturally occurring N_2O emissions from nitrification and denitrification by 0.0125 kg N_2O per kg nitrogen applied (Mosier *et al.*, 1998a). Agriculture contributes significantly to total global N_2O fluxes through soil emissions (35% of total global emissions), animal waste handling (12%), nitrate leaching (7%), synthetic fertilizer application (5%), grazing animals (4%), and crop residue management (2%). Agriculture is the largest source of N_2O in the United States (78% of total N_2O emissions), Canada (59%), and Mexico (76%).

10.1 INVENTORY

10.1.1 Background

Agricultural and grazing lands (cropland, pasture, rangeland, shrublands, and arid lands)[2] occupy 47% of the land area in North America (59% in the United States, 70% in Mexico, and 11% in Canada), and contain 17% of the terrestrial carbon. Most of the carbon in these ecosystems is held in soils. Live vegetation in cropland generally contains less than 5% of total carbon, whereas vegetation in grazing lands contains a greater proportion (5–30%), but still less than that in forested systems (30–65%). Agricultural and grazing lands in North America contain 78.5 ± 19.5 (±1 standard error) billion tons of organic carbon (Gt C) in the soil (Table 10.1). Significant increases in vegetation carbon stocks in some grazing lands have been observed and, together with soil carbon stocks from croplands and grazing lands, likely contribute significantly to the large North American terrestrial carbon sink (Houghton *et al.*, 1999; Pacala *et al.*, 2001; Eve *et al.*, 2002; Ogle *et al.*, 2003). These lands also emit greenhouse gases: fossil-fuel use for on-farm machinery and buildings, for manufacture of agricultural inputs, and for transportation account for 3–5% of total carbon dioxide (CO_2) emissions in developed countries (Enquete Commission, 1995); activities on agricultural and grazing lands, like livestock production, animal waste management, biomass burning, and rice cultivation emit 35% of global anthropogenic methane (CH_4) (27% of United States', 31% of Mexican, and 27% of Canadian CH_4 emissions) (Mosier *et al.*, 1998b; CISCC, 2001; Ministry of the Environment, 2006; EPA, 2006); and agricultural and grazing lands are the largest anthropogenic source of nitrous oxide (N_2O) emissions (CAST, 2004; see Box 10.1). However, agricultural and grazing lands are actively managed and have the capacity to take up and store carbon. Thus improving management could lead to substantial reductions in CO_2 and CH_4 emissions and could sequester carbon to offset emissions from other lands or sectors.

Agricultural and grazing lands are actively managed and have the capacity to take up and store carbon. Thus improving management could lead to substantial reductions in CO_2 and CH_4 emissions.



10.1.2 Carbon Dioxide Fluxes From Agricultural and Grazing Land

The main processes governing the carbon balance of agricultural and grazing lands are the same as for other ecosystems: the photosynthetic uptake and assimilation of CO_2 into organic compounds, the release of gaseous carbon through respiration (primarily CO_2 but also CH_4), and fire. Like other terrestrial ecosystems in general, for which CO_2 emissions are approximately two orders of magnitude greater than CH_4 emissions, carbon cycling in most agricultural and grazing lands is dominated by fluxes of CO_2 rather than CH_4. In agricultural lands, carbon assimilation is directed towards production of food, fiber, and forage by manipulating species composition and growing conditions (soil fertility, irrigation, *etc.*). Biomass, being predominantly herbaceous (*i.e.*, non-woody), is a small, transient carbon pool (compared to forests) and hence soils constitute the dominant carbon stock. Cropland systems can be among the most productive ecosystems, but in some cases restricted growing season length, fallow periods, and grazing-induced shifts in species

---

[2] We refer collectively to pasture, rangeland, shrublands, and arid lands as grazing lands since grazing is their primary use, even though not all of these lands are grazed.

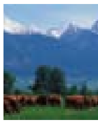
Table 10.1 Soil organic carbon pools in agricultural and grazing lands in Canada, Mexico, and the United States. The data values are given in Gt C. The area (in millions of hectares) for each climatic zone is in parentheses. Current soil carbon stocks are secondary quantities derived from an initial starting point of undisturbed native ecosystems carbon stocks, which were quantified using the intersection of (Moderate Resolution Imaging Spectroradiometer-International Geosphere-Biosphere Programme) MODIS-IGBP[a] land cover types (Friedl *et al.*, 2002) and mean soil carbon contents to 1-m depth from Sombroek *et al.* (1993), spatially arrayed using Food and Agriculture Organization soil classes (ISRIC, 2002), and summed by climate zone. These undisturbed native ecosystem carbon stock values were then multiplied by soil carbon loss factors for tillage- and overgrazing-induced losses (Nabuurs *et al.*, 2004; Ogle *et al.*, 2004) to estimate current soil carbon stocks (see Figure 10.2). Uncertainties (± one standard error) were derived from uncertainty associated with soil carbon stocks and soil carbon loss factors.

Practice	Temperate dry[b,c]	Temperate wet	Tropical dry	Tropical wet	Total
Agricultural lands					
Canada	1.79±0.35 (17.3)	1.77±0.36 (22.1)	–	–	3.60±0.77 (39.4)
Mexico	–	–	0.24±0.06 (3.9)	0.53±0.14 (10.2)	0.81±0.22 (14.1)
United States	3.31±0.74 (34.8)	8.66±2.18 (108.4)	0.35±0.08 (5.6)	1.53±0.33 (28.4)	14.05±3.20 (177.1)
Total	**5.16±1.07 (52.1)**	**10.57±2.42 (130.5)**	**0.61±0.14 (9.5)**	**2.18±0.54 (38.6)**	**18.5±4.16 (230.6)**
Grazing lands					
Canada	2.17±0.55 (18.4)	9.49±1.27 (40.8)	–	–	11.66±4.88 (59.2)
Mexico	–	–	7.20±1.62 (99.1)	2.19±0.58 (20.3)	9.99±2.60 (119.4)
United States	16.89±3.62 (209.9)	5.67±1.39 (55.0)	4.26±0.98 (68.1)	4.30±0.89 (46.7)	32.88±7.18 (379.7)
Total	**19.34±4.27 (228.3)**	**21.07±5.80 (95.8)**	**12.59±2.73 (167.1)**	**6.94±1.86 (67.0)**	**59.95±14.65 (558.2)**

[a] Cropland area was derived from the IGBP cropland land cover class plus the area in the cropland/natural vegetation IGBP class in Mexico and one-half of the area in the cropland/natural vegetation IGBP class in Canada and the United States. Grazing land area includes IGBP woody savannas, savannas, and grasslands in all three countries, plus open shrubland in Mexico and open shrublands (not in Alaska) in the United States.

[b] Temperate zones are those located above 30° latitude. Tropical zones (below 30° latitude) include subtropical regions.

[c] Dry climates were defined as those where the ratio of mean annual precipitation (MAP) to potential evapotranspiration (PET) is less than one; in wet areas, MAP/PET is greater than one.



BOX 10.2: Inorganic Soil Carbon in Agricultural and Grazing Ecosystems

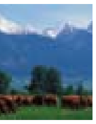
Inorganic carbon in the soil is comprised of primary carbonate minerals, such as calcite ($CaCO_3$) or dolomite ($CaMg[CO_3]_2$), or secondary minerals formed when carbonate (CO_3^{2-}), derived from soil CO_2, combines with base cations (*e.g.*, Ca^{2+}, Mg^{2+}) and precipitates within the soil profile in arid and semi-arid ecosystems. Weathering of primary carbonate minerals in humid regions can be a source of CO_2, whereas formation of secondary carbonates in drier areas is a sink for CO_2; however, the magnitude of either flux is highly uncertain. Agricultural liming involves addition of primary carbonate minerals to the acid soils to increase the pH. In Canada and the United States, about 0.1 and 1.1 Mt C per year is emitted from liming (Sobool and Kulshreshtha, 2005; EPA, 2006). Inorganic carbon stocks in North America have been estimated at 66.8 Gt C (Sombroek *et al.*, 1993).

composition or production can reduce carbon uptake relative to that in other ecosystems. These factors, along with tillage-induced soil disturbances and removal of plant carbon through harvest, have depleted soil carbon stocks by 20-40% (or more) from pre-cultivated conditions (Davidson and Ackerman, 1993; Houghton and Goodale, 2004). Soil organic carbon stocks in grazing lands (see Box 10.2 for information on inorganic soil carbon stocks) have been depleted to a lesser degree than for cropland (Ogle *et al*., 2004), and in some regions biomass has increased due to suppression of disturbance and subsequent woody encroachment (see Box 10.3). Woody encroachment is potentially a significant sink for atmospheric CO_2, but the magnitude of the sink is poorly constrained (Houghton *et al*., 1999; Pacala *et al*., 2001). Since woody encroachment leads to decreased forage production, management practices are aimed at reversing it, with consequent reductions in biomass carbon. Disturbance-induced increases in decomposition rates of above-ground litter and harvest removal of some (30–50% of forage in grazing systems, 40–50% in grain crops) or all (*e.g.*, corn for silage) of the above-ground biomass, have drastically altered carbon cycling within agricultural lands and thus the sources and sinks of CO_2 to the atmosphere.

Much of the carbon lost from agricultural soil and biomass pools can be recovered with changes in management practices.

BOX 10.3: Impacts of Woody Encroachment Into Grasslands on Ecosystem Carbon Stocks

Encroachment of woody species into grasslands—caused by overgrazing-induced reduction in grass biomass and subsequent reduction or elimination of grassland fires—is widespread in the United States and Mexico, decreases forage production, and is unlikely to be reversed without costly mechanical intervention (Van Auken, 2000). Encroachment of woody species into grassland tends to increase biomass carbon stocks by one million grams of carbon (1 Mg C) per hectare per year (Pacala *et al*., 2001), with estimated net sequestration of 120–130 Mt C per year in encroaching woody biomass (Houghton *et al*., 1999; Pacala *et al*., 2001). In response to woody encroachment, soil organic carbon stocks can significantly increase or decrease, thus predicting impacts on soil carbon or ecosystem carbon stocks is very difficult (Jackson *et al*., 2002). Invasion of grass species into native shrublands tends to lead to the release of soil organic carbon (Bradley *et al*., 2006).



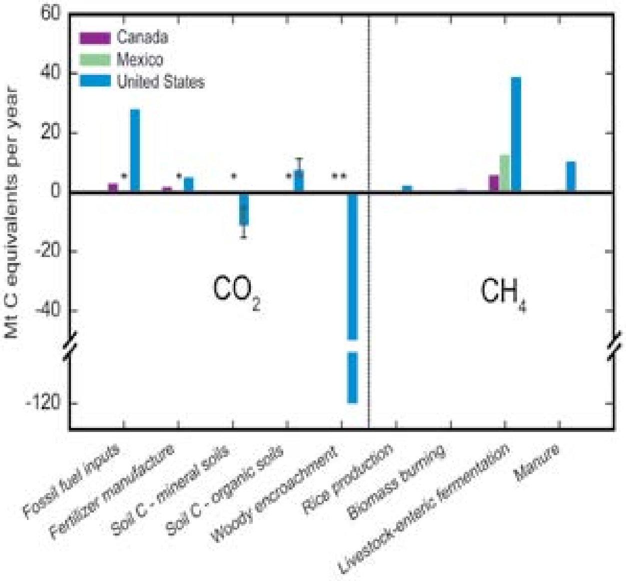


Figure 10.1 North American agricultural and grazing land CO_2 (left side) and CH_4 (right side), adjusted for global warming potential. All units are in Mt C-equivalent per year for years around 2000. Negative values indicate net flux from the atmosphere to soil and biomass carbon pools (*i.e.*, sequestration). All data are from Canadian (Matin *et al.*, 2004) and U.S. (EPA, 2006) National Inventories and from the second Mexican National Communication (CISCC, 2001), except for Canadian (from Kulshreshtha *et al.*, 2000) and U.S. fossil-fuel inputs (from Lal *et al.*, 1998) and woody encroachment (from Houghton *et al.*, 1999). Values are for 2003 for Canada, 1998 for Mexico, and 2004 for the United States. A global warming potential of 23 for methane was used to convert emissions of CH_4 to CO_2 equivalents (IPCC, 2001) and a factor of 12/44 to convert from CO_2 to carbon. Asterisks indicate unavailable data. Data ranges are indicated by error bars where available.

Much of the carbon lost from agricultural soil and biomass pools can be recovered with changes in management practices that increase carbon inputs, stabilize carbon within the system, or reduce carbon losses, while still maintaining outputs of food, fiber, and forage. Increased production, increased residue carbon inputs to the soil, and increased organic matter additions have reversed historic soil carbon losses in long-term experimental plots (*e.g.*, Buyanovsky and Wagner, 1998). However, the management practices that promote soil carbon sequestration would need to be maintained over time to avoid subsequent losses of sequestered carbon. Across Canada and the United States, mineral soils have been sequestering 2.5† and 17.0 ± 0.45 million metric tons of carbon (Mt C) per year[3] (Ministry of the Environment, 2006; Ogle *et al*., 2003; EPA, 2006), respectively, largely through increased production and improved management practices on annual cropland (Figure 10.1, Table 10.2). Conversion of agricultural land to grassland, like under the Conservation Reserve Program in the United States (7.6–11.5 Mt C per year on 31.5 million acres [12.5 million hectares] of land), and afforestation have also sequestered carbon in agricul-

---

[3] † A dagger symbol indicates that the magnitude and/or range of uncertainty for the given numerical value(s) is not provided in the references cited.

Table 10.2 North American agricultural and grazing land carbon fluxes for the years around 2000. All units are in Mt C per year. Negative numbers (in parentheses) indicate net flux from the atmosphere to soil and biomass carbon pools. Unless otherwise noted, data are from Canadian (Matin *et al.*, 2004) and United States' National Inventories (EPA, 2006), and from the Second Mexican National Communication (CISCC, 2001). Values are for 2003 for the United States and Canada, and 1998 for Mexico. A factor of 12/44 was used to convert from CO_2 to carbon and a factor of 12/16 to convert CH_4 to carbon

	Canada	Mexico	United States	Total
CO_2				
On-farm fossil-fuel use	2.9[a]	ND	28[b]	30.9
Fertilizer manufacture	1.7	ND	4.7	6.4
Mineral soil carbon sequestration	(2.5)	ND	(17±0.45)	(19.1) – (20.0)
Organic soil cultivation	0.1	ND	8.3±3.2	5.6 – 11.9
Agricultural liming	0.1	ND	1.1	1.2
Woody encroachment	ND	ND	(120)[c]	(120)
Total	2.3	ND	(114.7) – (120.1)	(117) – (122.4)
CH_4				
Rice production	0	0.011	0.25±0.28	0.26
Biomass burning	<0.01	<0.01	0.03±0.02	0.05
Livestock	0.62	1.48	3.67±0.53	5.93
Manure	0.18	0.05	1.28±0.24	1.60
Total	0.80	1.54	5.23	7.84

ND = no data reported.
[a] From Kulshreshtha *et al.* (2000).
[b] From Lal *et al.* (1998).
[c] From Houghton *et al.* (1999).

tural and grazing lands (Follett *et al.*, 2001a). In contrast, cultivation of organic soils (*e.g.*, peat-derived soils) is releasing an estimated 0.1 and 8.3 ± 3.2 Mt C per year[†] from soils in Canada and the United States (Matin *et al.*, 2004; Ministry of the Environment, 2006; Ogle *et al.*, 2003; EPA, 2006). Compared with other systems, the high productivity and management-induced disturbances of agricultural systems promote movement and redistribution (through erosion, runoff, and leaching) of organic and inorganic carbon, sequestering potentially large amounts of carbon in sediments and water (Raymond and Cole, 2003; Smith *et al.*, 2005; Yoo *et al.*, 2005). However, the net impact of soil erosion on carbon emissions to the atmosphere remains highly uncertain.

Production, delivery, and use of field equipment, fertilizer, seed, pesticides, irrigation water, and maintenance of animal production facilities contribute 3–5% of total fossil-fuel CO_2 emissions in developed countries (Enquete Commission, 1995). On-farm fossil-fuel emissions together with manufacture of fertilizers and pesticides contribute emissions of 32.7 Mt C per year[†] within the United States (Lal *et al.*, 1998) and 4.6 Mt C per year in Canada (Kulshreshtha *et al.*, 2000) (Table 10.2). Energy consumption for heating and cooling high intensity animal production facilities is among the largest CO_2 emitters within the agricultural sector (Enquete Commission, 1995).

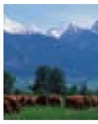
Much of the ammonia production and urea application (United States: 4.3 Mt C per year; Mexico: 0.4 Mt C per year; Canada: 1.7 Mt C per year) and phosphoric acid manufacture (United States: 0.4 Mt C per year; Mexico: 0.2 Mt C per year; Canada: not reported) are devoted to agricultural uses.

10.1.3 Methane Fluxes From Agricultural and Grazing Lands

Cropland and grazing land soils act as both sources and sinks for atmospheric CH_4. Methane formation is an anaerobic process and is most significant in waterlogged soils, like those under paddy rice cultivation (United States: 0.25 ± 0.28 Mt CH_4-C per year; Mexico: 0.01 Mt CH_4-C per year[†]; Canada: negligible, not reported; Table 10.2). Methane is also formed by incomplete biomass combustion of crop residues (United States: 0.03 ± 0.02 Mt CH_4-C per year; Mexico: <0.01 Mt CH_4-C per year; Canada: negligible, not reported; Table 10.2). Methane oxidation in soils is a global sink for about 5% of CH_4 produced annually and is mainly limited by CH_4 diffusion into the soil. However, intensive cropland management tends to reduce soil CH_4 consumption relative to forests and extensively managed grazing lands (CAST, 2004). Management-induced changes in CH_4-C fluxes have a smaller impact on terrestrial carbon cycling than changes in CO_2-C fluxes (Table 10.2), but relatively greater radiative forcing for CH_4 amplifies the impact of increasing atmospheric CH_4 concentrations on net radiative forcing (Figure 10.1). Recent research has shown that live plant biomass and litter produce substantial amounts of CH_4, potentially making plants as large a source of CH_4 as livestock (Keppler *et al.*, 2006). If this is the case, activities that increase plant biomass (and sequester CO_2) may lead to increased CH_4 production (Keppler *et al.*, 2006).

10.1.4 Methane Fluxes From Livestock

Enteric fermentation (the process of organic matter breakdown by gut flora within the gastrointestinal tract of animals, particularly ruminants) allows for the digestion of fibrous



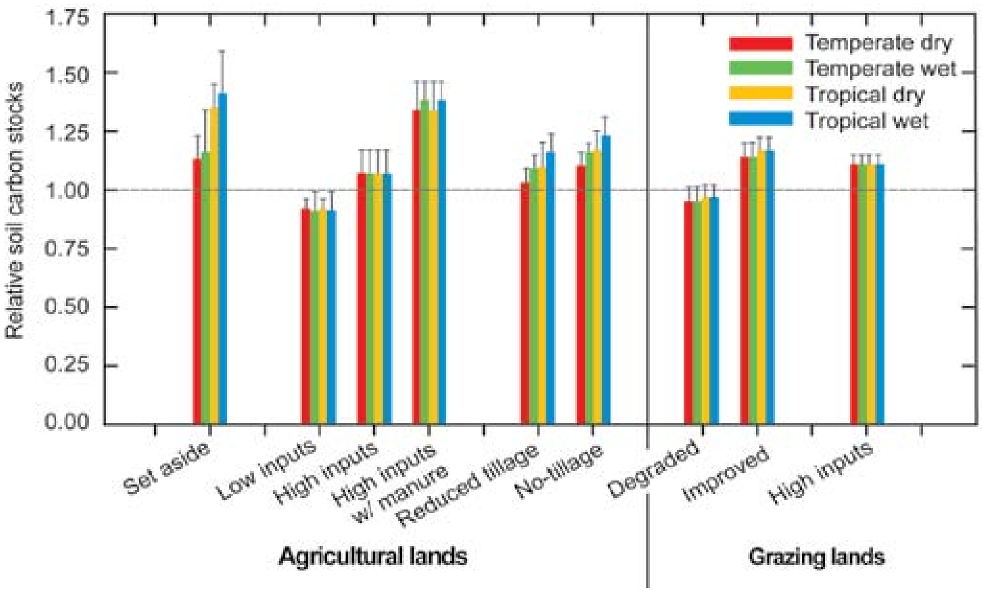
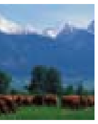


Figure 10.2 Relative soil carbon following implementation of new agricultural or grassland management practices. Conventionally tilled, medium-input cultivated land and moderately grazed grasslands with moderate inputs are defaults for agricultural and grazing lands, respectively. Default soil carbon stocks (like those in Table 10.1) can be multiplied by one or more stock change factors to estimate carbon sequestration rates (over a 20-year time period). The dashed horizontal line indicates default soil carbon stocks (*i.e.*, those under conventional-tillage cropland or undegraded grazingland, with medium inputs). Temperature/precipitation divisions are the same as those described in Table 10.1. Data are from Nabuurs *et al.* (2004) and Ogle *et al.* (2004).

materials by livestock, but the extensive fermentation of the ruminant diet requires 5–7% of the dietary gross energy to be belched out as CH_4 to sustain the anaerobic processes (Johnson and Johnson, 1995). Methane emissions from livestock contribute significantly to total CH_4 emissions in the United States (3.7 ± 0.53 Mt CH_4-C per year, 20% of total United States' CH_4 emissions), Canada (0.78 ± 0.14 Mt CH_4-C per year, 22% of total) (Ministry of the Environment, 2006; Sobool and Kulshreshtha, 2005), and Mexico (1.5 Mt CH_4-C per year, 27% of total)[†] with the vast majority of enteric CH_4 emissions from beef (72%) and dairy cattle (23%) (Table 10.2). Emissions from ruminants are tightly coupled to feed consumption, since CH_4 emission per unit of feed energy is relatively constant, except for feedlot cattle with diets high in cereal grain contents, for which the fractional loss falls to one-third to one-half of normal rates (Johnson and Johnson, 1995). Between 1990 and 2002, CH_4 emissions from enteric fermentation fell 2% in the United States but increased by 20% in Canada (EPA, 2000; Matin *et al.*, 2004).



Where the incentives (e.g., carbon offset market payments, government subsidies) to adopt new practices exceed the opportunity costs, farmers will adopt new practices.

Methane emissions during manure storage (United States: 1.3 ± 0.24 Mt CH_4 per year; Mexico: 0.06 Mt CH_4 per year [†]; Canada: 0.3 ± 0.05 Mt CH_4 per year) are governed by the amount of degradable organic matter, degree of anoxia, storage temperature, and duration of storage. Unlike enteric CH_4, the major sources of manure CH_4 emissions in the United States are from swine (44%) and dairy cattle (39%). Manure CH_4 production is greater for production systems with anoxic lagoons, largely anoxic pits, or manure handled or stored as slurry. Between 1990 and 2002, CH_4 emissions from manure management increased 25% in the United States and 21% in Canada (EPA, 2000; Matin *et al.*, 2004).

10.2 DRIVERS AND TRENDS

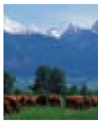
The extent to which agriculture will contribute to greenhouse gas mitigation will largely depend on government policy decisions, but mitigation opportunities will also be constrained by technological advances and changing environmental conditions (see discussion below). Estimates from national inventories suggest that United States' and Canadian agricultural soils are currently near neutral or small net sinks for CO_2, which has occurred as a consequence of changing management (*e.g.*, reduced tillage intensity) and government programs designed for purposes other than greenhouse gas mitigation (*e.g.*, soil conservation, commodity regulation). However, to realize the much larger potential for soil carbon sequestration (see section below) and for significant reductions in CH_4 (and N_2O) emissions, specific policies targeted at greenhouse gas reductions are required. It is generally recognized that farmers (and other economic actors) are, as a group, "profit-maximizers," which implies that to change from current practices to ones that reduce net emissions, farmers will incur additional costs (termed "opportunity costs"). Hence, where the incentives (*e.g.*, carbon offset market payments, government subsidies) to adopt new practices exceed the opportunity costs, farmers will adopt new practices. Crop productivity, production input expenses, marketing costs, *etc.* (which determine profitability) vary widely within (and between) countries. Thus, the payment needed to achieve a unit of emission reduction will vary, among and within regions. In general, each successive increment of carbon sequestration or emission reduction comes at a progressively higher cost (this relationship is often shown in the form of an upward bending marginal cost curve).

The interaction of changes in technological and environmental conditions, including crop growth improvements, impacts of CO_2 increase, nitrogen deposition, and climate change, will shape future trends in greenhouse gas emissions and mitigation from agricultural and grazing lands. A continuation of the yield increases seen in the past several decades for agricultural crops (Reilly and Fuglie, 1998) would tend to enhance the potential for soil carbon sequestration (CAST, 2004). Similarly, increased plant growth due to higher concentrations of CO_2 (and nitrogen deposition) has been projected to boost carbon uptake on agricultural (and other) lands, offsetting some or all of the climate-change induced reductions in productivity projected in some regions of North America (NAS, 2001). However, recent syntheses from field-scale FACE (Free-Air Carbon dioxide Enrichment) studies of croplands (Long *et al.*, 2006) and grasslands (Nowak *et al.*, 2004) suggest that the growth enhancement from CO_2 fertilization may be much less than previously thought. Feedbacks between temperature and soil carbon stocks could counteract efforts to reduce greenhouse gases via carbon sequestration within agricultural ecosystems. Increased temperatures tend to increase the rate of biological processes—including plant respiration and organic matter decay, and CO_2 release by soil organisms—particularly in temperate climates that prevail across most of North America. Because soil carbon stocks, including those in agricultural lands, contain such large amounts of carbon, small percentage increases in the rate of soil organic matter decomposition could lead to substantially increased emissions (Jenkinson *et al.*, 1991; Cox *et al.*, 2000). There is currently a scientific debate about the relative temperature sensitivity of the different constituents making up soil organic matter (*e.g.*, Kätterer *et al.*, 1998; Giardina and Ryan, 2000; Ågren and Bosatta, 2002; Knorr *et al.*, 2005), reflecting uncertainty in the possible degree and magnitude of climate change feedbacks. Despite this uncertainty, the potential for climate and other environmental feedbacks to influence the carbon balance of agricultural systems by perturbing productivity (and carbon input rates) and organic matter turnover, and potentially soil N_2O and CH_4 fluxes, cannot be overlooked.

10.3 OPTIONS FOR MANAGEMENT

10.3.1 Carbon Sequestration

Agricultural and grazing land management practices capable of increasing carbon inputs or decreasing carbon outputs, while still maintaining yields, can be divided into two classes: those that impact carbon inputs, and those that affect carbon release through decomposition and disturbance. Reversion to native vegetation or setting agricultural land aside as grassland, such as in the Canadian Prairie Cover Program and the U.S. Conservation Reserve Program, can increase the proportion of photosynthesized carbon retained in the system and sequester carbon in the soil[4] (Conant *et al.*, 2001; Post and Kwon, 2000; Follett *et al.*, 2001b) (Figure 10.2). In annual cropland, improved crop rotations, yield enhancement measures, organic amendments, cover crops, improved fertilization and irrigation practices, and reduced bare fallow tend to increase productivity and carbon inputs, and thus soil carbon stocks (Lal *et al.*, 1998; Paustian *et al.*, 1998; VandenBygaart *et al.*, 2003) (Figure 10.2). Tillage, traditionally used for soil preparation and weed control, disturbs the soil and stimulates decomposition and loss of soil carbon. Practices that substantially reduce (reduced-till) or eliminate (no-till) tillage-induced disturbances are being increasingly adopted and generally increase soil carbon stocks while maintaining or enhancing productivity levels (Paustian *et al.*, 1997; Ogle *et al.*, 2003) (Figure 10.2). Estimates of the technical potential for annual cropland soil carbon sequestration are on the order of 50–100 Mt C per year in the United States (Lal *et al.*, 2003; Sperow *et al.*, 2003) and 3.3–6.4 Mt C per year in Canada (Boehm *et al.*, 2004).



Within grazing lands, historical overgrazing has substantially reduced productive capacity in many areas, leading to loss of soil carbon stocks (Conant and Paustian, 2002) (Figure 10.2). Conversely, improved grazing management and production inputs (like fertilizer, adding (nitrogen-fixing) legumes, organic amendments, and irrigation) can increase productivity, carbon inputs, and soil carbon stocks (Conant *et al.*, 2001), potentially storing 0.44 Mt C per year† in Canada (Lynch *et al.*, 2005) and as much as 16–54 (mean = 33.2) Mt C per year in the United States (Follett *et al.*, 2001a). Such improvements will carry a carbon cost, par-

---

[4] The bulk of carbon sequestration potential in agricultural and grazing lands is restricted to soil carbon pools, though carbon can be sequestered in woody biomass in agroforestry systems (Sheinbaum and Masera, 2000). Woody encroachment on grasslands can also store substantial amounts of carbon in biomass, but the phenomenon is neither well-controlled nor desirable from the standpoint of livestock production, since it results in decreased forage productivity, and the impacts on soil carbon pools are highly variable and poorly understood.

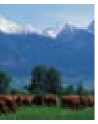
ticularly fertilization and irrigation, since their production and implementation require the use of fossil fuels.

10.3.2 Fossil-Fuel Derived Emission Reductions

The efficiency with which on-farm (from tractors and machinery) and off-farm (from production of agricultural input) energy inputs are converted to agricultural products varies several-fold (Lal, 2004). Where more energy-efficient practices can be substituted for less efficient ones, fossil-fuel CO_2 emissions can be reduced (Lal, 2004). For example, converting from conventional plowing to no-tillage can reduce on-farm fossil-fuel emissions by 25–80% (Frye, 1984; Robertson *et al.*, 2000) and total fossil-fuel emissions by 14–25% (West and Marland, 2003). Substitution of legumes for mineral nitrogen can reduce energy input by 15% in cropping systems incorporating legumes (Pimentel *et al.*, 2005). More efficient heating and cooling (*e.g.*, better building insulation) could reduce CO_2 emissions associated with housed animal facilities (*e.g.*, dairy). Substitution of crop-derived fuels for fossil fuels could decrease net emissions.

Converting from conventional plowing to no-tillage can reduce on-farm fossil-fuel emissions by 25–80% and total fossil-fuel emissions by 14–25%.

Energy intensity (energy per unit product) for the United States' agricultural sector has declined since the 1970s (Paustian *et al.*, 1998). Between 1990 and 2000, fossil-fuel emissions on Canadian farms increased by 35%[†] (Sobool and Kulshreshtha, 2005).



10.3.3 Methane Emission Reduction

Reducing flood duration and decreasing organic matter additions to paddy rice fields can reduce CH_4 emissions. Soil amendments such as ammonium sulfate and calcium carbide inhibit CH_4 formation. Coupled with adoption of new rice cultivars that favor lower CH_4 emissions, these management practices could reduce CH_4 emission from paddy rice systems by 16–70% (mean = 40%) of current emissions (Mosier *et al.*, 1998b).

Biomass burning is uncommon in most Canadian and United States' crop production systems; less than 3% of crop residues are burned annually in the United States (EPA, 2006). Biomass burning in conjunction with land clearing and with subsistence agriculture still occurs in Mexico, but these practices are declining. The primary path for emission reduction is reducing residue burning (CAST, 2004).

Practices that sequester carbon in agricultural and grazing land soils improve soil fertility, buffering capacity, and pesticide immobilization.

Refinement of feed quality, feed rationing, additives, and livestock production efficiency chains can all reduce CH_4 emissions from ruminant livestock with minimal impacts on productivity or profits (CAST, 2004). Boadi *et al.* (2004) review several examples of increases in energy intensity. Wider adoption of more efficient practices could reduce CH_4 production from 5–8% to 2–3% of gross feed energy (Agriculture and Agri-Food Canada, 1999), reducing CH_4 emissions by 20–30% (Mosier *et al.*, 1998b).

Methane emissions from manure storage are proportional to duration of storage under anoxic conditions. Handling solid rather than liquid manure, storing manure for shorter periods of time, and keeping storage tanks cool can reduce emissions from stored manure (CAST, 2004). More important, capture of CH_4 produced during anaerobic decomposition of manure (in covered lagoons or small- or large-scale digesters) can reduce emissions by 70–80% (Mosier *et al.*, 1998b). Use of digester systems is spreading in the United States, with 50 digesters currently in operation and 60 systems in construction or planned (NRCS, 2005). Energy production using CH_4 captured during manure storage will reduce energy demands and associated CO_2 emissions.

10.3.4 Environmental Co-benefits From Carbon Sequestration and Emission Reduction Activities

Many of the practices that lead to carbon sequestration and reduced CO_2 and CH_4 emissions not only increase production efficiencies but also lead to environmental co-benefits. Practices that sequester carbon in agricultural and grazing land soils improve soil fertility, buffering capacity, and pesticide immobilization (Lal, 2002; CAST, 2004). Increasing soil carbon content makes the soil more easily workable and reduces energy requirements for field operations (CAST, 2004). Decreasing soil disturbance and retaining more surface crop residues enhance water infiltration and prevent wind and water erosion, improving air quality. Increased water retention plus improved fertilizer management reduces nitrogen losses and subsequent nitrate (NO_3^-) leaching and downstream eutrophication.

10.3.5 Economics and Policy Assessment

Policies for agricultural mitigation activities can range from transfer payments (such as subsidies, tax credits, *etc.*) to encourage greenhouse gas mitigating practices or taxes or penalties to discourage practices with high emissions, to emission offset trading in a free market-based system with governmental sanction. Currently the policy context of the three North American countries differs greatly. Canada and the United States are both Annex 1 (developed countries) within the United Nations Framework Convention on Climate Change (UNFCCC), but Canada is obligated to mandatory emission reductions as a party to the Kyoto Protocol, while the United States currently maintains a national, voluntary

emission reduction policy outside of Kyoto. Mexico is a non-Annex 1 (developing) country and thus is not currently subject to mandatory emission reductions under Kyoto.

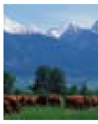
At present, there is relatively little practical experience upon which to judge the costs and effectiveness of agricultural mitigation activities. Governments are still in the process of developing policies and, moreover, the economics of various mitigation activities will only be known when there is a significant economic incentive for emission reductions, *e.g.*, through regulatory emission caps or government-sponsored bids and contracts. However, several economic analyses have been performed in the United States, using a variety of models (*e.g.*, McCarl and Schneider, 2001; Antle *et al*., 2003; Lewandrowski *et al*., 2004). Most studies have focused on carbon sequestration, and less work has been done on the economics of reducing CH_4 and N_2O emissions. While results differ between models and for different parts of the country, some preliminary conclusions have been drawn (see Boehm *et al*., 2004; CAST, 2004).

- Additional carbon (10–70 Mt C per year), above current rates, could be sequestered in soils at low to moderate costs ($10–100 per metric ton of carbon).
- Mitigation practices that maintain the primary income source (*i.e*., crop/livestock production), such as conservation tillage and pasture improvement, have a lower cost per ton sequestered carbon compared with practices where mitigation would be a primary income source (*i.e*., foregoing income from crop and/or livestock production), such as land set-asides, even if the latter have a higher biological sequestration potential.
- With higher energy prices, major shifts in land use in favor of energy crops and afforestation may occur at the expense of annual cropland and pasture.
- Policies based on per-ton payments (for carbon actually sequestered) are more economically efficient than per-hectare payments (for adopting specific practices, see Antle *et al*., 2003), although the former have a higher verification cost (*i.e*., measuring actual carbon sequestered versus measuring adoption of specific farming practices on a given area of land).

A recent study commissioned by the U.S. Environmental Protection Agency (EPA, 2005), evaluated some agricultural mitigation options for different policy scenarios, including constant CO_2 price scenarios for 2010–2110, where the price represents the incentive required for the mitigation activity. Annualized prices of $15/ton of CO_2 would yield mitigation amounts of 46 Mt C per year through agricultural soil carbon sequestration and 14.5 Mt C per year from fossil-fuel use reduction (compared with the estimated United States' national ecosystem carbon sink of 480 Mt C per year). At lower prices of $5/ton CO_2, the corresponding values would be 34 Mt C per year (for soil sequestration) and 9 Mt C per year (for fossil-fuel reduction), respectively, reflecting the effect of price on the supply of mitigation activities[5].

10.3.6 Other Policy Considerations

Agricultural mitigation of CO_2 through carbon sequestration and emission reductions for CH_4 (and N_2O), differ in ways that impact policy design and implementation. Direct emission reductions of CH_4 and CO_2 from fossil-fuel use are considered "permanent" reductions, while carbon sequestration is a "non-permanent" reduction, in that carbon stored through conservation practices could potentially be re-emitted if management practices revert back to the previous state or otherwise change so that the stored carbon is lost. This *permanence* issue applies to all forms of carbon sinks. In addition, soil carbon storage, with a given change in management (*e.g.*, tillage reduction, pasture improvement, afforestation), will tend to level off at a new steady state level after 15–30 years, after which there is no further accumulation of carbon (West *et al*., 2004). Enhanced management practices must be sustained to maintain these higher carbon stocks. Key implications for policy are that the value of sequestered carbon could be discounted compared to direct emission reductions to compensate for the possibility of future emissions. Alternatively, long-term contracts will be needed to build and maintain carbon stocks, which will tend to increase the price per unit of sequestered carbon. However, even temporary storage of carbon has economic value (CAST, 2004), and various proposed concepts of leasing carbon storage or applying discount rates could accommodate carbon sequestration as part of a carbon offset trading system (CAST, 2004). In addition, switching to practices that increase soil carbon (and hence, improve soil fertility) could be more profitable to farmers in the long-run, so that additional incentives to maintain the practices once they become well established may not be necessary (Paustian *et al*., 2006).



Another policy issue relating to carbon sequestration is *leakage* (also termed "slippage" in economics), whereby mitigation actions in one area (*e.g.*, geographic region, pro-

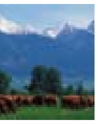
---

[5] These estimates were produced using a national-scale economic sector model which estimates the linkage between CO_2 prices and the supply of mitigation activities, for specified price scenarios. Hence, the model can produce a range of CO_2 mitigation amounts as a function of price, but the model was not used to estimate the uncertainty of mitigation amounts at a given price level.

BOX 10.4: Agricultural and Grazing Land N_2O Emission Reductions

When mineral soil nitrogen content is increased by nitrogen additions (*i.e.*, fertilizer), a portion of that nitrogen can be transformed to N_2O as a byproduct of two microbiological processes (nitrification and denitrification) and lost to the atmosphere. Coincidental introduction of large amounts of easily decomposable organic matter and NO_3^- from either a plow down of cover crop or manure addition greatly stimulates denitrification under wet conditions (Peoples *et al.*, 2004). Some practices intended to sequester atmospheric carbon in soil could prompt increases in N_2O fluxes. For example, reducing tillage intensity tends to increase soil moisture, leading to increased N_2O fluxes, particularly in wetter environments (Six *et al.*, 2004). Synchronizing organic amendment applications with plant nitrogen uptake and minimizing manure storage under anoxic conditions can reduce N_2O emissions by 10–25% and will increase nitrogen use efficiency which can decrease indirect emissions (in waterways) by 5–20% (CAST, 2004).

duction system) stimulate additional emissions elsewhere. For forest carbon sequestration, leakage is a major concern. For example, reducing harvest rates in one area (thereby maintaining higher biomass carbon stocks) can stimulate increased cutting and reduction in stored carbon in other areas, as was seen with the reduction in harvesting in the Pacific Northwest during the 1990s (Murray *et al.*, 2004). Preliminary studies suggest that leakage is of minor concern for agricultural carbon sequestration, since most practices would have little or no effect on the supply and demand of agricultural commodities. However, there are uncertain and conflicting views on whether land-set asides in which land is taken out of agricultural production, such as the Conservation Reserve Program in the United States, might be subject to significant leakage.



A further question, relevant to policies for carbon sequestration, is how practices for conserving carbon affect emissions of other greenhouse gases. Of particular importance is the interaction of carbon sequestration with N_2O emissions, because N_2O is such a potent greenhouse gas (Robertson and Grace, 2004; Six *et al.*, 2004; Gregorich *et al.*, 2005). (See Box 10.4). In some environs, carbon-sequestration practices, such as reduced tillage, can stimulate N_2O emissions, thereby offsetting part of the benefit; elsewhere, carbon-conserving practices may suppress N_2O emissions, amplifying the net benefit (Smith *et al.*, 2001; Smith and Conen, 2004; Conant *et al.*, 2005; Helgason *et al.*, 2005).

Similarly, carbon-sequestration practices might affect emissions of CH_4, if the practice, such as increased use of forages in rotations, leads to higher livestock numbers. These examples demonstrate that policies designed to suppress emission of one greenhouse gas, need to also consider complex interactions to ensure that *net* emissions of total greenhouse gases are reduced.

A variety of other factors will affect the willingness of farmers to adopt greenhouse gas reducing practices and the efficacy of agricultural policies, including perceptions of risk, information and extension efforts, technological developments, and social and ethical values (Paustian *et al.*, 2006). Many of these factors are difficult to incorporate into traditional economic analyses. Pilot mitigation projects, along with additional research using integrated ecosystem and economic assessment approaches (*e.g.*, Antle *et al.*, 2001), will allow us to get a clearer picture of the actual potential of agriculture to contribute to greenhouse gas mitigation efforts.

10.4 RESEARCH AND DEVELOPMENT NEEDS

Expanding the network of intensive research sites dedicated to understanding basic processes, coupled with national-level networks of soil monitoring/validation sites, could reduce inventory uncertainty and contribute to attributing changes in ecosystem carbon stocks to changes in land management (see Bellamy *et al.*, 2005). Expansion of both networks should be informed about how different geographic areas and ecosystems contribute to uncertainty and the likelihood that reducing uncertainty could inform policy decisions. For example, changes in ecosystem carbon stocks due to woody encroachment on grasslands constitute one of the largest, but least certain, aspects of terrestrial carbon cycling in North America (Houghton *et al.*, 1999; Pacala *et al.*, 2001). Better information about the spatial extent of woody encroachment, the amount and growth of woody biomass, and variation in the impacts on soil carbon stocks would help reduce that uncertainty. Identifying location, cause, and size of this sink could help identify practices that may promote continued sequestration of carbon and would constrain estimates of carbon storage in other lands, possibly helping to identify other policy options. Uncertainty in land use, land-use change, soil carbon responses to management (*e.g.*, tillage) on particular soils, and impacts of cultivation on soil carbon stocks (*e.g.*, impacts of erosion) are the largest contributors to uncertainty in the Canadian and United States' national agricultural greenhouse gas inventories (Ogle *et al.*, 2003; VandenBygaart *et al.*, 2003). Finally, if the goal of a policy instrument is to reduce greenhouse gas emissions, net impacts on CO_2, CH_4, and N_2O emissions, which are not as well understood, should be considered.