

## Chapter 10. Agricultural Lands, Grasslands, Shrublands, and Arid Lands

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### KEY FINDINGS

- Agricultural lands, including croplands and grazinglands (grasslands, shrublands, and arid lands), occupy 789 million ha (47% of the land area of North America) and contain  $78.5 \pm 19.5$  Gt C (17.4% of North American terrestrial carbon) in the soil alone.
- Agricultural lands in the United States and Canada are currently near neutral with respect to their soil carbon balance (but less so for Mexico because of ongoing land use change). Although agricultural soils are estimated to be sequestering currently  $6\text{--}15.5$  Mt C yr<sup>-1</sup>, the cultivation of organic soils releases  $5.3\text{--}10.3$  Mt C yr<sup>-1</sup>. The emissions of carbon from fossil fuel inputs to agriculture ( $46.3$  Mt C yr<sup>-1</sup>) and the manufacture of fertilizer ( $6.4$  Mt C yr<sup>-1</sup>) yields a net source from the agricultural sector of  $27\text{--}41$  Mt C yr<sup>-1</sup>.
- As much as  $120$  Mt C yr<sup>-1</sup> may be accumulating through woody encroachment of arid and semi-arid lands of North America. This value is highly uncertain.
- The emissions and sequestration 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 CO<sub>2</sub> are uncertain.

- 1 • Conservation-oriented management of agricultural lands (e.g., use of conservation tillage, improved  
2 cropping and grazing systems, reduced bare fallow, set-asides of fragile lands, and restoration of  
3 degraded soils) can significantly increase soil carbon sequestration.
  - 4 • Projections of future trends in agricultural land area and soil carbon stocks are unavailable or highly  
5 uncertain because of uncertainty in future land-use change and agricultural management practice.
  - 6 • Annualized prices of \$15/tonne CO<sub>2</sub>, would yield mitigation amounts of 168 Mt CO<sub>2</sub> yr<sup>-1</sup> through  
7 agricultural soil C sequestration and 53 Mt CO<sub>2</sub> yr<sup>-1</sup> from fossil fuel use reduction. At lower prices of  
8 \$5/tonne CO<sub>2</sub>, the corresponding values would be 123 Mt CO<sub>2</sub> yr<sup>-1</sup> and 32 Mt CO<sub>2</sub> yr<sup>-1</sup>, respectively.
  - 9 • Policies designed to suppress emissions of one greenhouse gas need to consider complex  
10 interactions to ensure that *net* emissions are reduced. For example, increased use of fertilizer or  
11 irrigation may increase crop residues and carbon sequestration, but may stimulate emissions of CH<sub>4</sub>  
12 or N<sub>2</sub>O.
  - 13 • Many of the practices that lead to carbon sequestration and reduced CO<sub>2</sub> and CH<sub>4</sub> emissions from  
14 agricultural lands not only increase production efficiencies, but lead to environmental co-benefits, for  
15 example, improved soil fertility, reduced erosion and pesticide immobilization.
  - 16 • An expanded network of intensive research sites is needed to better understand the effects of  
17 management on carbon cycling and storage in agricultural systems. An extensive national-level  
18 network of soil monitoring sites in which changes in carbon stocks are directly measured is needed to  
19 reduce the uncertainty in the inventory of agricultural carbon. Better information about the spatial  
20 extent of woody encroachment, the amount and growth of woody biomass, and variation in impacts  
21 on soil carbon stocks would help reduce the large uncertainty of the carbon impacts of woody  
22 encroachment.
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## 26 INVENTORY

### 27 Background

28 Agricultural lands, including croplands and grazing lands—grasslands, shrublands, and arid lands<sup>1</sup>—  
29 occupy 47% of the land area in North America (59% in the United States, 70% in Mexico, and 11% in  
30 Canada), and contain 17.4% of the terrestrial carbon (Pacala *et al.*, 2006). These lands differ from other  
31 types of ecosystems in that most of their carbon is held in soils. Live vegetation in cultivated systems  
32 generally contains less than 5% of the total carbon, whereas vegetation in grazing lands contains a greater  
33 proportion (5–30%), but still less than that in forested systems (30–65%). These systems in North  
34 America contain 78.5±19.5 (±1SE) Gt C in the soil (Table 10-1). Significant increases in vegetation

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<sup>1</sup>We refer collectively to these lands as grazing lands since grazing is their primary use, even though not all of these lands are grazed.

1 carbon stocks in some grazing lands have been observed and, together with soil carbon stocks from  
2 croplands and grazing lands, likely contribute significantly to the large North American terrestrial carbon  
3 sink (Houghton *et al.*, 1999; Pacala *et al.*, 2001; Eve *et al.*, 2002; Ogle *et al.*, 2003). These lands also emit  
4 greenhouse gases: fossil fuel use for on-farm machinery and buildings, for manufacture of agricultural  
5 inputs, and for transportation account for 3–5% of total CO<sub>2</sub> emissions in developed countries (Enquete  
6 Commission, 1995); activities on agricultural and grazing lands, like livestock production, animal waste  
7 management, biomass burning, and rice cultivation, emit 35% of global anthropogenic CH<sub>4</sub> (27% of  
8 United States, 31% of Mexican, and 27% of Canadian CH<sub>4</sub> emissions) (Mosier *et al.*, 1998b; CISCC,  
9 2001; Matin *et al.*, 2004; EPA, 2005); and agricultural and grazing lands are the largest anthropogenic  
10 source of N<sub>2</sub>O emissions (CAST, 2004; see Text Box 1). However, agricultural lands are actively  
11 managed and have the capacity to take up more carbon into soil; thus improving management could lead  
12 to substantial reductions in CO<sub>2</sub> and CH<sub>4</sub> emissions and could sequester carbon to offset emissions from  
13 other lands or sectors.

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16 **Table 10-1. Carbon pools in agricultural and grazing lands in Canada, Mexico, and the United**  
17 **States; the area (M ha) for each climatic zone are in parentheses.** Carbon pools for undisturbed native  
18 systems were derived using the intersection of MODIS-IGBP<sup>a</sup> land cover types (Friedl *et al.*, 2002) and  
19 mean soil carbon contents to 1m depth from Sombroek *et al.* (1993) spatially arrayed using FAO soil  
20 classes (ISRIC, 2002).

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## 22 **Carbon Dioxide Fluxes from Agricultural and Grazing Land**

23 The basic processes governing the carbon balance of agricultural and grazing lands are the same as  
24 for other ecosystems: the photosynthetic uptake and assimilation of CO<sub>2</sub> into organic compounds and the  
25 release of gaseous carbon through respiration (primarily CO<sub>2</sub> but also CH<sub>4</sub>). In agricultural lands, carbon  
26 assimilation is directed towards production of food, fiber, and forage by manipulating species  
27 composition and growing conditions. Biomass, being predominantly herbaceous (i.e., non-woody), is a  
28 small, transient carbon pool (compared to forests) and hence soils constitute the dominant carbon stock.  
29 Cropland systems can be among the most productive ecosystems, but restricted growing season length,  
30 fallow periods, and grazing-induced shifts in species composition or production can reduce carbon uptake  
31 relative to that in other ecosystems. These factors, along with tillage-induced soil disturbances and  
32 removal of plant carbon through harvest, have depleted soil carbon stocks by 20–40% or more from pre-  
33 cultivated conditions (Davidson and Ackerman, 1993; Houghton and Goodale, 2004). Soil organic carbon  
34 stocks in grazing lands (see Text Box 2 for information on inorganic soil carbon stocks) have been

1 depleted to a lesser degree than for cropland (Ogle *et al.*, 2004), and in some regions biomass has  
2 increased due to suppression of disturbance and subsequent woody encroachment (see Text Box 3).  
3 Woody encroachment is potentially a significant sink for atmospheric CO<sub>2</sub>, but the magnitude of the sink  
4 is poorly constrained (Houghton *et al.*, 1999; Pacala *et al.*, 2001). Increased decomposition rates of  
5 aboveground litter and harvest removal of some (30–50% of forage in grazing systems, 40–50% in grain  
6 crops) or all (e.g., corn for silage) of the aboveground biomass, have drastically altered carbon cycling  
7 within agricultural lands and thus the sources and sinks of CO<sub>2</sub> to the atmosphere.

8 Much of the carbon lost from agricultural land soil and biomass pools can be recovered with changes  
9 in management practices that increase carbon inputs, stabilize carbon within the system, or reduce carbon  
10 losses (Figure 10-1; Table 10-2), while still maintaining outputs of food, fiber, and forage. Within Canada  
11 and the United States, mineral soils have been sequestering 0.1 and 6.5–16 Mt C yr<sup>-1</sup> (Smith *et al.*, 1997;  
12 Smith *et al.*, 2001b; Ogle *et al.*, 2003), respectively, largely through improved practices on annual  
13 cropland. Conversion of agricultural land to grassland, like under the Conservation Reserve Program in  
14 the United States (6 Mt C yr<sup>-1</sup> on 14 M ha of land), and afforestation have also sequestered carbon in  
15 agricultural and grazing lands. In contrast, cultivation of organic soils (e.g., peat-derived soils) is  
16 releasing an estimated 0.1 and 5-10 Mt C yr<sup>-1</sup> from soils in Canada and the United States (Ogle *et al.*,  
17 2003; Matin *et al.*, 2004). Compared with other systems, the high productivity and management-induced  
18 disturbances of agricultural systems promote movement and redistribution (through erosion, runoff and  
19 leaching) of organic and inorganic carbon, sequestering potentially large amounts of carbon in sediments  
20 and water (Raymond and Cole, 2003; Smith *et al.* 2005; Yoo *et al.*, 2005). However, the net impact of  
21 soil erosion on carbon emissions to the atmosphere remains highly uncertain.

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23 **Figure 10-1. North American agricultural and grazing land CO<sub>2</sub> (left side) and methane (right side)**  
24 **fluxes for the years around 2000.** Negative values indicate net flux from the atmosphere to soil and  
25 biomass carbon pools. All data are from Canadian (Matin *et al.*, 2004) and U.S. (EPA, 2005) National  
26 Inventories and from the second Mexican National Communication (CISCC, 2001), except for Canadian  
27 [from Kulshreshtha *et al.* (2000)] and U.S. fossil fuel inputs [from Lal *et al.* (1998)] and woody  
28 encroachment [from Houghton *et al.* (1999)]. Values are for 2003 for the United States and Canada and  
29 1998 for Mexico. A global warming potential of 23 for methane was used to convert emissions of CH<sub>4</sub> to  
30 CO<sub>2</sub> equivalents (IPCC, 2001) and a factor of 12/44 to convert from CO<sub>2</sub> to carbon. Asterisks indicate  
31 unavailable data. Data ranges are indicated by error bars where available.

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33 **Table 10-2. North American agricultural and grazing land carbon fluxes for the years around 2000.**  
34 Negative numbers (in parentheses) indicate net flux from the atmosphere to soil and biomass carbon pools.  
35 Unless otherwise noted, data are from Canadian (Matin *et al.*, 2004) and U.S. (EPA, 2005) National

1 Inventories and from the second Mexican National Communication (CISCC, 2001). Values are for 2003 for  
2 United States and Canada and 1998 for Mexico. A global warming potential of 23 for methane was used to  
3 convert emissions of CH<sub>4</sub> to CO<sub>2</sub> equivalents (IPCC, 2001) and a factor of 12/44 to convert from CO<sub>2</sub> to  
4 carbon.

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6 Production, delivery, and use of field equipment, fertilizer, seed, pesticides, irrigation water, and  
7 maintenance of animal production facilities contribute 3–5% of total fossil fuel CO<sub>2</sub> emissions in  
8 developed countries (Enquete Commission, 1995). On-farm fossil fuel emissions plus CO<sub>2</sub> emissions  
9 embodied in applied fertilizers and pesticides contribute emissions of 28 Mt C yr<sup>-1</sup> within the United  
10 States (Lal *et al.*, 1998) and 2.8 Mt C yr<sup>-1</sup> in Canada (Sobool and Kulshreshtha, 2005). Energy  
11 consumption for heating and cooling high intensity animal production facilities is among the largest CO<sub>2</sub>  
12 emitters within the agricultural sector (Enquete Commission, 1995).

13 Much of the ammonia production and urea application (U.S.: 4.3 Mt C yr<sup>-1</sup>; Mexico: 0.4 Mt C yr<sup>-1</sup>;  
14 Canada: 1.7 Mt C yr<sup>-1</sup>) and phosphoric acid manufacture (U.S.: 0.4 Mt C yr<sup>-1</sup>; Mexico: 0.2 Mt C yr<sup>-1</sup>;  
15 Canada: not reported) are devoted to agricultural uses.

### 16 17 **Methane Fluxes from Agricultural and Grazing Lands**

18 Cropland and grazing land soils act as both sources and sinks for atmospheric CH<sub>4</sub> (Figure 10-1;  
19 Table 10-2). Methane formation is an anaerobic process and is most significant in waterlogged soils, like  
20 those under paddy rice cultivation (U.S.: 0.328 Mt CH<sub>4</sub> yr<sup>-1</sup>; Mexico: 0.015 Mt CH<sub>4</sub> yr<sup>-1</sup>; Canada:  
21 negligible, not reported). Methane is also formed by incomplete biomass combustion of crop residues  
22 (U.S.: 0.038 Mt CH<sub>4</sub> yr<sup>-1</sup>; Mexico: 0.011 Mt CH<sub>4</sub> yr<sup>-1</sup>; Canada: negligible, not reported). Methane  
23 oxidation in soils is a global sink for about 5% of CH<sub>4</sub> produced annually and is mainly limited by CH<sub>4</sub>  
24 diffusion into the soil. However, intensive cropland management tends to reduce soil methane  
25 consumption relative to forests and extensively grazing lands (CAST, 2004). Recent research has shown  
26 that live plant biomass and litter produce substantial amounts of CH<sub>4</sub>, potentially making plants as large a  
27 source of CH<sub>4</sub> as livestock (Keppler *et al.*, 2006). If this is the case, activities that increase plant  
28 biomass—and sequester CO<sub>2</sub>—may lead to increased CH<sub>4</sub> production (Keppler *et al.*, 2006).

### 29 30 **Methane Fluxes from Livestock**

31 Enteric fermentation (the process of organic matter breakdown by gut flora within the gastrointestinal  
32 tract of animals, particularly ruminants) allows for the digestion of fibrous materials that provide energy  
33 to microbes and their hosts, but the extensive fermentation of the ruminant diet requires 5–7% of the  
34 dietary gross energy to be belched out as CH<sub>4</sub> to sustain the anaerobic processes (Johnson and Johnson,

1 1995). Methane emissions from livestock contribute significantly to total CH<sub>4</sub> emissions in the United  
2 States (54 Mt CH<sub>4</sub> yr<sup>-1</sup>, 21% of total U.S. CH<sub>4</sub> emissions), Canada (0.8 Mt CH<sub>4</sub> yr<sup>-1</sup>, 22% of total)  
3 (Sobool and Kulshreshtha, 2005), and Mexico (2.0 Mt CH<sub>4</sub> yr<sup>-1</sup>, 27% of total) with the vast majority of  
4 enteric CH<sub>4</sub> emissions are from beef (72%) and dairy cattle (23%). Emissions from ruminants are tightly  
5 coupled to feed consumption, since CH<sub>4</sub> emission per unit of feed energy is consistent, except for feedlot  
6 cattle with diets high in cereal grain contents, for which the fractional loss falls to one-third to one-half of  
7 normal rates (Johnson and Johnson, 1995). Between 1990 and 2002, CH<sub>4</sub> emissions from enteric  
8 fermentation fell 2% in the United States but increased by 20% in Canada (EPA, 2000; Matin *et al.*,  
9 2004).

10 Methane emissions during manure storage (U.S.: 1.9 Mt CH<sub>4</sub> yr<sup>-1</sup>; Mexico: 0.06 Mt CH<sub>4</sub> yr<sup>-1</sup>;  
11 Canada: 0.3 Mt CH<sub>4</sub> yr<sup>-1</sup>) are governed by the amount of degradable organic matter, degree of anoxia,  
12 storage temperature, and duration of storage. Unlike enteric CH<sub>4</sub>, the major sources of manure CH<sub>4</sub>  
13 emissions in the United States are from swine (44%) and dairy cattle (39%). Manure CH<sub>4</sub> production is  
14 greater for production systems with anoxic lagoons, largely anoxic pits, or manure handled or stored as  
15 slurry. Between 1990 and 2002, CH<sub>4</sub> emissions from manure management increased 25% in the United  
16 States and 21% in Canada (EPA, 2000; Matin *et al.*, 2004).

## 17 18 **DRIVERS AND TRENDS**

19 The extent to which agricultural options will contribute to greenhouse gas mitigation will largely  
20 depend on government policy decisions, but mitigation opportunities will also be constrained by changing  
21 environmental conditions, i.e., global warming (NAS, 2001) may make it more difficult to reduce  
22 emissions from cropland and grazing lands (see discussion below). Estimates from national inventories  
23 suggest that U.S. and Canadian agricultural soils are currently near neutral or small net sinks for CO<sub>2</sub>,  
24 which has occurred as a consequence of changing management (e.g., reduced tillage intensity) and  
25 government programs designed for purposes other than greenhouse gas mitigation (e.g., soil conservation,  
26 commodity regulation). However, to realize the much larger potential for soil carbon sequestration and for  
27 significant reductions in CH<sub>4</sub> (and N<sub>2</sub>O) emissions, specific policies targeted at greenhouse gas reductions  
28 are required. It is generally recognized that farmers (and other economic actors) are, as a group, 'profit-  
29 maximizers,' which implies that to change from current practices to ones that reduce net emissions,  
30 farmers will incur additional costs (termed 'opportunity cost'). Hence, where the incentives (e.g., carbon  
31 offset market payments, government subsidies) to adopt new practices exceed the opportunity costs,  
32 farmers will adopt new practices. Crop productivity, production input expenses, marketing costs, etc.  
33 (which determine profitability) vary widely within (and between) countries. Thus, the payment needed to  
34 achieve a unit of emission reductions will vary, among and within regions. In general, each successive

1 increment of carbon sequestration or emission reduction comes at a progressively higher cost (this  
2 relationship is often shown in the form of an upward bending marginal cost curve).

3       Feedbacks between temperature and soil carbon stocks could counteract efforts to reduce greenhouse  
4 gases via carbon sequestration within agricultural ecosystems. Increased temperatures tend to increase the  
5 rate of biological processes—including plant respiration and organic matter decay and CO<sub>2</sub> release by soil  
6 organisms—particularly in temperate climates that prevail across most of North America. Because soil  
7 carbon stocks, including those in agricultural lands, contain such large amounts of carbon, small  
8 percentage increases in rate of soil organic matter decomposition could lead to substantially increased  
9 emissions (Jenkinson *et al.*, 1991; Cox *et al.*, 2000). There is currently a scientific debate about the  
10 relative temperature sensitivity of the different constituents making up soil organic matter (e.g., Kätterer  
11 *et al.*, 1998; Giardina and Ryan, 2000; Ågren and Bosatta, 2002; Knorr *et al.*, 2005), reflecting  
12 uncertainty in the possible degree and magnitude of climate change feedbacks. Despite this uncertainty,  
13 the potential for climate feedbacks to influence the carbon balance of agricultural systems by perturbing  
14 productivity (and carbon input rates) and organic matter turnover, and potentially soil N<sub>2</sub>O and CH<sub>4</sub>  
15 fluxes, cannot be overlooked.

## 17 **OPTIONS FOR MANAGEMENT**

### 18 **Carbon Sequestration**

19       Agricultural and grazing land management practices capable of increasing carbon inputs or  
20 decreasing carbon outputs, while still maintaining yields, can be divided into two classes: those that  
21 impact carbon inputs, and those that affect carbon release through decomposition and disturbance.  
22 Reversion to native vegetation or setting agricultural land aside as grassland, such as in the Canadian  
23 Prairie Cover Program and the U.S. Conservation Reserve Program, can increase the proportion of  
24 photosynthesized carbon retained in the system and sequester carbon in the soil<sup>2</sup> (Post and Kwon, 2000;  
25 Follett *et al.*, 2001b) (Figure 10-2). In annual cropland, improved crop rotations, yield enhancement  
26 measures, organic amendments, cover crops, improved fertilization and irrigation practices, and reduced  
27 bare fallow tend to increase productivity and carbon inputs, and thus soil carbon stocks (Lal *et al.*, 1998;  
28 Paustian *et al.*, 1998; VandenBygaart *et al.*, 2003) (Figure 10-2). Tillage, traditionally used for soil  
29 preparation and weed control, disturbs the soil and stimulates decomposition and loss of soil carbon.  
30 Practices that substantially reduce (reduced-till) or eliminate (no-till) tillage-induced disturbances are

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<sup>2</sup>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.

1 being increasingly adopted and generally increase soil carbon stocks while maintaining or enhancing  
2 productivity levels (Paustian *et al.*, 1997; Ogle *et al.*, 2003) (Figure 10-2). Estimates of the technical  
3 potential for annual cropland soil carbon sequestration are on the order of 50–100 Mt C yr<sup>-1</sup> in the United  
4 States (Lal *et al.*, 2003; Sperow *et al.*, 2003) and approximately 5 Mt C yr<sup>-1</sup> in Canada (Boehm *et al.*,  
5 2004).

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7 **Figure 10-2. Relative soil carbon following implementation of new agricultural or grassland**  
8 **management practices.** Conventionally tilled, medium-input cultivated land and moderately grazed  
9 grasslands with moderate inputs are defaults for agricultural and grazing lands, respectively. Default soil  
10 carbon stocks (like those in Table 10-1) can be multiplied by one or more emission factors to estimate  
11 carbon sequestration rates. Temperature/precipitation divisions are the same as those described in Table 10-  
12 1. Data are from Nabuurs *et al.* (2004) and Ogle *et al.* (2004).

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14 Within grazing lands, historical overgrazing has substantially reduced productive capacity in many  
15 areas, leading to loss of soil carbon stocks (Conant and Paustian, 2002) (Figure 10-2). Conversely,  
16 improved grazing management and production inputs—like fertilizer, organic amendments, and  
17 irrigation—can increase productivity, carbon inputs, and soil carbon stocks, potentially storing 0.44 Mt C  
18 yr<sup>-1</sup> in Canada (Lynch *et al.*, 2005) and as much as 33.2 Mt C yr<sup>-1</sup> in the United States (Follett *et al.*,  
19 2001a).

## 20 21 **Fossil Fuel-Derived Emission Reductions**

22 The efficiency with which on-farm (from tractors and machinery) and off-farm (from production of  
23 agricultural input) energy inputs are converted to agricultural products varies several-fold (Lal, 2004).  
24 Where more energy-efficient practices can be substituted for less efficient ones, fossil fuel CO<sub>2</sub> emissions  
25 can be reduced (Lal, 2004). For example, converting from conventional plowing to no-tillage can reduce  
26 on-farm fossil fuel emissions by 25–80% (Frye, 1984; Robertson *et al.*, 2000) and total fossil fuel  
27 emissions by 14–25% (West and Marland, 2003). Substitution of legumes for mineral nitrogen can reduce  
28 energy input by 15% in cropping systems incorporating legumes (Pimentel *et al.*, 2005). More efficient  
29 heating and cooling (e.g., better building insulation) could reduce CO<sub>2</sub> emissions associated with housed  
30 animal (e.g., dairy) facilities. Substitution of crop-derived for fossil fuels could decrease net emissions.

31 Energy intensity (energy per unit product) for the U.S. agricultural sector has declined since the 1970s  
32 (Paustian *et al.*, 1998). Between 1990 and 2000, fossil fuel emissions on Canadian farms increased by  
33 35% (Sobool and Kulshreshtha, 2005).

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## 1 **Methane Emission Reduction**

2 Reducing flood duration and decreasing organic matter additions to paddy rice fields can reduce CH<sub>4</sub>  
3 emissions. Soil amendments such as ammonium sulfate and calcium carbide inhibit CH<sub>4</sub> formation.  
4 Coupled with adoption of new rice cultivars that favor lower CH<sub>4</sub> emissions, these management practices  
5 could reduce CH<sub>4</sub> emission from paddy rice systems by as much as 40% (Mosier *et al.*, 1998b).

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

10 Refinement of feed quality, feed rationing, additives, and livestock production efficiency chains can  
11 all reduce CH<sub>4</sub> emissions from ruminant livestock with minimal impacts on productivity or profits  
12 (CAST, 2004). Boadi *et al.* (2004) review several examples of increases in energy intensity. Wider  
13 adoption of more efficient practices could reduce CH<sub>4</sub> production from 5–8% to 2–3% of gross feed  
14 energy (Agriculture and Agri-Food Canada, 1999), reducing CH<sub>4</sub> emissions by 20–30% (Mosier *et al.*,  
15 1998b).

16 Methane emissions from manure storage are proportional to duration of storage under anoxic  
17 conditions. Handling solid rather than liquid manure, storing manure for shorter periods of time, and  
18 keeping storage tanks cool will limit emissions from stored manure (CAST, 2004). More important,  
19 capture of CH<sub>4</sub> produced during anaerobic decomposition of manure—in covered lagoons or small- or  
20 large-scale digesters—can reduce emissions by 70–80% (Mosier *et al.*, 1998b). Use of digester systems is  
21 spreading in the United States, with 50 digesters currently in operation and 60 systems in construction or  
22 planned (NRCS, 2005). Energy production using CH<sub>4</sub> captured during manure storage will reduce energy  
23 demands and associated CO<sub>2</sub> emissions.

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## 25 **Environmental Co-benefits from Carbon Sequestration and Emission Reduction**

### 26 **Activities**

27 Many of the practices that lead to carbon sequestration and reduced CO<sub>2</sub> and CH<sub>4</sub> emissions not only  
28 increase production efficiencies but also lead to environmental co-benefits. Practices that sequester  
29 carbon in agricultural and grazing land soils improve soil fertility, buffering capacity, and pesticide  
30 immobilization (Lal, 2002; CAST, 2004). Increasing soil carbon content makes the soil more easily  
31 workable and reduces energy requirements for field operations (CAST, 2004). Decreasing soil  
32 disturbance and retaining more surface crop residues enhance water infiltration and prevent wind and  
33 water erosion, improving air quality. Increased water retention plus improved fertilizer management  
34 reduces nitrogen losses and subsequent NO<sub>3</sub><sup>-</sup> leaching and downstream eutrophication.

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## Economics and Policy Assessment

Policies for agricultural mitigation activities can range from transfer payments (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 countries differs greatly. Canada and the United States are both Annex 1 (developed countries) within the 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<sub>4</sub> and N<sub>2</sub>O 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).

- Significant amounts (10–70 Mt yr<sup>-1</sup>) of carbon sequestration in soils can be achieved 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), e.g., conservation tillage, pasture improvement, have a lower cost/ton sequestered carbon compared with practices where mitigation would be a primary income source, such as land set-asides, even if the latter have a higher biological sequestration potential.
- At higher 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 sequestered) are more economically efficient than per-hectare payments (for adopting specific practices), 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).

1 A recent study commissioned by the U.S. Environmental Protection Agency (EPA 2005b), estimated  
2 economic potential for some agricultural mitigation options, assuming constant price scenarios for 2010–  
3 2110, where the price represents the incentive required for the mitigation activity. Annualized prices of  
4 \$15/ton of CO<sub>2</sub> would yield mitigation amounts of 168 Mt CO<sub>2</sub> per year through agricultural soil carbon  
5 sequestration and 53 Mt CO<sub>2</sub> per year from fossil fuel use reduction (compare with estimated U.S.  
6 national ecosystem carbon sink of 1760 Mt CO<sub>2</sub> per year). At lower prices of \$5/ton CO<sub>2</sub>, the  
7 corresponding values would be 123 Mt CO<sub>2</sub> per year (for soil sequestration) and 32 Mt CO<sub>2</sub> per year (for  
8 fossil fuel reduction), respectively, reflecting the effect of price on the supply of mitigation activities.  
9

## 10 Other Policy Considerations

11 Agricultural mitigation of CO<sub>2</sub> through carbon sequestration and emission reductions for CH<sub>4</sub> (and  
12 N<sub>2</sub>O), differ in ways that impact policy design and implementation. Direct emission reductions of CH<sub>4</sub>  
13 and CO<sub>2</sub> from fossil fuel use are considered ‘permanent’ reductions, while carbon sequestration is a ‘non-  
14 permanent’ reduction, in that carbon stored through conservation practices could potentially be re-emitted  
15 if management practices revert back to the previous state or otherwise change so that the stored carbon is  
16 lost. This *permanence* issue applies to all forms of carbon sinks. In addition, a given change in  
17 management (e.g., tillage reduction, pasture improvement, afforestation) will stimulate carbon storage for  
18 a finite duration. For many practices, soil carbon storage will tend to level off at a new equilibrium level  
19 after 15–30 years, after which there is no further accumulation of carbon (West and Wali, 2002). Thus, to  
20 maintain these higher stocks, the management practices will need to be maintained. Key implications for  
21 policy are that the value of sequestered carbon will be discounted compared to direct emission reductions  
22 to compensate for the possibility of future emissions. Alternatively, long-term contracts will be needed to  
23 build and maintain C stocks, which will tend to increase the price per unit of sequestered carbon.  
24 However, even temporary storage of carbon has economic value (CAST, 2004), and various proposed  
25 concepts of leasing carbon storage or applying discount rates could accommodate carbon sequestration as  
26 part of a carbon offset trading system (CAST, 2004). In addition, switching to practices that increase soil  
27 carbon (and hence improve soil fertility) can be more profitable to farmers in the long-run, so that  
28 additional incentives to maintain the practices once they become well established may not be necessary  
29 (Paustian *et al.*, 2006).

30 Another policy issue relating to carbon sequestration is *leakage* (also termed ‘slippage’ in  
31 economics), whereby mitigation actions in one area (e.g., geographic region, production system) stimulate  
32 additional emissions elsewhere. For forest carbon sequestration, leakage is a major concern—for  
33 example, reducing harvest rates in one area (thereby maintaining higher biomass carbon stocks) can  
34 stimulate increased cutting and reduction in stored carbon in other areas, as was seen with the reduction in

1 harvesting in the Pacific Northwest during the 1990s (Murray *et al.*, 2004). Preliminary studies suggest  
2 that leakage is of minor concern for agricultural carbon sequestration, since most practices would have  
3 little or no effect on the supply and demand of agricultural commodities. However, there are uncertain  
4 and conflicting views on whether land-set asides—where land is taken out of agricultural production,  
5 such as the Conservation Reserve Program in the United States, might be subject to significant leakage.

6 A further question, relevant to policies for carbon sequestration, is how practices for conserving  
7 carbon affect emissions of other greenhouse gases. Of particular importance is the interaction of carbon  
8 sequestration with N<sub>2</sub>O emission, because N<sub>2</sub>O is such a potent greenhouse gas (Robertson and Grace,  
9 2004; Six *et al.*, 2004; Gregorich *et al.*, 2005). (See Text Box 4). In some environs, carbon-sequestration  
10 practices, such as reduced tillage, can stimulate N<sub>2</sub>O emissions thereby offsetting part of the benefit;  
11 elsewhere, carbon-conserving practices may suppress N<sub>2</sub>O emissions, amplifying the net benefit (Smith *et*  
12 *al.*, 2001a; Smith and Conen, 2004; Conant *et al.*, 2005; Helgason *et al.*, 2005).

13 Similarly, carbon-sequestration practices might affect emissions of CH<sub>4</sub>, if the practice, such as  
14 increased use of forages in rotations, leads to higher livestock numbers. These examples demonstrate that  
15 policies designed to suppress emission of one greenhouse gas need to also consider complex interactions  
16 to ensure that *net* emissions are reduced.

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

## 24 25 **RESEARCH AND DEVELOPMENT NEEDS**

26 Expanding the network of intensive research sites dedicated to understanding basic processes,  
27 coupled with national-level networks of soil monitoring/validation sites could reduce inventory  
28 uncertainty and contribute to attributing changes in ecosystem carbon stocks to changes in land  
29 management (see Bellamy *et al.*, 2005). Expansion of both networks should be informed by information  
30 about how different geographic areas and ecosystems contribute to uncertainty and the likelihood that  
31 reducing uncertainty could inform policy decisions. For example, changes in ecosystem carbon stocks due  
32 to woody encroachment on grasslands constitute one of the largest, but least certain, aspects of terrestrial  
33 carbon cycling in North America (Houghton *et al.*, 1999; Pacala *et al.*, 2001). Better information about  
34 the spatial extent of woody encroachment, the amount and growth of woody biomass, and variation in

1 impacts on soil carbon stocks would help reduce that uncertainty. Identifying location, cause, and size of  
2 this sink could help identify practices that may promote continued sequestration of carbon and would  
3 constrain estimates of carbon storage in other lands, possibly helping identify other policy options.  
4 Uncertainty in land use, land use change, soil carbon responses to management (e.g., tillage) on particular  
5 soils, and impacts of cultivation on soil carbon stocks (e.g., impacts of erosion) are the largest  
6 contributors to uncertainty in the Canadian and U.S. national agricultural greenhouse gas inventories  
7 (Ogle *et al.*, 2003; VandenBygaart *et al.*, 2004). Finally, if the goal of a policy instrument is to reduce  
8 greenhouse gas emissions, net impacts on CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions, which are not as well  
9 understood, should be considered.

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16

1 **[START OF TEXT BOX 1]**

2  
3 **Nitrous oxide (N<sub>2</sub>O) emissions from agricultural and grazing lands**

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

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14 **[END OF TEXT BOX 1]**

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19 **[START OF TEXT BOX 2]**

20  
21 **Inorganic soil carbon in agricultural and grazing ecosystems**

22  
23 Inorganic carbon in the soil is comprised of primary carbonate minerals, such as calcite (CaCO<sub>3</sub>) or dolomite  
24 [CaMg(CO<sub>3</sub>)<sub>2</sub>], or secondary minerals formed when carbonate (CO<sub>3</sub><sup>2-</sup>), derived from soil CO<sub>2</sub>, combines with base  
25 cations (e.g., Ca<sup>2+</sup>, Mg<sup>2+</sup>) and precipitates within the soil profile in arid and semi-arid ecosystems. Weathering of  
26 primary carbonate minerals in humid regions is a source of CO<sub>2</sub>, whereas formation of secondary carbonates in drier  
27 areas is a sink for CO<sub>2</sub>; however, the magnitude of either flux is highly uncertain. Agricultural liming involves  
28 addition of primary carbonate minerals to the acid soils to increase the pH. In the United States, about 1 Mt C yr<sup>-1</sup> is  
29 emitted from liming (EPA, 2006).

30  
31 **[END OF TEXT BOX 2]**

1 *[START OF TEXT BOX 3]*

2  
3 **Impacts of woody encroachment into grasslands on ecosystem carbon stocks**

4  
5 Encroachment of woody species into grasslands—caused by overgrazing-induced reduction in grass biomass  
6 and subsequent reduction or elimination of grassland fires—is widespread in the United States and Mexico,  
7 decreases forage production, and is unlikely to be reversed without costly mechanical intervention (Van Auken,  
8 2000). Encroachment of woody species into grassland tends to increase biomass carbon stocks by  $1 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$   
9 (Pacala *et al.*, 2001), with estimated net sequestration of  $0.12\text{--}0.13 \text{ Gt C yr}^{-1}$  in encroaching woody biomass  
10 (Houghton *et al.*, 1999; Pacala *et al.*, 2001). In response to woody encroachment, soil carbon stocks can significantly  
11 increase or decrease, thus predicting impacts on soil carbon or ecosystem carbon stocks is very difficult (Jackson *et*  
12 *al.*, 2002).

13  
14 *[END OF TEXT BOX 3]*

15  
16  
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18  
19 *[START OF TEXT BOX 4]*

20  
21 **Agricultural and grazing land N<sub>2</sub>O emission reductions**

22  
23 When mineral soil nitrogen content is increased by nitrogen additions (i.e., fertilizer), a portion of that nitrogen  
24 can be transformed to N<sub>2</sub>O as a byproduct of two microbiological processes (nitrification and denitrification) and  
25 lost to the atmosphere. Coincidental introduction of large amounts of easily decomposable organic matter and NO<sub>3</sub><sup>-</sup>  
26 from either a plow down of cover crop or manure addition greatly stimulates denitrification under wet conditions  
27 (Peoples *et al.*, 2004). Some practices intended to sequester atmospheric carbon in soil could prompt increases in  
28 N<sub>2</sub>O fluxes. For example, reducing tillage intensity tends to increase soil moisture, leading to increased N<sub>2</sub>O fluxes,  
29 particularly in wetter environments (Six *et al.*, 2004). Synchronizing organic amendment applications with plant  
30 nitrogen uptake and minimizing manure storage under anoxic conditions can reduce N<sub>2</sub>O emissions by 10–25% and  
31 will increase nitrogen use efficiency which can decrease indirect emissions (in waterways) by 5–20% (CAST, 2004).

32  
33 *[END OF TEXT BOX 4]*

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**Table 10-1. Carbon pools in agricultural and grazing lands in Canada, Mexico, and the United States; the area (M ha) for each climatic zone are in parentheses**

Carbon pools for undisturbed native systems were derived using the intersection of MODIS-IGBP<sup>a</sup> 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 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)

Practice	Temperate dry <sup>b,c</sup>	Temperate wet	Tropical dry	Tropical wet	Total
Gt C					
<b>Agricultural lands</b>					
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)
<b>Grazing lands</b>					
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)

<sup>a</sup>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

<sup>b</sup>Temperate zones are those located above 30° latitude. Tropical zones (<30° latitude) include subtropical regions.

<sup>c</sup>Dry climates were defined as those where the ratio of mean annual precipitation (MAP) to potential evapotranspiration (PET) is less than 1; in wet areas, MAP/PET >1.

1

**Table 10-2. North American agricultural and grazing land carbon fluxes for the years around 2000**

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 U.S. (EPA, 2005) National Inventories and from the second Mexican National Communication (CISCC, 2001). Values are for 2003 for United States and Canada and 1998 for Mexico. A global warming potential of 23 for methane was used to convert emissions of CH<sub>4</sub> to CO<sub>2</sub> equivalents (IPCC, 2001) and a factor of 12/44 to convert from CO<sub>2</sub> to carbon

	Canada	Mexico	United States	Total
	Mt C yr <sup>-1</sup>			
<b>CO<sub>2</sub></b>				
Total production and use of agricultural inputs	2.8 <sup>a</sup>	ND	28 <sup>b</sup>	46.3
Fertilizer manufacture	1.7	ND	4.7	6.4
Mineral soil carbon sequestration	(0.1)	ND	(6.5)–(16)	(6)–(15.5)
Organic soil cultivation	0.1	ND	5–10	5.3–10.3
Woody encroachment	ND	ND	(120) <sup>c</sup>	(120)
Total	19.8	ND	(88.8)–(93.3)	
	Mt C-equivalents yr <sup>-1</sup>			
<b>CH<sub>4</sub></b>				
Rice production	0	0.1	1.9	2.0
Biomass burning	0	0.1	0.2	0.3
Livestock	5.6	12.4	38.9	56.9
Manure	0.2	0.3	10.3	10.8
Total	5.8	12.9	51.3	70.0

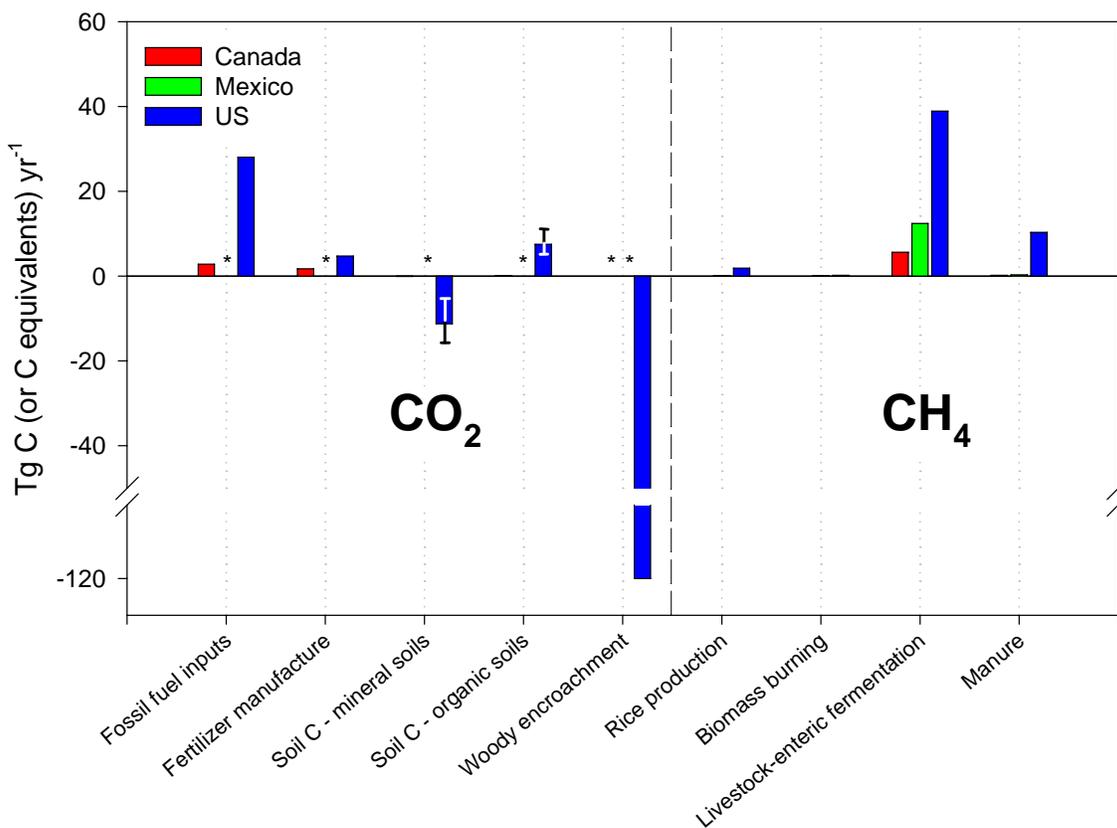
ND = no data reported.

<sup>a</sup>From Sobool and Kulshreshtha (2005).

<sup>b</sup>From Lal *et al.* (1998).

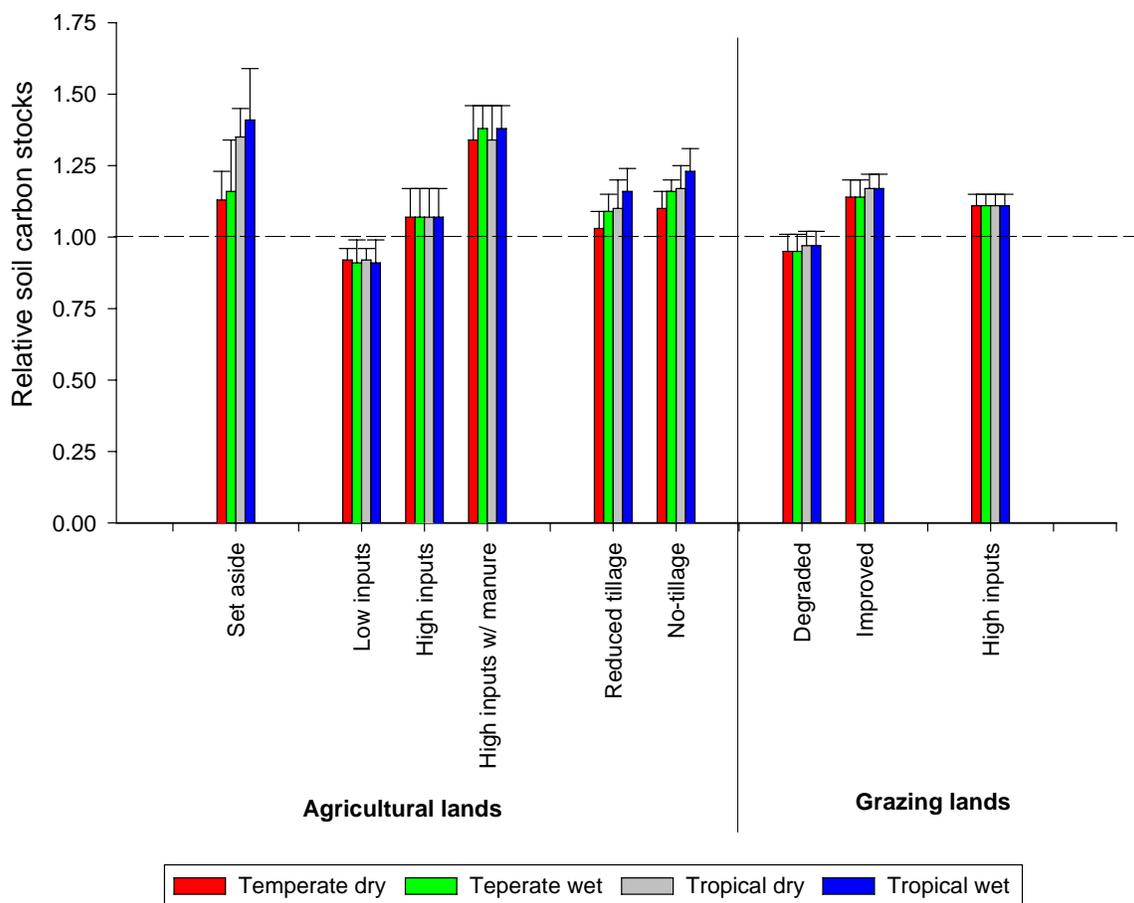
<sup>c</sup>From Houghton *et al.* (1999).

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 3 **Figure 10-1. North American agricultural and grazing land CO<sub>2</sub> (left side) and methane (right side)**  
 4 **fluxes for the years around 2000.** Negative values indicate net flux from the atmosphere to soil and biomass  
 5 carbon pools. All data are from Canadian (Matin *et al.*, 2004) and U.S. (EPA, 2005) National Inventories and from  
 6 the second Mexican National Communication (CISCC, 2001), except for Canadian [from Kulshreshtha *et al.* (2000)]  
 7 and U.S. fossil fuel inputs [from Lal *et al.* (1998)] and woody encroachment [from Houghton *et al.* (1999)]. Values  
 8 are for 2003 for the United States and Canada and 1998 for Mexico. A global warming potential of 23 for methane  
 9 was used to convert emissions of CH<sub>4</sub> to CO<sub>2</sub> equivalents (IPCC, 2001) and a factor of 12/44 to convert from CO<sub>2</sub> to  
 10 carbon. Asterisks indicate unavailable data. Data ranges are indicated by error bars where available.

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**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 emission factors to estimate carbon sequestration rates. 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).