IMPACTS OF SOIL EROSION ON THE PRODUCTION AND EMISSION OF GREENHOUSE GASES AND CARBON SEQUESTRATION IN THE CANADIAN PRAIRIES

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Abstract

Soil erosion by wind, water and tillage results in the redistribution of vast quantities of soil the within landscapes of the Canadian prairies. The magnitude of this redistribution is greatest in landscapes that are topographically complex and within landscapes that are intensively tilled. Eroded soil either remains within the cultivated area of the landscape (the field) or it is transported to the field boundary or beyond to adjacent lands and waters. Soil that is rich in organic carbon and nitrogen is lost from the upper slopes of hills and accumulates in lower slopes. In many landscapes, as soil is lost from hilltops, subsoil that is poor in organic carbon and rich in inorganic carbon is exposed at the surface. In landscapes that are or have been intensively tilled, these losses and accumulations of soil can exceed 100 cm in depth. As a consequence of tillage and the resulting soil erosion, the distribution of materials that are required to produce greenhouse gases (CO_2 and N_2O) has been dramatically altered – some source materials are buried while others may be exposed. This paper examines the potential impacts of soil erosion on the production and emission of these gases and on the sequestration of carbon. These impacts are demonstrated to have the potential to be very significant and to require better understanding.

Keywords: Soil erosion, Tillage erosion, Greenhouse gases, Carbon sequestration, Landscape variability

INTRODUCTION

The Canadian prairies were first cultivated about 100 years ago. Since that time, erosion by wind, water and tillage has resulted in the redistribution of vast quantities of soil within the cultivated, topographically complex landscapes of the region. Severe soil loss is commonly observed on upper slope landscape positions (Figure 1). Eroded soil either remains within the cultivated area of the landscape (the field) or it is transported to the field boundary or beyond to adjacent lands and waters – in many cases the majority of the eroded soil remains within the field. These losses and accumulations often exceed 50 cm in depth and can exceed 100 cm. The area affected by significant levels of either loss or accumulation is between 10 and 30 % of these landscapes.

Using 1996 agriculture census data and landscape data from the National Soil Data Base, Shelton et al. (2000) concluded that 12 % of the cropland in the prairie provinces (Alberta, Saskatchewan and Manitoba) was subjected to unsustainable levels of water erosion (Table 1). A similar assessment was made for tillage erosion by King et al. (2000) using the tillage translocation data of Lobb et al. (1995, 1999), the Tillage Erosion Risk Indicator (TERI) model (Lobb 1997), and it was found that 55 % of the cropland was subjected to unsustainable levels of tillage erosion (Table 2). (Tillage erosion is the progressive down slope movement of soil resulting directly from tillage.) Tables 1 and 2 indicate that the risk of water erosion and the risk of tillage erosion have decreased between 1981 and 1996. This decrease is due to the adoption of conservation tillage practices (Table 3). In 1996, 52 % of the cropland in the prairie provinces remained in conventional tillage. The adoption of conservation tillage since 1996 is believed to be minimal; consequently, soil degradation by erosion in the Canadian prairies continues to be widespread. Figure 2 shows the progressive impact of soil erosion on a typical prairie landscape, the severity and extent of erosion increasing under continued intensive tillage.

Figure 1. Typical cultivated, topographically complex landscape of the prairie region. Severe soil loss is observed on convex upper slope landscape positions. Light coloured soil on upper slopes is depleted in organic matter and enriched in carbonates.

Studies by Lobb and Kachanoski (1999) and others elsewhere in Canada and the world (e.g. Lindstrom et al. 1992) have shown that the contribution of tillage erosion to gross soil redistribution within cultivated, topographically complex landscapes can be equal to or greater than wind and water erosion. Water erosion results in significant soil losses from 40 to 60 % of the landscape (back and foot slopes) and tillage erosion results in significant soil losses from 10 to 30 % (shoulder slopes and crests); however, the rates of tillage erosion usually far exceed those of water erosion. The relative contribution of tillage erosion explains why only a minor portion of eroded soil leaves the cultivated area of many landscapes.

The redistribution of soil within cultivated, topographically complex landscapes results in highly variable soil properties. Given the variability in soil properties within the landscapes of the Canadian prairies, it is reasonable to assume that biophysical processes such as greenhouse gas production and carbon sequestration differ significantly between upper, mid and lower slope positions of these landscapes (e.g. Corre et al. 1996, Meixner and Eugster 1999). It is reasonable to assume that landscapes that are not currently cultivated but have been cultivated in the past also express differences in biophysical processes based on landscape position.

Several research groups around the world are investigating the impacts of agricultural land management on the emission of greenhouse gases and the consequential effects on global climate change. These efforts have focused on the sequestration of carbon and the emission of carbon dioxide as affected by cropping and tillage practices (e.g. Lal et al. 1998). Soil erosion has been recognized as a factor in the emission of greenhouse gases, but consideration has only been given to water erosion and its removal of organic-rich materials from cultivated landscapes and its delivery of these materials to waterways (e.g. Kimble et al. 2001). Again, cropping and tillage practices are implicated through their impacts on soil erosion by water. A small number of studies have been carried out in which soil erosion has been related to the redistribution of carbon within cultivated landscapes (e.g. Pennock and Frick 2001). A few studies have related soil erosion with the emission of CO_2 within cultivated landscapes (e.g. Reicosky et al. 2002). Understanding of the impacts of soil erosion on the production and emission of greenhouse gases and sequestration of carbon is extremely poor. This extremely poor understanding may greatly limit the general understanding and management of greenhouse gas emissions and carbon sequestration.

Table 1. Risk of water erosion on Canadian cropland[1] in 1981 and 1996

		Proportion of cropland (%) in various risk classes									
Province[3]	Cropland[4]	Tolerable[2]		Low[2]		Moderate[2]		High[2]		Severe[2]	
	(10^6 ha)	1981	199	1981	199	1981	198	1996	1981	1996	1981
British Columbia	0.5	56	56	25	19	12	19	5	5	2	1
Alberta	1	75	83	15	11	8	6	2	1	<1	<1
Saskatchewan	18.8	64	90	24	5	7	5	4	1	2	<1
Manitoba	4.9	88	89	5	4	3	4	1	1	3	2
Ontario	3.4	51	58	26	27	13	6	10	10	<1	<1
Ouebec	1.6	89	88	7	9	4	3	0	0	0	0
New Brunswick	0	43	48	23	30	22	14	6	5	6	3
Nova Scotia	0	74	72	14	15	10	10	<1	<1	2	2
P.E.I.	0.1	59	59	23	23	14	19	4	0	<1	0
Canada	40.1	70	84	19	9	7	5	3	2	1	<1

1. Includes seeded and summer fallow (tilled but not seeded).
2. Tolerable (sustainable) < 6 t ha-1 yr-1; Low = 6-11 t ha-1 yr-1; Moderate = 11-22 t ha-1 yr-1; High = 22-33 t ha-1 yr-1; Severe > 33 t ha-1 yr-1.
3. Newfoundland excluded based on the small area of cropland.
4. Average values for 1981 and 1996.

Source: Shelton et al. 2000.

Table 2. Risk of tillage erosion on Canadian cropland[1] in 1981 and 1996

		Proportion of cropland (%) in various risk classes									
Province[3]	*Cropland*[4]	*Tolerable*[2]		*Low*[2]		*Moderate*[2]		*High*[2]		*Severe*[2]	
	(10^6 ha)	*198*	*199*	*198*	*199*	*198*	*199*	*198*	*199*	*198*	*199*
British Columbia	0.5	30	50	42	36	28	14	<1	0	0	0
Alberta	10.	47	62	24	19	26	19	3	0	0	0
Saskatchewan	18.8	29	35	14	19	52	46	5	0	0	0
Manitoba	4.9	22	44	53	38	24	18	1	0	0	0
Ontario	3.4	33	41	21	35	43	24	3	<1	0	0
Ouebec	1.6	68	75	21	16	11	9	0	0	0	0
New Brunswick	0.1	33	38	26	32	32	21	3	8	6	1
Nova Scotia	0.1	40	66	52	28	8	6	0	0	0	0
P.E.I.	0.1	50	50	29	30	10	10	11	10	0	0
Canada	40.1	35	46	23	23	38	31	4	<1	<1	0

1, 2, 3 and 4 See notes for Table 1.

Source: King et al. 2000.

Table 3. Tillage statistics for seeded cropland in Canada from 1996 census of agriculture

Province	*Conventional tillage*		*Reduced tillage*[3]		*No tillage*		*Total seeded area*	
	(10^3 ha)	*(%)*[1]	*(10^3 ha)*	*(%)*[1]	*(10^3 ha)*	*(%)*[1]	*(10^3 ha)*	*(%)*[2]
British Columbia	117	65.5	44	24.4	18	10.1	179	0.6
Alberta	4,316	56.8	2,497	32.9	784	10.3	7,597	26.5
Saskatchewan	6,089	45.3	4,420	32.9	2,936	21.8	13,444	46.8
Manitoba	2,509	63.3	1,090	27.5	362	9.1	3,961	13.8
Ontario	1,485	59.5	557	22.3	455	18.2	2,497	8.7
Quebec	666	80.1	130	15.6	35	4.3	831	2.9
New Brunswick	47	79.5	11	18.4	1	2.1	59	0.2
Nova Scotia	19	77.4	5	19.6	1	3.0	24	0.1
P.E.I.	96	82.0	19	16.3	2	1.8	117	0.4
Newfoundland	1	87.7	<1	8.3	<0.1	4.0	1	<0.1
Canada	15,343	53.4	8,772	30.6	4,594	16.0	28,709	100.0

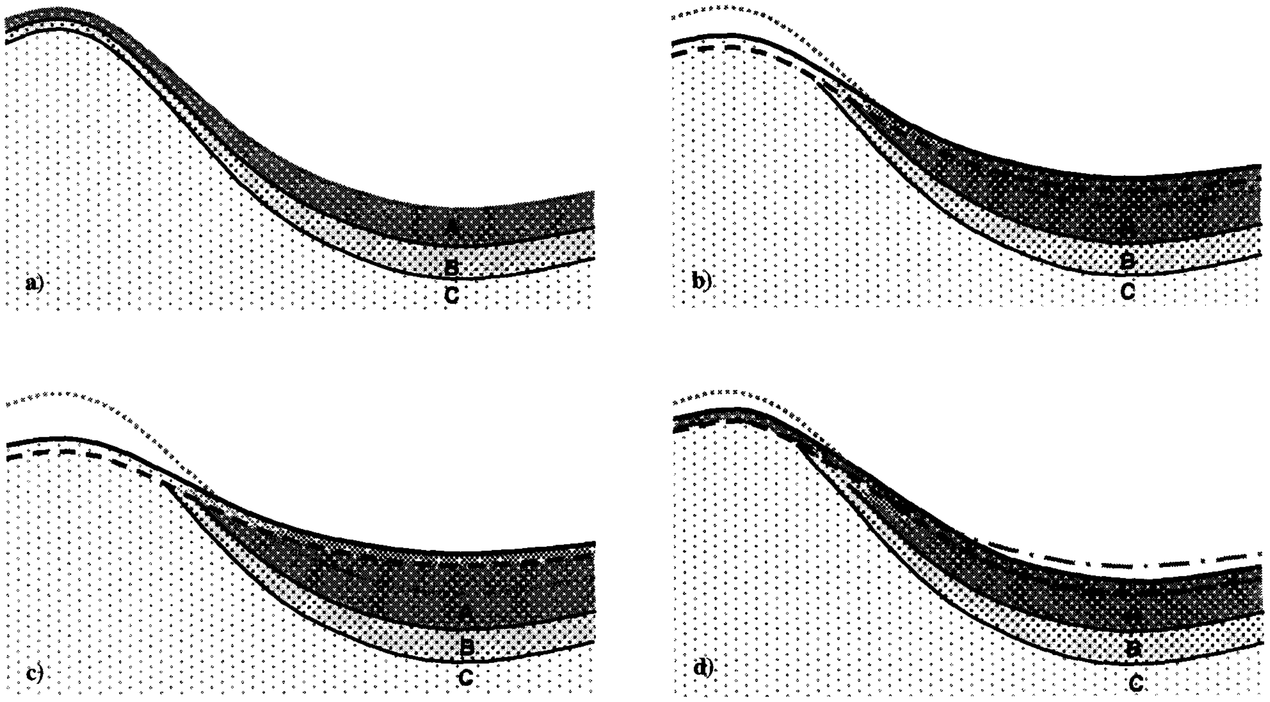
1 % of respective area.

2 % Canada.

3 Retaining most of residue on surface.

Source: Statistics Canada 1997.

Figure 2. The progressive impact of soil erosion on the redistribution of soil within a topographically complex prairie landscape and (adapted from Ellis 1938). a) uncultivated state, circa 1900; b) mature state of erosion, circa 1996; c) advanced state of erosion; and d) restored landscape. Dotted line indicates original surface. Dashed lined indicates till-layer.



This paper examines three hypotheses in the context of the cultivated, topographically complex landscapes of the Canadian prairies:

1) the loss of organic carbon- and nitrogen-rich materials from upper slopes decreases CO_2 and N_2O emissions from these landscape positions;

2) the organic carbon- and nitrogen-rich materials that are buried to depths of 100 cm on lower slopes do not contribute significantly to emissions of CO_2 and N_2O from these landscape positions; and

3) the exposure of carbonate-rich material on upper slopes increases CO_2 emissions from these landscape positions.

IMPACT OF LOST ORGANIC MATTER ON ERODED LANDSCAPE POSITIONS

In cultivated, topographically complex landscapes, soil erosion results in the physical removal of organic carbon- and nitrogen-rich materials from upper slope landscape positions, which represents a loss of sequestered carbon and nitrogen from these landscape positions. In the Canadian prairies, the amount of organic matter on these landscape positions prior to cultivation would have been about 67 % of the landscape average – lower slopes have twice the amount of upper slopes (Gregorich et al. 1998). When severely eroded, in excess of 75 % of organic carbon and nitrogen can be lost from these landscape positions (e.g. Verity and Anderson 1990). Clearly, with less carbon- and nitrogen-rich material, there is less material available to produce CO_2 and N_2O. If it is assumed that the production and emission of CO_2 and N_2O are directly proportional to levels of organic carbon and nitrogen, and that the area of severely eroded land in the Canadian prairies is 10 %, then severe erosion has resulted in a 5 % reduction in CO_2 and N_2O emissions from the region. The reduction in emissions from slightly and moderately eroded lands is probably an additional 5 %. The estimated current rate of emissions from agricultural soils across Canada is 1.8 Tg CO_2 yr^{-1} from organic carbon and 17.8 Tg CO_2 equivalent yr^{-1} of N_20 (Desjardins and Riznek 2000). Assuming that these emissions occur uniformly across Canada and that these values represent 90 % of emissions without soil loss, and based on the fact that the prairie provinces account for 86 % of the cropland in Canada, the estimated reduction in greenhouse gas emissions resulting from soil loss within the prairie region is 1.9 Tg CO_2 equivalent yr^{-1}.

The loss of soil results in adverse soil environment conditions: loss of well structured soil and exposure of poorly structured soil, reduced water holding capacity, increased runoff and reduced soil moisture, reduced nutrient holding capacity, reduced soil nutrient supply from mineralization; and alkaline conditions due to the exposure of carbonates. The consequence is a reduction in potential soil biological activity. The most dramatic evidence of this reduced potential is the reduction in crop yield on severely eroded soils. On severely eroded soils, crops commonly suffer yield losses of 30 to 70 % (e.g. Verity and Anderson 1990), and as much as 100 % in dry years. The effect of soil loss on the rate of soil biomass production is clear, but the effect on soil biomass decomposition is unclear; consequently, the combined effect on production and emission of CO_2 and N_2O and on sequestration of carbon and nitrogen is unclear. It is possible that the continued removal of organic carbon through erosion maintains accelerated rates of carbon sequestration.

The significance of the loss of soil organic matter must be assessed at a landscape scale – the net effect. The balance between the changes in areas of soil loss and changes in areas of soil accumulation is discussed below.

IMPACT OF BURIED ORGANIC MATTER

In cultivated, topographically complex landscapes, soil erosion results in the physical accumulation in lower slope landscape positions of organic carbon- and nitrogen-rich materials – the materials removed from upper slopes. Just as the loss of soil changes the conditions of the soil environment, so does the accumulation of soil; most notably, the layer of organic-rich soil thickens, often by as much as 50 cm. The soil environment conditions at the surface may not change appreciably, since the additional soil has been dragged from a position slightly upslope. However, the soil environment conditions of buried soil are changed. The buried organic-rich soil is subject to more moderate temperature and moisture conditions. The buried soil has increased moisture contents due to greater separation from the atmosphere and increased runoff from upslope, sustaining saturated conditions for greater lengths of time. Consequently, the production of CO_2 will decrease while N_20 will increase. In addition to the production of CO_2 and N_2O, buried organic-rich material may also produce CH_4. Greater separation from the atmosphere will reduce the emissions of CO_2, N_2O and CH_4. Buried soil is below the depth of tillage and, therefore, will not undergo tillage induced degassing. The total emissions from lower slope landscape positions will increase due to the accumulation of soil, but the contributions from buried material will be reduced, reducing the net emissions from the landscape. At a landscape scale, the burial of organic-rich soil may result in a net increase in carbon sequestration. However, given the relative global warming potentials of CO_2, N_2O and CH_4 (over 100 years: 1, 310 and 21, respectively), the increased production and emission of N_2O and CH_4 in lower slopes may increase the net global warming.

IMPACT OF EXPOSURE OF CARBONATES ON ERODED LANDSCAPE POSITIONS

The soils of the Canadian prairies have developed on calcareous parent materials which are rich in carbonates. Calcareous parent material undergoes weathering by acidification – the carbonate minerals when subjected to acids are decomposed to produce soluble bicarbonate and gaseous carbon dioxide. Sources of acid include: atmospheric deposition of H_2CO_3, HNO_3, H_2SO_4, production of organic acids by vegetation, and production of H_2CO_3 during the decomposition of vegetation. Human activity has intensified the acidification of soils and their parent materials through the application of organic and inorganic fertilizers, combustion of fossil fuels, etc.

Soil erosion exposes parent material on upper slope landscape positions and buries it on lower slope positions, affecting the weathering of the parent material throughout the landscape. To illustrate the potential impact of the exposure of calcareous parent materials on CO_2 emissions, a simple numerical exercise was conducted. The amount of CO_2 emitted from carbonates exposed through erosion was estimated for 1996 based on the following facts and assumptions:

- Of the total land area that in the prairie region (72.6 million ha), 91 % is topographically complex with calcareous soil parent material (Source: National Soil Data Base). Of that area, 34.3 million ha was cropped in 1996 (Source: Statistics Canada 1997). Of the cropland area, 91 % is topographically complex with calcareous parent material.
- The soils which were cropped in 1996 are intensively tilled or continue to be influenced by intensive tillage in the past. Conservation tillage has been practiced for 20 years or less on about one-half of the cropland (Source: Statistics Canada 1997).
- The management of this cropland makes the soils on topographically complex landscapes subject to erosion, severe erosion on convex upper slope landscape positions.
- Of the cropped, topographically complex landscapes, 10 % is severely eroded convex upper slope landscape positions. As a consequence of this severe erosion, calcareous parent material is exposed (the topsoil consists of cultivated parent material) on 9.1 % of total cropland area.
- A typical non-eroded soil has a carbonate content of 0 % in the solum (about 20 to 40 cm in depth on upper slopes) and 25 % in the underlying parent material (can reach 50 %). The difference is lost through acidification.
- Weathering of carbonates by acidification is accelerated on upper slope landscape positions where exposure occurs. It is not offset by a deceleration of weathering on lower slopes where burial occurs; consequently, there is a net increase of weathering of

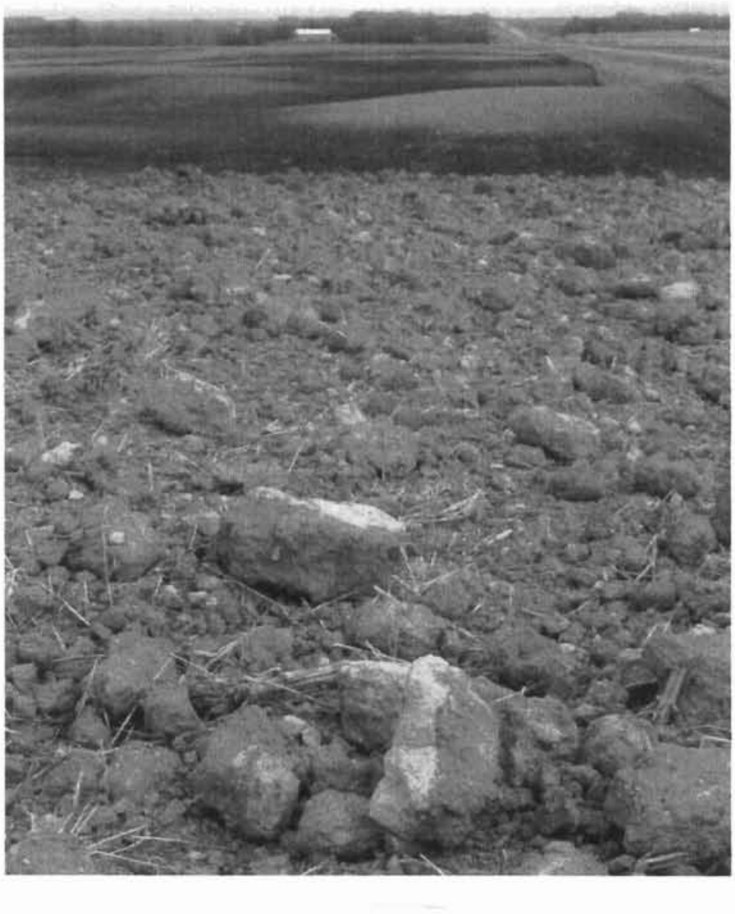
carbonates within the landscape.

- Acidification depletes carbonates to a depth of 30 cm on upper slopes. This occurs over 10,000 years under natural conditions and over 1,000 years under the influence of human activity.
- Of the carbonates acidified, only 10 % result in CO_2 gas emissions. The remaining 90 % are dissolved in solution which moves to surface or ground water. Dissolved CO_2 (bicarbonates) may precipitate to form secondary minerals. Dissolved CO_2 that moves elsewhere in the landscape may ultimately contribute to CO_2 emissions.

Based on these assumptions, 4,300 Tg C (15,700 Tg CO_2) will be lost as CO_2 gas produced from carbonates exposed by erosion. If it is assumed that this loss of inorganic carbon occurs over approximately the same length of time as it took to deplete the soil of carbonates prior to crop production (~10,000 years), the average rate of emission is 1.6 Tg CO_2 yr^{-1}. If it is assumed that human activities reduce this length of time to 1,000 years, the average rate of emission is 16 Tg CO_2 yr^{-1} (4,600 kg CO_2 ha^{-1} yr^{-1} from upper slopes).

In comparison, the net organic carbon loss from these prairie soils (1,700 Tg from 6,800 Tg, 0-30 cm) is estimated to have occurred at an average rate of 240 Tg CO_2 yr^{-1} between 1910 when tillage-fallow was a conventional practice, and 1930, and at an average rate of 70 Tg CO_2 yr^{-1} between 1910 and 1996 (Janzen et al. 1998). The rate from agricultural soils in Canada in 1996 was estimated to be 1.8 Tg CO_2 yr^{-1} (Janzen et al. 1998). This dramatic reduction in recent years is due to the reduced stores of soil carbon and changes in crop production practices. The total organic carbon in the first meter of agricultural soils in Canada is approximately 10,000 Tg (Janzen et al. 1998).

Figure 3. A prairie landscape that is severely eroded by soil erosion. In the foreground, note the calcareous subsoil tilled to the surface where it will be incorporated into the till-layer.



DISCUSSION

Clearly, both the loss of organic carbon- and nitrogen-rich material from upper slope landscape positions and accumulation in lower slopes will impact the production and emission of greenhouse gases. It is probable that there is a reduction in emissions on upper slopes and an increase in emissions on lower slopes, and on a landscape scale there is probably a net reduction. This could lead one to conclude that erosion is beneficial in terms of greenhouse gas emissions and carbon sequestration. This is not a sound conclusion. In terms of CO_2-equivalents, there is probably a net increase in emissions on a landscape scale. When CO_2 emissions from inorganic material are considered, it appears that an increase is certain.

Understanding the spatial and temporal structure of greenhouse gas emissions and the impact of tillage on the dynamics of this structure is critical to developing effective methods of prediction and scaling and, thereby, to develop effective strategies to address climate change. To do so requires an understanding of soil erosion and its impacts on biophysical properties and processes within landscapes. This knowledge is imperative when one considers that the variability in soil properties that exists within the cultivated, topographically complex landscapes, largely a result of soil erosion, is often greater than the variability between landscapes of different ecoregions.

Intensive cultivation continues to be widespread in the landscapes of the Canadian prairies; consequently, soil erosion also continues to be widespread. Consideration must be given to the impact of continued intensive tillage and the resultant soil erosion on topographically complex landscapes. In Figure 2 uncultivated and cultivated conditions are represented. Figure 2b represents the current condition where severe soil loss has removed organic-rich soil from the upper slopes, exposing carbonate-rich subsoil, and moved the eroded organic-rich soil to lower slopes where it accumulates. Over time this situation will advance to the stage where carbonate-rich soil will be moved from the upper slopes to the lower slopes, burying the organic-rich soil (Figure 2c). Evidence of this advanced condition has been observed. It is anticipated that as landscapes progress from a mature state of soil degradation to this advanced state, the absolute and relative production and emission of greenhouse gases from organic materials, the absolute production and emission of CO_2 from inorganic materials, and the relative contribution of CO_2 from organic and inorganic materials will all be affected.

Conservation efforts to control soil erosion within the prairie region have focused on conservation tillage. By reducing the number and intensity of tillage operations, soil erosion is reduced. The restoration of severely eroded landscapes is being assessed as a complementary conservation practice. Landscape restoration is the excavation of soil which has accumulated in lower slope landscape positions and the application of this excavated soil on the upper slopes where soil loss has occurred (Figure 2d). This practice has the potential to dramatically alter the production and emission of greenhouse gases and carbon sequestration, presumably a shift back towards the uncultivated state.

It has been very difficult to acquire funding to support a study in which the hypotheses addressed in this paper can be tested experimentally. These hypotheses were put forward four years ago and have been debated ever since. Recently, the Canadian Agricultural Research Council under the Biological Greenhouse Gas Sources (BGSS) and Sinks program awarded Lobb and his colleagues substantial funding to conduct the needed research. The objective of the BGSS project is to assess the impacts of soil erosion on the production and emission of greenhouse gases from soil within cultivated, topographically complex landscapes of the Canadian prairies. This study is being carried out in southwestern Manitoba with supporting activities in Saskatchewan and Minnesota. Gas emissions are measured across the surface of selected hillslopes, and gas production is measured over the depth of soil profiles on these hillslopes. This data will be related to measures of soil redistribution by wind, water and tillage erosion. This information will be used to predict changes in the redistribution of soil and in the emission of CO_2 and N_2O as a function of tillage system. The goal of this project is to reduce the adverse impacts of agriculture associated with greenhouse gas emissions through the selection of cultivation practices to control of soil erosion.

SUMMARY

This paper addresses a large and very significant gap in the understanding of the impacts of land management on climate change; more specifically, the impacts of soil erosion on the production and emission of greenhouse gasses and carbon sequestration. To date, researchers have assumed that the impacts of soil erosion are related solely to the delivery of organic carbon- and nitrogen-rich material from farm fields to water bodies. More significant impacts may be related to the redistribution of organic carbon- and nitrogen-rich materials within fields and the exposure of inorganic carbon. Whatever the impacts may be, they must be recognized that soil erosion persists under continued intensive tillage and that landscapes continue to evolve rapidly. Research on the impacts of soil on the production and emission of the greenhouse gases and carbon sequestration is desperately needed.

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