IMPACT OF AGRICULTURE AND FORESTRY ON LANDSCAPE-SCALE SOIL ORGANIC CARBON STORAGE IN SASKATCHEWAN

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Abstract

The development of sound management approaches to reduce soil organic carbon (SOC) losses from soils presuppose that we thoroughly understand the sources of these losses. We use a landscape-scale research design to estimate the magnitude of carbon losses due to human activity by comparing SOC storage in undisturbed landscapes with comparable landscapes disturbed by clear-cutting of forests in the Mixedwood/Gray Luvisolic zone of central Saskatchewan and by agricultural activity in the Black soil zone. A slight drop in median levels of soil organic carbon storage in the upper 45 cm of the soil (from 56.8 Mg ha-1 in mature mixedwood sites to 52.7 Mg ha-1 in clear-cut landscapes) occurs due to clear-cutting of the Mixedwood forest. The dominant soil type in these landscapes, Gray Luvisolic soils, experience no significant change in SOC storage; however significant losses occur from Brunisolic (29% loss) and Gleysolic (32% loss) inclusions in these landscapes. Changes in SOC from Black soil zone landscapes are strongly related to texture: sandy glacio-fluvial landscapes experience slight gains of SOC (from 54.1 to 60.1 Mg ha-l); silt and clay glacio-lacustrine landscapes experience a 15.3% decrease in SOC (from 145.2 to 122.9 Mg ha-l); and loamy glacial till landscapes undergo a major decrease in SOC storage (from 119.6 to 75.2 Mg ha^{-1}). Our results indicate that attempts to mitigate SOC losses from soils in Saskatchewan should concentrate on agricultural activities, especially in glacial till landscapes.

Introduction

The loss of soil organic carbon (SOC) due to human disturbance has major consequences for both the productivity of the soil and the contribution of soils to global environmental problems. The contribution of SOC to the productivity of the soil is very significant and well-understood: SOC is a major natural source of nutrients for plant growth and its chemical and physical interactions with soil minerals contribute to soil structure development, the creation of favourable tilth conditions, and to the water-holding capacity of soils. SOC also serves as the major terrestrial reservoir of carbon and hence plays a dominant role in global carbon cycling and the environmental concerns linked to changes in atmospheric CO2 levels. In particular, grassland soils are the largest single terrestrial reservoir for SOC storage (Intergovernmental Panel on Climate Change, 1990) and hence changes in the amount of SOC storage in these soils has a profound impact on the balance between atmospheric and terrestrial C levels.

The loss of SOC due to agricultural activity has been a major focus of research in the Prairies since cultivation of these soils began. The estimates of SOC loss have, however, differed greatly between different researchers: the most recent State of the Environment Report (Environment Canada, 1991) reports a loss of about 40-50% of the original soil organic matter, whereas Anderson (1992) estimates a 17% loss of SOC from agricultural soils in Saskatchewan. In part, these differences arise from the use of different methods to report the loss (e.g., using a concentration (%) basis for comparison rather than a mass per area basis for estimation) and of different portions of the soil (e.g., SOC in A horizon rather than on a solum basis) used to estimate the loss.

The impacts of forestry activity on SOC levels are less well-documented, especially in the broad Mixedwood forest zone which occupies the central portion of Saskatchewan. The recently developed model for the Carbon Budget of the Canadian forest sector (Kurz et al., 1992) estimates average SOC storage in the Boreal West ecozone (which the Mixedwood forest is part of) at 118 M; they go on to estimate that clear-cutting decreases the amount of SOC storage, especially in the fast- and medium-turnover SOC pools, over a period up to 100 years after harvest. Again, however, the studies they cite used a range of techniques and sample sizes to estimate the SOC changes, and the magnitude of error associated with such estimates are always very high.

Our objective in this study was to assess the impact of human disturbance on landscape-scale SOC storage under forestry and agricultural systems using a consistent sampling protocol. We focus on agricultural impacts in the Black soil zone of Saskatchewan and on forestry practices, specifically clear-cutting, in the Gray Luvisolic/Mixedwood landscapes of central Saskatchewan. Our goal is to provide accurate assessments of SOC losses in both zones such that the relative impact of human disturbance caused by forestry and agriculture can be reliably compared.

Materials and Methods

Site Selection

Our choice of sampling sites is governed by our understanding of the regional controls on SOC storage. In grassland areas such as the Black soil zone, both field based research and the existing models of soil organic carbon distribution suggest that the texture of the parent sediments exerts a strong, indirect control on levels of SOC storage. Our site selection in the Black zone was stratified by texture to reflect these differences. In the Gray Luvisolic/Mixedwood landscapes of central Saskatchewan, far less information was available on basic regional controls of SOC storage and our sampling program necessarily involved sampling in a range of mature Mixedwood sites to establish the regional range of SOC storage.

Our basic approach was to compare SOC storage in disturbed sites with storage in undisturbed sites in the same textural or landscape type. In the Black soil zone we initially stratified the landscape into three basic textural types: glacio-lacustrine silts and clays (GLSiCI), glacio-fluvial sands (GFSand), and loamy glacial till (Till) sites. The GLSiCl are classified as Blame Lake or Hamlin-Blaine Association map units, the GFSand sites as Meota or Hamlin-Meota map units, and the Till sites as Oxbow association soils. In each of the GLSiCl and GFSand landscapes we located one undisturbed site and three long-term cultivated sites in the same mapunit. For the Till sites we used sites which had previously been published in Pennock et al. (1994).

In the Gray Luvisolic/Mixedwood landscapes we used a much broader sampling of undisturbed sites because of the lack of information on regional-scale soil distribution. In all we sampled 12 mature Mixedwood ***(Populus tremuloides/Picea*** glauca) landscapes in the Prince Albert Model Forest using the basic landscape-scale design discussed below. Two distinct types of sites have emerged from a preliminary assessment of this data: high pH/high SOC storage landscapes (3 out of 12 sites) and lower pH/low SOC storage landscapes (9 out of 12). The impact of clear-cutting was assessed at six study sites with ages of recovery after clear-cutting ranging between 1 to 20 years. No clear-cut Mixedwood sites older than 20 years exist with the boundaries of the Prince Albert Model Forest. A preliminary analysis of the data indicates that all of the clear-cut sites fall into the low pH/low SOC storage sites, and hence they are compared to the group of nine mature Mixedwood landscapes discussed above. All of the study landscapes are mapped as either Waitville or as Bittern Creek Associations on the soil survey maps prepared for these areas.

Sampling Design and Laboratory Analysis

All of the sites discussed above were sampled using a basic square or rectangular grid sampling design. The standard spacing between sampling points was 10 meters. The number of samples differed, however, between the sites within a landscape and between landscape types. In the Black soil zone a 6 x 6 (36 sampling points) or 7 X 7 (49 sampling points) square sampling grid was used at all sites. In the forested landscapes three types of design were used. In the initial field season (1993) a very intensive 13 X 13 sampling grid with 7.5 m spacing between grid points was used our first mature Mixedwood site. The results from this were analyzed and based on the spatial analysis of the results a 3 X 3 sampling grid was used at the other mature Mixedwood sites in the 1994 sampling season. The clear-cut sites exhibit a greater range of surface conditions (mostly undisturbed, slash piles, skidder trails, access roads etc.) and a basic 6 X 6 or 7 X 7 design was again used.

At each site, the topography of the sampling grid was surveyed using a Total Station survey systemand the soil at each sampling point is sampled and described. In the Black soil zone the sampling is carried out using a truck-mounted hydraulic drill; in the forested areas a soil pit is dug and samples are taken using a core which is driven into the sides of the pit. In each case, however, samples are taken from three increments: 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm. The 0- to 15-cm increment in the forested areas include the LFH layer, or whatever remnant of it exists after disturbance. Hence in each landscape we are sampling a known volume of soil and all of our results are therefore reported in tonnes of SOC per hectare to 45 cm of soil depth (or, in other words, on a mass per area to a constant depth basis).

The topographical surveys of each research site are used to derive a Digital Elevation Model of the elevation surface. A series of slope morphological and positional attributes can be calculated for each 5m by 5 m cell of the Digital Elevation Model, and these attributes are used to classify each cell into one of seven landform elements: slope segments with a defined range of slope curvature and gradient (Pennock et al., 1987). These landform elements can then be combined into larger spatial units, termed landform element complexes (Pennock et al., 1994), using a spatial filtering algorithm.

By examining the association between the soil types present at the study sites and the landform elements and complexes, a landscape-scale soil distribution model can be developed for each of the study landscapes (the procedure is discussed in Pennock et al., 1994). The soil-landform units developed in this analysis have distinct rates of pedogenic processes associated with them, and form the basis for comparing levels of SOC storage between different research sites.

The SOC contents are assessed for each sample using a LECO CR-12 Carbon Determinator system. Organic carbon contents are assessed at a furnace temperature of 840°C and total carbon contents at a setting of 1100°C; inorganic carbon content where present) is the difference between the two measures of C content.

Results and Discussion

Development of Landscape-Scale Soil Distribution Models

The development of soil distribution models for the study landscapes is a critical stage in the analysis of SOC storage patterns. In this stage we assess the relationship between soil distribution and landform at the study sites; if a distinct association exists between landform and soil type then it indicates the occurrence of distinctive pedogenic regimes in the landscape. These different regimes are normally characterized by a differences in the rates of major pedogenic processes, including the processes which control the amount of SOC storage in the soils. Comparisons between landscapes are then made after stratifying the landscapes into the soil-landfoxm classes.

The soil-landform model used for the grassland sites in the Black soil zone is based on a clear association between landform and soil types (Figure 1). Shoulder landform complexes (defined in Pennock et al., 1994) experience high rates of runoff and soil loss and are dominated by Regosolic soils (thin soils which lack Chernozemic A horizons and B horizons) and thin Chemozemic soils. Footslopes which have low catchment areas (i.e., small areas of land contributing runoff to them) are dominated by well-developed Chemozemic soils. Footslopes with high catchment areas and level sites in the depressions in the landscapes are dominated by Gleysolic soils: soils which have experienced anaerobic conditions during their formation.

The soil-landform model in the Gray Luvisolic/Mixedwood landscapes is complicated by differences in parent materials. The high catchment-area footslopes are associated with Gleysolic soils as in the grassland areas (Figure 2). In the shoulders and low-catchment footslopes, however, the distribution of soil types is governed not by the morphology of the landscape but by the nature of the parent materials. The study landscapes in this zone exhibit a complex suite of glacial sediments: although dominated by glacial till, there are frequent, small (25 m^2 to 200 m^2) inclusions of well-sorted, glacio-fluvial sand. Gray Luvisolic soils have formed in the till portions of the landscape and dominantly Eutric Brunisolic soils in the glacio-fluvial portions. Unlike the grassland landscapes discussed above, these differences in glacial sediments (and hence in soil distribution) are not associated with distinctive slope morphological or positional segments; this lack of a basic landform-soil association makes the recognition and mapping of these soils very difficult in these landscapes.

Figure 1: Landscape-scale soil distribution model for Black soil zone landscapes.

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Figure 2: Landscape-scale soil distribution model for Gray Luvisolic Landscapes.

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Impact of Disturbance on Soil Organic Carbon Storage

Black Soil Zone Landscanes

There are major differences in SOC storage associated with undisturbed sites in the different textural types (i.e., parent materials) in the Black soil zone (Table 1). The low moisture-holding glaciofluvial sands have the lowest amount of SOC storage, whereas the more favourable moisture conditions associated with the GLSiCl lead to almost an almost three-fold increase in SOC storage compared to the sandy sites.

Table 1: SOC storage in the Black soil zone; sites are stratified by texture of parent materials and disturbance type

Texture and Parent Material	Undisturbed	Agricultural
	Mg ha-1 of SOC to 45 cm	
GFSand	54.11 (9.5)²	60.1 (35.7)
GLSiCl	145.2 (74.5)	122.9 (65.7)
Till	119.6 (25.2)	75.2 (65.7)

1: Median value2: Interquartile range

The losses of SOC due to land clearing and cultivation also show pronounced differences between the textural types (Table 1). The highest losses are associated with the glacial till soils, where an overall loss of 37.1% of the original SOC has occurred. Intermediate losses (15.3%) have occurred in the GLSiCl landscapes, while the GFSand landscapes have experienced an overall gain (11.0%) of SOC after disturbance.

The differences in the overall losses and gains of SOC are reflected in different responses of soil-landform groups within the three landscapes (Table 2). In the GFSand sites, the losses from the shoulder and low-catchment area footslopes have been negligible; the gains in SOC are concentrated in the high catchment-area footslopes and level depressional segments of the landscape. These positions are generally occupied by Gleysolic soils, and the anaerobic conditions associated with these sites in the undisturbed sites may inhibit primary production and hence limit SOC inputs to the positions. Upon clearing of the land and the additions of artificial fertilizers to the site, the improvement of fertility in these positions may lead to increased SOC additions (and ultimately storage) in these areas.

At the cultivated GLSiCl sites the losses which have occurred are concentrated in the shoulder complexes; negligible losses have occurred from the low catchment area footslopes and, as at the GFSand site, considerable gains of SOC have occurred in the high catchment-area footslope and level depressional landscape positions. Gains have also occurred in the upper level landscape positions, but these occupy only a small proportion (<5%) of the study landscapes.

Table 2: SOC storage (Mg ha-1 to 45 cm) in different textural groups and disturbance types in the Black zone stratified by landform element complexes.

Texture Group	Landform Element Complexes							
	Upper Level		Shoulder		Low-Catchment Footslopes		High Catchment Footslopes and Level Depressional	
	Undis.	Agric.	Undis.	Agric.	Undis.	Agric.	Undis.	Agric.
GFSand	NS[1]	65.52 (32.6)[3]	53.7 (9.1)	56.5 (29.2)	55.3 (13.5)	55.6 (41.7)	52.4 (19.3)	72.3 (64.7)
GLSiCl	140.1 (50.3)	162.6 (67.7)	164.4 (34.4)	97.1 (57.5)	158.6 (99.5)	150.4 (66.8)	125.6 (25.2)	167.6 (86.3)
Till	106.4 (16.8)	79.2 (40.1)	116.7 (24.0)	52.8 (20.7)	127.4 (29.7)	88.7 (31.1)	128.8 (25.0)	84.1 (47.5)

1: No samples were taken from this position2: Median
3: Interquartile range
4: Insufficient Data

Losses are considerable and occur in all landscape positions in the glacial till research sites. As at the GLSiCl sites the highest rates of loss are associated with shoulder landscape positions, but substantial losses occur in all landscape positions.

Grav Luvisolic/Mixedwood Landscanes:

Overall the losses of SOC due to clear-cutting of these landscapes is low: the six clear-cut sites show consistent losses of about 7% of the original SOC in these landscapes (Table 3). Different rates of loss are, however, associated with the different soil types in these landscapes (Table 3). The Gray Luvisolic soils dominate approximately 80% of the study landscapes and have experienced negligible losses of SOC; the Brunisolic soils, which occupy approximately 18 % of the landscapes have experienced losses of about 29% of their original SOC. The small percentage of the landscape occupied by Gleysolic soils have apparently experienced high losses, but the small sample size (only 4 Gleysolic samples from the undisturbed landscapes) limit our ability to test the significance of these losses.

Table 3: Changes in SOC storage due to disturbance in Gray Luvisolic/Mixedwood landscapes.

	Mature Mixedwood	Clear-Cut
	SOC storage (Mg ha-1 to 45 cm)	
all sites	56.81 (18.0)2	52.7 (30.1)
Luvisolic soils	56.4 (12.3)	54.0 (25.9)
Brunisolic soils	57.2 (26.9)	40.6 (27.0)
Gleysolic soils	90.7 (31.0)	61.9 (43.6)

1: Median2: Interquartile range

Conclusions

Agricultural activities in the Black soil zone have caused a significant loss of carbon from these systems in the 80 to 100 years of cultivation. These losses are most pronounced in the glacial till landscapes in the Black zone, but a considerable mass of carbon has also been lost from glacio-lacustrine silt and clay landscapes. A recent study by Pennock et al. (1994) has suggested that the losses of carbon are most pronounced in the first decade of cultivation and that the rate of carbon loss decreases in the subsequent decades.

The losses due to clear-cutting are minor compared to those associated with agricultural activity, especially when the relatively small area affected by clear-cutting is compared to the large percentage of the land mass in southern Saskatchewan cleared for agriculture.

The landscape-scale differences in the impact of disturbance on SOC storage suggest that the type and intensity of soil processes affecting carbon storage differ greatly in the landscape. Our ability to mitigate these observed changes would be greatly improved by tying observational data such as those presented above with physical and biochemical models of carbon dynamics in the landscape.

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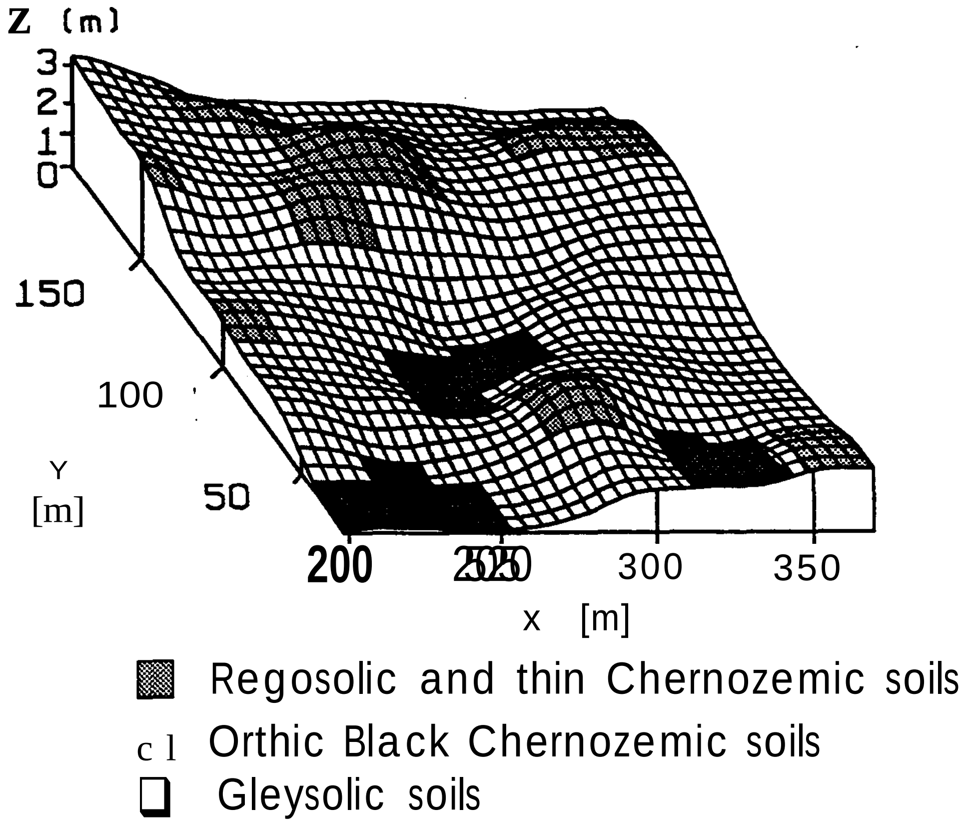

Figure 1: Landscape-scale soil distribution model for Black soil zone landscapes

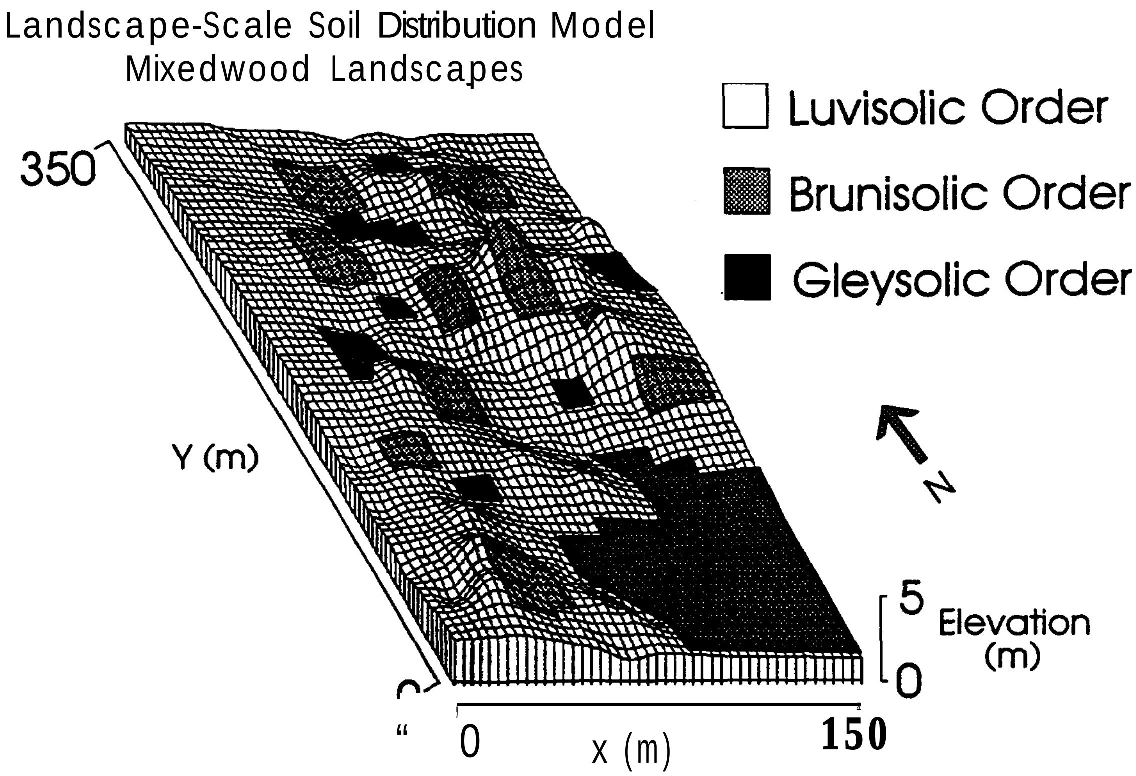

Figure 2: Landscape-scale soil distribution model for Gray Luvisolic Landscapes