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Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario

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Abstract

Soil organic carbon (SOC) in Canadian agricultural soils plays an important role in the global cycle of C, and management can influence its fate. Although the scientific literature suggests that practicing no-till (NT) can sequester C, this is not always the case. Furthermore, there are many other factors including climate, management history, soil type and soil landscape processes that may affect the dynamics of SOC under NT. We measured the changes in SOC under NT in southern Ontario, at varying positions in the landscape in Gleyic and Orthic Luvisols at the end of a 15-year-period. Soil cores taken to depths beyond the solum, were segmented with depth, and total SOC was determined for each segment on an equivalent mass basis. When the entire soil column was considered, there was a loss of SOC in more profiles than there were gains. Furthermore, the erosion/deposition history at each landscape position appeared to influence the dynamics of SOC. In depression areas where A_p horizons were greater than 27 cm thick due to a history of soil deposition from upslope and local hydrology, there was a loss of total SOC after 15 years of NT. While where the A_p thickness was less than 27 cm, there were 18 profiles with SOC gains and 15 with net losses. Multiple linear regression analysis revealed that the change in SOC after 15 years was negatively related to the initial total SOC content and positively related to mass of clay. The results of this study suggest that landscape position and erosion/deposition history play a significant role in the ability of NT soils to sequester SOC. Interpretations of long-term SOC monitoring studies must take into account the location of samples within fields if useful information is to be gained on C dynamics in agricultural soils.

Keywords: No-till; Soil organic carbon; Carbon cycle; Sequestration; Erosion; Landscape position

1. Introduction

Canadian agricultural soils are important in the global cycle of C (Dumanski et al., 1998; Janzen et al., 1998a,b), and soil management has a profound impact on the fate of organic C in terrestrial ecosystems (Lal et al., 1998b). Monitoring the changes in SOC over time in agricultural soils is key to understanding the role of soil management in sequestration of C from the atmosphere (Janzen et al., 1998a). There is a need to determine the quantity of C that can be sequestered at local to regional scales in agricultural soils (Lal et al., 1998a).

While there is evidence that a reduction in tillage, particularly NT can result in sequestration of C (Lal et al., 1994; Campbell et al., 1995), this is not always

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the case (Angers et al., 1997; Needelman et al., 1999; Wander and Yang, 2000). Angers et al. (1997) measured the differences in SOC in reduced tillage (NT and chisel plough) and conventional tillage (CT) (annual moldboard plow) for up to 11 years in cool, temperate soils of eastern Canada. They concluded that although most soils under reduced tillage had more SOC in the top 10 cm than under CT, this was compensated by less SOC at lower depths. Furthermore, most previous studies have been initiated in small, controlled field plots in uniform, level landscapes where there had presumably been little variability in profile characteristics due to variation in hydrology or erosion and redistribution. Little is known of the effects of soil erosion and redistribution on SOC dynamics at landscape and regional scales (Gregorich et al., 1998; Lal et al., 1998a). Past erosion and deposition have resulted in a redistribution of SOC in the landscape (VandenBygaart, 2001), and this has yet to be considered effectively in the study of SOC dynamics related to tillage in agro-ecosystems (Gregorich et al., 1998). In western Canada, Campbell et al. (1996) showed that the ability of NT to sequester C was related directly to the clay content of the soil. However, in more moist climatic areas, texture in NT soils does not appear to have an effect on the ability of the soil to sequester C (Angers et al., 1997; Yang and Wander, 1999). Inconsistent results of SOC dynamics in NT soils may be a result of varying soil types, hydrology, erosion histories and climates. It is the purpose of this study to elucidate soil and geomorphic factors that influence the dynamics of SOC at the end of 15 years of NT management in soils of varying texture and topography in southern Ontario.

2. Methods and materials

2.1. Management history of field sites

A side-by-side comparison of NT and CT was initiated on farms with variable landscapes in southern Ontario in 1985 to study the effect of tillage on erosion and crop yields (Aspinall and Kachanoski, 1993) (Fig. 1; Table 1). No-till at these sites involved leaving the soil undisturbed from harvest to planting except for

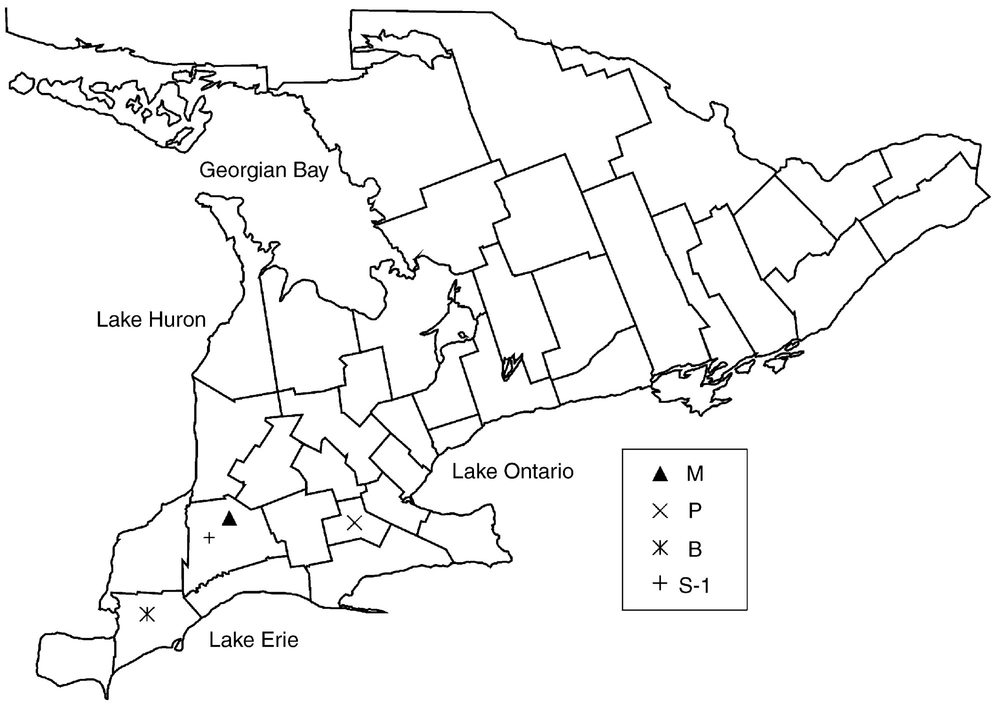

Fig. 1. Map of southern Ontario showing the four sampling locations of the study.

Table 1
Background soils information for each of the four sampling locations of the study

Study site	Dominant soil series	Sand (g/kg)[a]	Silt (g/kg)[a]	Clay (g/kg)[a]	Textural class	FAO classification
M	Honeywood	237.8	571.1	186.7	SiL	Gleyic (Lg) and Orthic (Lo) Luvisol
P	Teeswater	428.1	475.0	93.8	SL	Orthic Luvisol (Lo)
B	Brookston	278.0	440.0	278.0	CL	Gleyic Luvisol (Lg)
S-1	Fox	738.1	200.6	61.4	SL	Orthic Luvisol (Lo)

[a] Mean in A_p horizons.

nutrient injection. Planting or drilling was in a narrow seedbed or a slot, while weed control was primarily with herbicides. CT was annual moldboard plow tillage to a depth of approximately 20 cm. In four of the sites, the side-by-side comparison was terminated at the end of 1990 and the entire field maintained in NT until the end of the 2000 cropping season. Corn (*Zea mays* L.), soybean (*Glycine max* L.), and winter wheat (*Triticum aestivum* L.) were grown with different frequencies on the four fields. No animal manure was added to, or forage crops added to any of the sites.

2.2. Evidence of soil redistribution

In 1987, an assessment of soil erosion/redistribution was completed on three of the sites by characterizing the bomb-fallout ^{137}Cs content in profiles along duplicate transects (Kachanoski et al., 1992). It was presumed that the total ^{137}Cs content in the profile reflects net loss or gain in soil at a point in the landscape since the period when the radionuclide was deposited at the earth's surface during the 1950 and 1960s (Ritchie and McHenry, 1990). There was a positive relationship between A_p horizon thickness and total ^{137}Cs in three of the four fields utilized in this study (Fig. 2). Although there is uncertainty of the fate of ^{137}Cs when it was initially deposited at the earth's surface (VandenBygaart et al., 1999a), soil erosion and redistribution was likely largely responsible for the differences in A_p horizon thickness across each of the transects (Fig. 2).

2.3. Soil sampling and analysis

In 1985, samples were taken at the start of the tillage treatment along linear transects representing varying positions within the landscape (Aspinall and Kachanoski, 1993) (Fig. 3). A hydraulic soil coring

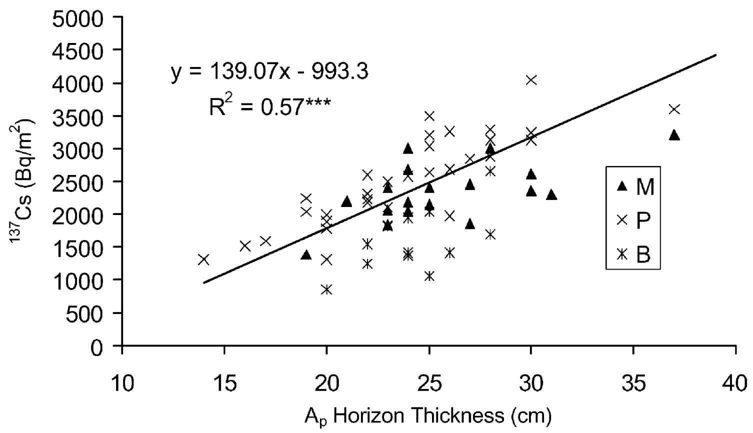

Fig. 2. Relationship between A_p horizon thickness and ^{137}Cs (Bq/m^2) in three of the four sites of the study (from Kachanoski et al., 1992).

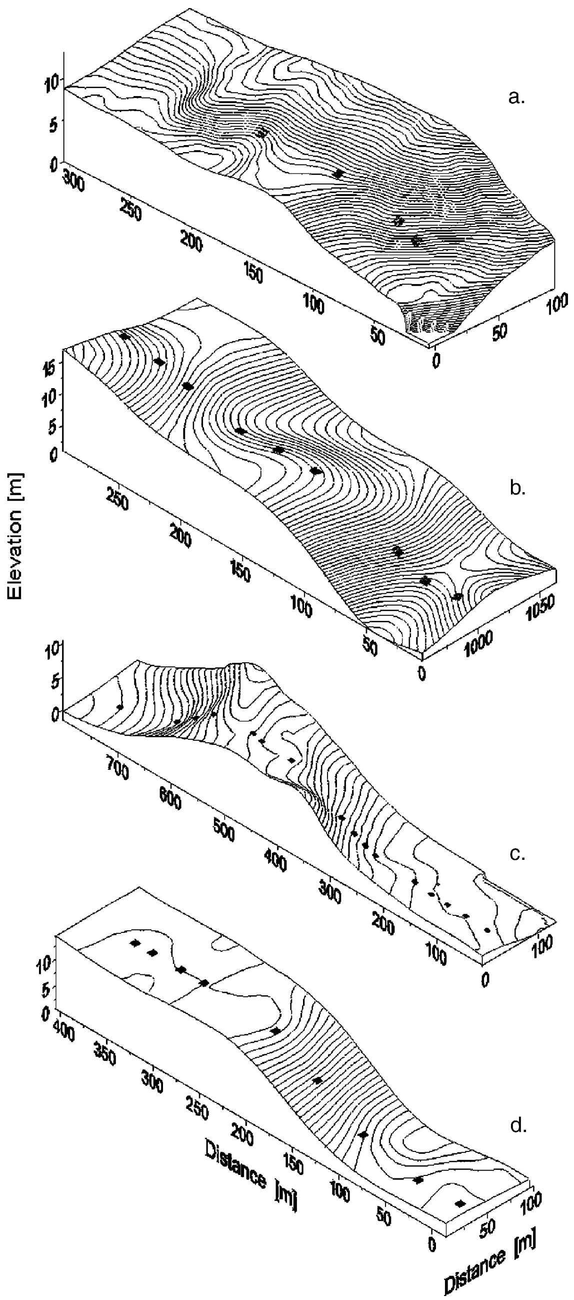

Fig. 3. Soil coring locations in both 1985 and 2000 within the landscapes of site: (a) B, (b) M, (c) P, and (d) S-1.

unit with a 5 cm diameter cylinder was used to sample a single soil core at each landscape position to a depth of at least 60 cm at each of the four fields (Fig. 3). The cores were segmented by horizon and bulk density determined on 5 cm thick portions of the horizons. The modified Walkley–Black method (Tiessen and Moir, 1993) was used to determine SOC on the segments after bulk density determinations. The SOC contents on the cores taken in 1985 were used in this study as the initial SOC content at each sample location. To assess the long-term influence of NT on SOC, soil samples at the exact position of the initial sampling in the NT treatment in 1985, were then collected in spring 2000 by a hydraulic corer (5 cm diameter). Each sample point on each field was relocated by finding sonds or metal plates buried during sampling in 1985. The soil cores from 2000 were then segmented into 0–5, 5–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm sections. Bulk density was first determined for each segment and then Leco combustion was used to determine SOC in the same segments. Total soil carbon and inorganic carbon were determined, and SOC was obtained by difference. In order to be confident that the modified Walkley–Black method determined on the 1985 samples and the Leco method were comparable in their outcome, 17 soil samples with varying degrees of SOC content were located from the original experiment and measured by the Leco combustion method. Linear regression analysis revealed that the y-intercept was not significantly different from 0 ($p > 0.05$), while the slope was not significantly different from unity ($p > 0.05$) (Fig. 4). Therefore, we were confident that the results for SOC content collected in 1985 and 2000 were not significantly influenced by the method of analysis.

Total SOC contents were determined for both 1985 and 2000 sample periods based on values expressed in terms of equivalent soil mass (Ellert and Bettany, 1995). Equivalent soil mass represented approximately the top 45 cm of soils for each site (6651 Mg/ha), but this depth varied due to the variation in bulk density with depth between core samples. The 6651 Mg equivalent mass represented the mass of soil at the sample position with the greatest depth of topsoil.

Clay (particles <2 μm) and A_p horizon thickness determined on the 1985 soil samples (Aspinall and Kachanoski, 1993) were used in the statistical analysis. Forward stepwise multiple regression analysis was performed using STATISTICA software (StatSoft, Tulsa, OK, USA).

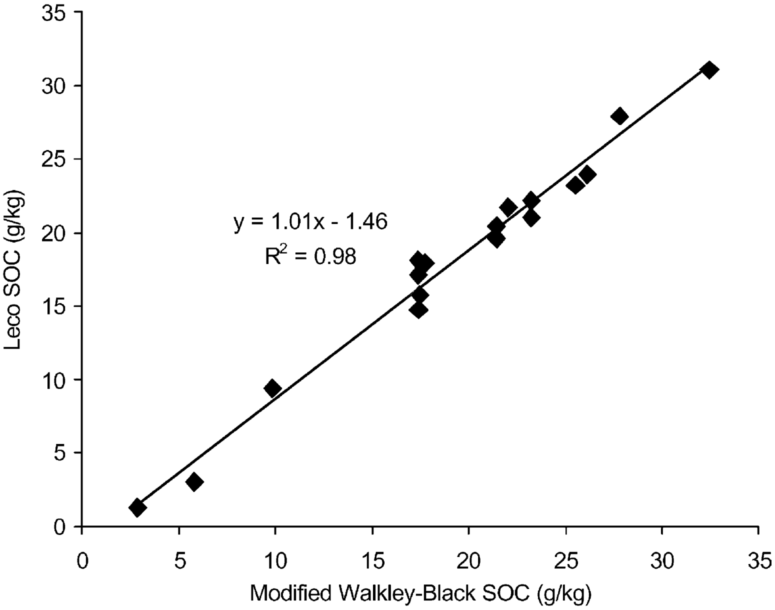

Fig. 4. Relationship between SOC determined by Leco combustion and modified Walkley–Black methods for samples taken in 1985.

3. Results

3.1. Changes in total SOC during 15 years of NT

Fig. 5 shows the histogram of changes in SOC since 1985 based on an equivalent mass of 6651 Mg/ha (approx. 0–45 cm) of soil in the 38 profiles. There were losses of SOC at more sites than there were gains at the end of 15 years of NT (Fig. 5). These results conflict with many studies of changes in SOC in NT soils, in that total SOC content had declined in many profiles since inception of the reduced tillage.

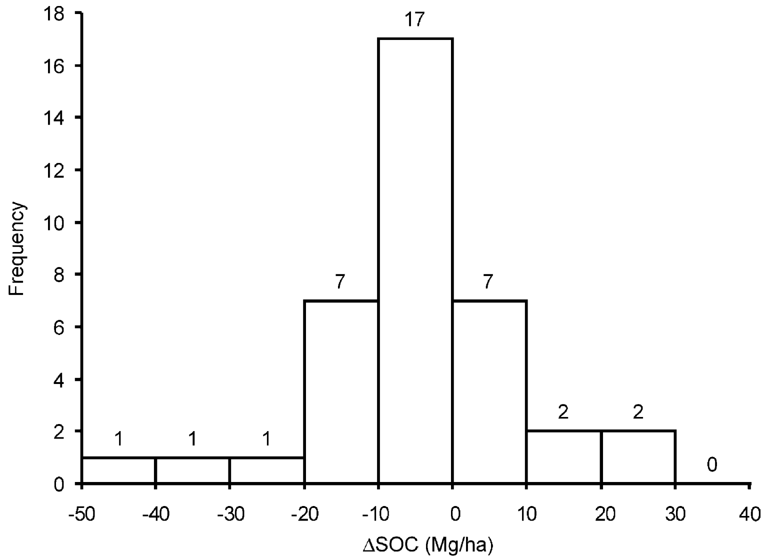

Fig. 5. Frequency distribution of changes in soil organic carbon (ΔSOC) in the top 0–45 cm (approx.) after 15 years of no-till.

3.2. Changes in total SOC with depth

Depth distribution of total SOC was studied by segmenting each profile into three equivalent mass depths (2217, 4434 and 6651 Mg/ha). In the top 2217 Mg/ha of soil (representing approx. the top 15 cm of soil), there was a gain of SOC in 24 of the 38 profiles, and losses of SOC in 14 (Fig. 6a).

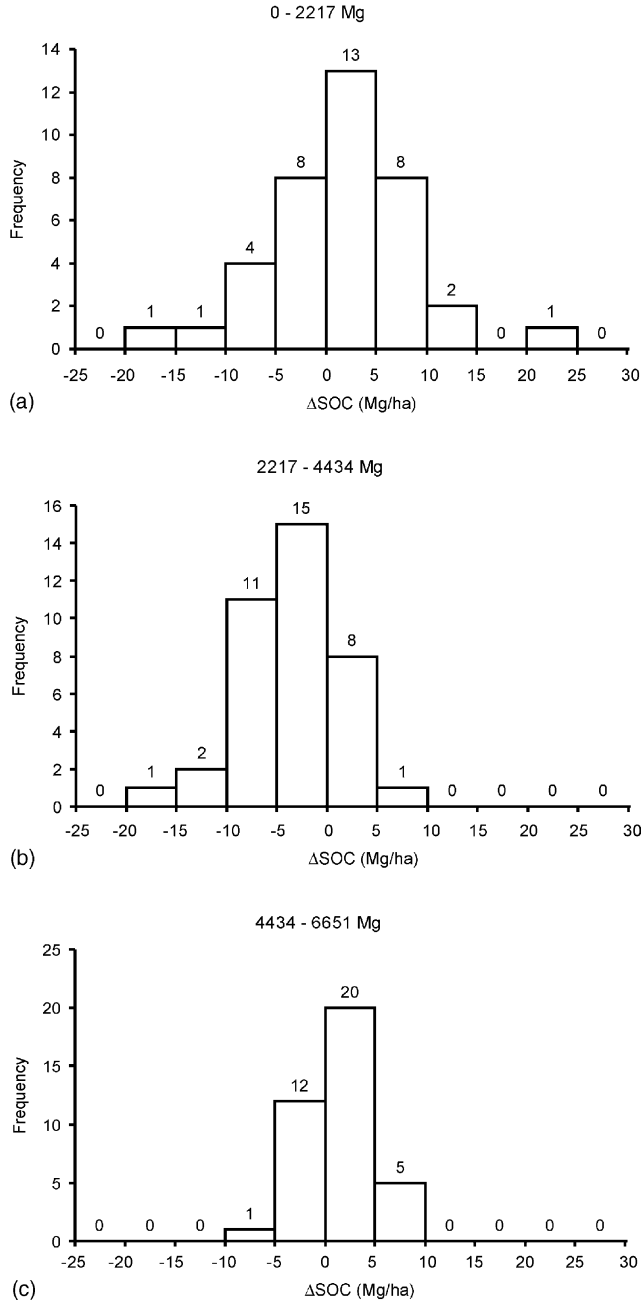

Fig. 6. Frequency distribution of the changes in soil organic carbon (ΔSOC) after 15 years of NT in equivalent mass depths from: (a) 0–2217 Mg/ha (approx. the top 15 cm); (b) 2217–4434 Mg/ha (approx. 15–30 cm); and (c) 4434–6651 Mg/ha (approx. 30–45 cm).

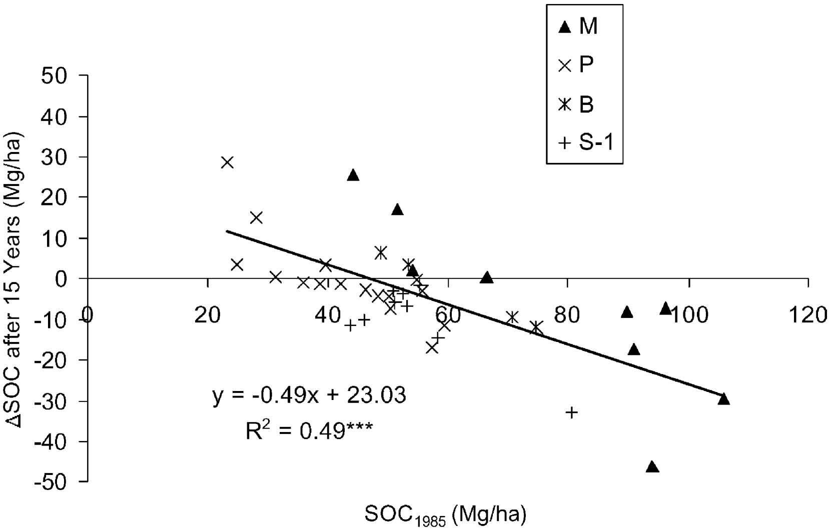

Fig. 7. Relationship between the initial soil organic carbon in 1985 (SOC_{1985}) and the change in SOC after 15 years of NT in the top 45 cm (approx.) for each of the 38 soil cores of the study.

Within the 15–30 cm depth (approx.) there was a gain of SOC in only 9 of the 38 soil profiles in 15 years of NT (Fig. 6b). There was a gain of SOC in 25 of the 38 profiles between 30 and 45 cm (approx.) (Fig. 6c).

3.3. Influence of initial SOC and A_p horizon thickness on changes in total SOC

A significant negative relationship was observed between the initial SOC content and the change in total SOC of the entire profile (0–45 cm approx.) at the end of 15 years (Fig. 7). The greatest increase in SOC occurred where the initial SOC content was the lowest, while there were losses of SOC after 15 years of NT where the initial SOC content was the greatest. This may be a reflection of the past soil erosion and redistribution within the landscape, along with catenary influences on hydrology. The initial total SOC content was positively related to the A_p horizon thickness in 1985 ($R^2 = 0.28; p < 0.05$). Because of this relationship between initial SOC and A_p horizon thickness, there was also a negative relationship between the change in SOC content and A_p horizon thickness ($R^2 = 0.20; p < 0.01$). Where A_p horizons were 27 cm and thicker, there were no profiles that had gained SOC. Where the A_p thickness was less than 27 cm, there were 11 profiles with SOC gains and 9 with net losses.

3.4. Multiple regression analysis

To further elucidate the effects of inherent soil properties on the changes in SOC in the entire profile, we regressed the initial total SOC content in 1985 and clay content on an equivalent mass basis along with interaction effects using forward stepwise multiple regression to model the change in SOC. The resulting equation was:

$$\Delta SOC = -0.57(OC_{1985}) + 0.01(ClayMass) + 19.18; \quad R^2 = 0.63 \qquad (1)$$

where OC_{1985} = SOC in 1985 (Mg/ha) and ClayMass = total clay content (Mg/ha) in an equivalent mass of 6651 Mg (approx. 0–45 cm) of soil. Both the OC_{1985} and ClayMass coefficients were significant at $p < 0.01$. The significant inclusion of ClayMass as a factor confirms the positive relationship of clay content on the change in SOC content in NT soils of western Canada found by Campbell et al. (1996).

4. Discussion

Many previous studies have reported an increase in SOC in the top 15 cm of the soil profile after implementing NT (Angers et al., 1997; Janzen et al., 1998b).

However, previous results were determined on side-by-side comparisons between NT and CT. In our study monitoring the changes in SOC with time after changing a management practice garnered the net change in SOC, which was a direct result of a change in the balance between net SOC mineralization and sequestration for the time period. While many other studies lacked a starting point for SOC, the result of an increase in SOC in the top 15 cm in 24 of the 38 sample locations in this study was consistent with results from other studies. Within the 15–30 cm depth (approx.) many of the sites (76%) had a decrease in SOC. This conforms with the study of Angers et al. (1997) whereby lower SOC at this depth in NT were interpreted to be due to the lack of incorporation of surface residue relative to soil inversion and placement of the surface residue at this depth by the moldboard plow.

The change in SOC in the top 45 cm was related to initial SOC content, which was further reflected by the contribution of A_p horizon thickness to the total SOC content at each sample location. A_p horizon thickness at varying positions in a landscape has been shown to reflect erosion and deposition history in this study (Fig. 2) and in other studies (King et al., 1983; Gregorich and Anderson, 1985; Phillips et al., 1999). Eroded shoulder slopes had shallow A_p horizons at the inception of the NT and thus would have had lower total SOC relative to depositional positions. Previously eroded landscape positions have the ability to gain soil carbon due to an improving overall soil quality after NT implementation (VandenBygaart et al., 1999b). Many studies have shown improvements in soil quality after implementing NT on previously degraded soils such as increased moisture retention capabilities which can result in increased residue C input, and maintenance of a stable soil structure (Reicosky et al., 1995; VandenBygaart et al., 1999b; Rhoton, 2000).

The reasons for losses in total SOC at sites with the greatest initial SOC content and A_p horizon thickness are not obvious. Under CT prior to 1985, annual tillage would have buried the surface residue from the crop for that year as well as incorporated any additional soil and residues that had accumulated from upslope. Thus the deposition of soil from upslope would gradually increase the thickness of the A_p horizon. After the conversion of the soil to NT in 1985, we assume that there were no longer any additions of SOC from upslope. In other words, the net change in SOC from 1985 to 2000 was due to the balance between mineralization and crop inputs of carbon, and not accumulation from tillage translocation and water erosion.

Moisture status would have been altered by the change in soil management, but also would have varied with position in the landscape. The thickness of the A_p horizon may also reflect the local hydrology. Moore et al. (1993) suggested that ‘‘to some extent the A horizon is a ‘fossil record’ of the root activity that reflects the redistribution of water by the terrain’’. Therefore, hydrological differences among slope positions may have also been a contributing factor on the changes in SOC after 15 years in NT. In sloping soils with shallow A_p horizons, the conversion to NT may have resulted in a better water use efficiency relative to CT, as the maintenance of surface residue increases infiltration and acts as a buffer to evaporative losses during the summer months (Walley et al., 1999). This may have led to better crop yields and thus greater C inputs to the soil. In the depression areas with thicker A_p horizons and greater initial SOC contents, water may have been non-limiting even before the change in management.

Earthworms also cannot be discounted as factors in the decrease in SOC in many of the landscape locations (Wander and Yang, 2000). Earthworm numbers were not determined in this study. However, it is well documented that earthworm numbers increase after NT is implemented in previously tilled soils (Edwards and Lofty, 1982; VandenBygaart et al., 1999b), sometimes increasing from just a few under CT, to several hundred per square meter under NT (Kladivko et al., 1997). Shuster et al. (2000) concluded that addition of 100 earthworms in 6.1×6.1 m^2 enclosures in NT and ridge-tilled soils for five consecutive years resulted in net losses of total SOC relative to control plots without earthworm additions. They suggested that the destabilization of macroaggregates and the creation of smaller water-stable aggregates invoked by the earthworm additions, resulted in exposure of unprotected labile C to decomposition relative to the control plots. Alban and Berry (1994) found a net SOC loss relative to that in control sites after additions of earthworms into a forest soil. This was presumably due to high microbial respiration rates in earthworm casts and guts relative to residue-rich soil that had not been passed through earthworms (Linden and Clapp, 1998). Furthermore, earthworms have also been shown to assimilate only more labile soil organic matter, while humified materials are essentially unassimilated (Martin et al., 1992). Such a mechanism may be occurring more readily in the depositional landscape positions, as these positions usually contain light, labile C fractions that have been translocated from upslope (Gregorich et al., 1998).

The increase in SOC at the 30–45 cm (approx.) depth in some profiles (Fig. 6c) may be explained by the presence of deep-burrowing earthworm species. *Lumbricus terrestris* (nightcrawler) earthworms create continuous, vertical burrows often exceeding 1 m in depth from the soil surface (Lee, 1985). In southern Ontario their numbers increase sharply upon conversion of soils to NT (VandenBygaart et al., 1998). They feed on surface residue and defecate their fecal material along their burrow walls, and thus can translocate significant quantities of SOC to depths below the plough layer (Stehouwer et al., 1993; Tomlin et al., 1995; VandenBygaart et al., 1998). As a result, earthworms may have the ability to deepen surface horizons due to their burrowing activities in NT soils (Shipitalo and Protz, 1987; Tomlin et al., 1995; VandenBygaart et al., 1998).

Although we found that initial SOC content and clay content were influencing the changes in SOC content during 15 years of NT, we were not able to explain 37% of the variability (Eq. (1)). Some of the remaining uncertainty may lie in the spatial variability of SOC, since single 5 cm diameter cores were taken in both sample periods. Although we were able to relocate precisely where the samples were taken in 1985, we acknowledge that a single core taken may not account for the spatial variability in SOC at the sample locations. We were also limited because our baseline data was acquired from a single core in 1985.

A comparison could not be made with an adjacent CT treatment, since the CT treatments were no longer maintained by the farmer after 1990 and no SOC analysis was performed on the sites between 1986 and 1990. As a result, we cannot be completely confident that there would not also have been losses in SOC under CT in those landscape positions having the highest initial SOC content.

The patterns of change in SOC contents in landscapes that have experienced soil redistribution, have profound implications for attempts to estimate the amount of C that may potentially be sequestered in NT soils on a local or regional scale. The extent of SOC redistribution and topographical features related to hydrology, appear to be much more important factors than characteristics that would be routinely available from soil survey reports. This would increase the difficulty in making accurate estimates where documentation would be required on the amount of C sequestered at a given farm. The sampling program would necessarily have to include a representative distribution of areas that have experienced different degrees of erosion or deposition prior to the implementation of the NT practices.

5. Conclusions

Erosion history and landscape position are important factors to consider when resolving the C dynamics after initializing changes in soil management at a landscape scale. Interpretations of past and future results of long-term studies must take into account the location of samples being taken within landscape units, if useful information is to be gained on C dynamics in agricultural soils. Further work is also required to understand the dynamics of SOC in depositional positions in the landscape, and the mechanisms responsible for the loss of C after several years in NT. This study demonstrated that changes in management can alter the SOC dynamics within the entire soil profile in eroded and depositional positions within the landscape. Therefore, C redistribution within landscapes has a major influence on the measurement of C dynamics and the potential for sequestration in agricultural soils.

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