Soil quality attributes, soil resilience and legacy effects following topsoil removal and one-time amendments

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ARTICLE

Soil quality attributes, soil resilience, and legacy effects following topsoil removal and one-time amendments

Francis J. Larney, Lingling Li, H. Henry Janzen, Denis A. Angers, and Barry M. Olson

Abstract: Inter-relationships among soil erosion, soil quality, soil resilience, and legacy effects of organic amendments have not been adequately quantified. Topsoil was mechanically removed (cuts) to simulate erosion in semiarid southern Alberta in 1990. Three cuts (0, 10, and 20 cm) superimposed with three one-time (1990 only) amendment treatments (check, N + P fertilizer, and manure) were chosen for this study. In the absence of amendments, light fraction C (C_{LF}) and mineralizable C (C_{min}) recovered sufficiently by 2004 to render the cut effect nonsignificant. Organic C (C_{org}) responded more slowly with the 10-cm cut recovering to the 0-cm cut concentration by 2004, and the 20-cm cut (13.9 g kg^{-1}) remaining significantly lower than the 0-cm cut concentration (16.3 g kg^{-1}) through to 2012. Nitrogen fractions behaved similarly. Among cuts and years (2004 and 2012), C fraction values were 19–27% greater on the manure versus check treatment (17.5 vs. 14.7 g kg^{-1} for C_{org}, 1.38 vs. 1.09 g kg^{-1} for C_{LF}, and 650 vs. 531 mg kg^{-1} for C_{min}) demonstrating a strong legacy effect of manure. Water-stable aggregation exhibited a 22-yr legacy effect of manure. Our findings help quantify soil resilience following major disturbance and legacy effects of one-time manure application under semiarid conditions.

Key words: soil resilience, legacy effect, topsoil removal, soil amendments, soil reclamation, soil organic matter, water-stable aggregation.

Résumé : On n'a jamais quantifié de manière adéquate les liens qui existent entre l'érosion du sol, sa qualité, sa résilience et les effets rémanents des amendements organiques. En 1990, les auteurs ont retiré mécaniquement la couche de surface (coupes) du sol dans une région semi-aride du sud de l'Alberta afin de simuler l'érosion. Dans le cadre de leur projet, ils ont procédé à trois coupes (0, 10 et 20 cm), puis appliqué ponctuellement (en 1990 seulement) trois traitements (aucun amendement, engrais N + P, fumier). Sans amendement, la fraction de C légère (C_{LF}) et la fraction de C minéralisable (C_{min}) s'étaient suffisamment rétablies en 2004 pour que les répercussions de la coupe ne soient plus significatives. Le C organique (C_{org}) a réagi plus lentement, sa concentration dans la coupe de 10 cm étant revenue à celle de 0 cm en 2004, mais celle de la coupe de 20 cm (13,9 g kg^{-1}) demeurant nettement sous la concentration relevée dans la coupe de 0 cm (16,3 g kg^{-1}) jusqu'en 2012. Les fractions de l'azote se sont comportées de façon analogue. Lorsqu'on compare les coupes et les années (2004, 2012), on constate que la valeur des fractions de C est de 19 à 27 % plus élevée dans les parcelles amendées avec du fumier que dans les parcelles témoin (17,5 c. 14,7 g kg^{-1} pour C_{org}, 1,38 c. 1,09 g kg^{-1} pour C_{LF}, et 650 c. 531 mg kg^{-1} pour C_{min}), signe que les effets du fumier perdurent longtemps. Ainsi, ceux relatifs à l'agrégation stable à l'eau persistent pendant 22 ans. Ces constatations concourent à quantifier la résilience du sol après une forte perturbation, ainsi que les effets rémanents d'une seule application de fumier en climat semi-aride. [Traduit par la Rédaction]

Mots-clés : résilience du sol, rémanence des effets, retrait du sol de surface, amendements, restauration du sol, matière organique du sol, agrégation stable à l'eau.

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Abbreviations: $\mathbf{C_{LF}}$, light fraction carbon; $\mathbf{C_{min}}$, mineralizable carbon; $\mathbf{C_{org}}$, organic carbon; **CT**, conservation tillage; **LF**, light fraction; $\mathbf{N_{LF}}$, light fraction nitrogen; $\mathbf{N_{min}}$, mineralizable nitrogen; $\mathbf{N_{inorg}}$, inorganic nitrogen; $\mathbf{N_{org}}$, organic nitrogen; **SOC**, soil organic carbon; **SOM**, soil organic matter; **WSA**, water-stable aggregation.

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Introduction

Increases in crop residue cover brought about by the widespread adoption of conservation tillage (CT) and the dramatic decline in summerfallow have reduced the risk of soil degradation on the Canadian prairies (Huffman et al. 2012). However, prairie landscapes have areas of inherently low productivity due to historical erosion, which occurred from the time the land was first broken (late 1800s to early 1900s) until the adoption of CT some 100 yr later. Relationships among erosion, soil productivity, and crop yield are complex and not easily quantified.

One of the most common approaches used to examine erosion-productivity relationships is topsoil removal (den Biggelaar et al. 2004) or desurfacing, also referred to as simulated or artificial erosion. Boardman (2006) suggested that the issue of imperceptible change versus catastrophic event has encumbered many erosion studies and argued that large-scale events, or a sequence of them, were responsible for high proportions of observed erosion. If we follow this argument, topsoil removal may be more akin to catastrophic event erosion rather than imperceptible change erosion and hence may better simulate natural large-scale events, which cause the greatest proportion of soil loss. Moreover, if the topsoil removal increments are many and closely spaced (e.g., 0, 5, 10, 15, and 20 cm) and the subsequent surfaces are cropped for a long period of time, the limitations of the approach may be overcome. Bakker et al. (2004) suggested that the longer the time span following desurfacing, the more realistic the results. As well as being a means of quantifying erosion-productivity relationships, the addition of amendments (e.g., fertilizer, manure) to restore productivity to the desurfaced soils may also be studied with the topsoil removal approach (Larney and Janzen 1996, 1997; Dormaar et al. 1997).

As topsoil removal causes a major reduction in soil productivity, the approach also allows the study of soil resilience. Resilience, a concept which emerged about 50 yr ago in the ecological literature, determines “the persistence of relationships within a system, and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist” (Holling 1973; Folke 2006). A resilient system, therefore, is not necessarily an unchanging one, but one which absorbs disturbance yet sustains essential functions. This concept has, more recently, been applied to “soil resilience” (Blum 1998; Seybold et al. 1999), which is defined as the capacity of a soil to recover its functional and structural integrity after disturbance or stress (Lal 1997; Herrick 2000), also known as a bounce-back or snap-back effect (Cooke and Johnson 2002). Soil resilience is related to soil quality in terms of the rate and the degree of recovery of soil function (Seybold et al. 1999). Soil resistance, which is distinguished from soil resilience, is defined as the capacity of a soil to continue to function despite a disturbance (Pimm 1984; Herrick and Wander 1998; Seybold et al. 1999). The magnitude of decline in the capacity to function defines the degree of resistance. Soil resistance is related to soil quality in terms of the degree of change in soil function as a result of disturbance.

Soil organic matter (SOM) encompasses a set of attributes, including total soil organic C (C_{org}) and N (N_{org}), light fraction C (C_{LF}) and N (N_{LF}), mineralizable C (C_{min}) and N (N_{min}), microbial biomass, soil carbohydrates, and enzymes (Gregorich et al. 1994). Each fraction of SOM responds differently to management practices (Srinivasan et al. 2012), for example, C_{LF} and N_{LF} are accepted indices of incompletely decomposed organic residues, which represent a large proportion of substrate available for soil microorganisms (Janzen et al. 1992), whereas C_{min} and N_{min} are accepted indices of the availability of organic C to soil organisms (Larney et al. 1997). The measurement of dynamic SOM fractions (e.g., C_{LF}, N_{LF}, C_{min}, and N_{min}), rather than whole SOM fractions (e.g., C_{org} and N_{org}), allows more precise and earlier detection of responses to soil management practices (Malhi et al. 2011). Water-stable aggregation (WSA) is often used as an index of soil quality and can serve as an indicator of a soil's resistance to water and wind erosion (Angers et al. 2008). Nonetheless, although much research has been conducted on the dynamics of SOM fractions (e.g., Six et al. 1999; Lal 2004) and their relationships with WSA (e.g., Angers and Giroux 1996; Chenu et al. 2000), little is known about SOM and WSA recovery with time on eroded soils and their relationships with soil resilience and resistance. Similarly, the legacy effect of amendments (manure and fertilizer) applied to eroded surfaces has not been quantified. Wurst and Ohgushi (2015) defined legacy effects as those that persist after the causal biotic interaction ceases, as soil characteristics are plastic and modifications may endure for long time periods.

Six soil erosion-productivity studies were initiated in Alberta in 1990–1991 (Larney and Janzen 2012) based on the topsoil removal approach; however, only two remain (Lethbridge Dryland and Irrigated sites). Erosion, but not amendment, effects in the initial year at all six sites (1990–1991) were reported by Larney et al. (1995). The early (first 2–3 yr) effects on soil (Larney et al. 2000*a*) and crop (Larney et al. 2000*b*) responses at the four southern Alberta sites has been reported as has crop response (1991–1995) at the two north-central Alberta sites (Izaurralde et al. 2006). Larney et al. (2009) reported yield responses on the Lethbridge Dryland and Irrigated sites for the first 16 yr (1990–2006). Average grain yield reductions during 16 yr were 10% for 5 cm, 20% for 10 cm, 29% for 15 cm, and 39% for 20 cm of topsoil removal (check plots, no amendment). During the first 16 yr, there was evidence that the restoration of productivity (based on grain yield) levelled off at a value less than the noneroded treatment (0 cm cut) rather than gradually converging on it. As cut increased, the average residual effect (1993–2006) of manure increased, for example, on the 5 cm cut, the residual effect (over the equivalent cut check treatment) was 21%, increasing to 42% on the 20 cm cut. Amendments ranked manure > topsoil > fertilizer in terms of restoring productivity to the desurfaced soils.

Using the Lethbridge Dryland site, the objective of this paper was to evaluate (1) recovery rates of soil quality attributes with time (1990–2012) in the absence of amendments; and (2) residual effects of one-time manure and fertilizer amendments at the outset of the study on soil quality attributes 14 and 22 yr later. Our study allows the examination of soil resistance (measurements made in 1990, immediately following topsoil removal). In addition, the application of one-time amendments (manure, fertilizer) versus a check treatment (no amendment) allows the study of their impact, defined in terms of legacy effects, at different levels of topsoil removal (simulating non-, moderate, and severe erosion) on both soil resilience and resistance.

Materials and Methods

Study site

The experiment was established in 1990, at the Agriculture and Agri-Food Canada Research Centre, Lethbridge, AB (49°43′N, 112°48′W) on a semiarid Dark Brown Chernozemic soil developed on glacio-lacustrine parent material. Prior to topsoil removal, the Ap horizon was 15 cm deep, and texture (0–7.5 cm layer) was sandy clay loam. The 30-yr (1981–2010) mean annual precipitation at Lethbridge is 399 mm and mean annual air temperature is 6.4 °C.

Experimental design

The study has been described in detail by Larney et al. (2000*a*, 2000*b*). Briefly, five topsoil removal treatments (12 m × 10 m main plots) were established by mechanically stripping 0, 5, 10, 15, or 20 cm of topsoil (referred to as cuts) using an excavator with a grading bucket. In the initial year only (1990), four amendment subtreatments (3 m × 10 m subplots) were superimposed (split-plot) on each of the main cut treatments: (1) check: no amendment; (2) fertilizer: an optimum rate of N and P (75 kg ha^{-1} N, 22 kg ha^{-1} P); (3) manure: 75 Mg ha^{-1} (wet weight) of beef feedlot manure (0.35 kg kg^{-1} water content, with 190 g kg^{-1} total C, and 22 g kg^{-1} total N, dry wt. basis); (4) topsoil: reapplication of 5 cm of topsoil. Plots were replicated four times in a randomized complete block design (5 cuts × 4 amendments × 4 replicates = 80 plots).

In 1990, seedbed preparation for spring wheat consisted of one pass of a powered rotary cultivator to 10 cm depth as the desurfaced plots were dry and compact. In subsequent years, the site was managed under no-till and all treatments were managed the same with broadcast applications of 40 kg ha^{-1} of N and 9 kg ha^{-1} of P prior to seeding for maintenance of crop productivity. Therefore, any differences in productivity were due to residual effects of the one-time treatments applied in 1990. Spring wheat (*Triticum aestivum* L.) was seeded at a 17.5 cm-row spacing in May or early June each year except in 2004 when plots were chemical fallowed in an effort to control the buildup of grassy weeds.

To address the specific objectives of this particular aspect of the study, three cuts (0, 10, and 20 cm) were chosen to represent non-, moderate, and severe erosion and three sampling years (1990, 2004, and 2012) were used. Soil samples (0–7.5 cm depth) included those archived from check plots in the initial year (1990) prior to application of amendment treatments (3 cuts × 1 amendment × 4 replicates = 12 samples), as well as those from check, fertilizer, and manure plots archived from 2004 and collected in 2012 (2 yr × 3 cuts × 3 amendments × 4 replicates = 72 samples) prior to annual fertilizer N and P application. The topsoil amendment treatment was not included in this particular aspect of the study due to resource limitations.

Soil analyses

All 84 soil samples were analyzed for C_{org}, N_{org}, C_{LF}, N_{LF}, C_{min}, and N_{min}. Finely ground (< 0.15 mm) air-dried soil samples were acidified with 6 mol L^{-1} HCl to release inorganic C, retaining only C_{org}. C_{org} and N_{org} were measured by dry combustion on an automated CNS analyzer (CE Instruments, Milan, Italy). For C_{LF} and N_{LF}, air-dried soils were sieved (<2 mm) and the light fraction (LF) isolated by flotation on NaI solution with a specific gravity of 1.7 g cm^{-3} (adapted from Strickland and Sollins 1987). Briefly, 10 g of soil was added to 25–30 mL of NaI in 100 mL jars and suspensions were allowed to equilibrate for 48 h before removing suspended LF material by suction. Further LF material was recovered following two resuspensions in NaI. All LF material was washed with 0.01 mol L^{-1} $CaCl_2$ and deionized H_2O, dried at 65 °C, ground to <0.15 mm and analyzed for C and N as described above. Determination of C_{min} and N_{min} involved incubating 75 g of soil (85% field capacity water content) at 25 °C for 10 wk in airtight 1-L glass jars (Hopkins 2008). Evolved CO_2 was trapped in 10 mL of 2 mol L^{-1} NaOH. Samples were aerated and NaOH traps changed at 1, 2, 4, 6, and 10 wk. The CO_2 trapped was measured using gas chromatography and summed over 10 wk to calculate C_{min}. Pre- and postincubation soils were extracted in 2 mol L^{-1} KCl to determine N_{inorg} (NH_4^- + NO_3–N) by segmented flow analysis (Maynard et al. 2008) and N_{min} estimated by difference.

Water-stable aggregation was assessed at two energy levels in 2012 only (3 cuts × 3 amendments × 4 replicates = 36 samples) on field-moist soil (0–7.5 cm layer) gently crumbled to pass through a 6.3 mm sieve and allowed to air-dry (Angers et al. 2008). For the low-energy level (prewet, slow-wetting), 40 g of air-dried soil was slowly prewetted in a humidifier prior to immersion. For the high-energy level (nonwet, fast-wetting), 40 g of air-dried

Table 1. Effect of year and cut on soil quality attributes of check plots.

	C_{org} (g kg^{-1})	C_{LF} (g kg^{-1})	C_{min} (mg kg^{-1})	N_{org} (g kg^{-1})	N_{LF} (g kg^{-1})	N_{min} (mg kg^{-1})	NO_3–N (mg kg^{-1})	N_{inorg} (mg kg^{-1})	C_{org}/N_{org} (ratio)	C_{LF}/N_{LF} (ratio)	C_{LF}/C_{org} (%)	C_{min}/C_{org} (%)	N_{LF}/N_{org} (%)	N_{min}/N_{org} (%)
Year														
1990	12.8	0.79	430	1.39	0.051	21	5.7c	10.3c	9.2b	17.4	6.8	3.2	3.7	1.5
2004	14.2	1.09	480	1.51	0.060	23	24.1a	25.2a	9.4b	18.2	7.8	3.4	4.0	1.6
2012	15.1	1.10	583	1.55	0.054	30	12.8b	18.3b	9.8a	20.5	7.1	3.8	3.5	1.8
P-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.18	**0.002**	**<0.001**	**<0.001**	**0.001**	**0.002**	0.11	**0.02**	0.38	0.23
Cut (cm)														
0	16.0	1.27	622	1.68	0.076	34	16.4a	23.1a	9.5a	17.5	8.8	3.9	4.8	2.0
10	14.4	0.80	441	1.52	0.043	22	13.0a	16.2b	9.5a	18.5	5.5	3.0	2.8	1.5
20	11.8	0.90	430	1.25	0.045	19	13.2a	14.5b	9.4a	20.1	7.4	3.5	3.5	1.4
P-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.003**	0.11	**<0.001**	0.91	0.08	**0.007**	**0.002**	**0.02**	0.09
Year × cut														
P-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.02**	0.91	0.09	0.54	**0.03**	**<0.001**	**<0.001**	**<0.001**	**0.03**

Note: Means separation provided only if year × cut interaction effect is nonsignificant. Within columns, year or cut means with different letters are significantly different from each other ($P \le 0.05$). *P*-values ≤0.05 are highlighted in bold.

soil was immersed directly in water. Prewet and nonwet soils were placed on a nest of two sieves (1 and 0.25 mm openings) and wet-sieving performed under total immersion for 10 min. Aggregate fractions retained on the 1 and 0.25 mm sieves (macroaggregates) were oven-dried, weighed, and expressed as percent of total soil (dry wt.). A correction was made for the presence of sand and coarse fragments in the stable aggregates. A stability ratio (nonwet, high-energy, fast-wetting/prewet, low-energy, slow-wetting) was calculated (Carter et al. 2003) for the 0.25–1 and >1 mm fractions.

Statistical analyses

All variables were tested for outliers (PROC UNIVARIATE) prior to analysis using PROC MIXED (SAS Institute Inc. 2009). To examine soil resilience in the absence of amendments, attributes from the check plots in 1990, 2004, and 2012 (3 yr × 12 plots = 36 samples) were analyzed with year as a repeated variable and cut as a fixed variable. To ascertain the residual effect of amendments, attributes from 2004 and 2012 (2 yr × 36 plots = 72 samples) were analyzed with year as a repeated variable and cut and amendment as fixed variables. For these analyses, appropriate covariance structures were selected according to the lowest Akaike's Information Criterion (Littell et al. 1996). Water-stable aggregation was analyzed with cut and amendment as fixed variables. Least-square means were calculated for all data and mean comparisons made using the LSD test ($P = 0.05$). Relationships among the three C fractions (C_{org}, C_{LF}, C_{min}) on the check plots were determined using regression analysis.

Results

Resilience of soil quality attributes in the absence of amendments

The check plots in 1990, 2004, and 2012 explored resilience of soil quality attributes following different depths of topsoil removal in the absence of amendments. Of the 14 soil attributes, 10 showed a significant effect of year, 10 a significant effect of cut, and 11 a significant year × cut interaction (Table 1). The three attributes showing nonsignificant interaction effects (NO_3–N, N_{inorg}, C_{org}/N_{org} ratio) were significant for year (among cuts). For NO_3–N and N_{inorg}, this may be explained by the dynamic nature of these parameters, which may reflect annual variation in soil moisture and temperature, even though N fertilizer inputs were similar each year. For the C_{org}/N_{org} ratio, 2012 (9.8) was significantly greater than both 1990 and 2004 (9.2–9.4) indicating accumulation of more C than N as the study matured. Although the cut effect (among years) was nonsignificant ($P = 0.11$) for NO_3–N, it was significant for N_{inorg}, showing that N availability for plant uptake was affected by topsoil removal, with significantly lower amounts for the 10 and 20 cm cuts compared with the 0 cm cut.

Fig. 1. Soil quality attributes (0–7.5 cm layer) on check treatment showing significant year × cut interactions: (*a*) organic carbon, C_{org}; (*b*) organic nitrogen, N_{org}; (*c*) mineralizable carbon, C_{min}; (*d*) mineralizable nitrogen, N_{min}; (*e*) light fraction carbon, C_{LF}; and (*f*) light fraction nitrogen, N_{LF}. Means separation provided for cuts within years. NS, nonsignificant change in concentration within cut between years; *, significant ($P < 0.05$) change in concentration within cut between years.

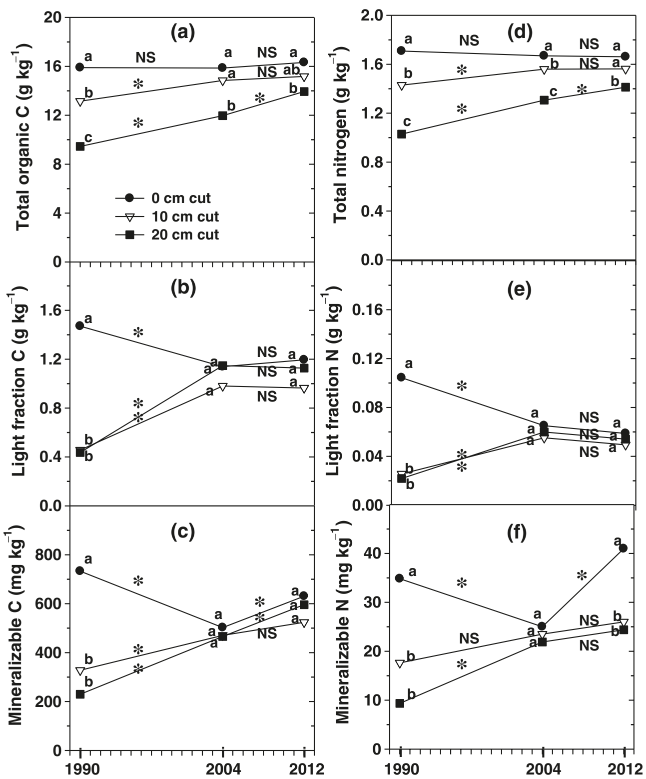
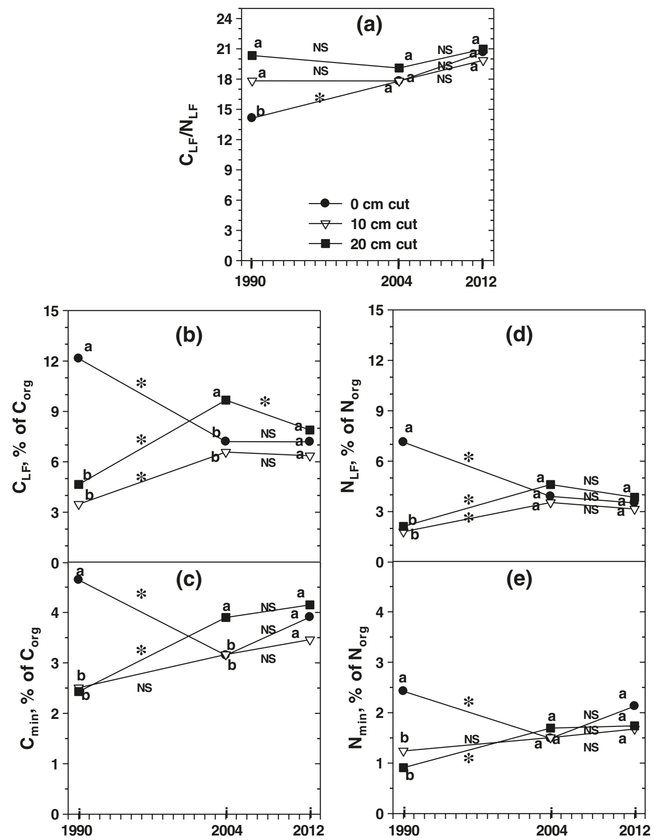


Fig. 2. Soil quality attributes (0–7.5 cm layer) on check treatment showing significant year × cut interactions: (*a*) light fraction carbon/light fraction nitrogen ratio, CLF/NLF; (*b*) mineralizable carbon as a percent of organic carbon; C_{min}/C_{org}; (*c*) mineralizable nitrogen as a percent of mineralizable nitrogen, N_{min}/N_{org}; (*d*) light fraction carbon as a percent of organic carbon, C_{LF}/C_{org}; and (*e*) light fraction nitrogen as a percent of organic nitrogen, N_{LF}/N_{org}. Means separation provided for cuts within years. NS, nonsignificant change in value within cut between years; *, significant ($P < 0.05$) change in value within cut between years.

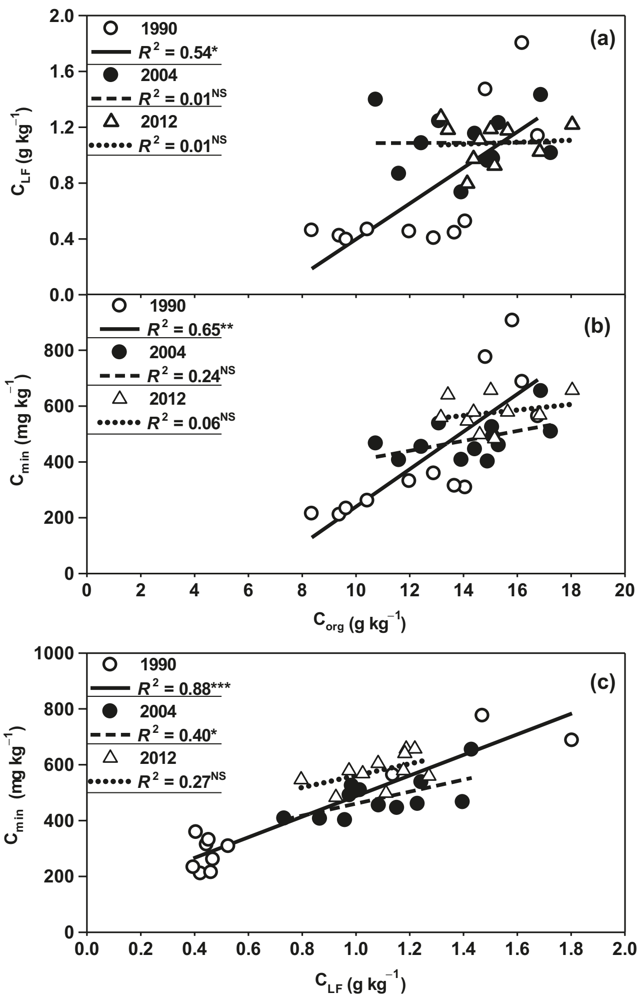


Significant year × cut interaction effects revealed that although C_{org}, C_{LF}, and C_{min} were significantly affected by cut at the outset of the study in 1990 (Figs. 1*a*–1*c*), C_{LF} and C_{min} had recovered sufficiently by 2004 (Figs. 1*b*, 1*c*) to show no evidence of a significant cut effect. However, for C_{org} (Fig. 1*a*), only the shallower 10 cm cut had recovered to the concentration of the 0 cm cut by 2004, whereas the deeper 20 cm cut (12.0 g kg^{-1}) remained significantly lower than both the 10 and 0 cm cuts (14.8–15.9 g kg^{-1}). However, the pattern of recovery differed among the C fractions. For C_{org}, there was essentially a flat response with time on the 0 cm cut (Fig. 1*a*), whereas significant accrual occurred in the first 14 yr on the 10 cm (from 13.2 to 14.8 g kg^{-1}) and 20 cm cuts (from 9.5 to 12.0 g kg^{-1}). In the 14- to 22-yr phase (2004–2012), only the 20 cm cut showed a significant increase in C_{org} (from 12.0 to 13.9 g kg^{-1}). For C_{LF} (Fig. 1*b*) and C_{min} (Fig. 1*c*), the lack of a significant effect of cut in 2004 was due to significant declines in these parameters on the 0 cm cut (C_{min}, 733 to 502 mg kg^{-1}; C_{LF}, 1.47 to 1.14 g kg^{-1}) combined with significant increases on the 10 cm (C_{min}, 328 to 471 mg kg^{-1}; C_{LF}, 0.46 to 0.98 g kg^{-1}) and 20 cm (C_{min}, 230 to 466 mg kg^{-1}; C_{LF}, 0.44 to 1.15 g kg^{-1}) cuts. From 2004 to 2012, C_{min} (Fig. 1*c*) recovered significantly on the 0 cm cut (from 502 to 631 mg kg^{-1}), did not change significantly on the 10 cm cut, and showed further significant recovery for the 20 cm cut (466 to 596 mg kg^{-1}), whereas C_{LF} did not change significantly on any cut (Fig. 1*b*).

The year × cut interaction behavior of the N fractions, N_{org} (Fig. 1*d*), N_{LF} (Fig. 1*e*), and N_{min} (Fig. 1*f*), essentially followed the patterns of their C fraction counterparts. An exception was the 0 cm cut for N_{min}, which showed a larger recovery between 2004 and 2012 than C_{min} (Fig. 1*c*) to render it significantly greater than the 10 and 20 cm cuts in 2012 (Fig. 1*f*).

The five soil quality ratios showed significant year × cut interaction effects (Table 1; Figs. 2*a*–2*e*). In 1990, the 20 cm cut (C_{LF}/N_{LF} only), or both the 10 and 20 cm cuts

Fig. 3. Effect of year (check treatment, among depths of cut) on relationships between (*a*) organic carbon (C_{org}) and light fraction carbon (C_{LF}); (*b*) organic carbon (C_{org}) and mineralizable carbon (C_{min}); and (*c*) light fraction carbon (C_{LF}) and mineralizable carbon (C_{min}), 0–7.5 cm layer.



(all other ratios), had significantly lower values than the 0 cm cut. By 2004, a significant cut effect remained for C_{LF}/C_{org} (Fig. 2*b*) and C_{min}/C_{org} (Fig. 2*c*) only, with the 10 and 20 cm cuts exhibiting lower values than the 0 cm cut. By 2012, none of the five ratios showed a significant cut effect (Figs. 2*a–e*). As with the absolute values for C and N fractions, four of the five ratio values, the exception being C_{LF}/N_{LF}, decreased significantly from 1990 to 2004 for the 0 cm cut, whereas they increased significantly for the 20 cm cut. For example, C_{LF}/C_{org} decreased from 12.1% to 7.2% on the 0 cm cut, whereas it increased from 4.7% to 9.7% on the 20 cm cut during the 1990–2004 period (Fig. 2*b*). Similarly, C_{min}/C_{org} decreased from 4.6% to 3.2% on the 0 cm cut, whereas it increased from 2.4% to 3.9% on the 20 cm cut (Fig. 2*c*). The 10 cm cut exhibited intermediate behavior, with LF ratios (C_{LF}/C_{org}, N_{LF}/N_{org}) showing significant increases from 1990 to 2004 (Figs. 2*b*, 2*d*), and mineralizable ratios (C_{min}/C_{org}, N_{min}/N_{org}) showing nonsignificant changes (Figs. 2*c*, 2*e*).

For the check treatment, relationships among the three C fractions (Figs. 3*a–*3*c*) differed by year. In 1990, all three relationships were significant in the order C_{LF} versus C_{min} ($R^2 = 0.88^{***}$), C_{org} versus C_{min} ($R^2 = 0.65^{**}$), and C_{org} versus C_{LF} ($R^2 = 0.54^{*}$). By 2004, only the C_{LF} versus C_{min} relationship (Fig. 3*c*) remained significant ($R^2 = 0.40^{*}$), whereas none of the relationships were significant in 2012 (Fig. 3). The decline of significant relationships with time was due to a convergence of C fraction concentrations, for example, values for C_{org} ranged from 8.4 to 16.8 g kg^{-1} in 1990, 10.7 to 17.2 g kg^{-1} in 2004, and 13.2 to 18.0 g kg^{-1} in 2012. Similarly, values for C_{LF} ranged from 0.40 to 1.80 g kg^{-1} in 1990, 0.73 to 1.43 g kg^{-1} in 2004, and 0.80 to 1.27 g kg^{-1} in 2012. For C_{min}, values ranged from 210 to 906 mg kg^{-1} in 1990, 402 to 653 mg kg^{-1} in 2004, and 483 to 657 mg kg^{-1} in 2012. Coefficients of variation also declined with time, for example, from 22% in 1990, to 14% in 2004, to 10% in 2012 for C_{org}; from 69% in 1990, to 19% in 2004, to 13% in 2012 for C_{LF}; and from 56% in 1990, to 15% in 2004, to 10% in 2012 for C_{min}.

Influence of amendments on soil quality attributes

The check, fertilizer, and manure treatments from 2004 and 2012 demonstrated the effects of year, cut, and amendment (and their interactions) on soil quality attributes (Table 2). Year (averaged among cuts and amendments) showed a significant effect on NO_3–N and N_{inorg} with 2012 significantly lower than 2004. Again, this was likely due to environmental conditions affecting these quite dynamic properties. Significant increases in C_{org} (15.2–16.0 g kg^{-1}), C_{org}/N_{org} (9.3–9.8), C_{min} (511–672 mg kg^{-1}), C_{LF}/N_{LF} (17.8–21.1), and C_{min}/C_{org} (3.4–4.2%) also occurred from 2004 to 2012, showing C fraction constituents continued to accrue with time.

In contrast to C fractions, changes in N fraction constituents from 2004 to 2012 (Table 3) were either nonsignificant (N_{min}, N_{min}/N_{org}) or declined (N_{LF}/N_{org}, 4.3–3.8%) or showed year × cut (N_{org}) or year × amendment interactions (N_{org}, N_{LF}). The year × cut interaction for N_{org} (Fig. 4*a*) showed a significant decline on the 0 cm cut (1.80–1.74 g kg^{-1}), no difference for the 10 cm cut, and a significant increase for the 20 cm cut (1.41–1.46 g kg^{-1}), from 2004 to 2012. Year × amendment interactions were similar for N_{org} (Fig. 4*b*) and N_{LF} (Fig. 4*c*) with no significant year effects on the check and fertilizer treatments, compared with significant declines for the manure treatment (N_{org}, 1.88–1.81 g kg^{-1}; N_{LF}, 0.088–0.063 g kg^{-1}) from 2004 to 2012. However, averaged among both years (Table 2), N_{org} for the manure treatment remained significantly greater (1.84 g kg^{-1}) than the check and fertilizer treatments (1.51–1.53 g kg^{-1}). The same was true of N_{LF} (Table 2).

Fewer parameters exhibited significant effects of cut (averaged among years and amendments) compared with effects of year (Table 2). N_{inorg} showed a significantly lower value on the 20 cm cut (20.7 mg kg^{-1}) than the

Table 2. Effect of year, cut, and amendments on soil quality attributes.

	C_{org} (g kg–1)	C_{LF} (g kg–1)	C_{min} (mg kg^{-1})	N_{org} (g kg^{-1})	N_{LF} (g kg^{-1})	N_{min} (mg kg^{-1})	NO_3–N (mg kg^{-1})	N_{inorg} (mg kg^{-1})	C_{org}/N_{org} (ratio)	C_{LF}/N_{LF} (ratio)	C_{LF}/C_{org} (%)	C_{min}/C_{org} (%)	N_{LF}/N_{org} (%)	N_{min}/N_{org} (%)
Year														
2004	15.2b	1.24a	511b	1.63	0.070	24a	26.4a	28.7a	9.3b	17.8b	8.3a	3.4b	4.3a	1.5a
2012	16.0a	1.26a	672a	1.63	0.060	28a	13.9b	18.9b	9.8a	21.1a	7.9a	4.2a	3.8b	1.7a
P-value	**<0.001**	0.77	**<0.001**	0.74	**0.005**	0.07	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.53	**<0.001**	**0.05**	0.09
Cut (cm)														
0	17.1a	1.28a	610a	1.77	0.066a	27a	21.9a	26.9a	9.7a	19.6a	7.4b	3.5b	3.9b	1.5a
10	16.0a	1.17a	567a	1.68	0.063a	25a	20.0a	23.7ab	9.5a	18.9a	7.3b	3.5b	3.7b	1.5a
20	13.7b	1.29a	597a	1.43	0.066a	26a	18.5a	20.7b	9.6a	19.7a	9.5a	4.4a	4.6a	1.8a
P-value	**0.004**	0.37	0.58	**<0.001**	0.78	0.73	0.22	**0.003**	0.79	0.49	**<0.001**	**0.02**	**0.01**	0.34
Amendment														
Check	14.7b	1.09b	531b	1.53	0.057	27a	18.4b	21.8b	9.6a	19.4ab	7.5a	3.6a	3.9a	1.7a
Fertilizer	14.6b	1.27ab	592ab	1.51	0.063	24a	19.0b	22.8b	9.7a	20.3a	8.8a	4.1a	4.2a	1.6a
Manure	17.5a	1.38a	650a	1.84	0.075	28a	23.0a	26.8a	9.5a	18.6b	8.0a	3.7a	4.1a	1.5a
P-value	**<0.001**	**0.01**	**0.03**	**<0.001**	**<0.001**	0.21	**0.003**	**0.009**	0.30	**0.04**	0.08	0.22	0.63	0.37
							P-value							
Year × cut	0.22	0.66	0.32	**0.01**	0.92	0.86	0.79	0.58	0.34	0.11	0.56	0.28	0.69	0.89
Year × amendment	0.08	0.19	0.48	**0.003**	**0.02**	0.15	0.39	0.20	0.46	0.42	0.32	0.30	0.12	0.40
Cut × amendment	0.82	0.49	0.41	0.63	0.44	0.23	0.38	0.17	0.75	0.93	0.44	0.43	0.22	0.37
Year × cut × amendment	0.40	0.14	0.24	0.71	0.50	0.35	0.80	0.39	0.20	0.67	0.19	0.25	0.43	0.53

Note: Means separation provided only if interaction effect(s) are nonsignificant. Within columns, year, cut, or amendment means with different letters are significantly different from each other ($P \leq 0.05$). *P*-values ≤0.05 are highlighted in bold.

Table 3. Effect of cut and amendment treatments on water-stable aggregation, fall 2012.

	Prewet soil		Nonwet soil		Stability ratio[a]	
Fraction	0.25–1 mm	>1 mm	0.25–1 mm	>1 mm	0.25–1 mm	>1 mm
	%					
Cut (cm)						
0	16a	62a	12a	28a	0.76ab	0.41
10	15a	66a	11a	37a	0.85a	0.59
20	18a	60a	11a	37a	0.63b	0.62
P-value	0.43	0.44	0.93	0.10	**0.02**	**0.002**
Amendment						
Check	17a	58b	11a	32	0.69a	0.52
Fertilizer	16a	63ab	12a	31	0.80a	0.52
Manure	16a	67a	12a	39	0.75a	0.58
P-value	0.74	**0.02**	0.30	**0.006**	0.39	0.15
Cut × amendment						
P-value	0.27	0.41	0.76	**0.02**	0.46	**0.05**

Note: Means separation provided only if interaction effect is nonsignificant. Within columns, cut or amendment means with different letters are significantly different from each other ($P \leq 0.05$). *P*-values ≤0.05 are highlighted in bold.

[a]Stability ratio = nonwet aggregates (high-energy, fast-wetting)/prewet aggregates (low-energy, slow-wetting).

0 cm cut (26.9 mg kg^{-1}), even though all cuts received equivalent amounts of N fertilizer with time. This may show that N availability was limited on the deeper cut, presumably because of reduced N mineralization from lower SOM levels on the 20 cm cut treatment. For C_{org}, the 20 cm cut was significantly lower (13.7 mg kg^{-1}) than both the 10 and 0 cm cuts (16.0–17.1 mg kg^{-1}). However, the other C fractions (C_{LF}, C_{min}) showed nonsignificant effects of cut as did their N counterparts (N_{LF}, N_{min}). The C_{LF}/C_{org}, C_{min}/C_{org}, and N_{LF}/N_{org} ratios showed significantly greater values on the 20 cm cut than the 0 and 10 cm cuts.

The effect of amendment (averaged over all years and cuts) was significant for six parameters (Table 2). Nitrate-N and N_{inorg} were significantly greater on the manure treatment than on the check and fertilizer treatments, showing the positive residual effect of manure on N availability even after 14–22 yr. Significant benefits from the one-time manure application were also observed for C_{org}, C_{LF}, and C_{min}. On average, C_{org} on the manure treatment (17.5 g kg^{-1}) was 19% greater than the check and fertilizer treatments (14.6–14.7 g kg^{-1}). The manure treatment was 27% greater than the check treatment for C_{LF}, and 22% greater for C_{min}. However, unlike C_{org}, the fertilizer and manure treatments were not significantly different for C_{min} and C_{LF}. As discussed above, N_{org} and N_{LF} were affected by significant year × amendment interactions. Unlike C_{min}, N_{min} did not show a significant response to amendment (Table 2). The C_{LF}/N_{LF} ratio was significantly lower for the manure treatment (18.6) than the fertilizer treatment (20.4) but not the check treatment (19.4), perhaps because of the lingering organic N added in manure. None of the four component ratios (C_{LF}/C_{org}, C_{min}/C_{org}, N_{LF}/N_{org}, N_{LF}/N_{org}) showed a significant effect of amendment.

Water-stable aggregation

In 2012, cut (averaged over amendments) showed no significant effect on WSA of either size fraction of prewet or nonwet soils (Table 3). However, the >1 mm fraction of prewet aggregates was significantly greater on the manure treatment (67%) than the check treatment (58%) among cuts (Table 3). Additionally, the >1 mm nonwet stable aggregate fraction showed a significant cut × amendment interaction (Fig. 5*a*). On the 0 cm cut, this fraction was significantly more abundant on the manure (33%) versus check treatment (22%), with the fertilizer treatment (29%) being intermediate. The same was true on the 20 cm cut (manure, 42%; check, 32%, fertilizer 37%), but not the 10 cm cut where a significantly lower value was observed for the fertilizer treatment (26%) than the check or manure treatments (42–43%).

The stability ratio of the 0.25 to 1 mm fraction (Table 3) was significantly greater on the 10 cm cut (0.85) compared with the 20 cm cut (0.63) with the 0 cm cut intermediate (0.76). However, the stability ratio of the >1 mm fraction showed a significant cut × amendment interaction (Fig. 5*b*). On the 0 cm cut, the manure (0.50) and fertilizer (0.45) treatments showed significantly greater stability ratios than the check treatment (0.29), but these effects were absent on the 10 and 20 cm cuts, except for the 10 cm cut where the fertilizer treatment (0.49) showed a significantly lower value than the others (0.63–0.65). For the >1 mm fraction, there was a strong

Fig. 4. (*a*) Year × cut interactions ($P < 0.05$) on organic nitrogen (N_{org}); year × amendment interactions ($P < 0.05$) on (*b*) organic nitrogen (N_{org}); and (*c*) light fraction nitrogen (N_{LF}), 0–7.5 cm depth.

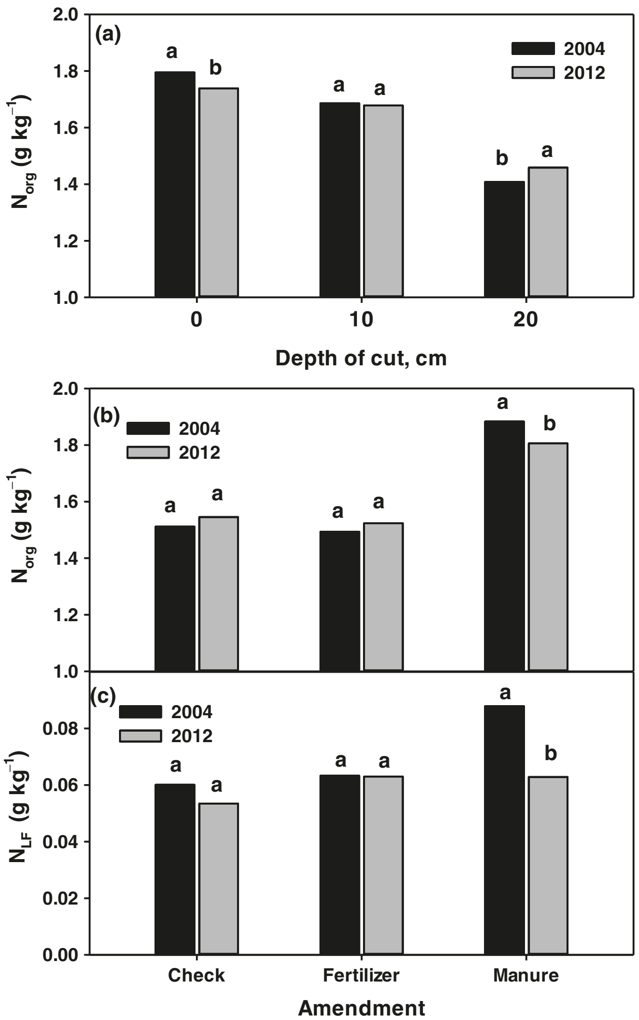
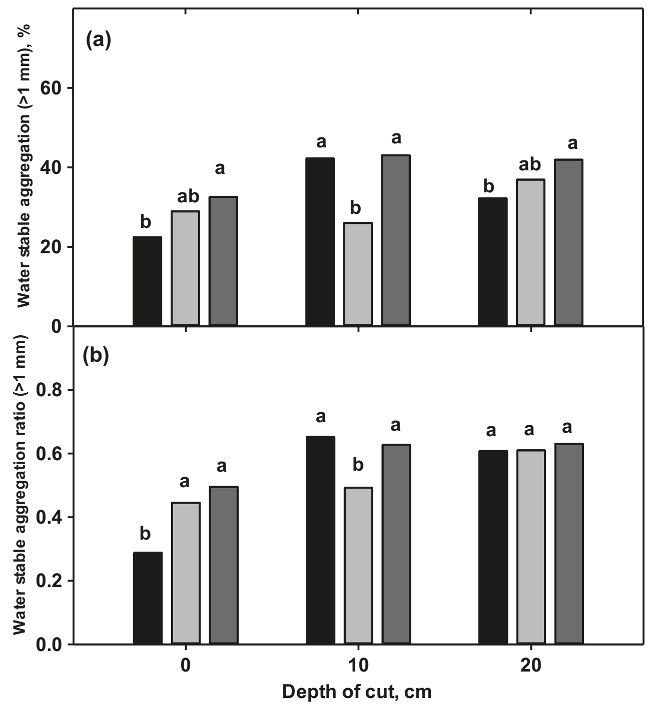


Fig. 5. Cut × amendment interactions ($P < 0.05$), on water-stable aggregation of (*a*) >1 mm diam. nonwet aggregates and (*b*) the stability ratio of >1 mm diameter aggregates, 0–7.5 cm layer.



overall effect of cut (Table 3, Fig. 5*b*) with the 10 and 20 cm cuts showing significantly greater stability ratios (0.59–0.62) than the 0 cm cut (0.41).

Discussion

Soil quality becomes a function of soil resistance during or immediately following a disturbance, whereas after a disturbance, soil quality becomes a function of soil resilience (Seybold et al. 1999). Our study provided information on soil resilience and resistance following major soil disturbance by topsoil removal and subsequent stresses imposed. It also addressed negative (erosion) and positive legacies (soil amendments).

Herrick and Wander (1998) suggested that after disturbance, the soil's capacity to recover has two components: the rate of recovery and the degree of recovery. The rate of recovery is the amount of time for soil to recover to its original potential or to some stabilized lower potential, whereas recovery to some stabilized potential relative to its predisturbance defines the degree. The greater the rate and (or) degree of recovery, the more resilient the soil system is to a specific disturbance. Seybold et al. (1999) pointed out that if the soil is inherently fragile or the disturbance too drastic, soil can undergo irreversible degradation in which its capacity to function will not recover within any reasonable time frame (e.g., human lifespan). In such cases, the soil's resilience capacity has been exceeded, resulting in permanent damage or the need for costly restoration.

Our results showed that, after various depths of quite aggressive simulated erosion, soil resilience as measured by SOM attributes, recovered with time in the absence of amendments. However, the recovery rate varied by SOM fraction. Labile components, such as light and mineralizable fractions (C_{LF}, N_{LF}, C_{min}, N_{min}) recovered faster (all three cuts were similar at 14 yr or earlier) than total components (C_{org}, N_{org}), which had not fully recovered by 22 yr (only the 10 cm cut had recovered to the level of the 0 cm cut). This agreed with Bolinder et al. (1999) who reported that C_{LF} and N_{LF} were more sensitive SOM attributes to conservation management practices than C_{org} or N_{org}. Sparling et al. (2003) found that microbial C (likely related to C_{min} in our study) was a more responsive indicator in monitoring topsoil recovery following landslips (shallow landslides) in New Zealand. Faster recovery of microbial C compared with total C also occurred at mine restoration sites (Ross et al. 1982; Insam and Domsch 1988). In our study, the degree of recovery (a component of soil resilience) depended on the fraction in question. On the 20 cm cut, C_{org} was 59% of the 0 cm cut in 1990 but had recovered to 85% of the 0 cm cut by 2012, which was still significantly lower, demonstrating a legacy effect of erosion on C_{org}. However, C_{LF} and C_{min} on the 20 cm cut, which started at proportionately much lower values of the 0 cm cut in 1990 (30–31%), had recovered to 94% of the 0 cm cut, which were not significantly different, denoting no legacy effect of erosion for these attributes. Recovery (20 cm/0 cm cut × 100) by 2012 was 85% for N_{org}, and 92% for N_{LF}, but only 60% for N_{min}. Apart from N_{min}, these findings reflect the relative turnover times of the various fractions: C_{org} and N_{org}, with slower turnover times, recovered to a lesser extent than LF and mineralizable fractions, which had more rapid turnover times, and therefore recovered more quickly. However, there was evidence on the 10 cm cut that LF ratios (C_{LF}/C_{org}, N_{LF}/N_{org}) were more sensitive indicators of recovery, showing increases from 1990 to 2004 (Figs. 2*b*, 2*d*), compared with nonsignificant changes in mineralizable ratios (C_{min}/C_{org}, N_{min}/N_{org}; Figs. 2*c*, 2*e*).

On the check plots, recovery of crop productivity (as measured by annual grain yield) on the 10 and 20 cm cuts was rapid in the first 3 yr and then levelled off with time (Larney et al. 2000*b*, 2009), at a point below the 0 cm cut, even though soil properties continued to improve. This indicated that although crop productivity may partially recover, it may not fully recover until C and N fractions attain indigenous levels.

The wider range of C conditions at the outset of the experiment explained the significant relationships between C fractions in 1990, for example, C_{LF} explained 88% of the variability in C_{min} (Fig. 3*c*), indicating that the availability of organic C to soil organisms (C_{min}) was derived from C_{LF} which agreed with Janzen et al. (1992). However, as time progressed these relationships became more tenuous (as indicated by reduced R^2 values in 2004 and 2012, Fig. 3), likely reflecting the convergence of labile SOM contents.

Although there is increasing awareness of the importance of ecological legacies in contemporary soil ecosystem processes, how legacies operate remains largely uncertain (Carrillo et al. 2012). Nevertheless, Foster et al. (2003) recognized that legacies of land use are remarkably consistent and that legacies interlinked with time-lags and feedbacks are a common response to perturbations in many biological systems. Land use can alter soil chemistry and hence nutrient cycling, plant mineral uptake, and crop productivity (Morris et al. 2013). However, legacy effects of erosion, often exacerbated by particular land uses, are rarely quantified in the literature. Some comparisons may be drawn from studies of abandoned agricultural land reverting to natural habitats, if we view both erosion and conventional agriculture as depletive of SOM. Studies at forested and grassland sites indicate that differences in pH, C, and N imposed by agriculture can endure for decades to centuries after agricultural use is discontinued and native species and processes re-established (Burke et al. 1995; Coffin et al. 1996; Compton et al. 1998). Knops and Tilman (2000) found that recovery trajectories of mineral soil reforesting after agricultural abandonment varied with soil attribute. C_{org} and N_{org} increased at different rates than the C:N ratio, and microbial C and N, which is in agreement with our findings. They estimated that legacies of past land use on soil C and N in a woodland landscape would persist for 150 yr. A comparable period was proposed by Burke et al. (1997) for the time required for soil C levels in shortgrass prairie to recover following two decades of cultivation. If the trajectory demonstrated for accrual of C_{org} on the 20 cm cut (Fig. 1*a*) was maintained, it would take an estimated 35 yr for C_{org} to attain the indigenous level of the 0 cm cut. This timeline is similar to the 30-yr recovery period for C_{org} on a range of grasslands restored to native prairie (Baer et al. 2002). However, it remains to be seen if crop productivity would be restored when C_{org} on the 20 cm cut attained the concentration of the 0 cm cut. Other scenarios include restoration of crop productivity prior to C_{org} reaching its predisturbance level, or lasting negative effects on productivity, even after C_{org} reached its predisturbance level.

In our study, in comparison to the check treatment, a one-time application of manure in 1990 left a lasting imprint on SOM fractions resulting in 19–27% higher values (e.g., C_{org}, C_{LF}, C_{min}) when averaged in 2004 and 2012. It is well known that the application of organic amendments such as manure elevates SOC (Larney and Angers 2012). However, the legacy effect of such practices is much more difficult to quantify and is often confounded by multiple rather than single applications, thus resulting in various overlapping nutrient cycling timelines and intersecting legacy effects. Our study benefited from having only one application of manure at the outset of the study. McLauchlan (2006) pointed out that the length of time for which organic amendments, such as manure, are applied to the soil is much shorter than the duration of elevated SOC and the longevity of the legacy depends on the magnitude of the alteration of SOC levels. In the classical Rothamsted experiment, one treatment received manure for 20 yr, yet the soil had elevated SOC levels 100 yr after applications ceased (Johnston 1986). Morris et al. (2013) suggested that compared with a noncultivated soil, higher concentrations of extractable K in soil cultivated for a decade (early 1910s to 1920s) in northwestern Utah and subsequently abandoned, were due to the application of manure, again denoting a manure legacy effect of at least 100 yr. However, in Peru, fields that had once been cultivated but abandoned approximately 400 yr ago still showed elevated levels of SOC (Sandor and Eash 1995).

New techniques hold promise for reconstructing details of past amendments that can persist in soil (Bull et al. 1998). For example, lipid biomarkers were able to distinguish three types of organic amendments on archaeological soils from 12th-century Britain: composted turf, ruminant animal manure, and omnivorous animal manure (Simpson et al. 1999). In our study, the N_{LF} fraction proved most sensitive in tracking the legacy effect of manure, being the only attribute to show a significant decline (28%) from 2004 to 2012. In addition, N_{org} showed a smaller (4%) but still significant decline from 2004 to 2012.

The legacy of the manure application can be attributed to two mechanisms: the lingering retention of SOM and nutrients initially applied, and the benefits of extra residue additions from higher yield responses to the manure. With time, the former mechanism will likely diminish, but the latter will likely gain prominence. In effect, the manure application instigates a self-perpetuating renewing cycle whereby greater productivity returns greater amounts of SOM which, in turn, produces higher yields.

Our results showed that a manure application exerted a positive influence on the proportion and stability of macroaggregates some 22 yr later, indicating the high resilience capacity of this treatment as well as its legacy effect. In fact, Candan and Broquen (2009) examined soil resilience through analysis of changes in WSA, suggesting that resilience in the physical sense can be best assessed using this parameter. There was no significant cut effect on WSA of macroaggregates in 2012. This could be due to convergence of SOC component concentrations on the three cuts, even though the C_{LF}/C_{org}, C_{min}/C_{org}, and N_{LF}/N_{org} ratios (average 2004, 2012) showed significantly greater values on the 20 cm cut than the 0 and 10 cm cuts. In addition, on a site adjacent to the present study, Sun et al. (1995) reported greater levels of inorganic C ($CaCO_3$) after 15 cm of topsoil removal. This caused a cementing effect that afforded stability comparable to a noneroded topsoil (0 cm cut).

Effects of manure on the stability ratio were confined to the 0 cm cut as this effect was likely masked by the cementing effect of $CaCO_3$ in the deeper cuts. A greater stability ratio reflects stronger resistance to slaking upon wetting (Nimmo and Perkins 2002), which would be considered a measure of soil resilience. The effects of cattle manure on WSA have often been reported and are likely due to the enhanced biological activity and production of binding agents induced by the manure application itself and indirectly by the plant-derived C input induced by manure (e.g., Larney and Angers 2012). On the 0 cm cut, it is noteworthy that the fertilizer treatment showed a greater stability ratio than the control, which corroborates the role that plant C input has on WSA through its effect on SOM.

Stimulation of soil biological activity (faunal and microbial) by organic amendments, such as manure, represents a fundamental tenet of soil resilience (Larney and Angers 2012). The discrete area where microbial activity is induced by organic amendments is localized and termed the detritusphere (Gaillard et al. 1999). Larney and Angers (2012) suggested that the detritusphere is fundamental to initiating, or essentially kick-starting, the process of soil recovery via its role in biogenic aggregate formation following incorporation of organic amendments. Initiation of biogenic aggregate formation has been observed in soils amended with cattle manure (Aoyama et al. 1999), wood-derived sludges (Chantigny et al. 1999), and green waste/papermill sludge compost (Séré et al. 2010). By feedback mechanisms, biogenic aggregation contributes to further protection of SOC (Angers and Chenu 1997; Balesdent et al. 2000) contributing to its buildup and early pedogenesis in highly degraded soils (Séré et al. 2010).

The check and fertilizer treatments were not significantly different for any of the measured soil quality attributes. This is unsurprising, given that the only difference between the treatments was application of 75 kg ha^{-1} N and 22 kg ha^{-1} P to the fertilizer treatment at the outset of the study in 1990. There was no legacy effect of the fertilizer amendment treatment. In terms of differentiating the fertilizer and manure treatments, C_{org} performed better (showing a significantly greater value on the manure treatment among cuts and years) than C_{LF} and C_{min}, which were not significantly different on the fertilizer and manure treatments.

Conclusions

Gains in soil quality on the Canadian prairies, as a result of adoption of CT and reduction in summerfallow since the early 1990s, have been well-documented (Janzen et al. 1998; Larney et al. 2004). However, such gains may become offset by a more recent shift in cropping practices from high-residue crops (cereals, forages) to more profitable low-residue crops (oilseeds, pulses). With the adoption of CT reaching a peak, Huffman et al. (2012) suggested that soil cover could decline during the next several decades if cropping changes continue, and residue harvest for biofuels becomes more common. There is also the uncertainty of climate change scenarios and their potential impact on crop productivity and the negative feedback loop to crop/residue cover, which is so important for soil protection against the forces of erosion and maintenance of SOM. Therefore, it is important to maintain long-term experiments such as the one outlined in this study to hopefully provide a more precise measurement of soil resilience in the face of erosion and the longevity of legacy effects of restorative organic amendments and their inter-relationships with soil quality and soil resilience.

Our results on legacy effects of erosion (albeit simulated and aggressive) and application of organic amendments have implications for long-term sustainability of prairie cropping systems. Enhanced awareness of soil conservation issues coupled with higher commodity prices on the Canadian prairies may promote the restoration of eroded soils in order to return them to their full potential. Restorative options include the addition of manure, which we have shown has a long legacy effect, even from a one-time application. In many areas of the prairies, intensive livestock production generates an abundant supply of manure for land application.

Our findings reinforce the damaging effects of severe erosion on soil productivity and emphasize the importance of effective soil conservation measures. At the same time, however, they demonstrate the remarkable resilience of our Canadian prairie soils. Given sufficient time, these soils have the capacity for gradual self-renewal of productivity, a capacity abetted by the initial application of carbon-rich substrates such as manure. Thus, while preventing erosion is unquestionably preferential, badly degraded soils, with good management, can slowly regain much of the productivity lost to erosion.

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