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Wheat yield and soil properties reveal legacy effects of artificial erosion and amendments on a dryland Dark Brown Chernozem

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Abstract: Erosion leads to substantial loss of soil productivity. To abate such decline, amendments such as manure or fertilizer have been successfully employed. However the longevities of erosion and soil amendment legacy effects are not well quantified. In 1957, a Dark Brown Chernozem soil at Lethbridge, AB was land-levelled, creating three degrees of topsoil removal or erosion: non-eroded, moderate erosion, or severe erosion. Two amendment studies (1980–85, 1987–91) were superimposed on the erosion treatments. Both studies were cropped to spring wheat (*Triticum aestivum* L.) from 1993–2010 to examine legacy effects of erosion and soil amendments on wheat yield and soil properties. Without amendment, mean wheat yield under moderate erosion was 40% of the non-eroded treatment, while severe erosion was 34% of the non-eroded treatment, 36–42 yr (1993–99) after erosion. Under moderate or severe erosion, the restorative power of manure diminished substantially in the first 10–15 yr following cessation of addition, but then levelled off resulting in wheat yields up to 35% higher than equivalent non-amended treatments. Legacy effects of erosion (54 yr) and amendment (27–31 yr) on soil organic C and total N were also observed.

Key words: soil erosion, soil amendment, legacy effect, carbon

Introduction

There is geomorphic evidence of soil erosion since the beginning of land use for agriculture (Dotterweich 2013). The recent *Status of the World's Soil Resources* report (FAO and ITPS 2015) reiterated that erosion by wind and water remains a global threat to soil and its many functions. In recent decades, remarkable progress has been made in reducing erosion risk on the Canadian prairies. However, with peak conservation tillage attained, Huffman et al. (2012) suggested that soil cover could decline during the next several decades if residue harvest for biofuels becomes more common, and a shift in cropping practices from high-residue (cereals, forages) to more profitable low-residue crops (oilseeds, pulses) continues. On irrigated land in southern Alberta, there has also been a decline in cereals and forages and an increase in low-residue specialty crops (e.g. potato, sugar beet, dry bean). Larney (2018) reported that the area of cereals + forages within Alberta's 13 Irrigation Districts, declined from 84% in 1996 to 66% in 2016 while the area of oilseeds and specialty crops increased from 16% to 34% in the same time period. These cropping changes, as well as uncertain future climate scenarios, could have long-term implications for surface residue cover which is the main line of defence against erosion.

Crop productivity and responses to fertilizer inputs are often reduced on eroded soils, which exacerbates the inter-weaved problems of low net primary productivity, low returns of organic matter to the soil, and further soil degradation from erosion. One of the problems in assessing erosion effects on soil productivity is the difficulty in detecting a decline in productivity that results from erosion (Larney et al. 2009). Topsoil removal (artificial or simulated erosion, de-surfacing), whereby incremental depths of topsoil are mechanically removed with an excavator, is a recognized method in quantifying erosion-productivity relationships (Bakker et al. 2004; den Biggelaar et al. 2004). The ability of soil amendments (e.g. manure, fertilizer, crop residues) to

restore productivity to variously ‘eroded’ surfaces may also be studied with this approach.

Bakker et al. (2004) suggested that the longer the time span following topsoil removal, the more realistic the results from such experiments. Longer-term studies also allow quantification of legacy effect timelines for both negative (erosion) and positive (amendments) past events.

Legacy effects, as they relate to land use, refer to the persistence of past land use actions which have now ceased (Cuddington 2012). This definition implicitly recognizes that because of legacy effects, the influence of past events, such as erosion, may persist into the future (Bürgi et al. 2017), often continuing beyond some expected or perceived temporal endpoint. Related concepts include ecological inheritance (Odling-Smee and Laland 2012), ecological memory (Ogle et al. 2015; Johnstone et al. 2016), soil memory (Targulian and Goryachkin 2004; Janzen 2016), and land-use imprints (Foster et al. 2003). Monger et al. (2015) acknowledged the role of legacy effects in the triad “environment ↔ processes ↔ properties” and showed that environmental conditions governed processes that, in turn, changed properties, using vegetative cover ↔ organic matter accumulation ↔ soil pH, as an example. They suggested that legacies in dryland regions were a function of three variables: (i) the magnitude of the historical phenomenon, (ii) the time elapsed since its occurrence, and (iii) the sensitivity of the ecological-soil-geomorphic system to change.

The artificial erosion approach has been widely used to examine erosion-productivity relationships in Alberta [Dormaar et al. (1986), Larney et al. (1995, 2000*a*, 2000*b*, 2009, 2011, 2016), Izaurrealde et al. (2006)]; Manitoba, (Morrison Ives and Shaykewich, 1985); Montana, (Allen et al. 2011); Idaho (Massee 1990); South Dakota (Gollany et al. 1992); Ohio (Srinivasan et al. 2012); Texas (Eck 1987); Chile (Brunel et al. 2011); Nigeria (Mbawagu et al. 1984); China (Zhou et al. 2015); and Indonesia (Anda and Kurnia 2010). Most of the above studies have

looked at short-term effects of erosion and subsequent soil amendments on soil productivity, with few reporting on longevity of legacy effects.

The oldest artificial erosion experimental site in Lethbridge, Alberta dates to 1957. Various sub-studies, aimed at restoring soil productivity, were imposed on the site including those which ran from 1965–79 (Dormaar et al. 1986); 1980–85 (Dormaar et al. 1988, Freeze et al. 1993); and 1987–91 (Dormaar et al. 1997*a*, 1997*b*). Using wheat yields from 1993–2010 and soil properties in 2011, objectives of the current study were to quantify legacy effects of (i) erosion (topsoil removal) which occurred in 1957; and (ii) amendments which were applied in 1980–85 and 1987–91. This places maximum legacy effect timelines at 54 yr for erosion and 31 yr for soil amendments.

Materials and methods

Site description and experimental design

The experimental site is located at the Agriculture and Agri-Food Canada Research and Development Centre, Lethbridge, AB (49° 42' N; 112° 46' W, elev. 913 m) on a 5.26 ha area (known as *13 Acres*) that was mechanically levelled in 1957 as part of a land development program for irrigation. The soil is a calcareous Dark Brown Chernozem (Lethbridge soil series) developed on loam to clay loam lacustrine material. The 30-yr (1981–2010) mean annual precipitation was 396 mm and mean annual air temperature was 6.4 °C. Detailed descriptions of experiments conducted on the site are provided by Dormaar et al. (1986, 1988, 1997*a*) and, as such, are only briefly described here.

At initial land-levelling in 1957, no effort was made to stockpile or replace topsoil resulting in areas of cut (erosion) and fill (deposition) across the site. The site was continuously cropped to

barley (*Hordeum vulgare* L.) from 1958–64. From 1965–79, an initial erosion-productivity experiment was conducted on a wheat-fallow rotation with six erosion treatments (i) >30 cm fill; ii) 8–10 cm of fill; (iii) undisturbed; (iv) 8–10 cm cut; (v) 10–20 cm cut; and (vi) >46 cm cut, and four fertilizer rates (Dormaar et al. 1986).

In 1980, a second erosion-productivity experiment was initiated (Dormaar et al. 1988) on unused areas of the site in a more intense attempt to restore soil productivity (Fig. 1), on three of the soil erosion treatments: (i) undisturbed; (ii) 10 to 20 cm cut; and (iii) >46 cm cut. These soil erosion treatments were deemed to approximate non-eroded, moderate erosion, and severe erosion conditions. Each main erosion plot was divided into three amendment sub-plots (check, manure, fertilizer) outlined in Table 1. Main erosion plots were 11×15.2 m, and subplots, in a split-plot design, were 3.7×15.2 m, for a total of 36 plots (three erosion levels $\times$ three amendments $\times$ four replicates). Dormaar et al. (1988) assumed that the plot layout approached that of a completely randomized design. This experiment (designated Expt_{80–85}) ran until fall 1985 in a fallow–wheat rotation (Fig. 1).

After the final harvest of Expt_{80–85} in 1985, the entire 5.26 ha area was re-cropped to wheat in 1986 and 1987, without restorative amendments (Fig. 1). Following the 1987 harvest, a third erosion-productivity experiment was established with three erosion treatments similar to Expt_{80–85} (non-eroded, moderate and severe, 18.3×15.2 m plots), again on unused and unamended areas of the site. Five amendment treatments (check, manure, fertilizer, straw and topsoil, Table 1) were superimposed on the erosion treatments as sub-plots (3.7×15.2 m) in a split-plot design for a total of 60 plots (three erosion levels $\times$ five amendments $\times$ four replicates), again in an assumed completely randomized design (Dormaar et al. 1997a). This erosion-productivity study (designated Expt_{87–91}) was continuously cropped to wheat for 4 yr (1988–91).

Tillage operations on the experiments included disc harrowing (to ~10 cm depth) to incorporate amendments (fertilizer, manure, straw) in fall or prior to seeding, and a wide-blade cultivator for weed control during fallow years (up to and including 1984).

Legacy phase measurements

Following final harvest of Expt_{87–91} in 1991, amendments were discontinued in order to monitor legacy effects of both erosion and amendment treatments on crop yield and soil properties on Expt_{80–85} and Expt_{87–91} plots. The entire *13 Acres* site was fallowed in 1992 and continuously cropped to hard red spring wheat from 1993–99 (7 yr). Fallow in 2000, to curb wild oat (*Avena fatua* L.) populations, was followed by continuous wheat from 2001–10 (10 yr), and fallow in 2011 (Fig. 1). Herbicides were used for weed control, rather than cultivation, in the fallow years. Nitrogen and P fertilizers were withheld until 2002, when the site received 40 kg ha⁻¹ N (as ammonium nitrate) and 9 kg ha⁻¹ P (as triple superphosphate) annually until 2010.

Wheat was seeded at 17.5-cm row spacing from late April–late May with minimum pre-seeding tillage (1993–96) or no-till (1997 onward). The following cultivars were grown: ‘Lancer’ (1993), ‘Katepwa’ (1994–99, 2001–04), ‘AC Abbey’ (2005–07) and ‘Lillian’ (2008–10). Wheat was harvested from mid-August–early October with a plot combine and grain yield expressed as air-dry weight after cleaning to remove weed seeds.

Soil samples (67 mm. diam. core) were taken in August 2011 to 60 cm depth at three locations (one quarter, half, and three-quarter-way points) on a transect at the centre long axis of each plot. Cores were split into 0–15, 15–30, and 30–60 cm depth increments, and the three locations pooled to give one composite sample for each depth increment.

Air-dried soils were coarse-ground (<2mm) and a sub-sample fine-ground (<150 μm) on a roller-mill for analysis of total C and total N by dry combustion (NA 1500 CNS analyzer, Carlo Erba, Milan, Italy), and inorganic C (CO_2 release following dissolution of CaCO_3 by acid, Amundson et al. 1988). Soil organic C was estimated as total C minus inorganic C. Nitrate-N was extracted using 2 M KCl and determined colorimetrically on a AutoAnalyzer II (Technicon Instruments Corp., Tarrytown, NY). Available P was determined colorimetrically on a modified Kelowna extract (Ashworth and Mrazek 1995). Archive soil samples (0–15 cm depth, <2 mm) from fall 1987 on Expt_{80–85} were also analyzed for the above properties.

Statistical Analyses

Grain yield and soil properties were tested for outliers (PROC UNIVARIATE) prior to analysis by year using PROC MIXED (SAS Institute Inc. 2009). Erosion and amendment were fixed variables while replicate and replicate $\times$ erosion were random variables. Least-square means were calculated for all data and mean comparisons made using the Tukey-Kramer adjustment ($P = 0.05$). Legacy effects of amendment treatments were derived using regression analysis.

Results

Weather conditions

At Lethbridge, the 30-year (1961–1990) normal growing season precipitation (GSP, 1 May–31 August) was 197 mm. The mean GSP from 1993 to 2010, excluding the fallow year in 2000, was 239 mm (121% of normal), with 2001 being the driest growing season (65 mm, 33% of normal), and 2002 the wettest (417 mm, 212% of normal).

Wheat grain yield

Erosion effects (across all amendments)

On Expt^{80–85}, significant erosion effects (across all amendments) were evident from 1993–98, and in 2004, 2006 and 2008, i.e. 9 of 17 yr (Table 2). Trends were similar in 8 of these 9 yr (1994 excepted), with the non-eroded treatment yielding significantly higher (by an average of 1.8 times) than moderate or severe erosion, which were not significantly different from each other.

On Expt^{87–91}, significant erosion effects were found in 16 of 17 yr, the exception being 2009 (Table 3). However, in 9 of these 16 yr, significant erosion × amendment interactions occurred (Table 3). Of the 7 remaining years without erosion × amendment interactions, five (1996, 1998, 1999, 2004, 2008) showed a similar trend to Expt^{80–85}, i.e. the non-eroded treatment was significantly higher-yielding (by an average of 2 times) than moderate and severe erosion, which were not significantly different from each other. In 2005, all three erosion treatments were significantly different from each other, with moderate erosion yielding 64% (1.17 Mg ha⁻¹), and severe erosion only 36% (0.66 Mg ha⁻¹) of the non-eroded treatment (1.83 Mg ha⁻¹). In 2007 (Table 3), both non-eroded and moderate erosion treatments (1.81–1.87 Mg ha⁻¹) were significantly higher-yielding than severe erosion (1.35 Mg ha⁻¹).

On Expt^{80–85}, averaging erosion treatments over 17 yr (Table 2), showed that the non-eroded treatment was significantly higher-yielding (1.99 Mg ha⁻¹) than severe (1.32 Mg ha⁻¹), but not moderate erosion (1.45 Mg ha⁻¹). On Expt^{87–91}, mean grain yield was qualified by a significant erosion × amendment interaction and will be discussed later.

Amendment effects (across all erosion levels)

Across all erosion levels, amendment was significant in five (1993–95, 1997–98) of the first 6 yr of legacy effect monitoring on Expt_{80–85} (Table 2). In all cases, the manure treatment out-yielded the check treatment by an average of 58% (2.33 vs. 1.47 Mg ha⁻¹). The manure treatment also out-yielded the fertilizer treatment in 1993–95 and 1997 by an average of 37% (2.53 vs. 1.84 Mg ha⁻¹). After 1998, a significant amendment effect was manifest in 2006 only (Table 2) with the manure treatment showing a significant yield advantage over both the check and fertilizer treatments ($\bar{x}$, +18%). There were no years, since 1993, when the fertilizer treatment yielded significantly higher than the check treatment on Expt_{80–85}.

On Expt_{87–91}, significant amendment effects were found in 16 of 17 yr, the exception being 2007 (Table 3). However, as mentioned above, significant erosion × amendment interactions occurred in 9 of these 16 yr. The remaining 7 yr without significant erosion × amendment interactions (1996, 1998–99; 2004–05; 2008–09, Table 3), showed a decline in average magnitude of the manure legacy effect on wheat yield over time (compared to the check treatment), from +69% (1996, 1998–99), to +42% (2004–05), to +30% (2008–09). Looking at these 7 yr, we found that (i) manure yielded significantly higher than the four other amendments, except in 2004, when there was no significant difference between manure and fertilizer amendments, and 2009, when manure was significantly higher-yielding than the check treatment only; (ii) there was no significant yield difference between check, fertilizer, straw or topsoil amendments.

Averaging amendment treatments (across all erosion levels) over 17 yr, grain yield on Expt_{80–85} with manure was significantly higher (1.83 Mg ha⁻¹) than both check and fertilizer treatments (1.42–1.51 Mg ha⁻¹), a mean difference of +24% (Table 2).

Erosion × amendment interaction effects

A significant erosion × amendment interaction meant that crop responses to erosion depended on amendment treatment or, *vice versa*, responses to amendment depended on erosion treatment. As mentioned previously, there were no significant erosion × amendment interactions on Expt^{80–85}. On Expt^{87–91}, significant interaction effects occurred in 9 of 17 yr (Table 3) and pertained mostly to a superior manure effect as erosion level increased. Fig. 2 selects grain yields from 4 yr along the legacy period timeline (1993, 1997, 2003 and 2010) to illustrate significant erosion × amendment interactions and their changes over time. Yields are expressed as a percent of the check treatment at each erosion level.

In 1993, there was no significant amendment effect on wheat yield on the non-eroded plots (Fig. 2*a*). Under moderate erosion, both manure and fertilizer amendments maintained grain yield significantly higher ($\bar{x}$, +286%) than check, straw and topsoil, while under severe erosion, manure was significantly higher-yielding than all four other amendment treatments (Fig. 2*a*). In fact, addition of manure masked all effects of erosion on grain yield.

In 1997 (Fig. 2*b*), there was no effect of amendment on grain yield on the non-eroded treatment, while at moderate erosion, manure out-yielded the check, straw and topsoil amendments ($\bar{x}$, +278%) but not fertilizer. At severe erosion, manure out-yielded all other amendments ($\bar{x}$, +280%), except straw. By 2003 (Fig. 2*c*), the only significant amendment effect occurred on the non-eroded treatment with the check out-yielding the straw amendment. Amendment effects were non-significant under moderate or severe erosion (Fig. 2*c*). In 2010, amendment treatments were not significantly different from each other under non-eroded conditions (Fig. 2*d*). However, the legacy effect of manure was manifest with significantly higher grain yield than the check treatment under moderate (+52%) and severe erosion (+58%).

The erosion $\times$ amendment interaction effect on mean wheat yield is shown for early (1993–99, Fig. 3a) and late (2001–10, Fig. 3b) periods of legacy effect monitoring on Expt_{87–91}. For both early and late periods, significant amendment effects were not apparent for mean wheat yield under non-eroded conditions (Figs. 3a, 3b).

For the early period (Fig. 3a), under moderate erosion the manure treatment (2.94 Mg ha^{-1}) yielded significantly higher than check, straw, and topsoil treatments ($0.96\text{--}1.26 \text{ Mg ha}^{-1}$), but not fertilizer (2.04 Mg ha^{-1}). The fertilizer treatment was also significantly higher than the check treatment. With severe erosion (Fig. 3a), the manure treatment was significantly higher yielding (2.49 Mg ha^{-1}) than all other amendments ($0.73\text{--}1.28 \text{ Mg ha}^{-1}$).

For the late period (2001–10, Fig. 3b), under moderate erosion, the manure treatment remained significantly higher-yielding (1.99 Mg ha^{-1}) than the check, straw, and topsoil treatments ($1.33\text{--}1.48 \text{ Mg ha}^{-1}$), but not fertilizer (1.66 Mg ha^{-1}). However, the fertilizer treatment no longer remained significantly lower than the check treatment. Under severe erosion (Fig. 3b), the manure treatment was only significantly higher-yielding (1.61 Mg ha^{-1}) than the check and topsoil treatments ($1.00\text{--}1.10 \text{ Mg ha}^{-1}$) but not straw or fertilizer ($1.25\text{--}1.30 \text{ Mg ha}^{-1}$).

The diminishment of the amendment effect can be seen by comparing the early and late legacy periods, e.g. the manure treatment out-yielded the check treatment by 3.1 times under moderate erosion and 3.4 times under severe erosion in 1993–99 (Fig. 3a). By 2001–10 (Fig. 3b), the yield advantage between manure and check treatments had fallen to 1.5 times for moderate, and 1.6 times for severe erosion.

Comparing erosion levels within amendments, the 144 Mg ha^{-1} of manure applied from 1987–90 (Table 1) compensated for moderate and severe erosion in both early (Fig. 3a) and late (Fig. 3b) legacy periods., i.e. for 3–20 yr (1993–2010) after application ceased, with no significant

yield differences between erosion levels. For the remaining four amendments (check, fertilizer, straw and topsoil), moderate erosion led to significantly lower yields than non-eroded, with no further yield reduction due to severe erosion during the early legacy period (Fig. 3a). In the later period, only the check treatment showed a yield decline due to moderate erosion. However, the fertilizer and topsoil treatments with severe erosion were significantly lower-yielding than equivalent non-eroded treatments (Fig. 3b). The flattening of the relationship between erosion level and productivity (across all amendments) is exemplified by the severely eroded check treatment which yielded 24% of the non-eroded check in 1993–99 (Fig 3a), compared with 49% in 2001–10 (Fig. 3b).

Erosion legacy effect

The relationship of the erosion legacy effect with time from 1957–2010 is shown in Fig. 4, where grain yields on moderate and severe erosion check treatments are expressed as a percent of the non-eroded check treatment. While there is some level of distinction between moderate and severe erosion (i.e. greater yield suppression with severe erosion), there was no clear recovery (or deterioration) of the eroded treatments as time progressed. It should be noted that data were drawn from three different sets of non-eroded, moderate and severe erosion plots on the *13 Acres* site: older experiments (Dormaar et al. 1986), Expt_{80–85}, and Expt_{87–91}. Overall mean yields (1993–2010, $n = 17$) on check treatments on Expt_{80–85}, were 1.88 Mg ha⁻¹ for non-eroded; 1.23 Mg ha⁻¹ for moderate; and 1.15 Mg ha⁻¹ for severe erosion. Equivalent mean yields on Expt_{87–91} were 2.43 Mg ha⁻¹ for non-eroded; 1.18 Mg ha⁻¹ for moderate; and 0.89 Mg ha⁻¹ for severe erosion. Therefore the apparent greater yield-suppressive legacy effect of erosion on Expt_{87–91} compared to the Expt_{80–85} (when expressed as a percent of non-eroded, Fig. 4) was in

fact due to higher productivity on the non-eroded treatment, rather than actual lower productivity on moderate or severe erosion treatments of Expt₈₇₋₉₁.

There was a cluster of very low yields under moderate and severe erosion from 1993–99, some 36–42 yr after erosion in 1957 (Fig. 4). Mean grain yield (Expt₈₀₋₈₅ and Expt₈₇₋₉₁) for this period was 40% ($\pm 3\%$ SE) of the non-eroded check under moderate erosion, and 34% ($\pm 3\%$ SE) under severe erosion. In contrast, a cluster of higher productivity on eroded surfaces followed 44–53 yr (2001–10) after erosion (Fig. 4), when mean grain yield was 77% ($\pm 6\%$ SE) of the non-eroded check under moderate erosion and 67% ($\pm 7\%$ SE) under severe erosion. Growing season precipitation data revealed no relationship with the magnitude of the erosion legacy effect.

Amendment legacy effects

Legacy effects were described by exponential decay equations of the form:

$$y = a + b\exp(-cx)$$

where y = grain yield on amendment treatments expressed as a percent of the check yield at the equivalent erosion level, and x = time elapsed (yr) since the last amendment application.

For manure, all relationships were significant on Expt₈₀₋₈₅ (Table 4, Fig. 5) with R^2 values of 0.55–0.89. The relationships revealed that the restorative power of manure diminished substantially in the first 10–15 yr following cessation of manure inputs, but then levelled off after 20–25 yr at values higher than the equivalent check treatments with a coefficient (or horizontal asymptote) values ranging from almost identical to (100.3%) the check treatment on the non-eroded treatment to 121.5% of the check treatment under moderate erosion, and 113.2% under severe erosion (Table 4, Fig. 5). On Expt₈₇₋₉₁, only the relationship under severe erosion was

significant for the manure amendment levelling off at 135% of the equivalent check treatment (Table 4, Fig. 5).

None of the relationships were significant (Table 4) for the legacy effect of fertilizer for Expt_{80–85} (data not shown), likely because the initial year (1993) was 9 yr after the last application of fertilizer to this study, by which time the yield vs. time elapsed since amendment relationship had started to level off. However, for Expt_{87–91}, the fertilizer amendment relationships were significant for all three erosion levels ($R^2 = 0.44–0.80$, Table 4, Fig. 6). Estimates for a coefficients showed a levelling-off value from 10% lower than the check treatment on the non-eroded treatment, to 19% higher than the check treatment under moderate erosion, and 34% higher under severe erosion (Table 4, Fig. 6), some 15–20 yr after amendment. This illustrated that the legacy effect of fertilizer was negative under non-eroded, but positive under eroded conditions. Legacy effects of straw, while also significant ($R^2 = 0.50–0.51$) on Expt_{87–91}, were less than fertilizer, ranging from negative (–17%) on non-eroded to positive (+5% on moderate, and +23% on severe erosion) [Table 4, Fig. 6]. Legacy effects of topsoil amendment were not detected (data not shown), being non-significant at all erosion levels (Table 4).

Soil properties

0–15 cm depth

On Expt_{80–85}, there was a significant erosion $\times$ amendment interaction on organic C and total N (0–15 cm depth) in 1987 (Table 5). On average (across all erosion levels), the manure treatment had ~40% more organic C and total N than the check and fertilizer treatments. However, the significant interaction showed that the magnitude of the manure effect on both

properties increased with erosion from a mean of +20% for non-eroded, to +34% for moderate, and +85% for severe erosion (data not shown). For $\text{NO}_3\text{-N}$, the effect of erosion was non-significant, while for available P, the non-eroded treatment (112 mg kg^{-1}) was significantly greater than moderate erosion (33 mg kg^{-1}), but not severe erosion (75 mg kg^{-1}) [Table 5]. In 1987, compared to the fertilizer and check treatments, the manure treatment had significantly greater $\text{NO}_3\text{-N}$ (18.4 vs. $4.5\text{--}5.1 \text{ mg kg}^{-1}$) and available P (130 vs. $20\text{--}69 \text{ mg kg}^{-1}$) [Table 5].

By 2011, the erosion $\times$ amendment interaction effects for organic C and total N were no longer observed on Expt_{80–85} (Table 5). Across all amendments, organic C and total N were, on average, ~60% higher on non-eroded vs. moderate or severe erosion. The erosion effect was non-significant for $\text{NO}_3\text{-N}$ in 2011, while available P was significantly higher on non-eroded (65 mg kg^{-1}) than moderate or severe erosion ($19\text{--}26 \text{ mg kg}^{-1}$) treatments (Table 5). In 2011, across all erosion levels, the manure treatment remained significantly higher than both check and fertilizer treatments for soil organic C (10.9 vs. $\bar{x} = 9.8 \text{ g kg}^{-1}$, or +11%) and total N (1.13 vs. $\bar{x} = 1.00 \text{ g kg}^{-1}$, or +13%). Nitrate-N remained significantly higher on manure vs. check and fertilizer treatments (11.5 vs. $\bar{x} = 9.1 \text{ mg kg}^{-1}$) in 2011, while the amendment means comparison for available P had a P -value of 0.09, showing that the 54 mg kg^{-1} value with manure was close to being significantly higher than the check (24 mg kg^{-1}).

The degree of change in all four soil properties over the 24-yr period between 1987 and 2011 on Expt_{80–85} was unaffected by erosion (Table 5). Averaged across erosion levels, change in organic C, total N and available P was negative, while $\text{NO}_3\text{-N}$ was positive. However, amendment treatment significantly affected the magnitude of change in soil properties (Table 5). Change on the manure treatment was significantly greater than check and fertilizer treatments, being negative for organic C (-2.2 g kg^{-1}), total N (-0.25 g kg^{-1}), and $\text{NO}_3\text{-N}$ (-7.1 mg kg^{-1}),

compared to positive on the check and fertilizer treatments, in the 24-yr period between samplings (Table 5). Also during this period, the manure treatment lost significantly more available P (-81 mg kg^{-1}) than the fertilizer treatment (-36 mg kg^{-1}), which in turn was significantly different than the check treatment ($+8 \text{ mg kg}^{-1}$).

On Expt^{87–91}, the erosion $\times$ amendment interaction was non-significant for all four soil properties at 0–15 cm depth (Table 6). Across all amendment treatments, the non-eroded treatment was significantly higher for organic C (14.8 g kg^{-1}) and total N (1.54 g kg^{-1}), than moderate erosion (organic C, 10.9 g kg^{-1} ; total N, 1.13 g kg^{-1}), which in turn was significantly higher than severe erosion (organic C, 7.9 g kg^{-1} ; total N, 0.80 g kg^{-1}). At all erosion levels, the effect of amendment was consistent across organic C, total N and available P, with significantly greater values on the manure treatment compared to all four other amendments (check, fertilizer, straw, topsoil, Table 6). Differences [manure vs. $\bar{x}$ (check, fertilizer, straw, topsoil)] were 13.7 vs. 10.6 g kg^{-1} , or +29% for organic C; 1.41 vs. 1.09 g kg^{-1} , or +30% for total N; and 98 vs. 24 mg kg^{-1} , or ~4-fold for available P. For $\text{NO}_3\text{-N}$, manure (13.1 mg kg^{-1}) was significantly higher than both check and fertilizer (9.5 mg kg^{-1}) treatments, but not straw or topsoil ($10.5\text{--}10.6 \text{ mg kg}^{-1}$) [Table 6].

15–30 and 30–60 cm depths

Erosion effects on soil properties were manifest at 15–30 and 30–60 cm depths since substantial depths of topsoil (up to 46 cm) were removed in 1957. However, there were limited amendment effects in these deeper layers. On Expt^{80–85} in 1987, organic C concentrations were significantly higher on non-eroded vs. moderate and severe erosion treatments at both 15–30 (11.6 vs. $3.9\text{--}5.1 \text{ g kg}^{-1}$) and 30–60 cm (9.9 vs. $3.8\text{--}4.9 \text{ g kg}^{-1}$) depths. By 2011, the trends were

similar and organic C concentrations were essentially unchanged: 10.8 vs. 4.0–5.6 g kg⁻¹ at 15–30 cm, and 9.6 vs. 3.3–4.6 g kg⁻¹ at 30–60 cm depth. The amendment effect on organic C was non-significant at both at the 15–30 and 30–60 cm depths in 1987 (data not shown). However, in 2011, the manure and check amendments had significantly higher organic C (6.0 g kg⁻¹) than the fertilizer amendment (5.5 g kg⁻¹) at 30–60 cm depth.

There was an erosion × amendment interaction on total N concentration at 15–30 cm depth in 1987, whereby the manure amendment under severe erosion was significantly higher (0.49 g kg⁻¹) than the fertilizer (0.34 g kg⁻¹). This effect persisted in 2011, when manure was significantly higher (0.47 g kg⁻¹) than fertilizer (0.37 g kg⁻¹). Total N behaviour at 30–60 cm depth followed the pattern of organic C in both 1987 and 2011 (data not shown).

For NO₃-N concentrations, there were significant erosion × amendment interactions at the 15–30 and 30–60 cm depths in 1987. At 15–30 cm, manure and fertilizer had significantly higher values (19–24 mg kg⁻¹) than check (4 mg kg⁻¹) on the non-eroded surfaces, amendment was non-significant under moderate erosion, while manure was significantly higher (15 mg kg⁻¹) than both check and fertilizer (1–2 mg kg⁻¹) under severe erosion. At 30–60 cm, manure led to significantly higher NO₃-N (46 mg kg⁻¹) than check (3 mg kg⁻¹) but not fertilizer (19 mg kg⁻¹) on the non-eroded treatment, while amendment effects were non-significant under moderate or severe erosion. By 2011, all amendment effects on NO₃-N concentrations had disappeared at both 15–30 and 30–60 cm depths.

There were significant erosion, but not amendment, effects on available P at both deeper depths in 1987 and 2011. In 1987, values were 13.7 mg kg⁻¹ on non-eroded vs. 0.8–0.9 mg kg⁻¹ on moderate and severe erosion at 15–30 cm depth, and 5.1 vs. 0.1–0.2 mg kg⁻¹ at 30–60 cm

depth. By 2011, overall available P concentrations (data not shown) had declined while erosion effects were similar to 1987.

On Expt₈₇₋₉₁, in 2011, organic C concentrations were significantly higher on non-eroded vs. moderate and severe erosion treatments at both 15–30 (11.3 vs. 4.5–5.9 g kg⁻¹) and 30–60 cm (9.9 vs. 4.1–4.2 g kg⁻¹) depths. Total N concentrations followed similar trends (data not shown) at both depths. Amendment effects were non-significant for both organic C and total N. For NO₃-N, there were significant erosion and amendment effects at 15–30 cm: with non-eroded > moderate and severe erosion (4.8 vs. 2.2–2.9 mg kg⁻¹), and manure > all other amendments (4.2 vs. 2.9–3.3 mg kg⁻¹). Erosion and amendment effects were non-significant for NO₃-N at 30–60 cm. For available P, the only significant effect at either depth was non-eroded > moderate and severe erosion (7.7 vs. 0.4 mg kg⁻¹) at 15–30 cm.

Discussion

Comparing erosion legacy effects (averaged across amendments) of the two experiments, the older Expt₈₀₋₈₅ showed less years (9 of 17 yr) with significant erosion effects than the newer Expt₈₇₋₉₁ (16 of 17 yr). One would expect the natural recovery of eroded surfaces on both experiments to be similar over time, since both were initially eroded in 1957. However, Fig. 4 revealed that the yield-suppressive nature of the erosion legacy effect was more prominent on Expt₈₇₋₉₁ compared to Expt₈₀₋₈₅. This may be due to different areas of the *13 Acres* site chosen to represent non-eroded, moderate and severe erosion treatments on each experiment, with subsequent greater effects of erosion on Expt₈₇₋₉₁.

Our findings showed that in the absence of amendments, recovery of artificially eroded soils was only partial, to a point below the level of non-eroded soil. Of the 91 data points in Fig. 4,

only 6 fell above 100% (i.e. grain yield on moderate or severe erosion > non-eroded), in the 53-yr timeline of the study. It should be noted that fallow (not a soil-building management practice) was a component of the study, especially in the early years. Also, no-till (a soil-building practice) was not fully implemented until 1997, i.e. 40 yr after erosion.

Manure application frequency and dose factors were reflected in manure legacy effects on wheat yield. As well as being established earlier, Expt₈₀₋₈₅ also received an overall lower rate of manure application, i.e. 93 Mg ha⁻¹ over 4 yr, (annualized to 23 Mg ha⁻¹ yr⁻¹) than Expt₈₇₋₉₁, which received 144 Mg ha⁻¹ over 3 yr (annualized to 48 Mg ha⁻¹ yr⁻¹). Also, applications were biennial (fallow–wheat) on Expt₈₀₋₈₅ vs. annual (continuous wheat) on Expt₈₇₋₉₁. Manure had a significant effect on wheat yields in 6 of 17 yr in the older Expt₈₀₋₈₅ with the lower manure application frequency and dose compared to 16 of 17 yr in the more recent Expt₈₇₋₉₁ with a higher frequency and dose. On Expt₈₀₋₈₅ the last significant manure effect on wheat yield occurred in 2006 (i.e. 22 yr after the final manure application) when the manure treatment was significantly higher ($\bar{x}$, +18%) than check and fertilizer treatments. For the 4 yr following 2006, the manure effect was non-significant. However, we cannot say for certain whether the manure effect would have re-occurred or not, since monitoring ceased in 2010. On Expt₈₇₋₉₁, significant manure effects occurred up to and including 2010 (i.e. 19 yr after cessation of manure).

The exponential relationships between time elapsed since last manure application and grain yield showed that after initially large yield responses following its application, the response to manure diminished (likely due to nutrient removal by higher net primary productivity), but nevertheless levelled-off to remain higher (up to +35% with severe erosion) than the non-amended (check) treatment (Fig. 5). Similar results were reported after 16 yr by Larney et al. (2009) from a more recent artificial erosion experiment (established in 1990), at Lethbridge, AB.

The superior ranking of the manure amendment agreed with previous findings from other artificial erosion experiments at Lethbridge, AB (Larney et al. 2009, 2016) and in wellsite reclamation studies in south-central Alberta (Larney et al. 2003, 2012; Zvomuya et al. 2007). On Expt₈₇₋₉₁ the fertilizer and straw amendments also demonstrated legacy effects on wheat yield under moderate and severe erosion. However, the topsoil amendment responses were not as effective as those reported by Larney et al. (2009, 2016), likely because the simulated erosion depths were shallower (0, 5, 10, 15, 20 cm) than those of the Expt₈₇₋₉₁ study.

All soil properties at 0–15 cm depth in 2011 reflected the negative legacy effect of erosion which occurred 54 yr prior. Across both Expt₈₀₋₈₅ and Expt₈₇₋₉₁ (all amendments), organic C concentration under moderate erosion averaged 70% of non-eroded (9.9 vs. 14.1 g kg⁻¹), while severe erosion organic C was 57% of non-eroded (8.1 vs. 14.1 g kg⁻¹). In the 54 yr since erosion, the eroded surfaces had been cropped to either barley (7 yr) or wheat (34 yr), or fallowed (13 yr), with only three fallow years between 1984 and 2011 (Fig. 1). However, return of residues from these crops failed to restore soil organic C on the moderate and severe erosion treatments. Soil total N was similarly unrestored. Soil NO₃-N was the property showing the least legacy effect of erosion, which is understandable, since NO₃-N is more dynamic than organic C, total N or available P, being more mobile in the soil profile and influenced by plant uptake. The erosion legacy effect on available P was more prominent than organic C and total N, with concentrations (mean of Expt₈₀₋₈₅ and Expt₈₇₋₉₁) under moderate erosion 42% of non-eroded (27 vs. 64 mg kg⁻¹), while under severe erosion, available P was only 34% of non-eroded (22 vs. 64 mg kg⁻¹). As well as removal of organic C and N, soil erosion also severely restricted soil P-supplying power which in turn impacted crop productivity.

McLauchlan (2006) reported that the duration of elevated soil organic C effects from manure is much longer than the duration of manure addition. Our findings bore this out. Expt^{80–85} received 93 Mg ha⁻¹ over 4 yr (1980–84) and this resulted in an 11% higher organic C content (0–15 cm depth, across all erosion levels) than the check treatment, 27–31 yr later (2011). Similarly, Expt^{87–91} received 144 Mg ha⁻¹ over 3 yr (1987–90), and this resulted in 29% higher organic C, some 21–24 yr later.

While erosion effects were evident at 15–30 and 30–60 cm depth, due to large incremental depths of topsoil removal in 1957, amendment effects were less evident at deeper soil depths. At 15–30 cm in 2011 on Expt^{80–85}, there remained a significant manure legacy effect on total N (0.47 vs. 0.37 g kg⁻¹ on the fertilizer treatment). At 30–60 cm, manure led to significantly higher NO₃-N (46 mg kg⁻¹) than both fertilizer and check (3–19 mg kg⁻¹) on the non-eroded treatment in 1987, while amendment effects were non-significant under moderate or severe erosion. This may have been due to greater NO₃-N leaching in the undisturbed non-eroded soil, compared with the eroded surfaces where adverse soil physical conditions may have restricted leaching. This effect had disappeared however by 2011 on Expt^{80–85}. However, on Expt^{87–91}, manure had a significantly higher NO₃-N concentration at 15–30 cm depth compared to all other amendments (4.2 vs. 2.9–3.3 mg kg⁻¹) in 2011. This may have been as a response to the higher frequency and dose effects, and more recent application of manure on Expt^{87–91} vs. Expt^{80–85}, as outlined earlier.

Larney et al. (2016) reported on soil properties from a more recent artificial erosion experiment established in 1990. Three erosion levels (non-eroded, 10, and 20 cm cuts) were established with three one-time amendment treatments (check, N + P fertilizer, manure) in 1990. In the absence of amendments, organic C on the the 10-cm cut recovered to the non-eroded

concentration by 2004, and the 20-cm depth (13.9 g kg^{-1}) remaining significantly lower than the non-eroded concentration (16.3 g kg^{-1}) through to 2012. Total N behaved similarly. Also in this study, among erosion levels and years (2004, 2012), organic C was 19% greater on the manure vs. check treatment (17.5 vs. 14.7 g kg^{-1}), demonstrating a strong legacy effect of manure. Additionally, water-stable aggregation exhibited a 22 yr legacy effect of manure.

Bürge et al. (2017) believed that determination of a measurable legacy effect was not only influenced by the intensity of an impact, but also by the ability of ecosystem functions to recover or to result in a new trajectory when the impact ended. McLauchlan (2006) pointed out that the longevity of the legacy effect of manure depends on the magnitude of the alteration of soil organic C. Larney et al. (2016) concluded that the legacy of manure application can be attributed to two concomitant mechanisms: (1) the enduring retention of soil organic matter and nutrients initially applied, (2) the benefits of extra residue additions (both above- and below-ground) resulting from higher yield responses to manure. With time, the former mechanism likely diminishes, but the latter likely gains prominence. In effect, the manure application instigates a self-perpetuating renewing cycle whereby greater productivity returns greater amounts of soil organic matter which, in turn, produces higher yields (Larney and Angers 2012). Morgan et al. (1994) and Keane et al. (2009) discussed the concept of historical range of variability (HRV) as it relates to land management change. This concept infers that if the intensity of disturbance or change in a site factor surpasses a specific threshold, conditions move outside the HRV and consequently ecosystem functions change. The system may remain in the new stage even if initial triggers are no longer present. The response may be a very long recovery or altogether switching to a new trajectory of change, therefore moving outside the HRV of the original system. Our findings for the erosion legacy effect would support this

concept, in that the initial ‘catastrophic’ erosion in 1957 created the intensity of disturbance which moved the soil outside its HRV and subjected it to a new trajectory of change. Organic amendments, like manure, have the ability to alter the trajectory of change and potentially speed up the recovery response.

Recently ‘land degradation neutrality’ (LDN) has become enshrined in various international agreements spearheaded by the United Nations (Akhtar-Schuster et al. 2017; Kust et al. 2017). In practical terms the LDN concept has two linked dimensions: (i) reducing the rate of degradation of non-degraded land; and (ii) increasing the rate of restoration of degraded land. Our work addresses the second dimension by assigning timelines to legacy effects of both erosion and soil amendments.

Conclusions

Long-term experiments, such as the ones reported in this paper, allow measurement of the longevity of both negative (erosion) and positive (soil amendments) legacy effects and their inter-relationships with crop productivity and soil health. Without any attempt at soil rehabilitation in this study, other than annual cropping (some fallow in early years), legacy effects of moderate and severe erosion were still measurable on wheat yield some 53 yr after erosion.

What would be considered low overall inputs of manure ($93\text{--}144\text{ Mg ha}^{-1}$), during narrow windows (3–4 yr) of the experimental timelines, had major repercussions for the legacy effect of restored productivity to eroded surfaces. Manure exerted long-term legacies on wheat yields, likely related to a self-perpetuating effect of increased net primary productivity over time. On the

more recent experiment, fertilizer and straw, but not topsoil, also elicited significant legacy effects (up to 20 yr) on yield, especially under severe erosion.

Imprints on soil properties after 54 yr (erosion) and after up to 31 yr (manure amendment) were also observed. There was also evidence of inhibited downward movement of $\text{NO}_3\text{-N}$ and available P to deeper profile depths (15–30 and 30–60 cm) on the moderate and severe erosion treatments compared to the non-eroded treatment. Our findings highlight the need for judicious soil management to avoid a return of increased erosion risk not seen on the Canadian prairies since the widespread adoption of conservation tillage in the 1990s.

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For Review Only

Table 1. Erosion (main plot) and amendment (sub-plot) treatments on Expt₈₀₋₈₅ and Expt₈₇₋₉₁.

Study	Duration	Management	Erosion	Amendment
Expt ₈₀₋₈₅	1980-85	Fallow-wheat	1. Non-eroded (undisturbed)	1. Check
			2. Moderate (10-20 cm cut)	2. Manure ^a
			3. Severe (>46 cm cut)	3. Fertilizer ^b
Expt ₈₇₋₉₁	1987-91	Cont. wheat	1. Non-eroded (undisturbed)	1. Check
			2. Moderate (10-20 cm cut)	2. Manure ^c
			3. Severe (>46 cm cut)	3. Fertilizer ^d
				4. Straw ^e
				5. Topsoil ^f

^a31 Mg ha⁻¹ (dry wt.) of manure in fall of fallow year (1980, 1982, 1984) prior to wheat (1981, 1983, 1985) = total of 93 Mg ha⁻¹ of manure added over a 4-yr time period (1980-84).

^b150 kg N (as urea) ha⁻¹ + 150 kg P (as triple superphosphate) ha⁻¹ in spring of crop year (1981, 1983, 1985).

^c36 Mg ha⁻¹ (dry wt.) of manure in fall 1987, fall 1988, fall 1989, and fall 1990 = total of 144 Mg ha⁻¹ added over a 3-yr time period (1987-90).

^d100 kg N (as urea) ha⁻¹ annually, fall 1987-90, + 100 kg N (as urea) ha⁻¹ and 75 kg P (as triple superphosphate) ha⁻¹ annually, spring 1988-91.

^e15 Mg ha⁻¹ of wheat straw (dry wt.) + fertilizer N (urea) to attain an equivalent C/N ratio of manure^c, annually, fall 1987-90.

^fOne-time addition of 5 cm of topsoil, fall 1987.

1   **Table 2.** Effect of erosion and amendment treatments on spring wheat grain yield, Expt_{80–85}, 1993–99 and 2001–10.

Year	1993	1994	1995	1996	1997	1998	1999	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Mean
Mg ha ⁻¹																		
Erosion																		
Non	3.06a	2.24a	3.44a	1.72a	1.79a	2.37a	1.54	1.67	1.24	1.64	2.30a	1.58	2.16a	1.71	2.27a	1.74	1.34	1.99a
Moderate	1.79b	1.19b	2.17b	0.79b	1.02b	1.46b	1.25	1.62	1.45	1.77	1.42b	1.01	1.57b	1.78	1.29b	1.64	1.45	1.45ab
Severe	1.67b	1.26ab	1.77b	0.75b	0.85b	1.26b	0.99	1.37	1.28	1.71	1.41b	0.77	1.56b	1.53	1.18b	1.62	1.43	1.32b
Amendment																		
Check	1.53b	1.01b	2.26b	0.91	1.07b	1.50b	1.16	1.43	1.34	1.69	1.49	0.99	1.70b	1.59	1.44	1.64	1.43	1.42b
Manure	3.17a	2.23a	2.86a	1.33	1.44a	1.95a	1.43	1.68	1.39	1.79	1.91	1.16	1.97a	1.79	1.62	1.79	1.52	1.83a
Fertilizer	1.82b	1.45b	2.26b	1.02	1.15b	1.64ab	1.19	1.54	1.24	1.64	1.73	1.22	1.63b	1.65	1.69	1.58	1.27	1.51b
P-value																		
Erosion	<0.001	0.04	0.001	0.03	0.01	0.008	0.23	0.47	0.49	0.89	0.04	0.12	0.01	0.41	0.02	0.75	0.89	0.02
Amend.	<0.001	<0.001	0.03	0.09	0.05	0.02	0.21	0.06	0.27	0.25	0.12	0.07	0.008	0.35	0.35	0.44	0.16	0.03
E × A ^a	0.31	0.60	0.64	0.74	0.66	0.17	0.29	0.12	0.64	0.20	0.88	0.17	0.36	0.71	0.76	0.26	0.94	0.51

2   **Note:** Within columns, and erosion and amendment treatments, means with different letters are significantly different from each other (Tukey-
3   Kramer, *P* < 0.05).
4   ^aErosion × amendment interaction effect.

1 **Table 3.** Effect of erosion and amendment treatments on spring wheat grain yield, Expt₈₇₋₉₁, 1993–99 and 2001–10.

Year	1993	1994	1995	1996	1997	1998	1999	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Mean
Mg ha ⁻¹																		
Erosion																		
Non	3.65 ^b	3.54 ^b	4.58 ^b	2.55 ^a	2.32 ^b	2.77 ^a	2.50 ^a	2.11 ^b	1.72 ^b	2.14 ^b	2.24 ^a	1.83 ^a	2.25 ^b	1.87 ^{a^b}	2.61 ^a	1.34	0.67 ^b	2.40 ^b
Moderate	2.27	1.92	2.53	1.07 ^b	1.09	1.57 ^b	1.27 ^b	1.46	1.48	1.75	1.72 ^b	1.17 ^b	1.61	1.81 ^a	1.53 ^b	1.54	1.57	1.61
Severe	2.01	1.40	2.03	0.69 ^b	0.81	1.17 ^b	1.07 ^b	1.05	1.21	1.49	1.43 ^b	0.66 ^c	1.25	1.35 ^b	1.04 ^b	1.58	1.47	1.28
Amendment																		
Check	1.83 ^c	1.37 ^c	2.58 ^c	1.13 ^b	1.14 ^c	1.56 ^b	1.37 ^b	1.30 ^c	1.39 ^c	1.85 ^c	1.62 ^b	1.07 ^b	1.58 ^c	1.71	1.61 ^b	1.34 ^b	1.07 ^c	1.50 ^c
Manure	4.01	3.75	3.96	2.20 ^a	2.01	2.53 ^a	2.15 ^a	1.96	1.75	1.92	2.23 ^a	1.58 ^a	2.00	1.85	2.12 ^a	1.71 ^a	1.44	2.31
Fertilizer	3.21	2.72	3.14	1.55 ^b	1.42	1.81 ^b	1.67 ^b	1.68	1.49	1.88	1.84 ^{ab}	1.24 ^b	1.77	1.71	1.76 ^b	1.51 ^{ab}	1.33	1.87
Straw	2.49	2.01	2.85	1.30 ^b	1.32	1.70 ^b	1.40 ^b	1.33	1.31	1.67	1.67 ^b	1.17 ^b	1.60	1.50	1.61 ^b	1.43 ^{ab}	1.18	1.62
Topsoil	1.70	1.59	2.70	0.99 ^b	1.16	1.58 ^b	1.47 ^b	1.42	1.40	1.6	1.62 ^b	1.04 ^b	1.55	1.61	1.53 ^b	1.45 ^{ab}	1.18	1.51
P-value																		
Erosion	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.003	0.04	0.004	<0.001	<0.001	0.04	0.003	0.46	<0.001	<0.001
Amend.	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.04	0.003	<0.001	<0.001	0.17	<0.001	0.01	0.006	<0.001
E × A ^c	<0.001	<0.001	<0.001	0.14	0.009	0.13	0.06	0.02	0.01	0.01	0.45	0.39	0.05	0.10	0.15	0.36	0.02	<0.001

2 **Note:** Within columns, and erosion and amendment treatments, means with the different letters are significantly different from each other
 3 (Tukey-Kramer, $P < 0.05$).

4 ^aErosion × amendment interaction effect.

5 ^bMeans separation not provided when erosion effect qualified by significant erosion × amendment interaction.

6 ^cMeans separation not provided when amendment effect qualified by significant erosion × amendment interaction.

Table 4. Parameter estimates for exponential decay relationships between time (yr) elapsed since last amendment application and grain yield (expressed as % of equivalent erosion check treatment).

Study	Erosion	Amendment	R ²	<i>P</i> -value, <i>a</i> coefficient ^a	<i>a</i> coefficient estimate, %	SE <i>a</i> coefficient, %
Expt ^{80–85}	Non	Manure	0.55	<0.001	100.3	5.3
		Fertilizer	0.29	0.09	n.a.	n.a.
	Moderate	Manure	0.73	<0.001	121.5	12.2
		Fertilizer	0.12	0.48	n.a.	n.a.
	Severe	Manure	0.89	<0.001	113.2	8.2
		Fertilizer	0.28	0.10	n.a.	n.a.
Expt ^{87–91}	Non	Manure	0.33	0.13	n.a.	n.a.
		Fertilizer	0.44	<0.001	90.3	10.2
		Straw	0.50	<0.001	82.6	7.3
		Topsoil	0.02	0.86	n.a.	n.a.
	Moderate	Manure	0.75	0.29	n.a.	n.a.
		Fertilizer	0.80	<0.001	119.1	14.7
		Straw	0.51	<0.001	104.7	4.9
		Topsoil	0.33	0.06	n.a.	n.a.
	Severe	Manure	0.71	0.03	135.1	55.6
		Fertilizer	0.74	<0.001	133.8	6.6
		Straw	0.51	<0.001	123.0	20.9
		Topsoil	0.07	0.62	n.a.	n.a.

Note: n.a = not applicable since *P*-value is non-significant.

^a*a* coefficient (horizontal asymptote) of equation $y = a + b\exp(-cx)$.

Table 5. Soil properties (0–15 cm depth) on Expt_{80–85}, 1987 and 2011, and change between 1987 and 2011.

Treatment	Organic C, g kg ⁻¹			Total N, g kg ⁻¹			NO ₃ -N, mg kg ⁻¹			Available P, mg		
	1987	2011	Change	1987	2011	Change	1987	2011	Change	1987	2011	Change
Erosion												
Non	14.0 ^b	13.4 ^a	-0.4	1.48 ^b	1.38 ^a	-0.08	13.4	11.3	-1.7	112 ^a	65 ^a	-47
Moderate	8.4	8.8 ^b	+0.4	0.91	0.92 ^b	+0.01	4.9	9.1	+4.2	33 ^b	19 ^b	-14
Severe	9.1	8.2 ^b	-0.8	0.94	0.84 ^b	-0.10	9.7	9.2	-0.5	75 ^{ab}	26 ^b	-49
Amendment												
Check	9.1 ^c	9.8 ^{ab}	+0.9 ^a	0.97 ^c	1.00 ^b	+0.05 ^a	4.5 ^b	9.1 ^b	+4.9 ^a	20 ^b	24	+8 ^a
Manure	13.0	10.9 ^a	-2.2 ^b	1.37	1.13 ^a	-0.25 ^b	18.4 ^a	11.5 ^a	-7.1 ^b	130 ^a	54	-81 ^c
Fertilizer	9.3	9.7 ^b	+0.6 ^a	1.00	1.00 ^b	+0.02 ^a	5.1 ^b	9.0 ^b	+4.1 ^a	69 ^b	33	-36 ^b
P-value												
Erosion	0.002	<0.001	0.12	0.001	<0.001	0.12	0.11	0.17	0.25	0.005	0.004	0.07
Amendment	<0.001	0.03	<0.001	<0.001	0.01	<0.001	0.002	0.02	0.005	<0.001	0.09	<0.001
E × A ^a	0.04	0.72	0.17	0.01	0.37	0.31	0.57	0.22	0.64	0.46	0.95	0.12

Note: Within columns, and erosion and amendment treatments, means with different letters are significantly different from each other (Tukey-Kramer, $P < 0.05$).

^aErosion × amendment interaction effect.

^bMeans separation not provided when erosion effect qualified by significant erosion × amendment interaction.

^cMeans separation not provided when amendment effect qualified by significant erosion × amendment interaction.

Table 6. Soil properties (0–15 cm depth) on Expt_{87–91}, 2011.

Treatment	Organic C	Total N	NO ₃ -N	Available P
	g kg ⁻¹		mg kg ⁻¹	
Erosion				
Non	14.8 <i>a</i>	1.54 <i>a</i>	9.5 <i>b</i>	62 <i>a</i>
Moderate	10.9 <i>b</i>	1.13 <i>b</i>	12.7 <i>a</i>	35 <i>b</i>
Severe	7.9 <i>c</i>	0.80 <i>c</i>	9.8 <i>b</i>	18 <i>b</i>
Amendment				
Check	10.3 <i>b</i>	1.08 <i>b</i>	9.5 <i>b</i>	26 <i>b</i>
Manure	13.7 <i>a</i>	1.42 <i>a</i>	13.1 <i>a</i>	98 <i>a</i>
Fertilizer	10.5 <i>b</i>	1.10 <i>b</i>	9.5 <i>b</i>	38 <i>b</i>
Straw	10.4 <i>b</i>	1.06 <i>b</i>	10.5 <i>ab</i>	17 <i>b</i>
Topsoil	11.0 <i>b</i>	1.13 <i>b</i>	10.6 <i>ab</i>	14 <i>b</i>
	<i>P</i> -value			
Erosion	<0.001	0.001	0.01	<0.001
Amendment	<0.001	<0.001	0.003	<0.001
E × A ^a	0.57	0.39	0.08	0.24

Note: Within columns, and erosion and amendment treatments, means with different letters are significantly different from each other (Tukey-Kramer, *P* < 0.05).

^aErosion × amendment interaction effect.

Figure captions

Fig. 1. History of crop management (1957–2011) on the *13 Acres* erosion-productivity site, Lethbridge, AB, including Expt_{80–85} and Expt_{87–91}. L = land-levelling; B = barley; W = wheat; F = fallow. Triangles on top x-axis represent manure amendment applications as detailed in Table 1.

Fig. 2. Significant erosion × amendment interaction effects on wheat grain yield on Expt_{87–91} in (a) 1993; (b) 1997; (c) 2003; and (d) 2010. Yields expressed as a percent of the check treatment (dotted line = 100%) at each erosion level. Within erosion levels, bars with different letters are significantly different from each other (Tukey-Kramer, $P < 0.05$).

Fig. 3. Effect of erosion and amendment on mean wheat grain yield (a) 1993–1999, and (b) 2001–2010, on Expt_{87–91}. Error bars represent standard errors. Within erosion treatments, amendment means with different letters are significantly different from each other (Tukey-Kramer, $P < 0.05$). *, significant ($P < 0.05$) difference in grain yield between incremental erosion treatments within amendments. NS, nonsignificant difference in grain yield between incremental erosion treatments within amendments. §, significant ($P < 0.05$) difference in grain yield between severe erosion and non-eroded treatment within amendment.

Fig. 4. Legacy effects of moderate and severe erosion treatments (established 1957) on grain yield (1958–2010). Estimated as (grain yield on moderate or severe erosion check treatment / grain yield on non-eroded check treatment) × 100. Older experiments severe erosion data from Dormaar et al. (1986). 1958–64 data is a mean of 7 yr. Expt_{80–85} data for 1981, 1983 and 1985

from Dormaar et al. (1988). Expt₈₇₋₉₁ data for 1988–91 from Dormaar et al. (1997a). Expt₈₀₋₈₅ and Expt₈₇₋₉₁ data for 1993–2010 from current study.

Fig. 5. Legacy effects of manure amendments last applied in 1984 (Expt₈₀₋₈₅) or 1990 (Expt₈₇₋₉₁) on grain yield at three erosion levels. Estimated as (grain yield on manure sub-treatment/grain yield on check sub-treatment) $\times$ 100 at each erosion level. Parameter estimates are shown in Table 4.

Fig. 6. Legacy effects of fertilizer and straw amendments on Expt₈₇₋₉₁, last applied in 1991 (fertilizer) or 1990 (straw), on grain yield at three erosion levels. Estimated as (grain yield on fertilizer/straw sub-treatment/grain yield on check sub-treatment) $\times$ 100 for each erosion level. Solid regression lines indicate fertilizer fits; dotted regression lines indicate straw fits. Parameter estimates are shown in Table 4.

209x147mm (300 x 300 DPI)

Fig. 2.

296x418mm (300 x 300 DPI)

Fig. 3.

296x418mm (300 x 300 DPI)

Fig. 4.

296x418mm (300 x 300 DPI)

Fig. 5.

120x95mm (300 x 300 DPI)

Fig. 6.

296x418mm (300 x 300 DPI)