PS&C
Prairie Soils &
Crops Journal

Long-Term Erosion-Productivity Relationships: The Lethbridge Soil Scalping Studies

Francis J. Larney and H. Henry Janzen
Agriculture & Agri-Food Canada, 5403 1st Avenue South, Lethbridge, Alberta T1J 4B1
francis.larney@agr.gc.ca

Summary
Soil erosion by wind or water removes valuable topsoil and decreases soil productivity. What is the value of this topsoil in terms of maintaining crop yield? When restoring eroded soils, how long do the effects of one-time applications of soil amendments last and is the magnitude or longevity of these effects influenced by the level of erosion? This study was conducted to answer these questions and ascertain the effects of simulated erosion on soil productivity and methods for its amendment. Incremental depths (0, 5, 10, 15, and 20 cm) of surface soil, or cuts, were mechanically removed to simulate erosion at two sites (one dryland, one irrigated) in southern Alberta in 1990. This approach is often referred to as 'soil scalping'. Three amendment treatments (nitrogen + phosphorus fertilizer, 5 cm of topsoil, or 75 Mg ha^{-1} of feedlot manure) and a check were superimposed on each cut. The sites have been cropped annually since 1990 with no further amendments. Average grain yield reductions during the first 16 yr were 10.0% for 5 cm, 19.5% for 10 cm, 29.0% for 15 cm, and 38.5% for 20 cm of topsoil removal. There was evidence that the restoration of productivity levelled off at a value less than the non-eroded treatment rather than gradually converging on it, within the timeline of the study. Also a one-time application of livestock manure at the outset of the experiment was able to compensate for topsoil loss, especially in the early years of the study. The study reinforces the need to prevent soil erosion and indicates that application of livestock manure is an option for restoring soil productivity in the short term.

Introduction
The Canadian prairies are dotted with areas of low productivity due to past soil erosion caused mainly by wind or water. The downslope movement of topsoil by successive tillage operations over many decades on hummocky land is also a form of erosion.[1] Yield responses to inputs (e.g. nutrients, herbicides) are often reduced on eroded areas of the fields compared to more productive areas, which only serves to exacerbate the interlinked problems of low yield, low return of organic matter to the soil, and further degradation from erosion.

To adequately assess the effects of soil erosion on agricultural production, an understanding of the response of crop productivity to soil erosion is essential. One of the problems in assessing erosion-productivity relationships is the difficulty in detecting a decline in productivity that results from erosion. Imperceptible yield change caused by imperceptible soil loss due to erosion is hard to recognize let alone measure. Topsoil removal (simulated or artificial erosion, de-surfacing or scalping), whereby incremental depths of topsoil, or cuts, are mechanically removed with an excavator, is one approach in quantifying erosion effects on soil productivity.

Levels of organic amendments necessary to restore productivity may also be studied with this scalping approach, where different amendments may be applied at various rates in an effort to restore soil productivity. Enhanced awareness of soil conservation issues coupled with higher commodity prices on the Canadian prairies may encourage the restoration of eroded soils in order to return them to full productivity. Restorative options include addition of manure, crop residues or fertilizer. Manure may directly enhance soil physical properties such as aggregate stability and water retention. In some areas of the prairies, intensive livestock production (e.g., beef cattle feedlots in southern Alberta, hog operations in southern Manitoba) generates an abundant supply of manure for land application.

A series of soil productivity studies was initiated on six sites in Alberta in 1990-91. Four sites were located in southern Alberta (two in the Dark Brown soil zone at the Lethbridge Research Centre, one dryland, one irrigated; one in the Brown soil zone near Taber, AB and one in the Black soil zone near Hill Spring, AB). Two further sites were located at Cooking Lake (Gray Luvisol) and Josephburg, (Black soil zone) east of Edmonton. At each site incremental depths of topsoil (0, 5, 10, 15, 20 cm) were mechanically removed. Following topsoil removal, the resulting surfaces were amended with: (1) check (no amendment); (2) fertilizer; (3) 5 cm of topsoil addition, or (4) feedlot manure as a single application aimed at restoring soil productivity. Erosion, but not amendment, effects in the initial year at all six sites established in 1990-91 have been reported.[2] The early impact (first 2-3 yr) on crop[3] and soil[4] responses at the four southern Alberta sites has also been reported as has crop response (1991-95) at the two north-central Alberta sites.[5] The Hill Spring site was terminated after 2 yr (1991-92), the Taber site after 4 yr (1990-93), and the Cooking Lake and Josephburg sites after 5 yr (1991-95). Results showed that organic amendments like manure were able to substitute for topsoil loss, at least in the short-term. The Lethbridge dryland and irrigated sites are still maintained in their original design and 2012 marks their 23rd year.

The above scalping studies were not the only ones conducted at the Lethbridge Research Centre. Also in 1990, a sister study was initiated at the four southern Alberta sites, alongside the above plots, to examine three levels of topsoil removal (0, 10, 20 cm cuts corresponding to uneroded, moderately and severely eroded conditions) and various combinations of nitrogen and phosphorus fertilizer application rates.[6, 7] In 1992, the fertilizer treatments were replaced by manure application rate treatments at the Lethbridge dryland and irrigated and Taber sites.[8] For this particular study, the Hill Spring site was terminated after 2 yr (1991-92) and the Taber site after 4 yr (1990-93) while the Lethbridge dryland and irrigated sites ran until the 2007 growing season.

Yet another scalping study, established in 1992, had only one level of topsoil removal (15 cm cut) and 14 one-time amendment treatments, including various livestock manures and plant residues (20 Mg ha^{-1} dry wt.) and inorganic fertilizers. Short-term (first 3 yr)[9] and long-term (first 18 yr)[10] findings have been published which showed that that the overall best amendments for restoring soil productivity were hog manure, poultry manure and alfalfa hay. This study is on-going. An older scalping study initiated in 1967 at the Lethbridge Research Centre had three levels of topsoil removal (created after land-leveling for irrigation) and five amendment treatments.[11,12,13,14] This experiment was cropped until 2010 and then terminated.

Soil scalping studies were also established in Manitoba[15,16,17,18] and Montana[19,20,21,22] but as far as the authors are aware, those at Lethbridge are the only remaining long-term scalping experiments in the northern Great Plains area.

Description of Studies

This paper will focus on the Lethbridge dryland and irrigated sites established in 1990.[3,4] In summary, two sites (one dryland, one irrigated) on Dark Brown Chernozemic sandy clay loam soils were scalped in spring 1990 at the Agriculture and Agri-Food Canada Research Centre at Lethbridge, Alberta (49° 43' N, 112° 48' W). Five simulated erosion treatments were established at each site by mechanically removing to various depths or cuts (Table 1) using an excavator with a grading bucket. Four sub-treatments were superimposed (split-plot) on each of the main treatments: check, fertilizer, feedlot manure and topsoil (Table 1). Plots were replicated four times in a randomized complete block design (5 cuts x 4 amendments x 4 replicates = 80 plots).

Major Findings from the Study

Relationships between depth of topsoil removal and average crop yield (1990-2006) were derived and used to predict values for grain yield losses due to topsoil removal and amendment treatments at both sites (Table 1).[23] The values show the relative effectiveness of the amendments in reducing yield losses associated with the scalping treatment in the order: manure > topsoil > fertilizer, that is, the manure application was the most beneficial. As an example, the large biomass response to manure on the 20-cm cut at Hill Spring is shown in Fig. 1.

For grain yield at the dryland site, yield responses ranged from a gain of 14.1% on the 0-cm cut-manure treatment to a loss of 42.9% on the 20-cm cut-check treatment. At the irrigated site, the same two treatments were the highest and lowest yielding with a gain of 9.7% on the 0- cm cut-manure treatment and a loss of 34.1% on the 20-cm cut-check treatment.

The magnitude of yield responses with addition of manure and topsoil (over the check treatments on equivalent cuts) increased with depth of cut. Using the values in Table 1, for example, dryland grain yield increases with manure compared to the corresponding check plots at each cut were 14.1% on the 0-cm cut, 21.5% (= absolute difference between +11.4 and -10.1% values in Table 1) on the 5-cm cut, 28% on the 10-cm cut, 34.5% on the 15-cm cut, and 41% on the 20-cm cut. This data is for the first 16 yr. However when the data is split into the first 8 yr (Fig. 2) and the second 8 yr (Fig. 3), differences emerge. While the trends are the same (*i.e.* increased yield response to manure as depth of erosion increases), the magnitude of the responses was lower (roughly about half at each level of erosion) for the second 8 yr period (Fig. 3). This is likely due to two concurrent developments at play: (1) the diminishing power of manure with time since application and (2) the build-up of productivity on the check plots due to continuous cropping and no-till management. If we look at the average of the first 8 yr (Fig. 2), at no point did the manure line fall below the 100% mark showing that addition of manure was able to compensate for >20 cm of topsoil loss. However for the second 8 yr (Fig. 3), the manure line crossed 100% at ~7.5 cm depth, showing that manure compensated for a shallower depth of topsoil loss as the study progressed. The second factor at play, *i.e.,* the "bounce-back" effect of the check (unamended plots) is shown by higher values for the check treatment in Fig. 3 *vs*. Fig. 2.

Compared with manure, lower grain yield increases for topsoil addition were found when averaged over 16 yr (Table 1): 5.8% on the 0-cm cut, 11.2% on the 5-cm cut, 15.7% on the 10-cm cut, 20.2% on the 15-cm cut and 24.7% on the 20-cm cut (dryland site). In contrast, fertilizer addition resulted in yield increases that were in a relatively consistent range with cut (5.2% on the 0-cm cut to 10.1% on the 20-cm cut for dryland grain). The ranges in grain yield increases due to manure and topsoil amendment on each cut on the irrigated site were lower than on the dryland site. For manure, the range was from 5.7% on the 0-cm cut to 25.8% on the 20-cm cut (compared with 14.1-41%). For topsoil the range was from 3.1% on the 0-cm cut to 14.1% on the 20-cm cut (compared with 5.8-24.7% on the dryland site). The grain yield response to fertilizer was also quite consistent and lower than the dryland site with a very narrow range from 1.1-2.9% across all cuts.

The average grain yield during 16 yr on the check treatment fell 2.1% cm^{-1} depth of topsoil removal on the dryland site and 1.7% cm^{-1} for the irrigated site. In contrast, grain yield on the manure treatment fell by 0.8% cm^{-1} on the dryland site and 0.9% cm^{-1} on the irrigated site. Declines in grain yield on the topsoil treatment were intermediate between the check and manure treatments at 1.2% cm^{-1} on the dryland site and 1.3% cm^{-1} on the irrigated site.

The behaviour of the check plots on each cut represents the effect of simulated erosion followed by no attempt to amend or rehabilitate the newly-created surface soils, other than continuous cropping under no-till management. Using linear equations for the check plots on each cut yield losses were derived per centimetre of simulated erosion for grain at both sites (over 16 yr). Average grain yield loss was 50 kg ha^{-1} cm^{-1} yr^{-1} at the dryland site and 59 kg ha^{-1} cm^{-1} yr^{-1} at the irrigated site. This represents the value of topsoil expressed in grain yield. If we take an average price of wheat at \$240 $tonne^{-1}$ in 2006 then 50 kg ha^{-1} cm^{-1} yr^{-1} represents \$12 ha^{-1} cm $soil^{-1}$ yr^{-1} (~\$12 ac^{-1} inch $soil^{-1}$ yr^{-1}).

Our results provide information on placement of amendments in naturally eroded fields and indicate that yield responses to manure or topsoil were greater as the severity of erosion increased. Our findings showed that in the absence of amendments, recovery of eroded soils is only partial, to a point below the level of non-eroded soil, even under continuous cropping and no-till management. Also while erosion severely limits crop yields and reduces soil carbon inputs, the deleterious effect may be mitigated with addition of an organic amendment such as manure. Even a one-time addition of manure has long-term consequences on wheat yields, likely related to a self-perpetuating effect of increased biomass production over time. Widespread adoption of conservation tillage practices has reduced erosion risks on the Canadian prairies but other areas of the world still rely heavily on conventional tillage operations that leave soil prone to erosion and jeopardize agricultural sustainability. Our results demonstrate that efforts to reduce erosion risk on agricultural soils must persist.

The experience gained from the above studies was very useful in implementing research projects on well-site reclamation in the oil and gas industry. A major issue in reclaiming older well-sites is the lack of available topsoil, so studies were set up to examine the effects of various topsoil replacement depths in combination with soil amendments (compost, manure, alfalfa hay, wheat straw, check) for reclamation purposes.[24,25,26,27]

An overall finding of erosion-productivity-soil amendment research is that once soil organic carbon is given an initial boost by addition of amendments (especially manure or compost with its high level of stable carbon), the effect may be self sustaining, provided land is farmed under a soil building management system (absence of fallow, continuous no till and fertilizer replacement of N and P removed).[28]

The Future

The incidence of soil erosion on dryland on the Canadian prairies has decreased dramatically since this study was initiated in 1990, due largely to the widespread adoption of no- till. However, erosion still occurs in some years on irrigated land in southern Alberta, where no- till management is less common. Additionally many areas of the prairies exhibit low productivity due to past erosion. These experiments will provide information on the recovery of eroded soils as well as yield losses associated with erosion over the long-term.

The plots at the Lethbridge dryland and irrigated scalping sites continue to be cropped to spring wheat on an annual basis and exist on a shoestring budget with few inputs apart from seed, fertilizer and herbicide and labour required for seeding and harvesting. The 2012 growing season represents 23 years of cropping. In the early years, soil sampling for nutrient analysis was conducted annually. Since then, soil sampling frequency has been reduced to once every 4-5 years. The hope is for continued monitoring of these plots every 4-5 years (annual wheat yield, soil organic C determinations) into the foreseeable future. They have a role to play in determining the recovery rates of eroded or disturbed soils (e.g. from oil and gas activity) either with or without organic amendments such as manure.

Land degradation is an increasing problem worldwide and organic amendments may play a role in restoring ecosystem health and services. Successful soil restoration has food security benefits by way of returning unproductive land to its full yield potential. This renders further environmental benefits, as increases in net primary productivity will result in increased C inputs to soil and C sequestration. Although there is ample work on short-term soil restoration trials, the long-term impact of soil erosion and organic amendments on degraded land requires continued exploration.

Acknowledgements

We value the foresight of Dr. Wayne Lindwall (retired), AAFC-Lethbridge, for his support in the establishment of soil scalping research plots in 1990. We thank Andrew Olson, Tony Curtis, and Paul DeMaere for technical assistance and the many field staff and students who have worked on the plots over the years. Dr. Barry Olson managed the study from 1991-92. The Canada-Alberta Soil Conservation Initiative (CASCI), a federal-provincial agreement under the National Soil Conservation Program, initially funded this research.

Table 1. Outline of experimental treatments established in 1990 at the Lethbridge scalping plots.

Treatment	Effect	Number	Description	Plot size
Main	Topsoil removal[1]	5	0 cm	12 x 10 m
			5 cm	
			10 cm	
			15 cm	
			20 cm	
Sub	Amendment	4	Check	3 x 10 m
			Fertilizer (75 kg ha^{-1} N; 22 kg ha^{-1} P)[2,3]	
			Manure (75 Mg ha^{-1})[2,4]	
			Topsoil (5 cm reapplied)[2]	

[1]After topsoil removal in 1990, seedbed preparation consisted of one pass of a powered rotary cultivator to 10 cm depth as the scalped plots were dry and compact. Subsequently the sites were managed under no-till.
[2]Applied in initial year (1990) only. After 1990 all plots (including check) received broadcast applications of 40 kg ha^{-1} N and 9 kg ha^{-1} P (rates doubled at the irrigated site). Spring wheat was seeded at a 17.5-cm row spacing in May-June each year from 1990-2011, except in 2004 when sites were chemical fallowed (herbicides used for weed control) in an effort to control build-up of wild oats and green foxtail.
[3]Fertilizer N and P rates were doubled at the irrigated site.
[4]Manure water content, 0.35 kg kg^{-1}; total carbon, 190 g kg^{-1}; total nitrogen, 22 g kg^{-1} (all dry wt. basis).

Table 2. Average wheat yield losses (negative values) or gains (positive values) with incremental depths of topsoil removal and amendment treatments at Lethbridge dryland and irrigated sites, 1990-2006 (predicted from equations in Larney et al.[23]).

Cut	Amendment	dryland	Irrigated
		%	
0-cm	Check	0.0[1]	0.0[1]
	Fertilizer	+5.2	+3.3
	Manure	+14.1	+9.7
	Topsoil	+5.8	+6.9
5-cm	Check	–11.4	–8.6
	Fertilizer	–4.3	–5.7
	Manure	+10.1	+5.2
	Topsoil	–0.2	+0.4
10-cm	Check	–21.9	–17.1
	Fertilizer	–13.8	–14.7
	Manure	+6.1	+0.7
	Topsoil	–6.2	–6.1
15-cm	Check	–32.4	–25.6
	Fertilizer	–23.3	–23.7
	Manure	+2.1	–3.8
	Topsoil	–12.2	–12.6
20-cm	Check	–42.9	–34.1
	Fertilizer	–32.8	–32.7
	Manure	–1.9	–8.3
	Topsoil	–18.2	–19.1

[1]The 0 cm cut-check treatment is set at zero and all other treatments are expressed relative to that.

Fig. 1. Productivity of spring wheat plots (3 x 10 m) following 20 cm of topsoil removal at Hill Spring, Alberta, July 17, 1991. Left: Check treatment (no amendment); Right: Manure treatment (75 Mg ha^{-1}, wet wt. cattle manure). See Larney et al.[3] for further details, including crop yields.

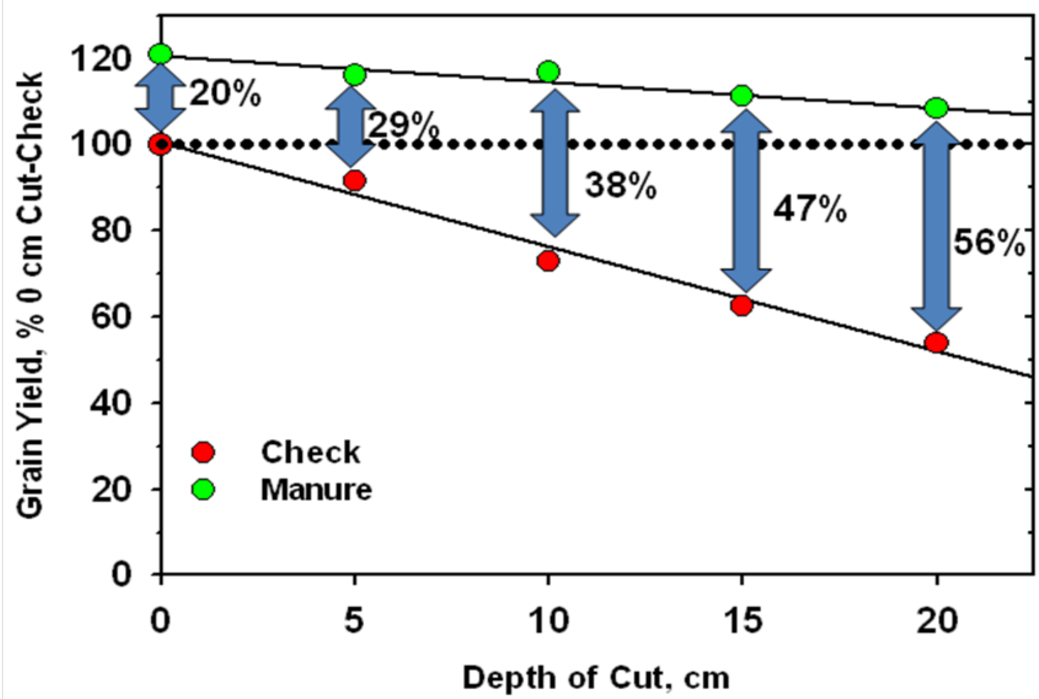

Fig. 2. Impact of erosion level (scalping depth) on yield response (%) to manure addition in first 8 yr (1990-97) at Lethbridge dryland site. All yields expressed relative to the 0-cm Cut-Check treatment set at 100%.

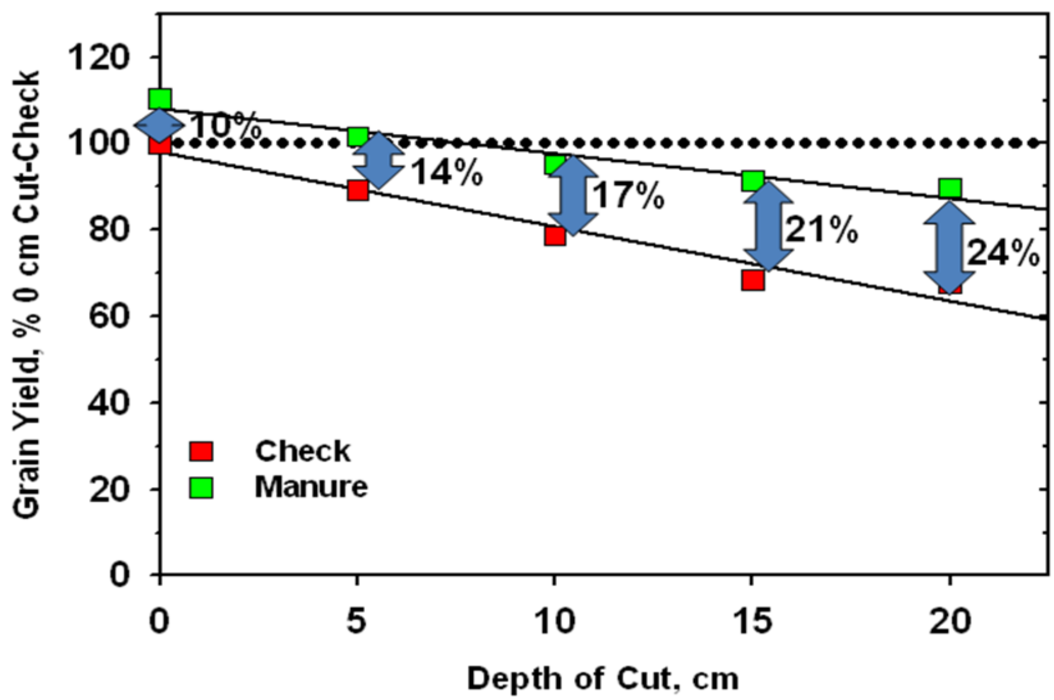

Fig. 3. Impact of erosion level (scalping depth) on yield response (%) to manure addition in second 8 yr (1998-2006) at Lethbridge dryland site. All yields expressed relative to the 0-cm Cut-Check treatment set at 100%.

References

1. Lobb, D.A., Kachanoski, R.G. and Miller, M.H. 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using ^{137}Cs as a tracer. Can. J. Soil Sci. 75: 211–218.
2. Larney, F.J., Izaurralde, R.C., Janzen, H.H., Olson, B.M., Solberg, E.D., Lindwall, C.W., and Nyborg, M. 1995. Soil erosion-crop productivity relationships for six Alberta soils. J. Soil Water Conserv. 50: 87–91.
3. Larney, F.J., Olson, B.M., Janzen, H.H. and Lindwall, C.W. 2000. Early impact of simulated erosion and soil amendments on crop productivity. Agron. J. 92: 948–956.
4. Larney, F.J., Janzen, H.H., Olson, B.M. and Lindwall, C.W. 2000. Soil quality and productivity responses to simulated erosion and restorative amendments. Can. J. Soil Sci. 80: 515–522.
5. Izaurralde, R.C., Malhi, S.S., Nyborg, M., Solberg, E.D. and Quiroga Jakas, M.C. 2006. Crop performance and soil properties in two artificially eroded soils in north-central Alberta. Agron. J. 98: 1298–1311.
6. Larney, F.J., Janzen, H.H. and Olson, B.M. 1995. Efficacy of inorganic fertilizers in restoring wheat yields on artificially eroded soils. Can. J. Soil Sci. 75: 369–377.
7. Smith, E.G., Peng, Y., Lerohl, M. and Larney, F.J. 2000. Economics of N and P fertilization to restore wheat yields on three artificially eroded sites in southern Alberta. Can. J. Soil Sci. 80: 165–169.
8. Larney, F.J. and Janzen, H.H. 1997. A simulated erosion approach to assess rates of cattle manure and phosphorus fertilizer for restoring productivity to eroded soils. Agric. Ecosyst. Environ. 65: 113–126.
9. Larney, F.J. and Janzen, H.H. 1996. Restoration of productivity to a desurfaced soil with livestock manure, crop residue and fertilizer amendments. Agron. J. 88: 921–927.
10. Larney, F.J., Janzen, H.H. and Olson, A.F. 2011. Residual effects of one-time manure, crop residue and fertilizer amendments on a desurfaced soil. Can. J. Soil Sci. 91: 1029–1043.
11. Dormaar, J.F. Lindwall, C.W. and Kozub, G.C. 1988. Effectiveness of manure and commercial fertilizer in restoring productivity of an artificially eroded Dark Brown Chernozemic soil under dryland conditions. Can. J. Soil Sci. 68: 669–679.
12. Freeze, B.S., Webber, C., Lindwall, C.W. and Dormaar, J.F. 1993. Risk simulation of the economics of manure application to restore eroded wheat cropland. Can. J. Soil Sci. 73: 267–274.

13. Dormaar, J.F., Lindwall, C.W. and Kozub, G.C. 1997. Role of continuous wheat and amendments in ameliorating an artificially eroded Dark Brown Chernozemic soil under dryland conditions. Can. J. Soil Sci. 77: 271–279.
14. Dormaar, J.F., Lukow, O.M., Lindwall, C.W. and Kozub, G.C. 1997. Effect of artificially eroded Dark Brown Chernozemic soil and subsequent amendments on the milling and baking quality of wheat under dryland conditions. Can. J. Soil Sci. 77: 27–32.
15. Ives, R.A. and Shaykewich, C.F. 1983. Effect of erosion on soil productivity. Pp. 114–120 *in* Soil Erosion and Land Degradation. Proc. 2nd. Ann. Western Prov. Conf. on Rationalization of Water and Soil Research and Management. November 29-December 1, 1983, Saskatoon, SK.
16. Morrison Ives, R. and Shaykewich, C.F. 1985. Effect of simulated soil erosion on wheat yields on the humid Canadian prairie. J. Soil Water Conserv. 42: 205–208.
17. Morrison Ives, R. and Shaykewich, C.F. 1985. The effect of soil erosion on soil productivity: preliminary findings of a two-year study. Pp. 30-34 *in* Proc. 7th. Ann. Manitoba-North Dakota Zero Tillage Workshop, January 10-11, 1985, Brandon, MB.
18. Kapoor, A. and Shaykewich, C.F. 1990. Simulated soil erosion and crop productivity. Pp. 125–130 *in* Proc. 33rd. Ann. Mtg. Manitoba Soc. Soil Sci., January 9-10, 1990, Winnipeg, MB.
19. Tanaka, D.L. and J.K. Aase. 1989. Influence of topsoil removal and fertilizer application on spring wheat yields. Soil Sci. Soc. Am. J. 53: 228–232.
20. Tanaka, D.L. 1990. Topsoil removal influences on spring wheat water-use efficiency and nutrient concentration and content. Trans. ASAE. 33: 1518–1524.
21. Williams, J.R., and D.L. Tanaka. 1996. Economic evaluation of topsoil loss in spring wheat production in the northern Great Plains, USA. Soil Tillage Res. 37: 95–112.
22. Allen, B.L., Cochran, V.L., Caesar, T. and Tanaka, D.L. 2011. Long-term effects of topsoil removal on soil productivity factors, wheat yield and protein content. Arch. Agron. Soil Sci. 57: 293–303.
23. Larney, F.J., Janzen, H.H., Olson, B.M. and Olson, A.F. 2009. Erosion-productivity-soil amendment relationships for wheat over 16 years. Soil Tillage Res. 10: 73–83.
24. Larney, F.J., Akinremi O.O., Lemke, R.L., Klaassen, V.E. and Janzen, H.H. 2003. Crop response to topsoil replacement depth and organic amendment on abandoned natural gas wellsites. Can. J. Soil Sci. 83: 415–423.
25. Larney, F.J., Akinremi, O.O., Lemke, R.L., Klaassen, V.E. and Janzen, H.H. 2005. Soil responses to topsoil replacement depth and organic amendments in wellsite reclamation. Can. J. Soil Sci. 85: 307–317.
26. Zvomuya, F., Larney, F.J., DeMaere, P.R. and Olson, A.F. 2007. Reclamation of abandoned wellsites with organic amendments: effects on soil carbon, nitrogen and phosphorus. Soil Sci. Soc. Am. J. 71: 1186–1193.
27. Zvomuya, F., Larney, F.J., DeMaere, P.R. and Olson, A.F. 2008. Organic amendment effects on crop productivity and nutrient uptake on reclaimed natural gas wellsites. Nutr. Cycl. Agroecosyst. 80: 223–232.
28. Larney, F.J. and Angers, D.A. 2012. The role of organic amendments in soil reclamation: A review. Can. J. Soil Sci. 92: 19–38.