SOIL EROSION EFFECTS ON SOIL QUALITY AND YIELD

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This study examines the cumulative effect of erosion on soil properties that are important to productivity, and estimates the effect of erosion on grain yields. Experiments were located in central Saskatchewan on Dark Brown soils of the Weyburn Association. The relationship between yields and relative distance down eroded hillslopes was described best by a third-order polynominal equation. Grain yields were lowest on the upper slopes and increased steadily through mid-slopes to maximum values that were often double the upper slope yield on the lower or foot slope, then decreased again in the more level parts of the fields away from the slope. The impact of varying degrees of erosion on productivity was estimated by adding back incremental depths of topsoil to eroded knolls. Grain yields were increased by 45–58% by adding 50 mm of topsoil, with additional topsoil (100 or 150 mm) generally increasing yields slightly, but at a decreasing rate. Changes in soil quality with increasing erosion were measured on otherwise similar soils on eroded knolls, with the period of cultivation ranging from 0 (native) to 75 yr. Reductions in the amount of ^{137}Cs in surface horizons with increasing period of cultivation indicated the cumulative effects of erosion, with general soil losses of 20 to 30 Mg ha^{-1} yr^{-1}. Consistent reductions in silt plus very fine sand fractions with time suggested that wind erosion had been dominant. Organic C and P, total N and S decreased with increasing erosion. Potentially mineralizable N descreased at a faster rate than total N. The $CaCO_3$ content of surface horizons increased, and inorganic P remained constant with increasing degree of erosion.

Key words: Nutrients, soil productivity, soil quality, eroded, catena.

[Effets de l'érosion sur la qualité et le rendement du sol.]
La présente étude avait pour but d'examiner l'effet cumulatif de l'érosion sur les propriétés du sol qui contribuent à sa productivité et d'estimer les effets de l'érosion sur le rendement en céréales. Les essais ont été effectués dans le centre de la Saskatchewan sur des sols brun foncé de l'association Weyburn. Une équation polynômiale de troisième ordre décrit le mieux la relation qui existe entre le rendement et la distance relative le long des pentes érodées et selon laquelle le rendement sur les épaulements est légèrement inférieur à celui au sommet, puis augmente de façon soutenue jusqu'au milieu de la pente pour atteindre une valeur maximale souvent deux fois supérieure au rendement dans les portions supérieures de la pente, avant de diminuer de nouveau dans les sections plus planes des champs, loin de la pente. Nous avons estimé les effets de différents degrés d'érosion sur la productivité, en ajoutant de la terre de surface aux monticules érodés. L'addition de 50 mm de terre arable a entraîné une augmentation de 45 à 58 % du rendement en céréales, l'addition de terre arable supplémentaire (100 ou 150 mm) provoquant généralement une légère hausse du rendement, à un rythme toutefois décroissant. Les changements dans la qualité du sol sous l'effet de l'érosion ont été mesurés sur des sols similaires de monticules érodés, la période de culture variant de 0 (état naturel) à 75 ans. La réduction de la teneur en ^{137}Cs dans les horizons de surface avec l'augmentation du nombre d'années de culture montre les effets

cumulatifs de l'érosion, les pertes de sol s'établissant généralement entre 20 et 30 Mg ha^{-1} an^{-1}. Par ailleurs, les réductions constantes des fractions de limon et de sable très fin avec le temps laisse croire que l'érosion éolienne a été un facteur dominant. Les teneurs en C et en P organiques, ainsi qu'en N total et en S total, ont diminué avec l'érosion. La teneur en N potentiellement minéralisable a diminué plus rapidement que celle en N total. Enfin, la teneur en $CaCO_3$ des horizons de surface a augmenté, alors que la teneur en P inorganique est demeurée stable sous l'effet d'un accroissement de l'érosion.

Mots clés: Eléments nutritifs, productivité du sol, qualité du sol, érodé, caténa

Loss of the organic-matter rich surface soil (topsoil) is known to decrease soil quality, which in turn reduces productivity. Research techniques aimed at estimating losses in soil productivity include comparing yields from eroded and non-eroded fields (Langdale et al. 1979; Olson and Nizeyimana 1988), or from artifically eroded (scalped) and control soils (Dormaar et al. 1986; Ives and Shaykewich 1987). A third technique is to estimate the incremental effects of topsoil added back to a severely eroded soil. Henning and Kalaf (1985) added 150 and 300 mm of topsoil, plus chemical fertilizers to exposed parent material in Iowa, and found that soybean yields generally increased with increasing depths of topsoil. They concluded that increasing topsoil depth provided more moisture storage capacity. Adding 100 or 200 mm of topsoil to severely eroded loess soils increased yields of corn and oat (Mielke and Scheper 1986). Yield increases were partly due to enhanced soil fertility, but were also related closely to improved soil physical conditions.

The organic matter content of cultivated grassland soils is generally much less than native equivalents, with the magnitude of organic matter losses related to management (McGill et al. 1988), period of cultivation (Gregorich and Anderson 1985), and the effects or erosion (de Jong and Kachanoski 1988). Losses of total N range from 20 to 81% depending on the kind of soil and period of cultivation (Tiessen et al. 1982). Potentially mineralizable N generally has been lost at a faster rate than total N (Campbell and Souster 1982). Gregorich and Anderson (1985) reported similar total phosphorus (P) contents for surface horizons of cultivated and native soil, in contrast to other studies where P decreased with time of cultivation, and postulated that the relative similarity in P is due to additions of fertilizer P to the cultivated soil.

The objectives of this study were: (1) to compare grain yields along eroded hillslopes, (2) to estimate losses in soil productivity utilizing the topsoil addition method as compared to a fertilizer treatment, and (3) to follow changes in various aspects of soil quality with increasing time of cultivation and degree of erosion.

MATERIALS AND METHODS

All experiments were located on a hummocky morainal landscape (slopes of 9–15%) at 52°N, 106°W. Dark Brown soils of the Weyburn Association are dominant (Mitchell et al. 1944). Duplicate 1-m^2 samples of spring wheat were harvested at intervals along six hillslopes to determine grain yields. At four of the six hillslope positions duplicate soil samples were taken with a soil corer of constant volume. Bulk density was measured and the samples were used subsequently for determining Cesium-137 (^{137}Cs) concentration and for soil analyses. The location of sampling points along each catena was converted to relative distance from the crest to the depression, with the crest assigned 0 and the lower end of the hillslope assigned 1.

The topsoil addition experiment involved moving topsoil from the lower slope positions to convex and eroded upper slopes. Grain yields on the eroded soil were compared to yields on the eroded soil with incremental thickness of topsoil added back. An advantage of this method is that yield reductions due to erosion were estimated without the complication of moisture differences normally associated with comparing eroded soils in upper slopes with thicker soils on middle or lower slopes. The added soil was placed inside wooden frames of appropriate depth, levelled and tamped to approximate the bulk density of an Ap horizon.

Four treatments were included: the control with no topsoil added, 50 mm, 100 mm, and 150 mm of topsoil added. Four replicates, each 3 m^2 in size, for each treatment were arranged in randomized complete block design with the blocks arranged parallel to the crest of the slope in order to minimize the influence of downslope variation. Two replicates were placed on each of two similar knolls, with a 1-m buffer zone between replicates to overcome any edge effect. A fertilizer treatment of four replicates was established on a single eroded knoll, similar and adjacent to a knoll used for the topsoil treatments. Nutrients were added according to soil test recommendations by either seed placement or broadcasting. The fertilizer treatment received broadcast applications of 30 kg N, 53 kg P, 17 kg S and 11 kg Zn ha^{-1} in addition to the fertilizer applied with the seed at a rate similar to the topsoil-amended plots.

Neepawa spring wheat (*Triticum aestivum* L. 'Neepawa') was seeded at 36 kg ha^{-1} and fertilizer (ammonium dihydrogen phosphate) was seed placed at 100 kg ha^{-1} as part of the farmer's normal seeding operations. Plots were seeded by press drill on 5 May in 1986 and by discer-seeder on 12 May in 1987. All plots in both years were treated with herbicides for control of grassy and broad-leafed weeds. Three 1-m^2 harvest samples were taken from each replicate, with the mean of the three samples used as a single value for each replicate.

To gauge the effects of erosion on soil quality a series of similar Rego Dark Brown soils with increasing periods of cultivation and, presumably, erosion were located on convex upper slopes. Fifteen soils were selected with the period of cultivation ranging from 0 (native pasture) to 75 y. All cultivated soils had been cropped the previous year. A pit was dug at each soil location to identify and measure the thickness of the Ah (native) or Ap (cultivated) horizons. Three samples were taken with a corer of constant volume to determine bulk density and used subsequently for determining ^{137}Cs concentration and soil analyses. Bulk samples were brought from the field and stored at field moisture content in sealed plastic bags at 4°C for future experiments.

Cumulative mineralization of N and S over a 21-wk period was obtained using the open incubation system described by Stanford and Smith (1972), as modified by Roberts (1985). Potentially mineralizable nitrogen (N_O) and sulphur (S_O) were calculated by fitting the first-order kinetics model to the cumulative mineralization curves. The fit was based on a nonlinear least squares regression, using the SAS™ computer software Marquardt (Statistical Analysis System Institute, Inc. 1985).

Bulk samples were air-dried and subsampled to determine the size distribution of dry aggregates, using a series of sieves with openings of 8, 4.75, 2, 1 and 0.25 mm). All aggregate fractions, except for the <0.25 mm fraction, were corrected for the sand and gravel that they contained. Concentrations of ^{137}Cs were determined by methods outlined by de Jong et al. (1982) and converted to an area basis using the bulk density values measured for those particular samples. Soils to be analyzed for ^{137}Cs were air-dried, ground and passed through a 2-mm sieve. ^{137}Cs values were used to determine soil loss according to the method described by Pennock and de Jong (1987). The mean ^{137}Cs content of two native soils sampled in this study was used to represent the control site. The rate of soil loss for soils cultivated since 1960 was calculated by dividing soil loss by years of cultivation, with rates for the remaining soils being based on 25 yr of cultivation, that is, since the time of maximum deposition of ^{137}Cs in the prairie region.

Soils to be analyzed for C, N and S were first air-dried, ground and passed through a 0.015-mm sieve. Total carbon and total nitrogen were determined on a C-H-N analyzer (Leco Model 600). Inorganic carbon was determined by the two endpoint titration (Tiessen et al. 1983). Organic carbon was calculated by subtracting inorganic from total carbon. Total and inorganic phosphorus were determined according to the method of Saunders and Williams (1955), as modified by Walker and Adams (1958). Organic phosphorus was calculated by subtracting inorganic from total phosphorus. Total sulphur was determined by the combustion-iodine titration on a Fisher Sulfur Analyzer, Model 475. Particle-size distribution was determined, after pretreatment to remove carbonates and organic matter, by the pipette method (McKeague 1978).

All the statistical analyses, except Duncan's multiple range test, were calculated using the Macintosh Statworks™ computer program. A probability level of 95% was considered to be the lowest at which statistical significance occurred.

RESULTS AND DISCUSSION

Hillslope Yield Measurements

Yields and distances along hillslopes from the six individual slopes were grouped together in order to determine the relationship between slope position and yield (Fig. 1). Grain yields were generally lowest on the upper slopes,

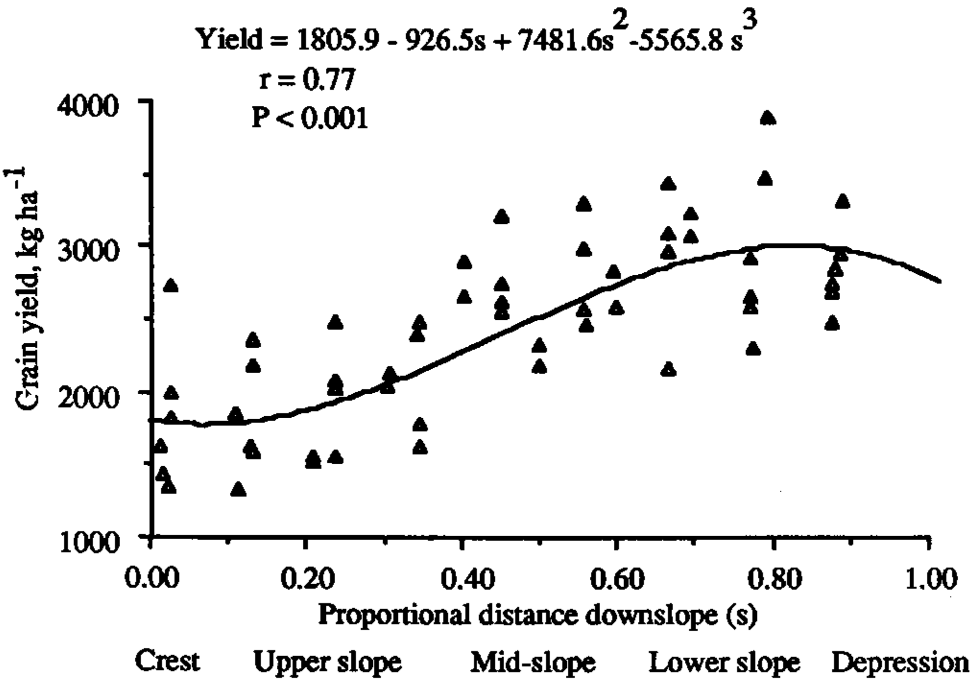

Fig. 1. Relationship between grain yield and proportional distance downslope.

and increased with distance downslope. The twofold difference between lowest and highest yields within the hillslope is larger than most comparisons reported previously. These yield values are consistent with the strongly eroded nature of the upper slopes of this study, as indicated by the redistribution of ^{137}Cs (Fig. 2). Differences in yield of this magnitude have been reported, with lowest yields on soils identified as eroded variants (Rennie and Clayton 1960).

Regression analysis indicated that the relationship between yield and distance was described best by a third-order polynomial equation. Yields on crests were similar to those on shoulders, with yield increasing through the midslope to a maximum yield on the lower slopes, then decreasing again away from the slope. Yields are best through the lower half of the hillslope, with maximum yields for the footslope. Lower yields were reported for footslopes in the study of Malo and Worcester (1975) and attributed to the occurrence of weakly saline soils. Similar soil toposequences were studied by King et al. (1983), who concluded, based on soil profile characteristics, that the hillslopes could be broken into convex upper slopes with thin soils and concave lower slopes with deep soils. Our yield results, although best fitted to a continuous curve, are not inconsistent with their description of slopes in that yield above the 0.50 distance downslope are consistently less than the yields on lower slopes.

Organic C increased from minimal values on the upper slopes to maxima in the footslopes, decreasing again in the general low area (Fig. 3). The footslope has been identified as the slope segment where soil eroded from upper slopes begins to be deposited, and generally has deep and productive soils (Pennock and de Jong 1987). Solum thickness followed a similar trend (Fig. 4) with some very thick soils in lower slopes where amounts of ^{137}Cs were high. Soils plotting well below the fitted surves (Figs. 2, 3 and 4) are thin soils with low organic C of the upper part of mid- or back-slopes that have been strongly

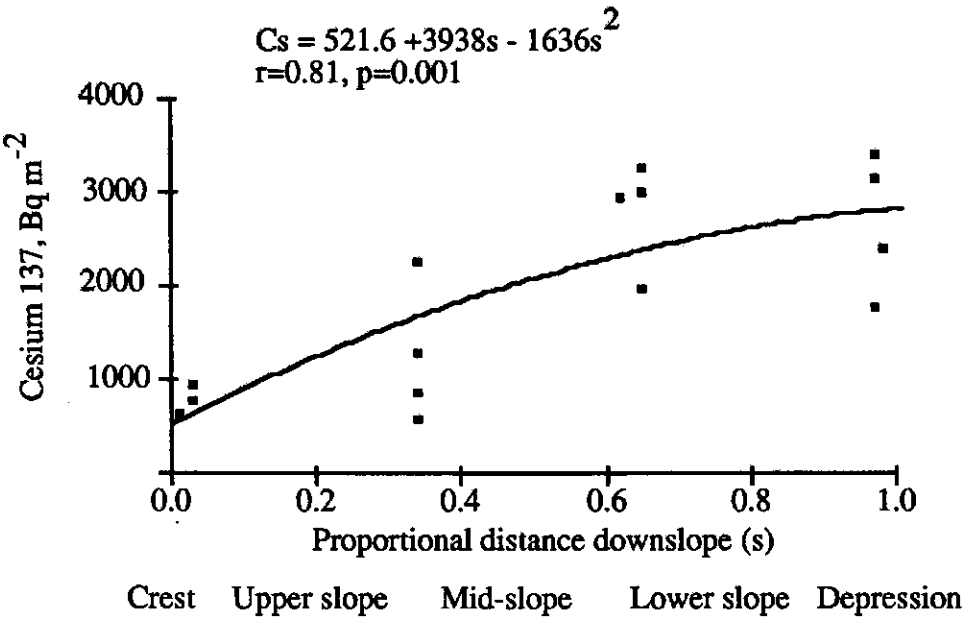

Fig. 2. Relationship between ^{137}Cs and proportional distance downslope.

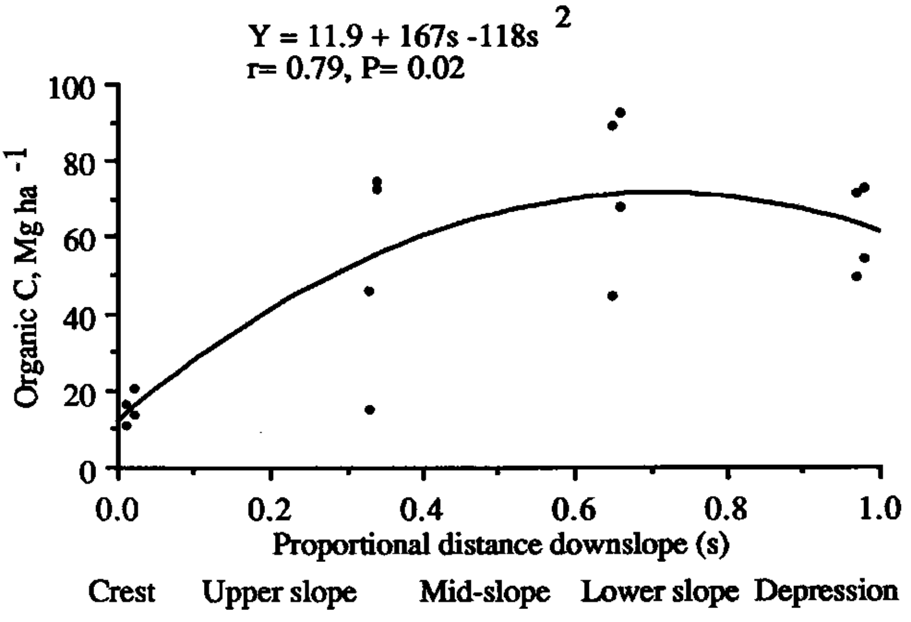

Fig. 3. Relationship between organic C and proportional distance downslope.

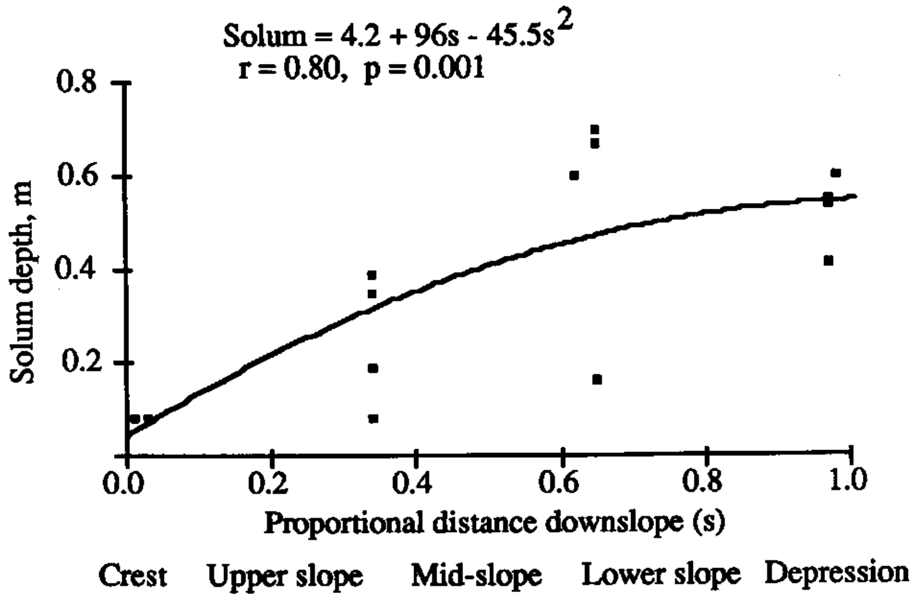

Fig. 4. Relationship between solum depth and proportional distance downslope.

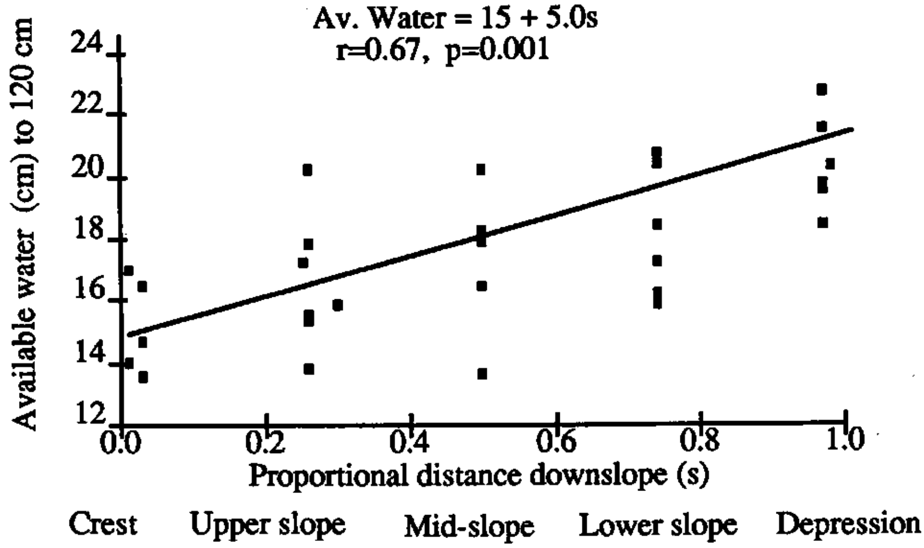

Fig. 5. Relationship between plant available water and proportional distance downslope.

eroded, probably by water erosion. Available soil water at planting increased from upper to lower slopes (Fig. 5). The results in this study are generally consistent with earlier studies in that differences in moisture supply and nutrients account for differences in yields along hillslopes (de Jong and Rennie 1969; Bauer et al. 1979). Soil erosion, by moving organic matter-enriched topsoil from upper, convex slopes to lower areas increases the magnitude of the yield differences along hillslopes.

Table 1. Mean dry matter yields associated with topsoil additions in 1986 and 1987

Topsoil addition (mm)	Grain		Straw	
	1986	1987	1986	1987
	(kg ha^{-1})			
0	914*a*	1143*a*	1290*a*	2030*a*
50	1343*b*	1627*b*	2094*b*	2389*a*
100	1443*b*	2150*b*	2187*bc*	2938*bc*
150	1327*b*	1964*b*	2369*b*	2917*bc*
Fertilizer treatment	1068	1955	1857	2700

a-*c*Means in the same column followed by different letters are significantly different at ≤0.05. Statistical comparisons do not include the fertilizer treatment.

Topsoil Addition Experiment

Results of the hillslope experiment indicated lower yields on eroded upper slopes, but did not give information on the magnitude of the decreases in yield. The yield response to incremental additions of topsoil to eroded soils was measured in order to estimate the effect of erosion on yield.

Grain yields in 1986 varied from 913 on the control to 1443 kg ha^{-1} on topsoil amended treatments (Table 1). Topsoil additions increased grain yields between 45 and 58% over the control. Increases in grain and straw production between the control and the three depths of topsoil addition were significant, while all other comparisons were not. The 50-mm treatment resulted in yield increases that were equivalent to the 100- or 150-mm treatments. Grain yields on the 150-mm treatments were limited in 1986 by poor germination in the loosely structured cultivated layer. The straw production for the topsoil additions varied from 62 to 84% more than the control. Greater straw production is important, both to increase cover on knolls and slow erosion, and to maintain or increase organic matter content.

There was more growing season rainfall in 1987 than the previous year, resulting in grain yields ranging from 1143 on the control to a maximum of 2150 kg ha^{-1} where topsoil was added. Topsoil additions increased grain yields between 42 and 88% over the control, with all increases in grain weight between the control and the topsoil additions being significant and equivalent among topsoil treatments. Straw yields from the 100- and 150-mm treatments were significantly greater than those from the control and 50-mm treatment. There was no significant difference in straw yield between the 100- and 150-mm treatments.

Grain yields from the fertilizer treatment were less than yields attained by the topsoil additions in 1986, while in the following year the fertilizer produced more grain than the 50-mm treatments, but less than the 100- and 150-mm treatments. The nature of the design precluded statistical evaluations of the yield increase due to fertilizer, but it appears that low fertility limits yields on eroded soils, particularly when soil moisture supplies are not strongly limiting as in 1987.

Soil Quality Experiment

Results from the topsoil addition experiment indicated the importance of topsoil to soil productivity, and the negative influence of erosion. The next step was to determine changes in soil quality with increasing degree of erosion, by sampling similar soils that had been cultivated for different periods.

Values for ^{137}Cs range between 2520 Bq m^{-2} for a native soil to 592 Bq m^{-2} for the soil cultivated for 75 years (Table 2). ^{137}Cs values indicate that rates of soil loss from convex upper slopes have been high, and probably responsible for the declining soil quality that was documented. The relationship between years of cultivation and ^{137}Cs was best described by a second-order polynominal equation (Fig. 6). Most of the ^{137}Cs deposited on western Canada fell between 1962 and 1964 (de Jong et al. 1982). The steeper portion of the curve includes soils broken since the early 1960s, with ^{137}Cs declining with years of cultivation and

Table 2. Changes in depth and bulk density of the A horizon, ^{137}Cs values and soil loss with increasing periods of cultivation on upper slopes

Years of cultivation†	A horizon depth (cm)	Bulk density (Mg m^{-3})	^{137}Cs content (Bg kg^{-1})	^{137}Cs amount (Bg m^{-2})	Calculated soil loss (Mg ha^{-1})	Erosion rate (Mg ha^{-1} yr^{-1})	Silt + very fine sand (0.10–0.002 mm) (g kg^{-1})	Silt (0.05–0.002 mm) (g kg^{-1})	MWD (dry agg.) (mm)
0	7	0.98±0.03	36.6	2520	—	—	427	356	1.4
0	10	1.06±0.03	18.1	1918	—	—	431	316	2.1
2	8	1.01±0.06	13.8	1112	398.7	199.3	424	353	1.7
3	8	0.97±0.07	14.7	1150	371.0	123.7	401	322	2.3
8	10	0.98±0.01	14.5	1428	343.0	42.9	422	329	1.8
11	12	1.09±0.02	16.1	2098	57.1	5.2	438	351	1.5
14	9	1.16±0.03	12.7	1329	412.7	29.5	405	315	2.0
19	11	1.02±0.01	9.0	1007	606.0	31.9	378	310	2.5
25	6	1.19±0.12	6.4	458	562.9	22.5	398	322	2.5
28	7	1.05±0.07	10.1	744	485.4	19.4	401	299	1.8
32	10	1.00±0.02	19.6	1962	105.4	4.2	381	305	2.4
37	8	1.25±0.05	8.0	801	636.8	25.5	408	321	—
53	8	0.99±0.05	9.6	757	518.7	20.7	391	324	2.5
61	8	1.19±0.03	9.5	903	558.4	22.3	359	257	1.7
75	8	1.41±0.04	5.3	593	821.8	32.9	385	306	3.2

†0 indicates a native soil.

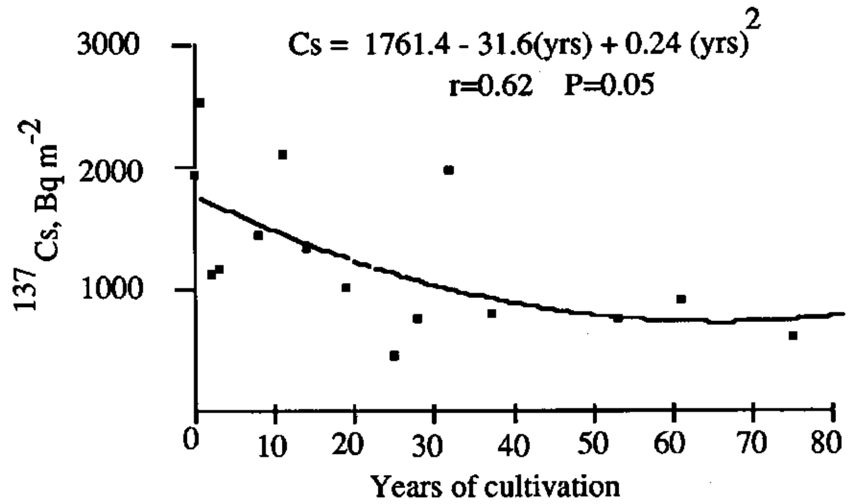

Fig. 6. Relationship between years of cultivation and the amount of ^{137}Cs in upper slope soils.

erosion. The flatter portion includes soils that were cultivated prior to the early 1960s; these soils have lost about the same amounts of ^{137}Cs over time. There was a marked decrease in the amounts of ^{137}Cs in the recently cultivated soils, and it is probable that the cesium method overestimates soil loss when the ^{137}Cs is concentrated in the first few centimeters, as it is in native soils (Kachanoski and de Kong 1984). Downslope movement of soil by tillage, or preferential loss of the ^{137}Cs-enriched fractions by wind erosion may be additional factors contributing to the large reductions in ^{137}Cs after only 2 or 3 yr. Organic-rich silt- to sand-sized aggregates that are easily eroded by wind contained one-half of the ^{137}Cs activity of an Alberta soil (Maulé and Dudas 1989).

Organic C concentrations generally decrease from 48.3 g C kg^{-1} soil for the native soil, to 9.9 g C kg^{-1} soil for the soil that has been cultivated for 75 yr (Fig. 7). de Jong and Kachanoski (1988) compared soils sampled in the mid-1960s and again in the 1980s and concluded that organic C losses were caused mainly by erosion on upper slope soils that had been cultivated since the mid-1940s. Inorganic carbon concentration generally increases with years of cultivation. The increase is due to progressively more calcareous subsoil being worked into the Ap horizon as topsoil is lost by erosion. The relationship between organic C and years of cultivation indicates that the organic C has been lost from the eroded soils at the rate of 0.32 Mg ha^{-1} yr^{-1}. An organic C loss of 0.32 Mg, if mainly due to erosion, is approximately equivalent to a soil loss of 20 Mg ha^{-1} yr^{-1} for a soil containing 16 g kg^{-1} of organic C. Gregorich and Anderson (1985) reported losses of organic C by erosion of 0.53 to 0.67 Mg ha^{-1} yr^{-1} for Black soils with higher organic C contents.

Total nitrogen (N_T), total sulphur (S_T) and organic phosphorus (P_o) concentrations were significantly related to cultivation, generally decreasing as the length of the cultivation period increased (Table 4). Inorganic phosphorus (P_i) concentrations showed no significant trend with years of cultivation. The decrease in N_T, coincident with a general decrease in organic C, is probably due to erosion. The different responses of P_i and P_o to years of cultivation relate to erosion and the distribution of the P forms with depth. Inorganic P concentrations increase slightly with depth, whereas P_o concentrations decrease markedly with depth. When erosion removes

Table 3. Effect of years cultivation on the amounts of nitrogen, phosphorus and sulphur, and C:N and C:P_O of upper slope soils

Years of cultivation†	Total N (N_T)	Total P	Inorganic P	Organic P	C:N	C:P_O	N_O (mg g^{-1})	N_O/N_T	Total S (S_T)	S_O	S_O/S_T
	(mg g^{-1})								(μg g^{-1})		
0	5.0	0.99	0.41	0.58	9.6	83	0.77	0.153	730	101	0.138
0′	4.4	0.71	0.23	0.47	10.8	100	—	—	480	—	—
2	3.9	0.90	0.41	0.49	9.5	75	0.69	0.177	420	84	0.200
3	3.6	0.91	0.42	0.48	9.1	67	0.39	0.108	480	60	0.124
8	3.4	0.73	0.33	0.40	9.1	77	—	—	340	—	—
11	2.7	0.77	0.41	0.35	8.9	68	0.30	0.112	230	44	0.192
14	2.5	0.69	0.35	0.34	9.3	67	0.23	0.092	230	35	0.154
19	3.4	0.83	0.37	0.45	8.7	65	0.39	0.115	400	72	0.179
25	2.7	0.71	0.40	0.31	7.4	63	0.20	0.074	200	33	0.162
28	2.4	0.75	0.38	0.37	9.5	61	0.21	0.085	200	40	0.202
32	4.2	0.80	0.35	0.44	9.4	87	0.30	0.072	400	63	0.157
37	2.6	0.74	0.40	0.33	7.2	56	0.19	0.073	170	33	0.195
53	2.6	0.75	0.38	0.37	9.5	67	0.21	0.080	130	28	0.214
61	2.0	0.58	0.33	0.24	6.3	50	0.12	0.059	120	21	0.175
75	1.4	0.57	0.41	0.16	7.0	61	0.12	0.085	80	19	0.238

†0′ indicates a native soil.

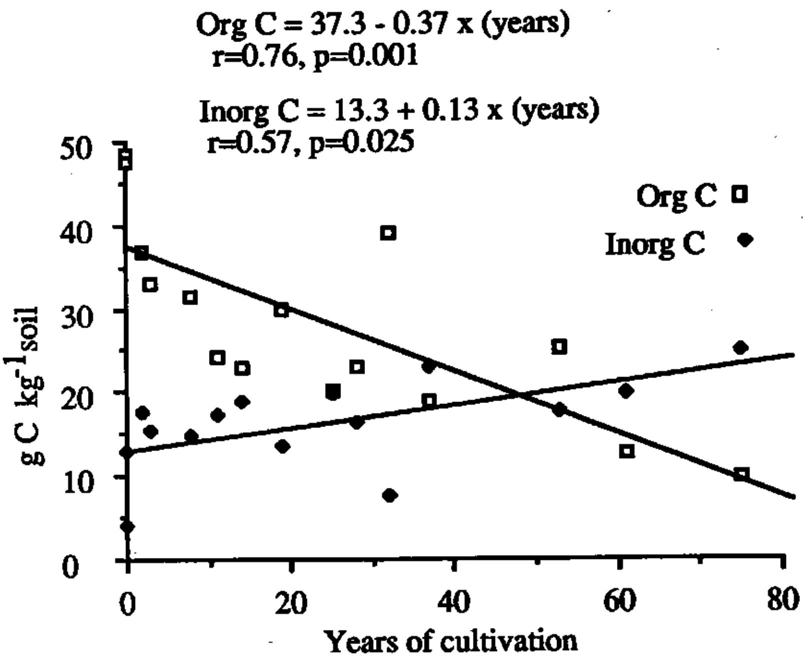

Fig. 7. Relationship between years of cultivation and the organic and inorganic C content of Ap horizons of upper slope soils.

the organic matter-rich surface horizon, the subsoil worked into the plow layer has a lower concentration of P_o, and a similar concentration of P_i.

Organic C:N and organic C:P_T ratios decreased with increasing period of cultivation (Table 3). Tiessen et al. (1982) report a decrease in organic C:P_T for a Black silty soil cultivated for 90 years, but found no trends in C:N with increasing cultivation. Output from a simulation model suggests that C:N ratios will decrease with period of cultivation, as the large proportions of plant residues of wide C:N ratio decompose and C is evolved (Parton et al. 1983). The drop in C:N may also be attributed to erosion. Stevenson (1959) found that the C:N ratio decreases with profile depth; consequently, any erosion and subsequent cultivation would work subsoil with a lower C:N ratio into the cultivated layer. Spearman rank correlations between years of cultivation and the content of organic C and associated N, S and P were negative (Table 4), supporting a general decline in organic matter and fertility with increasing cultivation and erosion.

Table 4. Spearman rank correlations (r) for soil properties and years of cultivation

Dependant variable	r	P
^{137}Cs (Bq m^{-2})	−0.67	0.007
Organic C (g kg^{-1})	−0.78	0.001
Inorganic C (μg g^{-1})	0.66	0.008
Total N (g kg^{-1})	−0.79	0.001
Total S (g kg^{-1})	−0.89	<0.001
Organic P (μg g^{-1})	−0.79	<0.001
C:P ratio	−0.69	0.005
C:N ratio	−0.62	0.014
S_0 (g kg^{-1})	−0.83	0.001
N_0 (g kg^{-1})	−0.85	0.001
N_0/N_T	−0.81	0.001
Total silt	−0.63	0.012
Total silt + VFS	−0.75	0.001
MWD of dry aggregates	0.51	0.061

Cumulative mineralization curves were used in estimating the potentially mineralizable pool of N (N_o) and S (S_o), except for the years 0′ and 8 which did not fit the first order kinetics model (Table 3). N_o and S_o decreased with period of cultivation, both on an area basis, and on a concentration basis. Decreases of N_0 and S_0 occurred at the rate of 4.9 and 0.62 kg ha^{-1} yr^{-1}, respectively. N_0 declined more rapidly than N_T with period of cultivation, concurring with work done by Campbell and Souster (1982) for similar soils.

There were negative relationships between years of cultivation and total silt and total silt plus very fine sand (Table 4). The gradual reduction in these size fractions suggests that wind erosion has been the dominant erosive agent at the crest of knolls, in that particles or aggregates of this size are most easiy moved by wind. Gregorich (1984) and Malo et al. (1974) found that mean particle size increased from the knoll to lower slopes within cultivated toposequences, and attributed the increase to preferential movement of fines by water erosion. Removal of very fine sand and silt from knolls may be an additional process that results in an increase in the mean particle size of soils on eroded knolls.

Field observations indicated that the native Ah horizons had a coarse blocky, breaking to fine granular structure, whereas the cultivated soils were cloddy breaking to a fine powder, particularly on those cultivated for a long time. The mean weight diameter (MWD) of dry aggregates was directly and significantly related to years of cultivation (Table 4). The increases in dry aggregate size may be related to decreases in organic matter. This would allow other factors, such as Ca, to play a larger role, and thus change the nature of the aggregates. Chepil (1954) found increases in dry cloddiness with increasing additions of $CaCO_3$ on a loamy fine sandy soil with 0.85% organic matter. Chepil's findings coupled with findings of this study seem to indicate that in loamy and sandy soils the interaction of decreasing organic matter and the presence of carbonates leads to larger dry aggregate sizes, which are easily broken down when wet.

CONCLUSIONS

Grain production from the crest to the lower parts of six hillslopes was described best by a third-order polynominal equation, with yields at the lower slope positions often more than double those on the upper slopes. Yields were least on shoulder positions due to the slightly increased gradient which increases runoff and erosion, and highest on depositional, footslope positions that gain soil and water. Yields decrease in moving away from the base of hillslopes to generally low areas within the landscape.

Measurements of ^{137}Cs indicated that erosion rates on convex upper slopes were high, and that erosion was the main process reducing the quality of soil. Decreases in silt and silt plus very fine sand suggest that wind erosion has been the dominant erosive agent. Organic P and total and potentially mineralizable N and S decreased with period of cultivation, indicating the negative impacts of erosion on soil fertility.

Additions of as little as 50 mm of topsoil to severely eroded soils increased yields by 45 to 58%, indicating that yield loss on convex and eroded uplands are substantial. Landscapes like those studied have 25–30% of landform elements that are strongly eroded (Pennock and de Jong 1987). Yield losses of 40% on 25% of a landscape indicate that yields on fields with hummocky or hilly landscapes are being reduced by 10% because of erosion. Battiston et al. (1987) estimated that corn yield on two eroded fields was about 92% of that expected if no erosion had occurred. Analyses of this kind may be difficult to extend areally and to place in economic terms, but certainly do indicate the severe impact of erosion on productivity, and the critical need for conservation and remedial measures.

Battiston, L. A., Miller, M. H. and Shelton, I. J. 1987. Soil erosion and corn yield in Ontario. I. Field evaluation. Can. J. Soil Sci. **67:** 731–745.
Bauer, A., Omodt, H. W. and Schroer, F. W. 1979. Effect of nitrogen-fertilized wheat on water loss from soils of the Barnes catena. North Dakota Research Report 73. North Dakota State University. Fargo, N.D.
Campbell, C. A. and Souster, W. 1982. Loss of organic matter and potentially mineralizable

nitrogen from Saskatchewan soils due to cropping. Can. J. Soil Sci. **62:** 651–656.
Chepil, W. S. 1954. Factors that influence clod structure and erodibility of soil by wind. III. Calcium carbonate and decomposed organic matter. Soil Sci. **77:** 473–480.
de Jong, E. and Kachanoski, R. G. 1988. The importance of erosion in the carbon balance of prairie soils. Can. J. Soil Sci. **68:** 111–119.
de Jong, E. and Rennie, D. A. 1969. Effect of soil profile type and fertilizer on moisture use by wheat grown on fallow or stubble land. Can. J. Soil Sci. **49:** 189–197.
de Jong, E., Villar, H. and Bettany, J. R. 1982. Preliminary investigations on the use of Cesium-137 to estimate erosion in Saskatchewan. Can. J. Soil Sci. **62:** 673–683.
Dormaar, J. F., Lindwall, C. W. and Kozub, G. C. 1986. Restoring productivity to an artifically eroded Dark Brown Chernozemic soil under dryland conditions. Can. J. Soil Sci. **66:** 273–285.
Gregorich, E. G. 1984. Soil landscapes: a pedological study of the effect of cultivation on soil properties. III. Sc. Thesis. University of Saskatoon, Saskatoon, Sask.
Gregorich, E. G. and Anderson, D. W. 1985. Effects of cultivation and erosion on soil of four toposequences in the Canadian Prairies. Geoderma **36:** 343–354.
Henning, S. J. and Khalaf, J. A. 1985. Topsoil depth and management effects on crop production in north central Iowa. Pages 59–65 *in* Erosion and soil productivity. American Society of Agricultural Engineers, St. Joseph, Mich. Publ. No. 8–85.
Kachanoski, R. G. and de Jong, E. 1984. Predicting the temporal relationship between soil Cesium-137 and erosion rate. J. Environ. Qual. **13:** 301–304.
King, G. J., Acton, D. F. and St. Arnaud, R. J. 1983. Soil-landscape analysis in relation to soil distribution and mapping at a site within the Weyburn Association. Can. J. Soil Sci. **63:** 657–670.
Ives, R. M. and Shaykewich, C. F. 1987. Effect of simulated soil erosion on wheat yields on the humid Canadian prairie. J. Soil Water. Conserv. **42:** 205–208.
Langdale, G. W., Box, J. E. Jr., Leonard, R. A., Barnett, A. P. and Fleming, W. G. 1979. Corn yield reduction on eroded Southern Piedmont Soils. J. Soil Water. Conserv. **34:**226–228.
Malo, D. D. and Worcester, B. K. 1975. Soil fertility and crop responses at selected landscape positions. Agron. J. **67:** 397–401.
Malo, D. D., Worcester, B. K., Cassel, D. K. and Matzdorf, K. D. 1974. Soil-landscape relationships in a closed drainage system. Soil Sci. Soc. Am. Proc. **38:** 813–818.
Maulé, C. P. and Dudas, M. J. 1989. Preliminary identification of soil separates associated with fallout ^{137}Cs. Can. J. Soil Sci. **69:** 171–176.
McGill, W. B., Dormaar, J. F. and Reinl-Dwyer, E. 1988. New perspectives on soil organic matter quality and dynamics on the Canadian Prairies. Pages 30-48 *in* Proc. Can. Soil Sci. Soc. Symp., Land Degradation: Assessment and Insight into a Western Canadian Problem. Calgary, Alta.
McKeague, J. A. 1978. Manual on soil sampling and methods of analysis. Canadian Society of Soil Science, Ottawa, Ont. 212 pp.
Mielke, L. N. and Schepers, J. S. 1986. Plant response to topsoil thickness on an eroded loess soil J. Soil Water. Conserv. **42:** 59–63.
Mitchell, J., Moss, H. C. and Clayton, J. S. 1944. Soil survey of Southern Saskatchewan. Soil Survey Report No. 12. University of Saskatchewan, Saskatoon, Sask.
Olson, K. R. and Nizeyimana, E. 1988. Effects of soil erosion on corn yields of seven Illinois soils. J. Prod. Agric. **1:** 13–19.
Parton, W. J., Anderson, D. W., Cole, C. V. and Stewart, J. W. B. 1983. Simulation of soil organic matter formations and mineralization in semiarid agroecosystems. Pages 533–550 *in* R. Lowrance, R. Todd, L. Asmussen and R. Leonard eds. Nutrient cycling in agricultural ecosystems. University of Georgia College of Agricultural Experimental Stations, Athens, Ga. Special Publ. 23.
Pennock, D. J. and de Jong, E. 1987. The influence of slope curvature on soil erosion and deposition in hummock terrain. Soil Sci. **144:** 209–217.
Rennie, D. A. and Clayton, J. S. 1960. The significance of local soil types to soil fertility studies. Can. J. Soil Sci. **40:** 146–156.
Roberts, T. L. 1985. Sulfur and its relationship to carbon and nitrogen and phosphorus in a climotoposequence of Saskatchewan soils. Ph.D. Thesis, University of Saskatchewan, Saskatoon Sask.
Statistical Analysis System Institute, Inc. 1985. SAS® user's guide: statistics, Version 5 Edition. SAS Institute Inc., Cary, N.C.
Saunders, W. M. H. and Williams, E. G. 1955. Observations on the determination of total organic phosphorus in soils J. Soil Sci: **6:** 254–267.
Stanford, G. and Smith, S. J. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. Proc. **36:** 465–472.

Stevenson, F. J. 1959. Carbon-nitrogen relationships in soil. Soil Sci. **88:** 201–208.

Tiessen, H., Roberts, T. L. and Stewart, J. W. B. 1983. Carbonate analysis in soils and minerals by acid digestion and two-endpoint titration. Commun. Soil Sci. Plant Anal. **14:** 161–166.

Tiessen, H., Stewart, J. W. B. and Bettany, J. R. 1982. Cultivation effects on the amounts and concentrations of carbon, nitrogen and phosphorus in grassland soils. Agon. J. **74:** 831–835.

Walker, T. W. and Adams, A. F. R. 1958. Studies on soil organic matter. I. Influence of phosphorus contents of parent materials on accumulations of carbon nitrogen, sulfur and organic phosphorus in grassland soils. Soil Sci. **84:** 307–318.