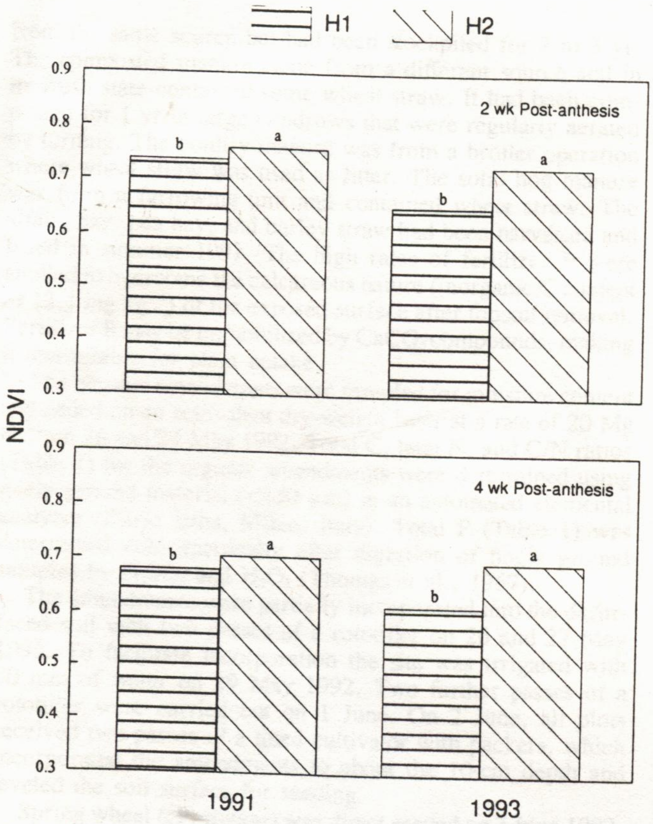

Fig. 3. Differences in the normalized difference vegetation index (NDVI, calculated from CropScan multispectral radiometer readings) between two contrasting maize hybrids (H1 = Pride 5, an early senescing hybrid; H2 = Pioneer 3902, a stay-green hybrid) in 1991 and 1993. LSD (0.05) = 0.05.

hybrids were significantly different at 4 wk but not at 2 wk after anthesis (data not shown). The NDVI values were significantly different between the two hybrids (Fig. 3). Thus, measurements of canopy light reflectance post anthesis could be used in selecting for leaf senescence, which may help plant breeders, producers, and extension personnel distinguish stay-green from early-senescing characters.

In summary, canopy light reflectance values at 600 and 800 nm were used to derive the NDVI, which better differentiated N treatment effects than any single wavelength band. The NDVI was strongly correlated with field greenness (a product of leaf greenness measured with a chlorophyll meter and plant leaf area); both NDVI and field greenness, measured preanthesis, were correlated with grain yield at harvest. Light reflectance measured at or post anthesis differentiated hybrid differences in leaf senescence. Our data suggest that light reflectance measurements prior to anthesis predict grain yield and may provide in-season indications of N deficiency.

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Restoration of Productivity to a Desurfaced Soil with Livestock Manure, Crop Residue, and Fertilizer Amendments

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ABSTRACT

Many agricultural fields on the semiarid Canadian prairies have areas of inherently low productivity associated with loss of soil quality due to erosion. This study compared the efficacy of various amendments in restoring productivity to a desurfaced fine-loamy, mixed Typic Haploboroll (Lethbridge series) in southern Alberta. In spring 1992, 14 amendment treatments (including livestock manures, crop residues, combinations of straw and chemical fertilizer, and fertilizer alone) were applied to a site where the Ap horizon (≈15-cm depth) had been mechanically removed to simulate erosion. The manures and crop materials were incorporated into the degraded surface on an equivalent dry-weight basis at 20 Mg ha^{-1}. The plots were seeded to spring wheat (*Triticum aestivum* L.) in 1992, 1993, and 1994. The overall best amendments were hog manure, poultry manure, and alfalfa hay. In all years, yields from desurfaced plots amended with hog or poultry manure were not significantly different from plots with no topsoil removal. Nitrate-N concentration in the 0- to 60-cm soil depth explained 71% of the variation in restorative ability of the amendments, while extractable P concentrations in the 0- to 15-cm depth explained 16% of this variation. Results demonstrate that livestock manures and crop residues can restore productivity to eroded soils by substituting for lost topsoil. Application of high rates of manure to severely eroded soils offers a means of utilizing the large amounts of manure generated by southern Alberta feedlot operations.

Despite increased awareness of the need to conserve our soil resource, wind and water erosion remain major forces of soil degradation on the Canadian prairies (Acton, 1995). Agricultural fields throughout the region exhibit characteristic areas of low soil productivity associated with erosion. While much attention has been focused on the prevention of further erosion through conservation tillage and residue management (Larney et al., 1994; Lindwall et al., 1994), little has been directed toward the restoration of previously eroded areas.

Farm managers have several options for restoring productivity to their eroded soils. One of the most common approaches is application of additional chemical fertilizer to eroded areas (e.g., knolls) to improve crop growth and to reduce the potential for further erosion. However, Larney et al. (1995) showed that P fertilizer has poor restorative capabilities on southern Alberta soils due to its immobilization by inherently high amounts of Ca carbonates, which render it unavailable for plant uptake.

Application of livestock manure is another restorative option (Dormaar et al., 1988; Frye et al., 1985). The county of Lethbridge has the highest density of intensive livestock feeding operations in the province of Alberta and manure disposal from large confined operations has become a growing concern (Bennett et al., 1995). Hauling distance is a major factor in the economics of manure disposal. Freeze et al. (1993) showed that the value of manure as an amendment for restoring the productivity of slightly eroded land is sufficient to allow manure to be hauled farther than would be the case on noneroded land.

Recently, there has been wide interest in composting manures to reduce environmental problems such as odor and leaching of NO_3^- into groundwater. While composted manures have been applied to noneroded soils (Eghball and Power, 1995; Schlegel, 1992), the restorative properties of composted manure compared with fresher materials has not been determined for eroded soils.

For farmers who do not have access to a manure supply within a short hauling distance, a possible restorative strategy may involve transporting crop residues (straw, hay) from productive areas to eroded areas of the farm. These residues could then be shredded and incorporated into the eroded surfaces, either alone or in combination with chemical fertilizer to approximate a manure. However, the efficacy of such procedures in the restoration of soil productivity has not been field tested.

The objective of this study was to compare the effectiveness of various forms of cattle manure (fresh, old, composted, or admixed with wood shavings), hog manure, poultry manure, alfalfa (*Medicago sativa* L.) and pea (*Pisum sativum* L.) hay, and N and P fertilizer (alone and with straw) in the restoration of productivity to a desurfaced soil.

MATERIALS AND METHODS

The study was located 5 km east of Lethbridge, Alberta (49°43′ N, 112°48′ W), on a fine-loamy, mixed Typic Haploboroll where the mean annual precipitation is 402 mm. Before desurfacing, the soil texture was sandy clay loam (52% sand, 20% silt, and 28% clay) and the organic C content of the 0- to 7.5-cm layer was 19 g kg^{-1}.

On 29 Apr. 1992, about 15 cm of topsoil (Ap horizon) was mechanically removed with an excavator to simulate erosion. The plot layout was a randomized complete block design with four replications of 14 amendments. The plots were 10 by 6 m.

The amendments included six animal manure treatments: fresh, old, and composted cattle manure, cattle manure + wood shavings, hog manure, and poultry manure; four crop residue treatments: alfalfa hay, pea hay, barley (*Hordeum vulgare* L.) straw + 200 kg ha^{-1} of N (as NH_4NO_3), and barley straw + 200 kg ha^{-1} of P (as triple superphosphate); two phosphate fertilizer treatments: 200 and 400 kg P ha^{-1}; and two checks: eroded check (topsoil removed, no amendment) and topsoil check (no topsoil removed, no amendment). All rates of P fertilizer are in units of kg P_2O_5 ha^{-1}.

The fresh cattle manure was about 6 mo old and contained a large amount of wheat straw. The old cattle manure was

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Abbreviations: DAS, days after seeding.

from the same source but had been stockpiled for 2 to 3 yr. The composted manure came from a different source and in its fresh state contained some wheat straw. It had been composted for 1 yr in large windrows that were regularly aerated by turning. The poultry manure was from a broiler operation where wheat straw was used as litter. The solid hog manure was from a farrowing unit and contained wheat straw. The alfalfa hay, pea hay, and barley straw had been harvested and baled in summer 1991. The high rates of fertilizer P were applied to overcome the calcareous nature (inorganic C content of 12.1 mg kg^{-1}) of the exposed surface after topsoil removal. Fertilizer P may be immobilized by $CaCO_3$ compounds, making it unavailable for plant uptake.

The organic amendments were sampled for moisture content and added on an equivalent dry-weight basis at a rate of 20 Mg ha^{-1} on 26 and 27 May 1992. Total C, total N, and C/N ratios (Table 1) for the organic amendments were determined using finely ground material (<150 μm) in an automated elemental analyzer (Carlo Erba, Milan, Italy). Total P (Table 1) was determined colorimetrically after digestion of finely ground samples by H_2SO_4 and H_2O_2 (Thomas et al., 1967).

The amendments were partially incorporated into the desurfaced soil with two passes of a rototiller on 26 and 27 May 1992. To facilitate incorporation the site was irrigated with 50 mm of water on 29 May 1992. Two further passes of a rototiller were carried out on 1 June. On 2 June, all plots received two passes of a tined cultivator with packers, which incorporated the amendments to about the 10-cm depth and leveled the soil surface for seeding.

Spring wheat (cv. Biggar) was direct seeded on 3 June 1992. However, a severe hailstorm devastated the crop on 2 Aug. 1992. The site was direct seeded to spring wheat on 20 May 1993 (Biggar) and 9 May 1994 (cv. Katepwa) to monitor carryover effects from the one-time application of amendments in 1992. The seeding rate in all 3 yr was 100 kg ha^{-1}. Supplemental N and P fertilizers were not applied in 1992. In 1993 and 1994, all amendment treatments received recommended rates of N and P for irrigated land: 80 kg N ha^{-1} (as NH_4NO_3) broadcast before seeding, and 40 kg P ha^{-1} (triple superphosphate) applied with the seed.

Each year (1992–1994), plant counts were taken on five 1-m row lengths from each plot for plant density determination. Plant count dates were 13 July 1992, 21 June 1993, and 10 June 1994. Each year, plants were harvested from 1 m^2 of each plot for plant dry matter yield determination. Plant dry matter sampling dates were 5 Aug. 1992 (63 DAS [days after seeding]; sampling was possible after hail damage), 2 Aug. 1993 (74 DAS), and 15 July 1994 (67 DAS). In 1993 and 1994, plant dry matter sampling was at the flowering stage. At harvest, a 1.52-m width was harvested through the center of each 10-m-long plot with a plot combine for grain and straw yield determination. There was no grain harvest in 1992 due to hail damage. Harvest dates in the second and third years were 29 Sept. 1993 (101 DAS) and 29 Aug. 1994 (112 DAS). Wheat straw was not removed from the study site.

Table 1. Total C concentration, total N concentration, C/N ratio, and total P concentration of organic amendments applied in May 1992 to a desurfaced Haploboroll soil.

Amendment	Total C	Total N	C/N ratio	Total P
	g kg^{-1}			g kg^{-1}
Fresh cattle manure	296	18.8	15.7	2.6
Old cattle manure	129	14.3	9.1	5.6
Composted cattle manure	100	9.7	10.3	4.3
Cattle manure + wood shavings	330	8.3	39.6	1.3
Hog manure	358	23.9	15.8	10.0
Poultry manure	315	39.6	8.0	13.0
Alfalfa hay	413	26.5	15.9	1.7
Pea hay	397	26.0	15.4	2.2
Barley straw	414	4.3	99.1	0.4

Total P concentrations were determined on finely ground subsamples of plant dry matter from 1992 and grain and straw from 1993 after digestion with H_2SO_4 and H_2O_2 (Thomas et al., 1967).

Before seeding in 1993 and 1994, soil samples were taken at the 0- to 15-, 15- to 30-, and 30- to 60-cm depths. Extractable P (ascorbic acid method, Olsen and Sommers, 1982) and extractable NO_3–N (colorimetric analysis after extraction of 10 g soil with 50 mL of 2 *M* KCl) concentrations were determined for all three depths. Nitrate-N, expressed as kilograms per hectare for the 0- to 60-cm depth, was calculated by assuming a soil bulk density of 1.25 Mg m^{-3} for the 0- to 15-cm layer, 1.35 Mg m^{-3} for the 15- to 30-cm layer, and 1.45 Mg m^{-3} for the 30- to 60-cm layer.

The General Linear Models procedure in SAS (SAS Inst., 1989) was used to analyze plant and soil parameters. When significant *F*-tests occurred, least significant differences [LSD (0.05)] were used to separate amendment treatment means.

RESULTS

Weather and Crop Growing Conditions

In addition to the 50 mm of irrigation the site received before seeding in 1992, 202 mm of precipitation was recorded in June and July 1992, compared with the long-term normal of 115 mm. Before the hailstorm on 2 Aug. 1992, plant dry matter production was satisfactory, considering that this was in the initial year of the study and seedbed conditions were less than optimal.

The 1993 growing season was exceptionally cool and wet. A total of 427 mm of precipitation occurred at Lethbridge between 1 May and 30 Sept. 1993, compared with the long-term normal of 251 mm. This resulted in near-record yields for southern Alberta. Because of the high rainfall, the site was not irrigated during the 1993 growing season.

The 1994 growing season was characterized by a wetter than normal May (154% of normal), about-normal June precipitation (108%), and below-normal July (58%) and August (60%) precipitation. A total of 211 mm of precipitation was recorded from 1 May to 31 Aug. 1994. Due to the drier-than-normal July to August period, an additional 200 mm of water was applied as irrigation in 1994.

Crop Performance

There was no significant amendment treatment effect on plant densities in any of the 3 yr of the study (Table 2). This demonstrates that differences in plant dry matter production and grain and straw yield among amendment treatments were not related to a plant density effect. The average plant density of the study site increased from 97 plants m^{-2} in 1992 to 119 plants m^{-2} in 1993, and to 153 plants m^{-2} in 1994. This suggests that seedbed conditions improved as the study progressed, resulting in better seed germination and seedling establishment across all treatments.

In 1992, plant dry matter yields showed that hog manure, poultry manure, alfalfa hay, pea hay, and fresh,

Table 2. Effect of amendments on spring wheat plant density, 1992–1994.

Amendment	Plant density 1992	1993	1994
	plants m^{-2}		
Fresh cattle manure	113	118	146
Old cattle manure	89	126	153
Composted cattle manure	93	125	153
Cattle manure + wood shavings	95	108	151
Hog manure	90	127	144
Poultry manure	93	123	156
Alfalfa hay	98	119	160
Pea hay	103	119	182
Barley straw + 200 kg N ha^{-1}	102	110	161
Barley straw + 200 kg P ha^{-1}	96	117	147
200 kg P ha^{-1}	91	117	148
400 kg P ha^{-1}	101	113	146
Eroded check	100	114	156
Topsoil check	96	125	145
LSD (0.05)	NS	NS	NS

Table 3. Effect of amendments on spring wheat plant dry matter yields, 1992–1994.

Amendment	Dry matter yield 1992	1993	1994
	Mg ha^{-1}		
Fresh cattle manure	2.5bcd†	6.0bcd	2.9abcd
Old cattle manure	3.1abc	6.1abcd	2.4cde
Composted cattle manure	2.9abc	5.1def	2.6bcde
Cattle manure + wood shavings	1.6def	5.3cdef	2.4bcde
Hog manure	4.0a	6.7ab	3.8a
Poultry manure	3.6ab	6.5abc	3.7a
Alfalfa hay	3.3ab	5.7bcde	3.3ab
Pea hay	2.6bcd	5.1def	2.3de
Barley straw + 200 kg N ha^{-1}	0.7f	4.3f	2.2de
Barley straw + 200 kg P ha^{-1}	2.0cde	4.8ef	2.5bcde
200 kg P ha^{-1}	1.6def	5.9bcde	1.7e
400 kg P ha^{-1}	1.9cdef	5.8bcde	2.2de
Eroded check	1.2ef	4.4f	2.5bcde
Topsoil check	3.7ab	7.3a	3.3abc

† Within columns, means followed by the same letter are not significantly different from each other [LSD (0.05)].

old, and composted cattle manure were capable of restoring productivity to levels comparable with the topsoil check treatment (Table 3). Crop residues proved to be an adequate alternative to livestock manures. Alfalfa hay was just as effective as the livestock manures in restoring productivity. Pea hay was as good as all the livestock manures except hog manure. Barley straw + 200 kg P ha^{-1} was as good as cattle manure (old, composted, or fresh).

In 1993, there were no significant plant dry matter yield differences among hog manure, poultry manure, old cattle manure, fresh cattle manure, 200 kg P ha^{-1}, 400 kg P ha^{-1}, or alfalfa hay (Table 3). The lowest yielding group of treatments included cattle manure + wood shavings, composted cattle manure, pea hay, barley straw + 200 kg P ha^{-1}, the eroded check, and barley straw + 200 kg N ha^{-1}.

In 1994, the hog and poultry manure amendments resulted in the highest yields (Table 3). The lowest yielding group of treatments, which were not significantly different from each other, included old cattle manure, composted cattle manure, cattle manure + wood shavings, pea hay, both barley straw + fertilizer treatments, both P fertilizer treatments, and the eroded check treatment.

The variation in plant dry matter yields decreased as the study progressed, with differences between the highest and lowest yielding treatments falling from 3.3 Mg ha^{-1} in 1992 to 3.0 Mg ha^{-1} in 1993, and to 2.1 Mg ha^{-1} in 1994.

In 1993, grain and straw yields (Table 4) followed similar trends to plant dry matter yield. The highest yielding group of treatments for grain included poultry manure, topsoil check, hog manure, and old and fresh cattle manure. For straw yield, the alfalfa hay amendment replaced old cattle manure in the highest yielding group of treatments. In 1994, there was no significant difference in grain or straw yield between the topsoil check treatment and the poultry manure, hog manure, or alfalfa hay treatments.

Amendment had a significant effect on total P concentrations of plant dry matter in 1992 (Table 5). The trend closely mirrored dry matter production, with the highest yielding treatments (hog manure and poultry manure) having significantly higher P concentrations than all the other amendment treatments. In 1993, grain P concentrations were significantly higher on the hog and poultry manure treatments than all the other treatments. Straw P concentrations were significantly higher on the hog manure treatment than on all of the other treatments except poultry manure and pea hay. The barley straw + 200 kg P ha^{-1} treatment had a significantly higher grain P concentration than the barley straw + 200 kg N ha^{-1} treatment. In 1993, plant P uptake on the hog and poultry manure treatments was significantly higher than the other amendments.

Soil Nutrient Status

The hog manure treatment had significantly higher extractable P in the 0- to 15-cm depth than all other

Table 4. Effect of amendment on spring wheat grain and straw yields, 1993–1994.

Amendment	1993 Grain yield	1993 Straw yield	1994 Grain yield	1994 Straw yield
	Mg ha^{-1}			
Fresh cattle manure	4.8abc†	3.1abcde	4.3bc	11.5abc
Old cattle manure	4.9ab	3.0bcdef	3.4cde	10.2de
Composted cattle manure	4.5bcde	2.6def	3.4cde	10.3cde
Cattle manure + wood shavings	3.9cdef	2.4ef	3.8cde	10.9bcd
Hog manure	5.5a	3.9ab	5.9a	12.6a
Poultry manure	5.6a	3.7abc	6.2a	12.5a
Alfalfa hay	4.4bcde	3.5abcd	5.3ab	11.9ab
Pea hay	3.9def	2.9bcdef	3.9cd	10.6bcde
Barley straw + 200 kg N ha^{-1}	3.2f	2.0f	3.5cde	10.5cde
Barley straw + 200 kg P ha^{-1}	3.7ef	2.2ef	4.0cd	10.6bcde
200 kg P ha^{-1}	4.5bcd	2.6def	3.0de	10.0de
400 kg P ha^{-1}	4.5bcd	2.9cdef	2.7e	9.3e
Eroded check	3.4f	2.2ef	3.4cde	9.9de
Topsoil check	5.5a	4.1a	6.1a	11.9ab

† Within columns, means followed by the same letter are not significantly different from each other [LSD (0.05)].

Table 5. Effect of amendment on total P concentration in spring wheat plant dry matter (DM), grain, and straw, and on plant P uptake.

Amendment	Total P: Plant DM (1992)	Total P: Grain (1993)	Total P: Straw (1993)	P uptake (1993)
	g kg^{-1}			kg ha^{-1}
Fresh cattle manure	2.3cd†	2.9cdef	0.7bc	15.9cd
Old cattle manure	2.2cde	3.1cde	0.6bc	16.7bc
Composted cattle manure	2.0de	3.0cde	0.5c	14.7cde
Cattle manure + wood shavings	2.0de	3.0cde	0.5c	13.1cde
Hog manure	3.1ab	3.4ab	1.1a	23.6a
Poultry manure	3.2a	3.5a	0.9ab	23.2a
Alfalfa hay	2.0de	2.7ef	0.7bc	14.9cde
Pea hay	2.1de	2.7ef	0.8abc	13.1cde
Barley straw + 200 kg N ha^{-1}	1.1f	2.2g	0.6bc	8.4f
Barley straw + 200 kg P ha^{-1}	1.2f	2.8def	0.7bc	12.0def
200 kg P ha^{-1}	2.0de	2.8def	0.5c	14.4cde
400 kg P ha^{-1}	2.1de	3.1bcd	0.7bc	16.2cd
Eroded check	1.8e	2.6f	0.6bc	10.7ef
Topsoil check	2.7bc	3.2abc	0.7bc	20.8ab

† Within columns, means followed by the same letter are not significantly different from each other [LSD (0.05)].

amendment treatments in spring 1993 (Table 6). The cattle manure + wood shavings and fresh cattle manure had significantly lower P-supplying power than poultry manure.

There was a significant effect of amendment on NO_3–N concentrations in all three soil layers in spring 1993 (Table 6). In the 0- to 15-cm layer, the topsoil check, alfalfa hay, poultry manure, hog manure, fresh cattle manure, and pea hay had significantly higher NO_3–N concentrations than the eroded check, 400 kg P ha^{-1}, 200 kg P ha^{-1}, barley straw + 200 kg P ha^{-1}, barley straw + 200 kg N ha^{-1}, and cattle manure + wood shavings treatments. In the 15- to 30-cm layer, there was no significant difference in NO_3–N concentrations between the alfalfa hay, hog manure, topsoil check, poultry manure, and pea hay (Table 6).

Table 6. Effect of soil amendment on extractable P and NO_3–N concentration in various soil depth increments, spring 1993.

Amendment	Extr. P (0–15 cm)	NO_3–N conc.: 0–15 cm	NO_3–N conc.: 15–30 cm	NO_3–N conc.: 30–60 cm	NO_3–N (0–60 cm)
	mg kg^{-1}				kg ha^{-1}
Fresh cattle manure	6.7d†	8.2ab	8.1bcd	4.2bc	49.9cde
Old cattle manure	20.2bcd	4.0bc	3.8cd	3.5bc	30.5de
Composted cattle manure	15.3bcd	4.5bc	4.1cd	2.9bc	29.3de
Cattle manure + wood shavings	2.2d	1.1c	2.0d	2.1bc	15.4e
Hog manure	51.5a	9.1a	14.6a	8.6ab	84.1abc
Poultry manure	31.4b	9.6a	12.1ab	15.1a	108.3ab
Alfalfa hay	4.0d	9.9a	15.4a	14.1a	111.2a
Pea hay	2.1d	8.1ab	9.2abc	7.3bc	65.3bcd
Barley straw + 200 kg N ha^{-1}	0.5d	1.8c	2.3d	2.3bc	18.2e
Barley straw + 200 kg P ha^{-1}	14.8bcd	1.3c	2.1d	1.9c	14.9e
200 kg P ha^{-1}	14.2bcd	2.6c	2.8d	2.2bc	20.1e
400 kg P ha^{-1}	27.5bc	2.9c	4.3cd	4.2bc	32.5de
Eroded check	0.9d	3.4c	5.3cd	5.2bc	39.9cde
Topsoil check	8.6cd	11.3a	12.4ab	5.3bc	69.3abcd

† Within columns, means followed by the same letter are not significantly different from each other [LSD (0.05)].

Since 15 cm of topsoil was mechanically removed, the NO_3–N concentration for the 30- to 60-cm layer of the topsoil check treatment (5.3 mg kg^{-1}) should be compared with its equivalent profile depth (i.e., the 15- to 30-cm layer of the other treatments). This shows that substantial NO_3–N enrichment occurred in the 15- to 30-cm layer of the alfalfa hay, hog manure, and poultry manure treatments (12.1–15.4 mg kg^{-1}).

In the 30- to 60-cm layer, the poultry manure and alfalfa hay had significantly higher NO_3–N concentrations than all other treatments except the hog manure (Table 6), which provided further evidence for downward transport of NO_3–N 1 yr after application of these amendments.

The mass of NO_3–N in the 0- to 60-cm soil depth increased significantly after application of alfalfa hay and poultry manure compared with the eroded check treatment (Table 6). The 200 kg P ha^{-1}, barley straw + 200 kg N ha^{-1}, cattle manure + wood shavings, and barley straw + 200 kg P ha^{-1} amendment treatments were the only ones that had a significantly lower mass of NO_3–N in the 0- to 60-cm layer than the topsoil check treatment.

In spring 1994 (2 yr after incorporation), there was still a significant effect of amendment on extractable P concentrations in the 0- to 15-cm depth (Table 7). The trend was similar to spring 1993, although there was a general decline in concentrations since no further amendments had been applied. Significant differences in NO_3–N concentrations were present in the 30- to 60-cm depth only in spring 1994 (Table 7). There was no significant amendment effect on mass of NO_3–N in the 0- to 60-cm depth (Table 7).

Restoration of Productivity, 1992 to 1994

The restorative ability of the various amendments was assessed using plant dry matter yields from 1992 to 1994 (Fig. 1), since grain and straw yields were unavailable

Table 7. Effect of soil amendment on extractable P and NO_3–N concentration in various soil depth increments, spring 1994.

Amendment	Extr. P (0–15 cm)	NO_3–N conc.: 0–15 cm	NO_3–N conc.: 15–30 cm	NO_3–N conc.: 30–60 cm	NO_3–N (0–60 cm)
	mg kg^{-1}				kg ha^{-1}
Fresh cattle manure	8.8de†	7.6a	6.8a	2.8abc	40.3a
Old cattle manure	10.2cde	2.2a	3.1a	1.1c	15.1a
Composted cattle manure	9.8cde	3.8a	2.2a	1.2c	16.6a
Cattle manure + wood shavings	4.3de	3.1a	4.0a	0.8c	17.5a
Hog manure	42.4a	10.3a	5.7a	1.8bc	38.8a
Poultry manure	18.1bc	7.7a	4.7a	3.6ab	39.8a
Alfalfa hay	11.1cde	6.1a	4.0a	3.7ab	35.5a
Pea hay	2.2e	4.7a	4.3a	1.9bc	25.8a
Barley straw + 200 kg N ha^{-1}	5.4de	6.3a	2.4a	0.7c	20.0a
Barley straw + 200 kg P ha^{-1}	12.4bcd	3.9a	4.9a	0.9c	21.3a
200 kg P ha^{-1}	5.2de	2.3a	2.6a	1.0c	13.9a
400 kg P ha^{-1}	21.2b	3.4a	3.5a	2.0bc	22.1a
Eroded check	3.4de	4.5a	6.7a	4.4a	41.2a
Topsoil check	7.5de	6.0a	4.6a	2.0abc	29.2a

† Within columns, means followed by the same letter are not significantly different from each other [LSD (0.05)].

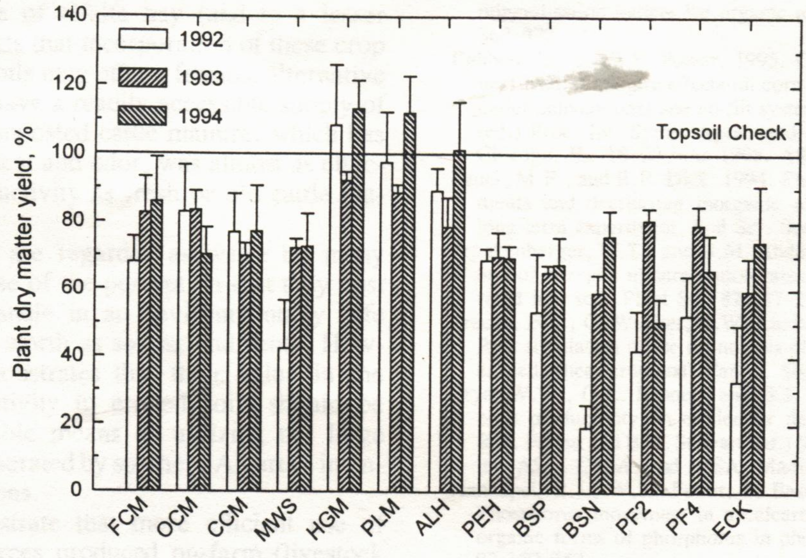

Fig. 1. Plant dry matter yield expressed as a percentage of the topsoil check treatment (1992–1994) (FCM, fresh cattle manure; OCM, old cattle manure; CCM, composted cattle manure; MWS, manure + wood shavings; HGM, hog manure; PLM, poultry manure; ALH, alfalfa hay; PEH, pea hay; BSP, barley straw + 200 kg P ha^{-1}; BSN, barley straw + 200 kg N ha^{-1}; PF2, 200 kg P ha^{-1}; PF4, 400 kg P ha^{-1}; ECK, eroded check). Vertical lines above mean bars indicate standard errors.

from 1992 due to hail damage. The poultry and hog manure treatments showed no evidence of reduced effectiveness even after 3 yr of cropping. The straw + fertilizer treatments, which yielded poorly in the first 2 yr, showed improved effectiveness in the third year, probably due to the release of nutrients from the slowly decomposing straw residue that had been tied up in the early part of the study.

In all years, yields from desurfaced plots amended with hog or poultry manure were not significantly different from plots with no topsoil removal, while yields from the cattle manure + wood shavings and the barley straw + 200 kg N ha^{-1} treatments were not significantly different from the eroded check treatment.

There was little yield difference due to age of cattle manure (Fig. 1). Composted cattle manure was almost as efficient as fresh or old cattle manure. Major benefits of composted manure include lower moisture content and volume (which decreases haulage costs), reduced odor, and reduced potential for leaching of NO_3^- into groundwater.

The barley straw + fertilizer N and P did not prove to be an effective surrogate for manure and performed poorly in the early part of the study. This may be related to its high C/N ratio, which caused slow decomposition and hence a slow release of N.

Using the topsoil check treatment as a baseline (100%), restoration ranged from 19 to 108% in 1992, 59 to 92% in 1993, and 51 to 113% in 1994. The mean restoration was 64% in 1992, 75% in 1993, and 80% in 1994. The trend of increased restoration with time is attributed to enhancement of soil productivity by root and residue inputs from continuous cropping. Restoration rankings are shown in Table 8. The overall best amendments were hog manure (105%), poultry manure (99%), and alfalfa hay (90%), while the poorest ones were cattle manure + wood shavings, barley straw + 200 kg P ha^{-1} (both 62%), 200 kg P ha^{-1} (58%), and barley straw + 200 kg N ha^{-1} (52%).

DISCUSSION

Our results agree with other studies in that the beneficial effects of manure in restoring soil productivity were much larger than those from inorganic fertilizers (Aina and Egolum, 1980; Dormaar et al., 1988; Herron and Erhart, 1965; Whitney et al., 1950). Abbott and Tucker (1973) found that manure applications assured adequate P availability in calcareous soils, while P availability from phosphate fertilizers may be negligible. Hannapel et al. (1964a) found that organic matter amendments increased the movement of P in calcareous soils. This increase was associated with an increase in organic P

Table 8. Annual and average yield rankings for 14 soil amendment treatments and average restoration percentage.

Amendment	Yield ranking 1992†	1993‡	1994‡	Avg.	Restoration§
					%
Fresh cattle manure	8	5	5	5	79
Old cattle manure	5	4	10	6	79
Composted cattle manure	6	8	11	7	75
Cattle manure + wood shavings	11	10	8	10	62
Hog manure	1	3	3	1	105
Poultry manure	3	1	1	1	99
Alfalfa hay	4	9	4	4	90
Pea hay	7	11	7	7	69
Barley straw + 200 kg N ha^{-1}	14	14	9	13	51
Barley straw + 200 kg P ha^{-1}	9	12	6	9	62
200 kg P ha^{-1}	12	6	13	11	58
400 kg P ha^{-1}	10	7	14	11	66
Eroded check	13	13	12	14	56
Topsoil check	2	2	2	3	100

† Based on plant dry matter yields.
‡ Based on grain yields.
§ Based on plant dry matter yields, 1992–1994; topsoil check = 100%.

in the soil solution and the mobilization of native soil P by the microbial population. Hannapel et al. (1964b) also reported that the P contained in microbial cells and cellular debris can move physically, redistributing throughout the soil and, hence, increasing plant uptake of P.

Abbott and Tucker (1973) believed that manure P can be mixed and dispersed throughout the plow layer without affecting its availability, and can resist the mechanisms that remove fertilizer P from solution in calcareous soils. Manure P also has the advantage of positional availability described by Spencer and Stewart (1934). It penetrates or moves vertically with water through the root zone and remains in a form subject to continued mineralization and cycling, as inorganic P cannot. There was a positive linear relationship ($R^2 = 0.66$, $P = 0.01$) between the total P concentrations in the amendments and the average (1992–1994) restoration percentage (Fig. 2). The nine amendments used in this comparison included the six livestock manures, alfalfa hay, pea hay, and barley straw.

The amounts of N released from different manure sources have been related to both their total N content (Douglas and Magdoff, 1991; Rees et al., 1993) and C/N ratios (Frankenberger and Abdelmagid, 1985). In this study, the average restoration percentage (1992–1994) of nine amendment materials showed a significant linear relationship ($R^2 = 0.58$, $P = 0.05$) with the total N content of the amendments (Fig. 2). The higher the total N content of the amendment, the greater its restorative ability.

Cattle manure containing wood shavings was not as effective in restoring soil productivity as the other types of cattle manure. This was probably due to its lower N content and higher C/N ratio. Sommerfeldt and MacKay (1987) recommended supplemental fertilizer N on land that received manure + wood shavings to offset N immobilized by the slower decay of the shavings fraction.

Restoration percentage had a weaker relationship ($R^2 = 0.32$) with C/N ratio (data not shown). McKenney et al. (1995) found that N immobilization and mineralization rates for residue-amended soils could not be explained simply on the basis of C/N ratio, as residues with similar C/N ratios had very different effects. Similarly, Fauci and Dick (1994) reported that C/N ratios may not be the best indicator of organic residue quality.

A stepwise regression technique was used to prioritize the role of P- and N-supplying power in the restorative ability of 12 amendment treatments in this study. The two check (topsoil and eroded) treatments were omitted. This analysis showed that NO_3–N in the 0- to 60-cm soil depth and extractable P in the 0- to 15-cm soil depth in spring 1993 accounted for 87% of the variability in restorative ability of the amendments (Fig. 3). This was partitioned into 71% explained by NO_3–N and 16% by extractable P.

Part of the remaining 13% variation in restorative ability may be explained by soil structural improvements brought about by incorporation of the amendments. Sun et al. (1995) reported that the crop residues, either alone (pea and alfalfa hay) or in combination with fertilizer (barley straw + N or P), resulted in higher wet aggregate stabilities than livestock manures, which were in turn higher than the fertilizer-alone (200 and 400 kg P ha^{-1}) and eroded check treatments on this study. This was related to more readily available organic material in the crop residues than the livestock manures. They also reported that the addition of hog manure, alfalfa hay, pea hay, fresh cattle manure, barley straw + 200 kg P ha^{-1} of, barley straw + 200 kg N ha^{-1}, and manure + wood shavings significantly increased (33–70%) organic C concentrations in the 0- to 2.5-cm depth compared with the eroded check treatment (11 g kg^{-1}).

CONCLUSIONS

Overall, the best amendment was hog manure, followed by poultry manure and alfalfa hay. Based on plant dry matter production, the hog manure and poultry manure amendments resulted in significantly higher yields than the eroded check treatment in all 3 yr of the study, thereby substituting for the 15 cm of lost topsoil. However, the longevity of this effect is unknown. The

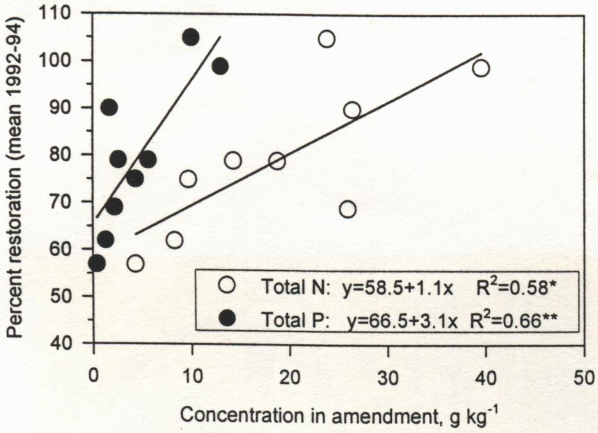

Fig. 2. Effect of total N and total P concentrations of organic amendments on their restorative ability (1992–1994). Restorative ability is expressed as a percentage of the topsoil check treatment. *, Relationship significant at the 0.05 and 0.01 probability levels, respectively.**

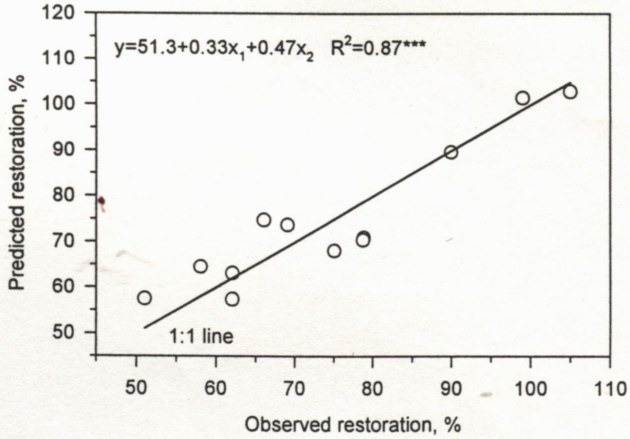

Fig. 3. Observed vs. predicted restorative ability (based on average plant dry matter yield, 1992–1994) as a function of NO_3–N- and P-supplying power of 12 amendment treatments (X_1 = NO_3–N, kg ha^{-1}, 0- to 60-cm depth, spring 1993; X_2 = extractable P, mg kg^{-1}, 0- to 15-cm depth, spring 1993).