Nutrient Cycling in Agroecosystems 66: 165–180, 2003.

The long-term effects of manures and fertilisers on soil productivity and quality: a review

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Received 20 October 2000; accepted in revised form 25 March 2002

Key words: Environment, Fertilisers, Manures, Organic, Productivity, Quality, Soils

Abstract

The results from 14 field trials comparing the long-term (20 to 120 years) effects of fertilisers and manures (farmyard manure, slurry, and green manure) on crop production and soil properties are reviewed. In total there were 24 paired comparisons of the effects of manure and fertiliser. Some of the trials also contained a control (no nutrient inputs) treatment. The input of nutrients as either fertilisers or manures had very large effects (150–1000%) on soil productivity as measured by crop yields. Manured soils had higher contents of organic matter and numbers of microfauna than fertilised soils, and were more enriched in P, K, Ca and Mg in topsoils and nitrate N, Ca and Mg in subsoils. Manured soils also had lower bulk density and higher porosity, hydraulic conductivity and aggregate stability, relative to fertilised soils. However, there was no significant difference ($P < 0.05$) between fertilisers and manures in their long-term effects on crop production. In the context of this set of international trials, the recent evidence from the Rothamsted classical long-term trials appears to be exceptional, due to the larger inputs of manures and larger accumulation of soil OM in these trials. It is suggested therefore that manures may only have a benefit on soil productivity, over and above their nutrient content, when large inputs are applied over many years. The evidence from these trials also shows that, because the ratio of nutrients in manures is different from the ratio of nutrients removed by common crops, excessive accumulation of some nutrients, and particularly P and N, can arise from the long-term use of manures, relative to the use of fertilisers. Under these conditions greater runoff of P, and leaching of N may result, and for soils with low P retention and/or in situations where organic P is leached, greater P leaching losses may occur. The use of manures, relative to fertilisers, may also contribute to poor water quality by increasing its chemical oxygen demand. It is concluded therefore that it cannot generally be assumed that the long-term use of manures will enhance soil quality – defined in terms of productivity and potential to adversely affect water quality – in the long term, relative to applying the same amounts of nutrients as fertiliser.

Introduction

There is currently world-wide concern regarding the impact of modern farming practices on soil and water quality and much recent research has focussed on management options for reducing nutrient runoff and leaching (Sharpley et al. 1994; Jarvis et al. 1995; Gillingham and Thorrold 2000; Ledgard et al. 2000) and improving soil quality (Dick 1992; Liebig and Doran 1999). Within this context the use and management of fertilisers is a specific concern.

Alternative management systems, such as organic and biodynamic farming, are being promoted on the basis that they are more environmentally benign and specifically enhance soil and water quality relative to conventional practices (Reganold 1995; Conacher and Conacher 1998). These systems place much emphasis on the importance of soil organic matter and biological activity and promote the use of 'natural' sources of nutrients (i.e. unprocessed raw materials) and manures*. The use of fertilisers* is either limited or prohibited (Reganold 1995; NZ Biological Producers and Consumers Council 1998; FAO/WHO 1999). It appears to be implicit in these philosophies that fertilisers *per se* have detrimental effects on soil and water quality.

At the farm-system level there is evidence showing that, relative to conventional management practices, organic and biodynamic farming can increase soil organic matter and related soil chemical, biological and physical properties (Fraser et al. 1988; Reganold et al. 1993; Wander et al. 1994; Reganold 1995; Conacher and Conacher 1998; Clark et al. 1998; Liebig and Doran 1999). Other evidence is contradictory (Nguyen et al. 1995; Muller et al. 1992). However, farm-system experiments are often confounded (Werner and Dindal 1990), and because of this it is not possible to be specific as to the cause for the observed effects, given that more than one input variable has been changed. For example, the frequently observed increase in soil organic matter following the conversion of conventional to organic farming practices could be attributed to either the use of manures or a change in cropping rotation, including green manure crops.

At a mechanistic level there is an abundance of evidence showing that the application of fertilisers to nutrient deficient soils generally increases soil organic matter content (see reviews by Dick 1992; Paustian et al. 1997). The primary reason for this is that fertilisers increase crop production, thereby increasing the amount of plant residue, including roots, returned to the soil, although Paustian et al. (1997) suggest other possible mechanisms. A consequence of the increase in soil organic matter is that some soil chemical, biological and physical properties are also improved (Walker et al. 1958; Sears et al. 1965; Jackman 1964; Perrott and Sarathchandra 1987; Perrott et al. 1992; Fraser et al. 1994; Haynes et al. 1995).

Based on this it is likely that manures will have a greater effect on soil organic matter and related soil properties than fertilisers, when applied at the same nutrient inputs, because they supply an additional exogenous source of organic matter. However, this may not always be the case as organic matter accumulation depends on the net incorporation of organic matter in the soil, which in turn depends on the cropping and management system employed (Dick 1992; Paustian et al. 1997).

The question arises therefore: does the long-term use of manures, relative to fertilisers, confer any benefits to soils in terms of their productivity and quality and are there any possibly detrimental effects of manures? This review attempts to address these issues using the results from 14 international, long-term soil fertility trials.

Description of database

From the international literature, field trials were selected for which the following criteria applied: (1) they compared treatments of fertiliser(s) with manure(s), and (2) crop or pasture yield data was available for 20 years. It was not necessary, although desirable, that the trials contained a control (i.e. no treatment) and/or soil data (soil chemical, biological and physical measurements).

A total of 14 trials were identified. Their location, key dates and references are given in Table 1. Of the 14 trials, 4 were on pasture and the remainder used a range of crops, mainly cereals, to test the treatment effects (Table 2). Nine trials were commenced over a century ago and the most recent in 1975. The older trials were not replicated – they commenced before the science of biometrics was developed.

Only 2 trials (Askov and Cockle Park) were balanced with respect to the amounts of N, P, K and S applied in the fertiliser and manure treatments (Table 2). Only one (Askov) was both replicated and balanced. A further 3 were balanced with respect to N inputs alone. The remainder was either not balanced (7 trials) or the balance was not known (2 trials) because the chemical composition of manure was unknown or not given.

Of these 7 unbalanced trials, 4 (Pendalton, Broadbalk, Barnfield and Hoosefield) compared manure at known N inputs with rates of fertiliser N, and 2 (East Lansing and Hillsborough) compared rates of manure with a given rate of fertiliser N. The data from such trials can be used to compare yields at comparable N inputs.

There was evidence from the trials that had been in progress for more than 100 years that crop yields had increased over time due to the introduction of more

* Throughout this review the word 'fertiliser' will be used to refer to chemical fertiliser and 'manure' will be used to refer to organic fertilisers including farmyard (FYM), pig and cow slurry and green crops.

Table 1. Summary of trials, locations, dates and references.

Location and identification		Important commencement dates		Reference
		Trial site	Fertilizer vs. manure comparison	
USA	Morrow	1876	1955	Darmody et al. (1997)
				Aref and Wander (1998)
	Sanborn	1888	1888	Buyanovsky et al. (1997)
	Magruder	1892	1930	Boman et al. (1996)
	Pendalton	1931	1931	Rasmussen and Smiley (1997)
	East Lansing	1963	1963	Vitosh et al. (1997)
	Nebraska	1975	1975	Lesoing and Doran (1997)
Canada	Breton	1930	1930	Juma et al. (1997)
England	Broadbalk	1843	1852	Rothamsted Experimental Station (1991)
				Johnston (1994)
				Johnston (1997)
	Barnfield	1843	1876	As above
	Hoosefield	1849	1856	As above
	Park Grass	1856	1856	As above
	Cockle Park	1896	1896	Arnold et al. (1976)
Ireland	Hillsborough	1970	1970	Christie (1987)
Denmark	Askov	1894	1894	Christensen (1989), Christensen et al. (1994)

efficient cultivars and the use of insecticides and herbicides. This gave rise to an interaction between time and treatment. Because of this, only data from the last 10–20 years of each trial is used in this review to compare the treatment effects. Soil data, where available, from the end of the reported trial period only, are reported.

As noted, many of the trials are not replicated. This means that some care is required when interpreting data from individual trials. However, the collective data (Table 3) can be viewed as an international experiment with 24 paired comparisons of the effect of manure and fertilisers. Summaries of the essential data for each trial (treatments, crop yields and soil properties) extracted from the original papers and reports, and relied upon in this review, are available from the author on request.

Results

Long-term effects of nutrient inputs on crop yields

The effects of some of the key treatments on winter wheat yields grown at Broadbalk (UK) since 1850 are shown in Figure 1. The yields of the best treatments are now about 8 tonnes ha^{-1} yr^{-1}. The increase in yield relative to the control (no nutrients) is about 800% and represents the combined effects of improved cultivars, the use of pesticides and weedicides, together with the input of nutrients from either fertilisers or manures. Figure 2 shows the comparable data from the continuous corn plots at Morrow (USA). In this case the increase in production due to the adoption of the best management practices was about 300–400% by 1984–88. Qualitatively similar trends in yields have been observed in the continuous corn and wheat plots at Sanborn (USA) (Figure 3). In the period 1970–1990 the relative increases due to nutrient inputs, and other best management practices, were about 400% for wheat and over 1000% for corn. On two different soils in Denmark the increases in production due to nutrient inputs were about 300–400% for spring cereals (Figure 4). Generally smaller effects due to nutrient inputs (150%–300%) have been observed in the Magruder (USA) continuous wheat experiment (Table 4) and at Breton (USA) (Juma et al. 1997).

In the absence of fertiliser or manure additions, the yields at Broadbalk have changed little over time and typically are about 1 tonne ha^{-1} yr^{-1}. There was a trend for declining production up to 1920, due to problems with weed control (Johnston 1997), and a small increase with the introduction of more efficient cultivars up to 1980. The yields of the control treatments at the Morrow (Figure 2) and Breton (not shown) experiments show generally similar trends. At Sanborn the yields of the control plots declined over time from about 0.8 to 0.5 tonnes ha^{-1} yr^{-1} and at Askov the control yields are currently about 50% of

Table 2. Summary of trial designs and treatments.

Identification	Design[1]	Manure and fertiliser treatments[2]	Other treatments	Crop and system
Morrow	Unreplicated, balance unknown	FYM (1); Fertiliser [LNPK] (3)		Continuous corn
Sanborn	Unreplicated, balance unknown	FYM (1); Fertiliser [NPKS] (1)		Continuous wheat and corn
Magruder	Unreplicated, balance wrt N	FYM (1); Fertiliser [NPK] (1)	Fertiliser [P], [NP], [NPL]	Continuous wheat
Pendalton	Replicated, not balanced	FYM & Green crop (1); Fertiliser [N] (2)	Stubble burned and not burned	Continuous wheat
East Lansing	Replicated, not balanced	FYM (3); Fertiliser [N] (1); Fertiliser [NPK] (1)	Irrigated and non-irrigated	Continuous corn
Nebraska	Replicated, balanced wrt N	FYM (1); Fertiliser [N] (1)	Herbicide and insecticide	Continuous corn and rotation (corn–soybean–corn–oats–clover)
Breton	Unreplicated, balanced wrt N	FYM (1); Fertiliser [NPKS] (1)		5 yr rotation (wheat–oats–barley–forage–forage) and 2 yr (wheat–fallow)
Broadbalk	Unreplicated, unbalanced	FYM (1); Fertiliser [PKNaMg] (1) × 7 levels of N		Continuous wheat, potatoes
Barnfield	Unreplicated, unbalanced	FYM (1); Fertiliser [PKMg] (1)	Both at 4 levels of fertiliser N	Pasture since 1983, previously root crops
Hoosefield	Unreplicated, unbalanced	FYM (1); Fertiliser [NPK] (2)	All at 4 levels of fertiliser N	Continuous barley
Park Grass	Unreplicated, unbalanced	FYM (1); Fertiliser [NPKNaMg] × 4 levels of fertiliser N	All at 4 levels of soil pH	Pasture
Cockle Park	Unreplicated, balanced	FYM (1); Fertiliser [NPK] (2)		Pasture
Hillsborough	Replicated, unbalanced	Pig & cow slurry (3); Fertiliser [NPK]		Pasture
Askov	Replicated, balanced	FYM (1); Fertiliser [NPK] (1)	2 soil types	Rotation (wheat–barley–beet–clover)

[1]Balance unknown = analysis of manure not known or given. Balanced wrt N = fertiliser and manure treatments apply same N input. Balanced = NPK inputs for manure and fertiliser treatments are the same. [2]The source of FYM is not always given. The number in () indicates the number of rates of application. Letters in [ ] indicate nutrients included in the fertiliser treatment.

Table 3. Summary of the effects of manures and fertilisers on crop yields.

Trial	Crop[1] and measurement period[2]	Sub-treatment or comment	Average annual yield[3] (tonnes/ha)		Difference[4] (%)
			Fertiliser	Manure	
Morrow	Corn (1985–93)		8.4	6.0	28
Sanborn	Wheat (1970–90)		2.7	2.6	4
	Corn (1970–90)		7.5	3.8	49
Magruder[5]	Wheat (1988–94)		2.2	1.90	14
Pendalton	Wheat (1982–92)	FYM	4.9	5.6	−14
		Green crop	4.5	4.3	4
East Lansing	Corn grain (1974–82)	Irrigated	10.5	10.5	0
	Corn grain (1974–82)	Non-irrigated	7.3	8.0	−10
Nebraska[5]	Corn (1976–91)	3 yr rotation (corn–soybean–oats)	4.8	4.7	2
	Soybean (1976–91)	3 yr rotation (corn–soybean–oats)	2.4	2.3	4
	Oats (1976–91)	3 yr rotation (corn–soybean–oats)	2.2	2.4	−9
Breton[5]	Wheat (1982–92)	5 yr rotation	3.1	2.9	6
	Oats (1982–92)	5 yr rotation	4.4	4.1	7
	Barley (1982–92)	5 yr rotation	3.3	2.7	18
Broadbalk	Wheat (1985–90)		8.3	7.9	5
	Potatoes (1985–90)		35.6	32.9	8
Barnfield	Pasture (1983–90)	Residual effect, mean over 4 N levels	8.4	9.4	−12
Hoosefield	Barley (1984–90)	Mean of 4 N levels	5.5	6.4	16
Park Grass	Pasture (1986–90)	Mean of 4 soil pH levels	6.4	6.7	−5
Cockle Park[5]	Pasture (1897–1975)		5.3	5.3	0
Hillsborough	Pasture (1970–85)	Manure = pig slurry	12.1	13.4	−11
	Pasture (1970–85)	Manure = cow slurry	12.1	12.2	−1
Askov[6]	Various crops in rotation (1973–84)	Coarse soil (yields in feed units)	3800[7]	3350[7]	12
	Various crops in rotation (1973–84)	Sandy soil (yields in feed units)	5890[7]	5460[7]	7

[1]All continuous cropping or in pasture unless stated otherwise. [2]Years from which given yields are recorded. [3]Where treatments are not balanced, the yields from the nearest comparable N treatments are given. [4][(fertiliser − manure) / fertiliser] × 100. [5]Trial balanced with respect to N inputs. [6]Balanced with respect to N, P and K inputs. [7]Yields are in feed units (see Christensen 1989).

their initial levels. On the Magruder plots there was no net change in the control yields, which have ranged between 0.6–1.3 tonnes ha^{-1} yr^{-1}.

Comparative effects of fertiliser and manure

Crop yields

Analysis of the data in Table 3, as 24 paired comparisons, shows that there is no difference (paired t-test, $P < 0.05$) between manures and fertilisers on crop or pasture production. This comparison is, however, confounded. As noted earlier not all the trials were balanced with respect to nutrient inputs and different types of manures were used in the various trials. Some of these confounding effects are removed by comparing only those trials balanced with respect to N and to which FYM was applied as the manure. For this subset of 5 trials (see Table 3) there was no difference in crop yields between the manure and fertiliser treatments.

The Askov trials are of particular relevance in this regard, because they are not only balanced with respect to N, P and K, but also fully replicated. The essential results for the two sites Lermarken (on a fine textured soil) and Sandmarken (a sandy soil) are given in Tables 5 and 6, respectively. At both sites fertiliser inputs gave higher yields ($P < 0.05$) than manure for both winter and spring cereals, and lower yields ($P < 0.05$) for legumes. There was no difference between fertiliser and manure on the yield of root crops.

Soil properties

The comparative effects of fertilisers and manures on some soil properties are summarised in Table 8. There was no consistent effect of manure on soil pH, but treatment with manure resulted in higher soil organic matter as measured by total soil carbon and nitrogen. Similarly, manure, especially when applied on an equivalent N basis, enriched topsoils with P and K relative to treatment with fertilisers. There is evidence from some individual trials that soil Ca and Mg are similarly increased.

Nutrient concentrations in the subsoil were reported

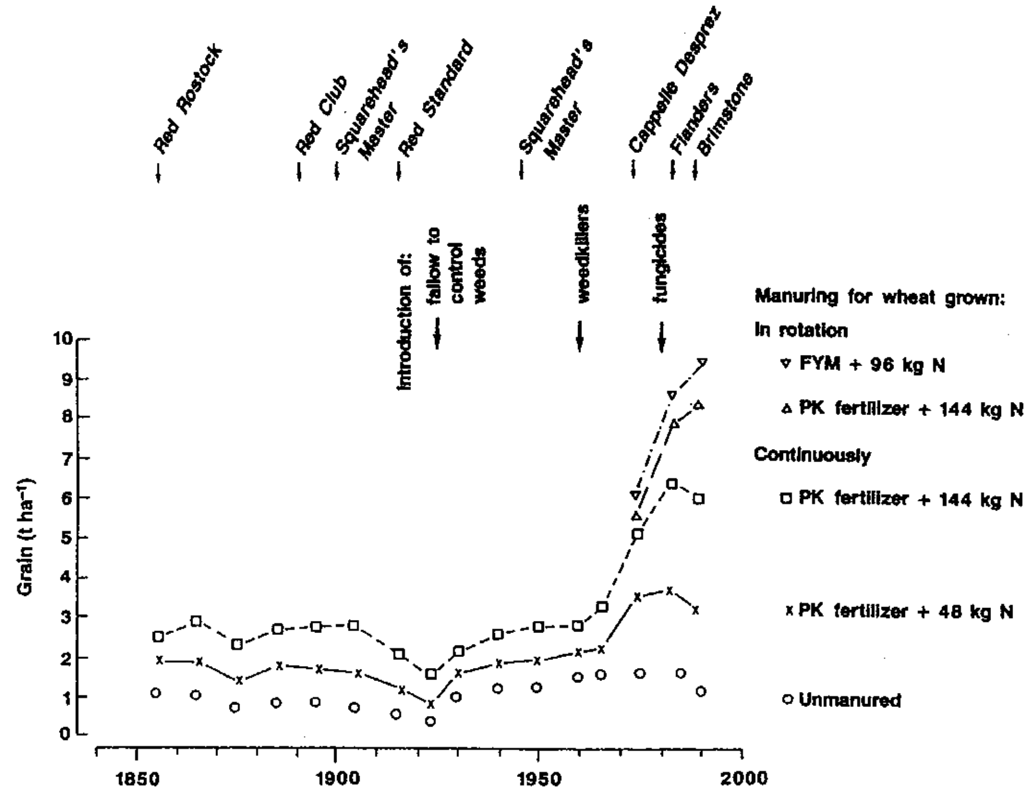


Figure 1. Yields of winter wheat grown on Broadbalk, Rothamsted, from 1852 to 1990 with fertilizers and with farmyard manure, showing the effects of changing cultivars and the introduction of weed control, fungicides, and crop rotations to minimise effects of soil-borne pathogens. Reprinted from Johnston (1994).

for the Magruder plots and showed that relative to the fertilised plots, manure increased nitrate, calcium and magnesium levels.

Soil bulk density was decreased in 3 of the 4 trials where such measurements were made and decreased hydraulic conductivity at the 1 site where this was measured, by the application of manure relative to where fertiliser was applied. At Askov, manure application increased porosity, aggregate stability, and plastic limit relative to fertiliser treatments (Christensen 1997).

Soil biological properties were measured in one trial (Broadbalk). In this case, relative to fertiliser, manure increased soil bacteria and actinomycetes but had no effect on soil fungi.

Discussion

Effects of nutrient applications

The results from the six long-term trials which measured the effects of nutrient inputs, either as manure or fertiliser, on crop yields, demonstrate very clearly the combined effects of nutrient inputs, improved cultivars and appropriate weed and pest control on long-term crop yields. The size of this effect is site specific and ranged from 150% to > 1000% and typically was of the order 300–400%. The size of this effect will depend on the initial fertility of the soil and the rate at which weathering and net mineralization of organic matter will replenish plant available soil nutrients. It may also depend on the crop and cultivar being grown.

The examples above are from arable soils. By comparison, Figure 5 shows the effects of fertiliser on pasture yields at Winchmore (NZ) (Nguyen et al. 1989). Control yields decreased from about 7 to about 4 tonnes DM ha^{-1} yr^{-1} over a 30-year period in the absence of nutrient inputs. Where optimal P and S were applied, pasture yields have remained constant between 10–12 tonnes DM ha^{-1} yr^{-1}, an increase in the mid-1980s of about 250–300%.

There are undoubtedly many other examples inter-

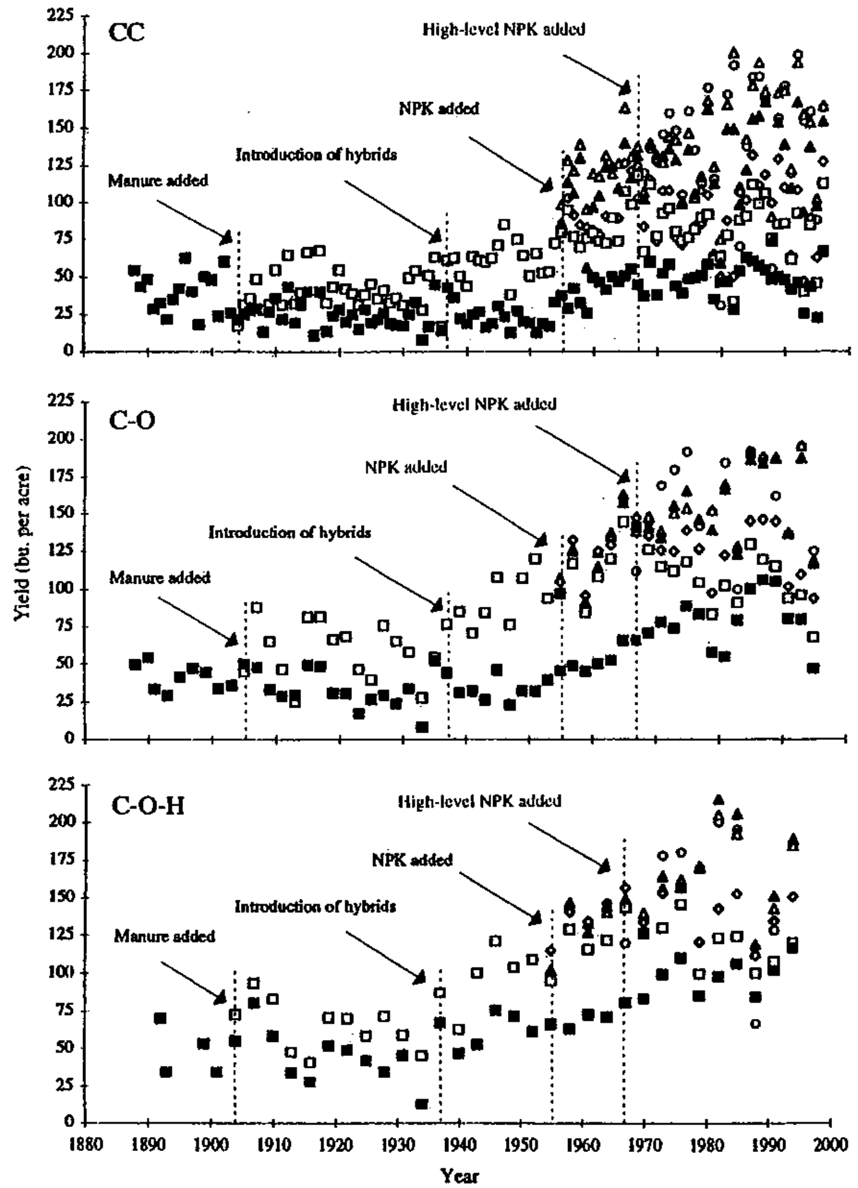


Figure 2. Morrow plot yield from 1888 to 1996 by three rotations: continuous corn (CC), corn–oats (C-O), and corn–oat–hay (C-O-H). Vertical lines indicate changes from one phase to the next (solid squares = untreated, open squares = manured, open diamonds = manured with high density planting, solid triangles = previously untreated, now NPK treated, open triangles = previously manured, now NPK treated, open circles = previously manured, now high level of NPK) (from Aref and Wander 1998).

nationally showing the large effects of nutrient inputs on crop production. However, the results discussed here are compelling because of the long-term nature of the trials and, if it is reasonable to generalise, they suggest that nutrient inputs increase crop production by 300–400% depending on the site-specific factors noted above. Accordingly, nutrient inputs must be regarded as essential on most soils to maintain long-term sustainability.

Comparative effect of fertilisers and manures

Relative to fertilisers, manures increased soil organic matter contents (Table 8). This is consistent with

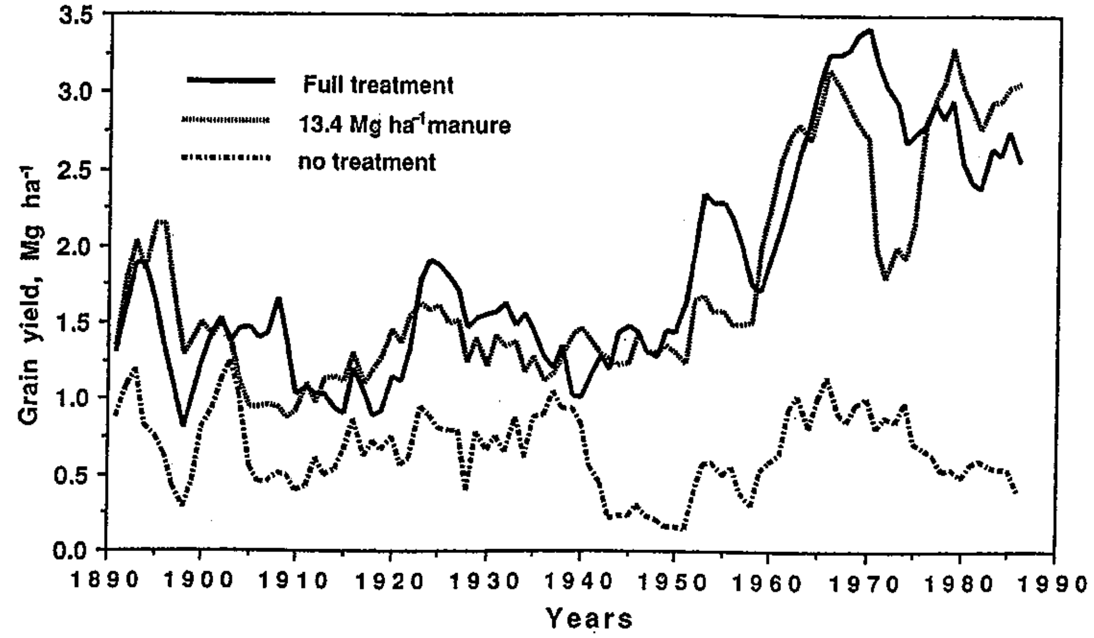


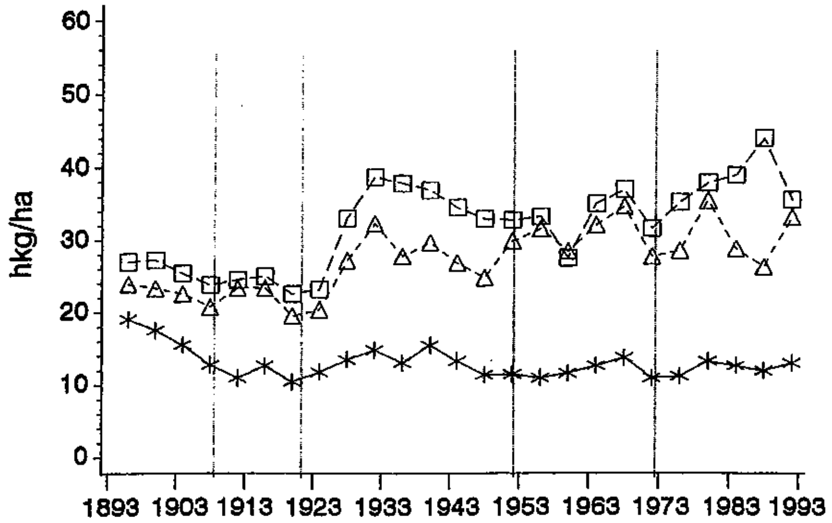
Figure 3. Effect of manure (13.4 tonnes/ha) and fertiliser (NPK), relative to no treatment on the long-term yields of winter wheat grown continuously at Sanborn (five year moving averages) (from Buyanovsky et al. 1997).

other evidence (Dick 1992) and is not surprising, as manures contain significant amounts of organic matter. For example, a typical application of fresh farmyard manure of 35 tonne ha^{-1} will supply about 7000–8000 kg ha^{-1} of organic matter. However, the results from this set of international trials, whether considered in total or as a subset of 5 trials balanced with respect to N, or taking the results from the only replicated and balanced trial at Askov, collectively suggest that manures do not generally confer any advantage to crop yields that cannot be derived from the application of nutrients. This suggests that manures and fertilisers, when applied at equivalent rates of N, P, K and S, have similar effects on crop yields as demonstrated by the results reported by Christie (Figure 6).

This is a surprising conclusion, given the generally assumed link between soil productivity, soil fertility and organic matter (Cooke 1967; Stevenson 1982; Tate 1987). However, it is not new. Johnston (1986, 1994), in summarising the earlier Rothamsted data (up to about 1980), reached a similar conclusion. However, subsequent data from these trials (Johnston 1986, 1994, 1997) showed that crop yields were greatest on plots treated with manures.

It appears, however, that the Broadbalk and Hoosefield trials may be unique in the international context. In these trials the increase in soil organic matter (as indicated by the soil C or N contents) due to the long-term application of manure, relative to the fertiliser treatment, was > 300% (Table 8). At Hoosefield the soil carbon contents of the fertiliser treatments are about 1% and the manured soils are now above 3% (Johnston 1986). The soil carbon levels for the respective treatments at Broadbalk are 1% and 2.7% C. In comparison, while the soil carbon levels in the fertiliser treated soils in all the other international trials were typically between 1–2%, the percentage increase due to treatment with manures ranged from −15% to 81% (Table 8). It is noted in particular that the effects of manure relative to fertiliser on soil organic matter levels in the Askov trials were modest (Table 8). Cockle Park and Park Grass are atypical in that the carbon contents in the fertiliser treatments are relatively high, being 4.1% and 2.8% respectively.

The input of manure on all the Rothamsted experiments – Broadbalk, Hoosefield, Park Grass and Cockle Park – was 35 tonnes ha^{-1} annually. The manure inputs in all the other trials, except East Lansing, were much less than this and ranged from 4 to 22 tonnes ha^{-1} yr^{-1}. Thus, it is likely that the major reason for the larger effects of manures relative to fertilisers on soil organic matter in the Rothamsted experiments is



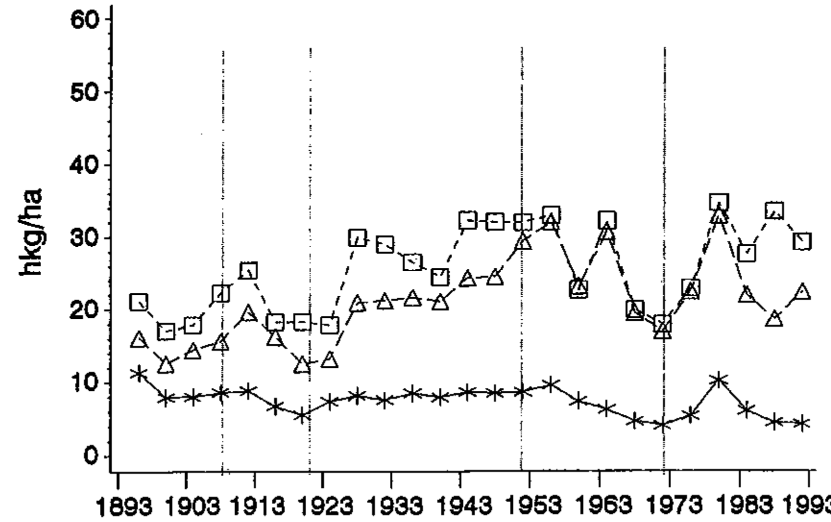


Figure 4. Effect of manure (triangles) and fertiliser (squares), relative to no treatment (stars), on the long-term yields of spring cereals grown at Askov. (Top) Sandmarken; (bottom) Lermarken (from Christensen et al. 1994).

Table 4. Effect of manure (FYM) and fertiliser on wheat yields on the Magruder plots (USA) (Boman et al. 1996).

Decade	Relative yield (control = 100)	
	Manure (FYM)	Fertiliser (NPK)
1930–37	145	134
1938–47	182	182
1948–57	135	169
1958–67	158	174
1968–77	167	208
1978–87	173	168
1988–94	175	205

the greater input of organic matter. It appears therefore that the four Rothamsted experiments are unique, either with respect to the increase in soil organic matter achieved with continuous inputs of manure, or the higher soil organic matter level in the fertiliser treatments.

In the East Lansing trial, commenced in 1963, three rates of manure were applied; 22, 45 and 67 tonnes ha^{-1} yr^{-1}. The results (Table 7) show that while soil carbon levels and crop yields increase with increasing rates of input of manure, the fertiliser treatment has

Table 5. Effects of fertiliser and manure on crop yields (kg/ha/yr) at Lermarken Askov 1973–1992 (Christensen et al. 1994).

Treatment	Winter wheat		Spring barley		Root crops (beet root & turnips)		Grass/clover
	Grain	Straw	Grain	Straw	Root	Tops	Forage
Control	1710	1610	1250	880	1680	570	3780
Manure	3100	3090	3080	2870	8380	2250	6680
Fertiliser	4520	4640	3820	3180	8260	2830	5540
Lsd ($P < 0.05$)	550	520	310	320	820	820	850

Table 6. Effects of fertiliser and manure on crop yields (kg/ha/yr) at Sandmarken, Askov 1973–1992 (Christensen et al. 1994).

Treatment	Winter rye		Spring barley		Root crops (potatoes &	Peas
	Grain	Straw	Grain	Straw	turnips; roots and tops)	
Control	740	1200	600	340	1370	1420
Manure	1700	2720	2360	1540	5370	3510
Fertiliser	3470	4440	2940	2310	5180	2750
Lsd ($P < 0.05$)	300	340	380	370	990	390

Table 7. Effects of fertiliser or manure on crop yields and soil carbon and nitrogen at East Lansing (Vitosh et al. 1997).

Treatment	Corn yield[1]	Soil carbon (%)	Soil nitrogen (%)
Fertiliser NPK	10.5 (7.3)	0.78	0.07
Manure (22 t ha^{-1})	9.6 (6.9)	0.98	0.09
Manure (45 t ha^{-1})	10.5 (8.0)	1.08	0.10
Manure (67 t ha^{-1})	10.6 (7.8)	1.23	0.10

[1]Irrigated and, in parentheses, non-irrigated.

Table 8. Summary of the effects of manures on soil properties relative to fertilisers.

Trial	Effect of manure relative to fertiliser[1] on soil property (fertiliser = 100)					
	pH	N (%)	C (%)	P	K	Other properties
Morrow	103	–	128	177	113	Bulk density decreased, hydraulic conductivity increased
Sanborn	100	127	–	195	252	
Magruder[2]	120	94	85	140	164	Topsoil Ca & Mg increased. Subsoil nitrate N, Ca and Mg increased
Pendalton	–	123	121	–	–	Bulk density no change
East Lansing	106	157	138	73	106	
Nebraska[2]	103	114	121	520	161	Bulk density decreased
Breton[2]	88	128	181	45	123	Biomass C and water soluble C increased
Broadbalk	–	330	–	–	–	Bacteria and actinomycetes increased, fungi no change
Barnfield	–	–	–	–	–	
Hoosefield	–	–	320	–	–	
Park Grass	79	–	116	–	–	
Cockle Park[2]	107	–	137	188	–	Bulk density decreased
Hillsborough	107	–	–	273	159	Mg increased
Askov[3]	–	108	105	97	–	Porosity increased, aggregate stability increased, plastic limit increased

[1]Where treatments are not balanced, the soil properties of the nearest comparable treatment are given. [2]Balanced wrt fertiliser N inputs. [3]Balanced wrt N, P and K.

produced similar yields to the highest manure input, but with lower soil organic matter levels, noting that the soil carbon level, even at the highest input of manure, is only 1.2%.

Thus, the evidence suggests that perhaps very large differences in soil organic matter are required before the additional benefit of organic matter, over and above its nutrient content, on crop yield can be

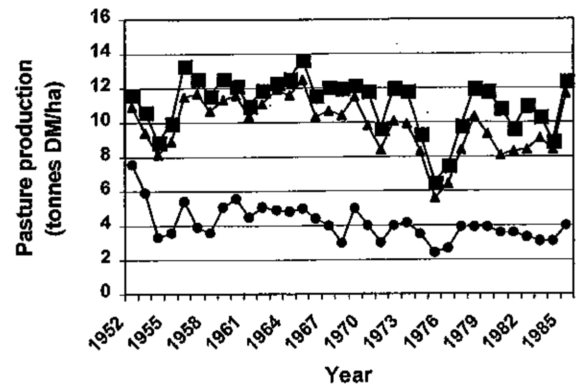


Figure 5. Long-term effects of no fertiliser (circles) and fertiliser (188 (triangles) and 375 (squares) kg superphosphate/ha/yr) on pasture production at Winchmore, New Zealand (from Nguyen et al. 1989).

observed. As indicated by the Rothamsted trials, large inputs of manures (> 35 tonnes ha^{-1} yr^{-1}) over long periods of time (> 100 yrs) may be required to achieve this. This could also be a further reason to explain why the benefits of organic matter have taken so long to become apparent at Hoosefield and Broadbalk. To date this has been attributed to a combination of factors: the greater yield potential of the newer cultivars, improved control over pests and diseases, more efficient use of soil N, increased soil nutrient status arising from the mineralization of the organic matter including N, P and S, improved water holding

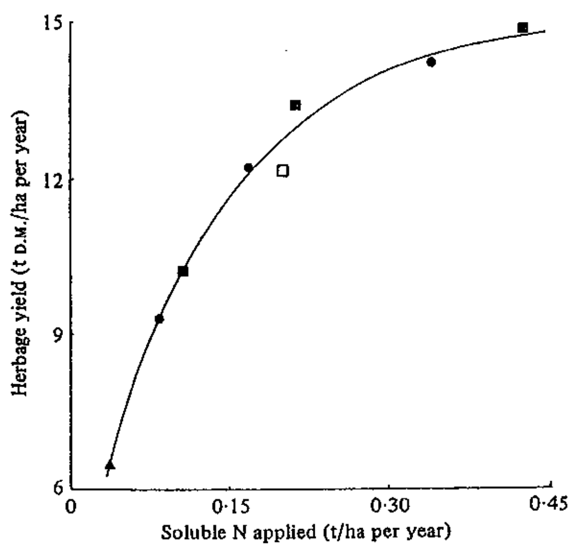


Figure 6. Effect of soluble N applied as either pig slurry (solid squares), cow slurry (solid circles) and fertiliser annually (open squares) or in 1970–72 only (solid triangle) (from Christie 1987).

capacity and better soil structure (Johnston 1986, 1994, 1997; Greenland 1997). Christensen and Johnston (1997), while noting the difficulties of separating these potential and possibly related mechanisms, calculated that the benefit of the accumulated organic matter in the Broadbalk winter wheat trial was equivalent to 1.39 t/ha of yield or 69 kgN/ha.

Management can also have an effect on the relative effects of manures and fertilisers. Christensen et al. (1994) attributed the significant difference between manure and fertilisers on cereal production at Askov to the time of application. During the years 1972 to 1992, fertilisers were applied in the spring but manure was applied in the autumn. The implication is that some of the manure N applied in autumn is lost, probably by leaching. This is supported by other data to be discussed later and is consistent with the greater yield difference between spring applied fertiliser and autumn applied manure on the coarser textured Sandmarken soil. Also, it is noted that during the forage rotation no fertiliser or manure was applied and thus the treatment effects observed at both sites are due to the residual effects of both fertiliser and manure. This possibly explains why during this rotation yields were higher for the manure treatments. Thus the results from Askov are not necessarily inconsistent with the general conclusion given above, once these management factors are considered.

It is generally accepted that many soil physical properties are related to the organic matter content (McLaren and Cameron 1996). For instance, Haynes et al. (1991) reported a good example of the relationship between soil carbon content and aggregate stability. The results from the long-term trials examined here, particularly those from Askov, showing that manured soils have a lower soil bulk density and increased porosity and aggregate stability, and in one case greater hydraulic conductivity, are consistent with this. Such changes in soil physical properties may not always be beneficial. For example, if the permeability of water through the soil profile is enhanced, then greater leaching of nutrients may result, although this could simultaneously reduce surface runoff (Powlson et al. 1989; Johnston 1997).

Dick (1992), in a review, noted that there is generally a positive relationship between soil C content and soil microbial biomass, and concluded that any practice that increases the amount and incorporation of organic residues into the soil increases biological activity. Since both organic and inorganic inputs, when coupled with appropriate management, increase the amount of residue returning to the soil, it follows that both can have beneficial effects on soil biological activity. It is also predictable that manures, when applied at the same nutrient inputs, will have a larger effect, relative to fertilisers, on soil biological activity. The results from Broadbalk with respect to the number of bacteria and actinomycetes are consistent with this generalisation. Dick (1992) did, however, note some exceptions to this, related to the application of N fertiliser on specific soil enzymes, in semi-arid soils.

Importantly, this effect of manure on soil organic matter, relative to fertilisers, was not due to fertilisers decreasing soil organic matter levels. Indeed, the evidence from these trials (not given) shows that fertilisers also increase soil organic matter. Paustian et al. (1997) have summarised the international literature on the effects of fertiliser N inputs on soil carbon concentrations. They concluded that there was a general tendency of increases in soil C with fertiliser N additions. This occurs primarily because fertiliser N inputs increase crop production and thereby increase the amount of crop residue, including roots, returned to the soil. The application of other nutrients, both macro and micro, will predictably have the same effect if they also stimulate further plant growth.

Paustian et al. (1997) noted that there are other mechanisms by which fertilisers can result in the accumulation of organic matter, such as when fertilisers acidify the soil (as with ammonium fertiliser used without lime) or decrease available soil moisture (by increasing plant transpiration). In these situations the rate of decomposition of the existing organic matter is decreased rather than the more normal effect of enhancing the rate of organic matter addition.

The data summarised by Paustian et al. (1997) was largely from arable soils. The pasture system, especially as practiced in New Zealand with *in situ* all-weather grazing, is more 'closed' with respect to losses of organic matter. Also a forage legume is used as the primary source of N, rather than fertiliser N. This returns to the soil not only N but also organic matter-rich residues. It is not surprising therefore that under these conditions the application of fertiliser P, K, S and trace elements results in the accumulation of large amounts of soil organic matter and consequential changes in related soil properties. There are many examples of this in New Zealand (Walker et al. 1958; Sears et al. 1965; Jackman 1964; Perrott and Sarathchandra 1987; Perrott et al. 1992; Fraser et al. 1994; Haynes et al. 1995).

While the addition of organic matter to soils is generally regarded as beneficial, it is also necessary to consider the possible negative effects of applying manures. The evidence from these long-term trials shows that the use of manures relative to fertilisers can result in soils becoming excessively enriched with some nutrients, particularly P, K, Ca and Mg in the topsoils and with nitrate-N, Ca and Mg in the subsoils (Table 8). The accumulation of excessive levels of Ca, Mg and K in soils, while not desirable in terms of nutrient efficiency, is unlikely to pose an environmental risk. However, levels of P and N above those required for optimal crop production will increase the potential for nutrient runoff and leaching (Sharpley et al. 1994; Ledgard et al. 2000).

Powlson et al. (1989) reported that soil nitrate concentrations were higher during the winter in soils treated with manure compared to soils treated with fertilisers. Similarly, Johnston (1997) reported that large quantities of the N applied as manure were unaccounted for in the soil organic matter and crop N uptake, and suggested that this was due to the loss of nitrate N. The direct evidence from the Margruder trial, where manure was applied every 4 years in July, and the indirect evidence from the Askov trials discussed earlier (manure applied annually in autumn) confirm this. In both of these trials N was balanced. However, Waddell et al. (2000) found very little difference in total N leaching losses from manure (applied and worked into the soil in April) and fertiliser when applied on an equivalent N basis.

The evidence suggests that the leaching losses of N from manured soils can be greater than where fertiliser is applied and that it may be possible to reduce the leaching losses of manure N with appropriate management, including spring applications worked into the soil and matched to the plant N demand. However, this may be difficult to achieve. Manures are normally ploughed into the soil, and time is allowed for the organic material to mineralise to mineral N. If the timing is incorrect and/or the prevailing soil and climatic conditions are not appropriate, either the initial plant demands for N will not be met or conversely, nitrate N in excess of the plant requirements will accumulate and become subject to leaching.

Furthermore, as Sharpley et al. (1994) explained, applying manure on an N basis, while desirable from the point of view of minimising nitrate leaching, leads to soils becoming excessively enriched with respect to P. This arises because of the high ratio of P relative to N, which does not match crop requirements and nutrient removal. They suggested a number of strategies to overcome this problem, including limiting the use of manures to P deficient soils or applying manures on a P basis only. Shepherd and Withers (1999) suggested that manures should be applied rotationally, for example one year in three, to avoid unnecessary P accumulation. Presumably this would require the use of fertiliser N when manure is not applied. A further option to overcome this potential environmental problem is to adjust the N:P ratio using either fertilisers or other manures with different N:P ratios.

If manured soils become enriched with P then this could decrease water quality by increasing leaching of P or increasing surface P runoff. Johnston and Poulton (1992) reported that manure enriched soil P below 30 cm relative to fertiliser P, and suggested that this may be due to leaching of organic forms of P. Similar results were reported by Eghball et al. (1996) on a sandy loam (pH >7.0). But Heckrath et al. (1995) found no difference in the concentration of total P in water draining soils treated with either fertiliser or manure. Shepherd and Withers (1999) compared large loadings of P applied as either fertiliser or poultry litter and found no treatment effect on soil P down to 1 m. Further work is required to resolve this issue: is there a unique mechanism by which organic P can be leached, as suggested by Johnston and Poulton (1992) and Eghball et al. (1996), or is the saturation of soil P retention the only factor that needs to be considered?

Several studies have compared the amount of runoff of P and N generated from plots treated with either manures or fertiliser (Wood et al. 1999; Eghball and Gilley 1999; Nichols et al. 1994; Macleod and Hegg 1984). Restricting this discussion to those trials which were balanced with respect to total N and P inputs, Macleod and Hegg (1984) found that while fertiliser N (ammonium nitrate) gave higher initial runoff of N, the total amounts of N lost by runoff from fertiliser were similar to those from dairy and poultry manure. Municipal sludge gave the lowest runoff. Also the chemical oxygen demand (COD) of the runoff was much higher for both manures. Nichols et al. (1994) compared poultry litter and fertiliser (ammonium nitrate) and found that there was no difference in the amounts of total N and P in the runoff but that the COD was higher for the manure treatment.

The general conclusion is that, when compared on an equal nutrient basis, losses of N and P, either from leaching or runoff, will be similar in the long term providing both are applied to meet the plant demand for nutrients both quantitatively and in terms of timing. This is especially critical for N and may require that manures are not applied in the autumn and should be worked into the soil. This conclusion is supported indirectly by the agronomic data reviewed in this paper. The fact that both fertilisers and manures are generally equally effective, with normal field experimental error as sources of nutrients, at least for N and P, implies that the long-term utilisation of nutrients is similar for both sources. This can only be true in the long term if the nutrient losses are similar. Other evidence supports this (Boran and Gianquinto 1995; Shepherd and Withers 1999; Waddell et al. 2000), although, as Blake et al. (2000) have shown for P, this may depend on the soil type and the presence or absence of other nutrient limitations.

Although this review is primarily concerned with the effect of nutrients and organic matter on soil productivity and quality, it must be noted that some fertilisers and manures contain significant amounts of inorganic pollutants. Johnston (1997) reviewed data from the Rothamsted experiments and noted that relative to fertiliser inputs, manure (FYM) applied at 35 t/ha increased soil levels of Cu, Pb and Zn.

Conclusions

A comprehensive definition of soil quality should embrace not only those properties which contribute to a soil's productivity but also include soil properties that affect their potential to contribute to water quality through leaching or runoff.

Manures and fertilisers have similar and very large effects on the long-term productivity of soils, relative to applying no nutrients, and thus the addition of nutrients in either form must be regarded as essential for the maintenance of soil quality. Manures have a greater effect on increasing soil organic matter levels – and hence soil biological activity – relative to fertilisers. Because of this, the long-term use of manures can also affect some soil physical properties. Despite this, it appears that typical applications of manure over many years confer no advantage to soil productivity, relative to applying the same amounts of nutrients as fertilisers. Only when there are large inputs of manures over many years, such that there are large accumulations of soil organic matter, do manures have benefits for soil productivity over and above the nutrients they contain.

Because the ratios of nutrients in manures are different from the ratio of nutrients removed by common crops, excessive accumulation of some nutrients, and particularly P and N, can arise in the long term, relative to the situation where fertilisers are used as a source of nutrients. While this problem can be minimized with respect to N by applying manures on an N input basis, matched to the plant N requirements this gives rise to soil P enrichment. Under these conditions greater runoff of P may result, and for soils with low P retention and/or in situations where organic P is leached, greater P leaching losses may occur. Manures are more likely to contribute to poor water by the addition of material with a high chemical oxygen demand.

It is concluded therefore that the long-term use of manures may not necessarily enhance soil quality in the long term relative to applying the same amounts of nutrient as fertiliser.

Acknowledgements

The assistance of Dr Steve Smith (Rothamsted) in identifying the trials is appreciated. The financial support of Fert Research (New Zealand) is acknowledged.

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