Nutrient Cycling on Organic Farms

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Introduction

In his book *The Control of Soil Fertility*, Cooke (1967) began by reminding his readers that 'The inevitable result of farming is always to diminish *natural* fertility because portions of the total supply of plant nutrients … are removed.' Cooke believed that the use of fertilisers within agriculture was necessary to meet food requirements and regarded such systems as efficient and productive. Organic farmers disagree. Soluble fertilisers such as ammonium nitrate and superphosphate, which feed the plant directly and are thought to bypass the natural processes of the soil, are not acceptable. In organic farming systems, nutrient supplies to crop plants are sustained through recycling, the management of biologically-related processes such as nitrogen (N) fixation by clover and other legumes, and the limited use of off-farm materials. The aim is to achieve as far as possible a closed nutrient cycle on the farm and to minimise adverse environmental impact (Lampkin, 1990).

Effective waste management is obviously a key to nutrient cycling on organic farms. However complete recycling is limited by the prohibition of the use of sewage sludge because of current concerns over the introduction of potentially toxic elements, organic pollutants and disease transmission. In addition, the current global market, in which food is transported large distances from the farm, results in a significant export of nutrients. These nutrients must be replaced otherwise, as Cooke (1967) said, soil is impoverished and the system unsustainable. Johnston (1991) has expressed concern that, on organic farms, phosphorus (P) and potassium (K) may be mined from soil reserves because of the paucity of acceptable sources of these nutrients. This dilemma is recognised by the organic farming movement and a list of allowed amendments is published (UKROFS, 1999). Most of these are organic materials such as calcified seaweed, or relatively insoluble mined products such as rock phosphate. However, in certain circumstances, where plant or soil analysis clearly demonstrates a need and permission is obtained from the certifying organisation, more soluble materials such as potassium sulphate are allowed. Such exceptions can appear contradictory to conventional farmers. This problem is acknowledged by the organic movement, which is seeking to base its list of approved products on a more sound scientific footing (Personal Communication, Peter Crofts, UKROFS).

The Ministry of Agriculture, Fisheries and Food (MAFF, 1999) recently concluded that "organic farming brought environmental benefits … and the significance of the environmental benefits would depend on the nature of the enterprise". Therefore, aid is provided to farmers who are converting to organic production under EC regulation 2078/92. In addition, Cobb *et al*. (1999) argued for permanent support for organic farmers of at least

£25/ha on the basis of social and environmental benefits; the environmental benefits are thought to include increased biodiversity, improved soil quality and reduced pollution. In contrast, the Royal Commission on Environmental Pollution (1996) concluded that 'organic systems are inherently liable to nitrogen leaching'.

In this paper we examine the sustainability of nutrient cycling on organic farms. After a brief consideration of the principles of nutrient cycling in organic agriculture, we use data on soil P and K indices and farm nutrient budgets to assess the integrity of nutrient cycling, including some consideration of losses to the environment. We also attempt to assess the wider sustainability of organic farming in the context of the limited amount of recycling possible.

Nutrients on organic farms

Nitrogen

Low intensity livestock systems, completely based on rough grazing and in which no attempt is made to increase N supply, are common in the uplands; they represented 43% of the land area converted to organic production in the UK in 1997 (MAFF, 1999). The remaining organic farms are mostly lowland livestock or mixed arable-livestock enterprises, with a substantial part (at least 50%) of the farm in a ley in any one year. In such systems, N is supplied by biological fixation, usually through the inclusion of red and /or white clover in grass mixtures. Estimates of fixation in organically managed grass-white clover leys range from 100 to 235 kg N ha^{-1} (Vinther & Jensen, 2000).

Stockless systems are possible. In an exemption to the set-aside rules, organic farmers are permitted to use green cover containing more than 5% legumes in the seed mixture (MAFF 1999). Most common is a two year grass-red clover ley, which can accumulate 250-370 kg N ha^{-1}, and is cut and mulched to return N to the soil for subsequent crops (Stopes *et al.*, 1996). Clearly such systems are dependent on EU policy. Good growth of legumes is also dependent on adequate amounts of P and K in soils. In much of the UK and Western Europe these have been achieved through many years of applications of fertilisers.

Cultivation and subsequent mineralization are key to the release of this fixed N, but mineralization is difficult to control. Poor matching of soil supply and crop demand for N can lead to losses by leaching or denitrification or both (Philipps and Stopes, 1995; Lord *et al*., 1997). The transition from ley to arable cropping in an organic rotation is generally associated with the highest loss, with up to 180 kg N ha^{-1} leached in the winter after ploughing. Season, timing and intensity of cultivation have been shown to have a substantial effect on this loss. Cultivation of leys in spring, followed by spring cropping, reduces nitrate leaching very markedly (Watson *et al.*, 1993). However, where autumn sowing is an option, winter cereals tend to dominate, due to their greater profitability.

The careful management of animal manure to minimise losses and optimise nutritional benefits is a key feature of stocked organic systems. At present there is no limit to the application of N in manures and slurries in organic systems, other than guidance provided by the Codes of Good Agricultural Practice. New EU legislation (Council Regulation (EC) No 1804/1999), which comes into force in August 2000, requires that a maximum of 170 kg N ha^{-1} yr^{-1} applied in manure; where necessary stocking rate must be reduced to meet this limit.

Phosphorus and potassium

In mixed and animal-based systems, animal feeds and bedding represent relatively large inputs of P and K to organic farms (Fowler *et al.* 1993, Nolte and Werner, 1994). Any necessary additional P and K is applied strategically within the rotation, with one application of rock phosphate expected to supply P for a number of following crops. However, organic farming seeks to optimise the recycling of P and K and to keep imports as small as possible. In animal-based and mixed systems, good manure management is therefore essential. Manure and slurry are used to redistribute nutrients around the farm. However the grazing patterns of livestock, such as 'camping' under trees, in the lea of hedges and at fixed feed troughs, can increase the spatial heterogeneity of P and K returns, which may persist for many years. Phosphorus dominantly occurs in organic forms in manures, while K is found in soluble forms; large leaching losses of K can therefore occur during manure storage and composting (Fowler *et al.* 1993).

Other nutrients

Liming is standard practice in organic farming, using ground chalk, limestone and seaweed; slaked or quick lime are not permitted. Deficiencies of other minor nutrients are not widely reported in organic crops because trace amounts of these are often present in purchased feeds and approved amendments. Some concern has been expressed over sulphur and zinc requirements to achieve bread-making quality in wheat (Starling & Richards, 1993). There is also concern over trace element deficiencies in organic livestock (Weller *et al*., 1996; Andrews, 1999). However, little research has been carried out in this area. We have confined our study to N, P and K.

Sustainability of nutrient supplies in organic farm systems

Soil analyses and Indices

Soils in England and Wales are routinely analysed for available P using Olsen's method (extraction with 0.5M sodium bicarbonate; Olsen *et. al.*, 1954) and for available K by extraction with ammonium nitrate (MAFF, 1973) or ammonium acetate (Metson, 1965). Depending on their content of available P and K, soils are grouped into Indices from 0 to 9. Generally soils at Index 0 and 1 are deficient and in conventional production the aim is to maintain an Index of 3 (MAFF, 1994). Indices of available P and K in England and Wales are measured in the Representative Soil Sampling Scheme (RSSS; Skinner and Todd, 1998).

The double lactate (calcium lactate + lactic acid) method is used for the analysis of P and K in soils from organic farms (EFRC, 1999). For arable and grassland soils, between 100 and 300 mg lactate-extractable P kg^{-1} soil and between 100 and 200 mg lactate-extractable K kg^{-1} soil, respectively, are regarded as sufficient. These amounts cannot be easily related to conventional 'Available' P and K contents. However, we have made a limited comparison of organic and conventional soils using conventional P and K indices. Data for soils submitted for analysis to the Organic Advisory Service during 1997 were compared with those from conventionally-farmed soils. Some 39% of soils from organic farms were at an 'Olsen' P index of 0 or 1, 23% at Index 2 and 38% at Index 3 or above (Figure 1). Double lactate extraction of P and K showed that 86% of these soils were deficient in available P and 36% were deficient in available K. By contrast, for approximately the same years, only 15% of conventional arable soils were at an 'Olsen' P Index of 0 or 1 (Figure 1), and only 20-25% of conventional grassland soils were at a P Index of 0 (Chambers *et al.*, 1996). Some 30% of conventional arable soils were at a K index of 0 or 1, 50% at Index 2 and 20% at Index 3 or above.

These data suggest that the amounts of available P in soils farmed organically are significantly less than those in conventional soils, while the levels of available K are about the same. It should be noted, however, that the soils from organic farms are not randomly sampled in the same way as those in the RSSS; farmers are more likely to send soils for analysis when a deficiency is suspected. Also, data from the RSSS showed that P levels were decreasing under conventional arable and grassland systems (Skinner and Todd, 1998), but this was probably because farmers were responding to concerns over P loss to waters.

Other research has found both increases (Clark *et al.*, 1998) and decreases (Penfold *et al.*, 1995) in amounts of available P and K in soils after conversion to organic farming. Loes and Ogaard (1997) attributed decreases accompanying conversion to the reduction in net imports, but decreases in available P and K generally (i.e. in all farming systems) can be due to slow, natural lock-up in some soils (Chalmers *et al.*, 1997). There are suggestions that, because of the less intensive nature of production, organic farms can produce sustainable yields at lower soil nutrient levels (Loes and Ogaard, 1997).

Nutrient budgets

Clark *et al.* (1998) showed that most changes in nutrient indices, such as those reported above, could be predicted from a consideration of the inputs and outputs of nutrients, i.e. the nutrient budget. Nutrient budgets have been compiled around the world, using a variety of scales and methodological approaches (Scoones and Toulmin, 1998; Watson and Atkinson, 1999). They measure or estimate the inputs and outputs of nutrients (usually N, P and K) to a field, farm or system, usually at the ‘farm gate’. Farm gate budgets do not usually include the necessarily very detailed measurements of losses such as leaching, denitrification and ammonia volatilisation, consider each field separately, or measure transfers between fields. Nor do they provide information on soil processes or biological inputs and outputs of nutrients, which are particularly important for N.

Tables 1, 2 and 3 show ‘farm gate’ N, P and K budgets for three typical organic farms (upland/hill farm, Table 1; lowland dairy farm, Table 2; stockless arable, Table 3). The budgets include inputs from atmospheric deposition, seed, feed and imported fertilisers and manures, and outputs in saleable produce; losses are considered below. Major sources of P and K are feed and bedding in the animal–based systems and compost in the stockless arable system. In all the systems, fixation of N by legumes is important, and in the extensive upland system atmospheric deposition also represents a major component of the N input. The main outputs are in crop and animal sales.

The nutrient budgets show these organic farms to be reasonably well balanced for P and K. This is in contrast to many conventional systems which display large P surpluses (Tunney *et al.*, 1997). However budgets vary due to different farm management practices. Other mixed organic farms monitored had significant P and K surpluses where large imports in feed were not matched by small outputs in stock sales, or deficits where small feed imports were exceeded by significant exports of P and K in grain sales. On a farm that imported poultry manure, P and K surpluses of 21 and 53 kg ha^{-1} yr^{-1} were observed (Fowler *et al.*, 1993), comparable with those on conventional farms (Tunney *et al.*, 1997). Although this practice has ceased, and organic standards now limit the import of manures, it demonstrates that organic farms may show a surplus that could lead to an accumulation of soil nutrients and adverse environmental impact.

The budgets all show significant surpluses for N. While N budgets are usually positive on organic farms (Nguyen *et al.*, 1995), the surplus is usually smaller than in comparable conventional systems (Halberg *et al.*, 1995). However, our calculations of nutrient budgets on large arable farms in East Anglia showed N surpluses of only 20 kg N ha^{-1} yr^{-1} where no manures were used, increasing c 100 kg ha^{-1} yr^{-1} where manures were imported, i.e. comparable to these organic farms.

Impact of nutrient losses

Measuring full nutrient budgets, including losses and internal flows, is essential for proper interpretation. An analysis of spatial flows can highlight the enrichment or depletion of nutrients from different parts of the farm. For example, the practice of spreading manure and slurry preferentially on fields nearest the manure store can lead to preferential enrichment at the expense of other fields (Bacon *et al*., 1990). The quantification of internal flows is also particularly important for organic farming because of the desire to maintain and improve the internal recycling of nutrients (UKROFS, 1999). However, as the complexity of the approach increases there is a need to measure or estimate increasing numbers of variables; either costs or errors increase. Below we estimate N, P and K losses from organic farms to enhance the budgets in Tables 1-3.

Nitrogen. Lord *et al*. (1997) found no difference in N leaching from a number of comparable organic and conventional farms; all had an average loss of 50 kg N ha^{-1} yr^{-1} over a whole rotation. Using modelling approaches, the Organic Farming Study (OFS; Cobb *et al*., 1999) found losses from organic farms (52 kg N ha^{-1} yr^{-1}) to be two-thirds those from conventional farms (78 kg N ha^{-1} yr^{-1}) (Goulding *et al*., 1999). The amount of nitrate leaching was related to the timing of cultivation, crop patterns and management. Table 4 shows measurements of nitrate leached from organic ley-arable systems, providing a consistent estimate of N loss by leaching of *c* 50 kg ha^{-1} yr^{-1}. Leaching losses from the lowland dairy farm are taken to be the same. Leaching from an upland hill farm was estimated by Shepherd *et al*. (1999) at 5 kg N ha^{-1} yr^{-1}.

Few measurements of losses by ammonia volatilisation have been made. Losses of ammonia from the OFS mixed farm were estimated at *c* 25 kg N ha^{-1} yr^{-1}; Goulding *et al*. (1998, 1999) estimated losses of 50-100 kg N ha^{-1} yr^{-1} on a nearby conventional mixed system. In general, losses are determined by stocking rates, which are lower for organic farms than for comparable conventional systems. We have used values of 25 kg N ha^{-1} $yr^{-1}$for the mixed upland farm and 50 kg N ha^{-1} $yr^{-1}$for the lowland dairy farm. There may be significant losses of ammonia from stockless systems where leys are cut and mulched, but no data are available so we have put such losses at zero.

There are few measurements of N loss by denitrification from organic farms. Losses of 5 kg N ha^{-1} yr^{-1} were measured on the OFS and 20 kg N ha^{-1} yr^{-1} on the nearby conventional system on the same soil type (Goulding *et al*., 1998, 1999), but both farms are on shallow soils over limestone so this is probably a minimum. We have used values of 5 kg N ha^{-1} yr^{-1} for the upland farm (likely to be on shallow soils) and 20 kg N ha^{-1} yr^{-1} for the other farms.

We can thus estimate N losses of very approximately 35, 120 and 70 kg N ha^{-1} yr^{-1} from the upland farm, the lowland dairy farm and the stockless arable farm, respectively (Table 5). Adding these values to the budgets in Tables 1-3 shows the upland/hill farm to have a small N deficit, the lowland dairy farm to be in balance, and the stockless system to have a significant N surplus. The importance of including losses in N budgets was shown in the OFS. If only a simple farm gate budget is calculated, the farm uses N at about 55% efficiency with a surplus of 40 kg N ha^{-1} yr^{-1}. However, when losses are added to product sales, efficiency of N use is reduced to about 40% and an N deficit of 30 kg ha^{-1} yr^{-1} is found. An N deficit suggests net mineralization and the mining of soil reserves.

Phosphorus and potassium. Losses of P and K are generally small and so are not likely to change P and K budgets significantly, although even small P losses have a major impact on the environment. Research to date on conventional systems suggests that, on undrained land for both P and K, a loss of 1-2 kg ha^{-1} yr^{-1} is a reasonable estimate (Catt *et al*., 1998; Johnston and Goulding, 1992). On drained land, however, losses can be much larger. Heckrath *et al*. (1995) showed that P losses increase exponentially when soil P levels exceed a critical value, and Johnston and Goulding (1992) found that K losses increased linearly with drainage at a rate of 1 kg K ha^{-1} yr^{-1} per 100 mm drainage. Also, losses of P by erosion on undrained land can be up to 30 kg ha^{-1} yr^{-1} (Catt *et al*., 1998). It is not sensible to include these extreme and episodic data in farm nutrient budgets, but they should act as a warning of potentially large losses and P and K deficits in certain circumstances, especially in the wetter west of the UK and over the whole country if extreme events increase with Climate Change.

Discussion

Long-term trends

Care must be taken when reaching conclusions about the sustainability of farming from farm gate nutrient budgets such as those in Tables 1-3. Applications of P and K are often made during the ley phase of an organic rotation to supply the whole rotation. Thus on the lowland dairy farm (Table 2), rock phosphate is used occasionally to redress the small P deficit. This does not appear in its nutrient budget because the P was not applied in the year the budget was compiled. An annual budget may also mask important differences between fields. Several years' data or preferably a whole rotation, should really be considered.

The weather also has an important effect through its impact on losses. Nitrogen budgets have been calculated for the Broadbalk Continuous Wheat Experiment at IACR-Rothamsted, now in its 157^{th} year. On this experiment, all the inputs and outputs of N to the various plots, including the accumulation or depletion of soil reserves, can be measured or calculated. From 1990-98 no single year produced a balanced budget. Only for the full 8-year period, when the mean rainfall equalled the long-term average, could a balanced budget be obtained. In dry years a net surplus of inputs over outputs was observed, with the reverse in wet years. This can be explained by net immobilization of N in soil organic matter in dry years and net mineralization in wet years leading to large leaching losses. The deficits seen in the OFS and in the organic upland farm above, and the surplus in the stockless arable farm, may therefore be temporary, balanced by corresponding surpluses and deficits in other years as on Broadbalk.

Nutrient cycling at the wider scale

Organic produce is sold into the national and international markets that dominate food production, leading to a net export of plant nutrients from most organic farms. We have shown that organic farms remain sustainable only through the use of bought-in feed and bedding, composts and, in some cases, air pollution. UKROFS rules state that, ideally, all imported feed should be from feedstuffs produced to UKROFS standards. However, at present between 10 and 30% of the dry matter, on a daily basis, may be imported from non-organic sources, depending on the type of animal (UKROFS, 1999). At a wider scale there are issues concerning the import of nutrients in fertilising materials over long-distances. The concept of food miles, that is the distance travelled by food products between production and consumption, is now in common use (Paxton, 1994). There is a similar issue in relation to sustainability in terms of 'resource miles' or the distance travelled and energy costs associated with freight of products such as rock phosphate being brought from as far away as

Tunisia and Morocco to the UK for use on organic farms. In the long-term, organic farming standards may need to consider more fully the use of locally sourced by-products and waste materials for nutrient supply. The ideal of sustainable organic farms that do not consume non-renewable resources or pollute the environment will remain elusive while the Global Market Economy dominates agriculture.

Conclusions

The data presented here suggest some cause for concern over the sustainability of organic systems because of their dependence on feedstuffs and bedding for inputs of P and K, and on the very variable fixation by legumes or imports of manure or compost for N. Air pollution and net mineralization from soil reserves appear to comprise a large part of the N supply on some organic farms. Losses of N from organic systems can also be as large as those from conventional systems. Being dependent on cultivation and the weather, they are even more difficult to limit than those from fertilisers applied to conventional farms. There is some evidence of P deficiency in soils under organic production. However, with careful management of manure and the effective use of legumes and by using permitted inputs for P and K, organic farms can be managed sustainably.

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Table 1. Estimates of N, P and K inputs and outputs for an organic upland/hill farm with sheep and suckler beef (Total area 390ha).

INPUTS	**N**	**P**	**K**	**OUTPUTS**	**N**	**P**	**K**
	(kg ha^{-1})				(kg ha^{-1})		
Fixation	6.2	0	0	**Stock sales:**			
Deposition	12.5	0.1	3.3	- Cattle	1.2	0.4	0.1
Stock purchases	~ 0	~ 0	~ 0	- Sheep	1.3	0.2	0.1
Bought-in feed	2.4	0.2	0.5	**Wool**	0.4	~ 0	0.1
Seed	~ 0	~ 0	~ 0				
Straw	0.2	0.1	1.1	**Burning**	0.1		
TOTAL	21.3	0.4	4.9		3	0.6	0.3
BUDGET					**+18.3**	**-0.2**	**+4.6**

Table 2. Estimates of N, P and K inputs and outputs for an organic lowland dairy farm (Total area 56 ha).

INPUTS	N	P	K	OUTPUTS	N	P	K
	(kg ha^{-1})				(kg ha^{-1})		
Fixation	117			**Stock sales**	4	1.0	0.3
Deposition	20	0.2	3.3	**Milk**	33	6.0	9.0
Bought-in feed	18	2.0	5.0				
Seed	1	0.1	0.2				
Straw	3	0.9	7.0				
TOTAL	159	3.2	15.5		37	7.0	9.3
BUDGET					**+122**	**-3.8**	**+6.2**

Table 3. Estimates of N, P and K inputs and outputs for an organic stockless arable/horticultural farm.

INPUTS	N	P	K	OUTPUTS	N	P	K
	(kg ha^{-1})				(kg ha^{-1})		
Fixation	79			**Crop sales**	58	10.0	64
Deposition	20	0.2	3				
Seed	5	0.7	3				
Compost	50	11.0	38				
TOTAL	154	11.9	44		58	10.0	64
BUDGET					**+96**	**+1.9**	**- 20**

Table 4. Nitrate leaching from organic ley-arable systems measured using porous cups over four seasons by Elm Farm Research Centre.

Previous crop	Crop in winter of measurement	Average nitrate loss (kg ha^{-1})	Range of values (kg ha^{-1})
Arable	Grass 1	36	1 - 114
Grass	Grass	11	0 - 52
Grass	Arable	82	8 - 187
Arable 1	Arable 2	50	7 - 182

Philipps *et al*. (1998)

Table 5. Estimated losses of nitrogen from the three organic farms in Tables 1-3.

Farm type	Upland/hill farm	Lowland dairy	Stockless arable
Loss process		N loss (kg ha^{-1} yr^{-1})	
Leaching	5	50	50
Ammonia volatilisation	25	50	0
Denitrification	5	20	20
Total loss	35	120	70
Previous N budget	+18	+122	+96
New N budget	-17	+2	+26

Figure 1. Phosphorus index values for soils farmed organically and conventionally.