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Optimizing nutrient management for farm systems

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Increasing the inputs of nutrients has played a major role in increasing the supply of food to a continually growing world population. However, focusing attention on the most important nutrients, such as nitrogen (N), has in some cases led to nutrient imbalances, some excess applications especially of N, inefficient use and large losses to the environment with impacts on air and water quality, biodiversity and human health. In contrast, food exports from the developing to the developed world are depleting soils of nutrients in some countries. Better management of all essential nutrients is required that delivers sustainable agriculture and maintains the necessary increases in food production while minimizing waste, economic loss and environmental impacts. More extensive production systems typified by 'organic farming' may prove to be sustainable. However, for most of the developed world, and in the developing world where an ever-growing population demands more food, it will be essential to increase the efficiency of nutrient use in conventional systems. Nutrient management on farms is under the control of the land manger, the most effective of whom will already use various decision supports for calculating rates of application to achieve various production targets. Increasingly, land managers will need to conform to good practice to achieve production targets and to conform to environmental targets as well.

Keywords: nutrient management; nutrient cycling; nutrient audit; soil; farm system studies

1. INTRODUCTION

'You do not get something for nothing'; 'You get out what you put in'. These simple phrases are usually applied to life in general but are very relevant to nutrient management in agriculture. Farmers have known for many years that they need to replace nutrients removed in crop plants to maintain soil nutrient levels, i.e. maintain a nutrient balance, and that some soils need those levels increased if sufficient food is to be grown and land kept fertile—what is often described as 'in good heart'. Before man-made fertilizers became widely available, there was usually a deficiency of nutrients, and yields of crops such as wheat were small and very variable. Nutrients in animal wastes (manures) were recycled and many other materials tested for their ability to enhance crop growth, such as bones and industrial waste products (Hall 1948, p 10). There was never enough manure for all crops and it was applied to those that responded best. The availability of industrially produced fertilizers, proved to be effective by experiments such as those at Rothamsted (Rasmussen *et al.* 1998; Smil 1999*a*,*b*; 2002), made it possible to supply sufficient nutrients to crop plants and greatly increase yields. The long-term experiments at Rothamsted show that yields with fertilizers (before modern pest and disease controls further improved crop agronomy) were two to three times those without fertilizers or manures (figure 1; Johnston 1994). Nutrient management has therefore always been a critical part of the economic and social sustainability of agriculture, but with very few effective options until cheap sources of plant nutrients in fertilizers became readily available.

However, the fact that the economic response in crop yield far outweighs the cost of the fertilizer has encouraged the over-application of fertilizers and manures in many countries, and led to nutrient surpluses—the excess of those applied in fertilizers, manures, composts, etc. over those removed from the farm in saleable produce. Thus, the environmental sustainability of farming is threatened by an over-emphasis on agronomy and economics, but this is not the case everywhere. For example, sub-Saharan Africa (SSA) is still exporting nutrients to developed countries: its average nutrient balance in 1983 was estimated at -22 kg nitrogen (N) ha^{-1} yr^{-1}, -2.5 kg phosphorus (P) ha^{-1} yr^{-1} and -15 kg potassium (K) ha^{-1} yr^{-1} by Stoorvogel & Smaling (1990) and the N balance deficit had increased to -26 kg ha^{-1} yr^{-1} in 2000 (Smaling *et al.* 2002). Intra- and intercontinental transfer of nutrients in products is a double-edged sword, depleting limited stocks at the site of production and contributing in many cases to nutrient surpluses and environmental pollution in the country of consumption.

Nitrogen use per person in 2001 was only 1.1 kg ha^{-1} in SSA compared with 22 kg ha^{-1} in China and 38 kg ha^{-1} in the USA (Mosier *et al.* 2004). Table 1 shows recommended and actual fertilizer rates for two SSA countries. Grote *et al.* (2005) examined nutrient flows in detail. They noted that although SSA countries imported nutrients, these

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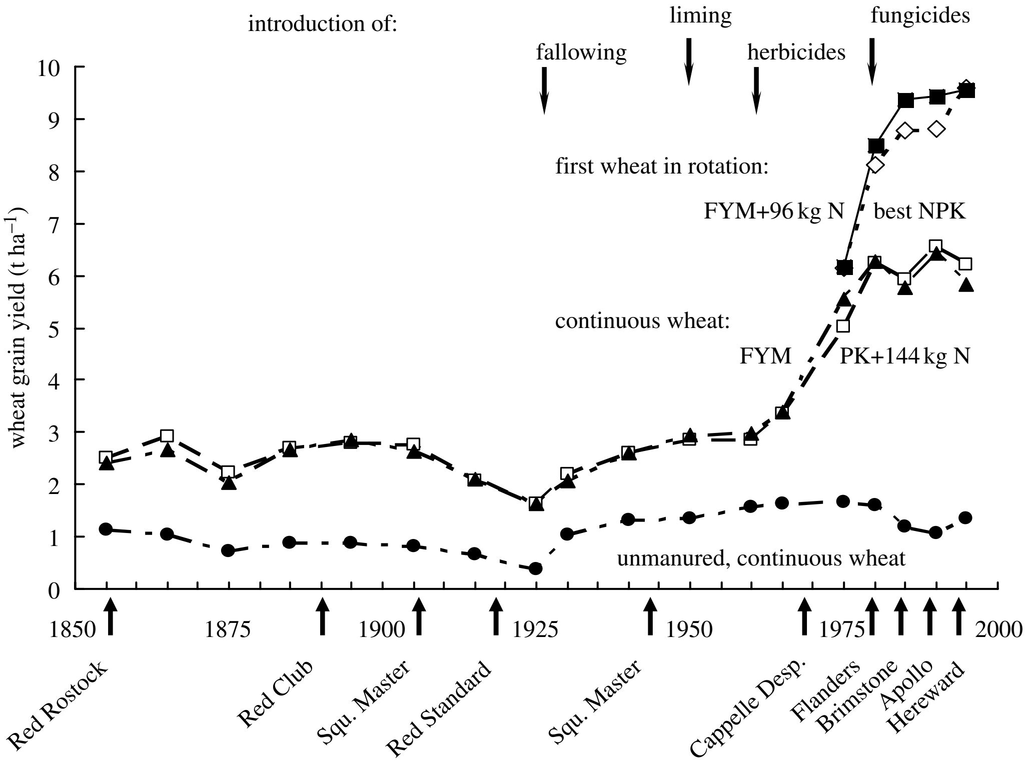

Figure 1. Yields of winter wheat (grain only, t ha^{-1}) on selected plots of the Broadbalk wheat experiment over time showing changes in varieties of wheat along the x-axis and changes in farming practice along the top of the graph (FYM, farmyard manure; Rasmussen *et al.* 1998).

went to cities, leaving a waste disposal problem that was not managed to balance nutrient losses on farmland. Such intra- and international transfers and exports of nutrients are not sustainable, and the effect is all too apparent on the soils and the lives of people trying to survive in SSA (Syers 1997).

So, for most of the developed world, fertilizers have provided the means to increase and maintain soil nutrient levels (Smil 1999*a*). However, sustainable agriculture demands the correct balance of the economic, social and environmental aspects of nutrient management. It is essential that nutrients removed from land in plants and animals are replaced and, in some nutrient-poor soils, increased, but not at the expense of environmental pollution. Nutrient use efficiency (NUE) has become a critical part of sustainable agriculture. (NUE can be defined and calculated in many ways. Here we use the simple definition of the proportion of the nutrients applied in fertilizers, manures and other manageable inputs such as biological fixation (i.e. excluding atmospheric deposition) that is recovered in farm produce.)

As already noted, N is a particular problem. Its importance as a growth- and yield-determining nutrient has led to large and rapid increases in application rates, but with often very poor efficiencies of use (table 2). For livestock systems, the recovery of N in product is, on average, even less efficient than in cropping systems: for a European dairy herd, it is unusual to find recoveries that are more than 25–30% in the meat or milk products of the farm (Jarvis & Aarts 2000). Intensive livestock production systems therefore generate large nutrient surpluses unless the recycling of manures from these systems is very effective (Chadwick & Chen 2002). Much

Table 1. Recommended and actual fertilizer application rates for two sub-Saharan African countries. (Adapted from table 8.1 in Vanlauwe *et al.* (2004).)

	Southern Benin	Northern Nigeria
recommended national rates (kg ha^{-1} yr^{-1})		
N	60	120
P	17	26
K	0	50
current national rates (kg ha^{-1} yr^{-1})		
N	2.3	1.5
P	0.5	0.2
K	1.1	0.3

Table 2. Average recovery (%) of nitrogen fertilizer by maize, rice and wheat as measured using ^{15}N-labelled fertilizer. (Adapted from Krupnik *et al.* (2004).)

region	average amount of N fertilizer applied (kg ha^{-1})	N recovery in crop (%)		
		maximum	minimum	mean
Africa	121	59	10	26
Australia	132	77	7	37
Eurasia	117	54	7	31
Europe	156	87	6	43
North America	115	87	6	36
South America	162	86	24	52
South Asia	116	93	7	41

international research effort has been invested in improving the recycling of nutrients from manures and other ‘wastes’ (e.g. Chambers *et al.* 2000).

In addition, many question the sustainability of food produced with fertilizers owing to declining oil reserves (for industrial N fixation) and declining reserves of ores containing P and K. There are also significant carbon/energy costs in transporting nutrients as fertilizers from production sites to the areas of application. A recent review (Isherwood 2003) suggests that reserves of P and K ores are adequate for many years to come, but effective nutrient management is still a key target for sustainable agriculture. This paper reviews the current state of nutrient management and probable developments that will lead to more sustainable agricultural systems.

2. NUTRIENTS IN FARM SYSTEMS

(**a**) ***Nitrogen***

As the yield-determining nutrient in most farming systems, adequate, but not excessive, amounts of N are needed to sustain yields and contribute to the maintenance of soil organic matter (SOM). The relative cheapness of N fertilizer in relation to its impact on maintaining yield, and in allowing farmers considerable management flexibility, has been an important contributory factor in determining its extensive and sometimes over-use and the environmental impacts noted previously and elsewhere in these proceedings. The need to effectively use N from whatever source—fertilizer, legumes or recycled as manures and composts—has led to numerous reviews and conferences (e.g. Follett & Hatfield 2001; Hatch *et al.* 2004; Mosier *et al.* 2004) and the International Nitrogen Initiative (see http://www.initrogen.org/). A key target for improved nutrient management and a more sustainable agriculture must be the more efficient use of N to maintain food production but greatly reduce its impact on the environment.

(**b**) ***Phosphorus***

Phosphorus is the yield-limiting nutrient in impoverished soils such as those in many parts of Africa. Its importance in crop nutrition has long been recognized in developed countries where critical levels for P in soils are well established. However, the view that P is strongly held in soils and so applying more than enough P is ‘money in the bank’ has resulted in the build-up of excessive P levels in some soils, resulting in enhanced leaching (e.g. Heckrath *et al.* 1995). Even where soil P levels are at or near the optimum, the loss by erosion of small amounts of P adsorbed on sediments or in solution can trigger the eutrophication of freshwaters (Leinweber *et al.* 2002), which is the primary cause of concern. A particular problem is the build-up of very large P surpluses from P in animal feed in countries with intensive livestock production systems. In the Netherlands, very large P (and N) surpluses have been halved since 1985, but are still excessive (figure 2); the annual N and P surpluses for the Netherlands in 2002 were 130 and 12 kg ha^{-1}, respectively, but the target is to reduce that for P to zero (Biewinga 2005). More information on national surpluses was given by De Clercq *et al.* (2001) and related to the level of intensification and its interaction with climatic and other geographical factors.

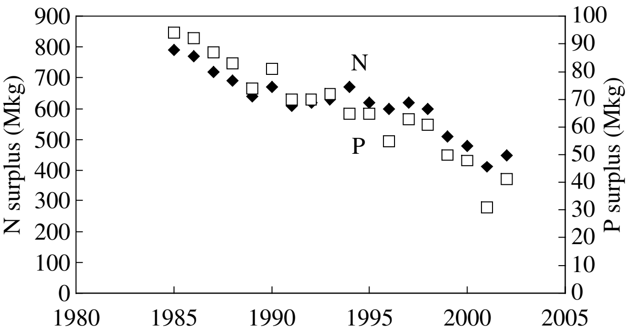

Figure 2. Nitrogen (N, filled diamonds) and phosphorus (P, open squares) surpluses in the Netherlands between 1985 and 2002 (Biewinga 2005).

(**c**) ***Potassium***

As much K as N is taken up by many crops, so its supply is critical. Often, the ability of many soils to supply adequate amounts of K for many years leads to its under-application, and there are concerns that the UK and other countries are applying too little K (and P) owing to the need to save costs (Johnston *et al.* 2001). Recent data (AIC 2005) show that the percentage of arable land in the UK not receiving K (and P) has increased from approximately 25% in the 1990s to approximately 35% at present. The supply of acceptable forms of K to organic systems is a particular problem (Watson *et al.* 2004). There appear to be no health or environmental problems associated with K leaching and there are no gaseous emissions.

(**d**) ***Calcium and magnesium***

Calcium (Ca) is applied as lime to maintain soil pH. Monitoring in the UK’s representative soil sampling scheme (Skinner & Todd 1998) suggested that most UK farmers are aware of the need to maintain optimum soil pH values for nutrient supply at approximately 6.0 for grassland and 6.5 for arable land (MAFF 2000). However, recent data (AIC 2005) show 20–30% reductions in lime applications to both tillage crops and grass in the UK since the mid-1990s. Magnesium (Mg) is often applied as magnesian lime and, in some cases, this can result in excessive Mg levels in soils and problems with K supply (Goulding & Annis 1998).

(**e**) ***Sulphur***

In many industrialized countries burning fossil fuels, sufficient sulphur (S) to meet crop requirements was supplied from atmospheric deposition (i.e. air pollution) until recently. In the UK, the change from coal to gas, industrial recession and the removal of S from power stations by flue gas desulphurization has resulted in S deposition to farmland returning to pre-industrial levels, making the application of S fertilizers once again cost-effective (Zhao *et al.* 2002). Brown *et al.* (2000) found that applying S to S-deficient grassland greatly increased the efficiency of N use, increasing dry matter production and reducing the potential for pollution from N losses. Data on ammonium sulphate imports to

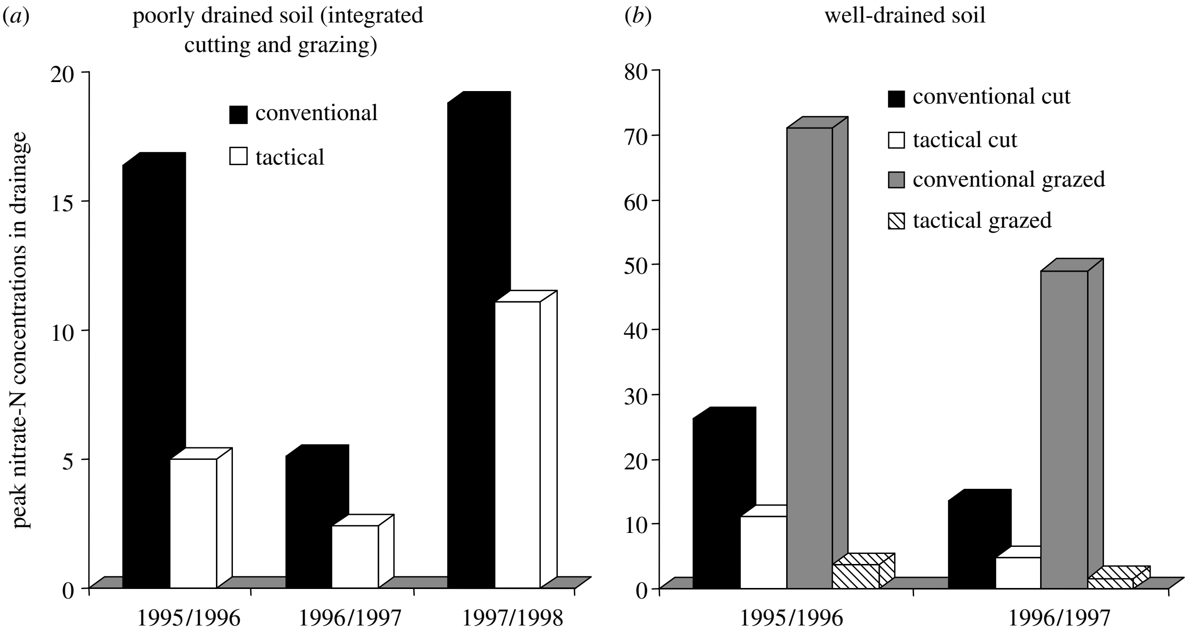

Figure 3. Peak nitrate-N concentrations (mg NO_3-N l^{-1}) in drainage from the 'Rowden' farmlets at the Institute of Grassland and Environmental Research. (*a*) Poorly drained soil (integrated cutting and grazing) and (*b*) well-drained soil (adapted from Jarvis (2000)).

the UK show these to have increased over threefold since 1999 from approximately 55 000 to 190 000 t (AIC 2005).

(f) *Trace elements*

The emphasis on the major nutrients, especially N, and the adequate supply of most trace elements from soils has led to neglect in considering their needs for crop nutrition in most intensive systems. Known local deficiencies in soils are corrected with annual applications to crops and dietary supplements for animals. However, with crop yields in developed countries continuing to increase, the demands on soils to supply trace elements is also increasing (Fisher 2004; Richards 2004). The supply of selenium (Se) in the UK diet used to be adequate because UK bread was made with a large proportion of wheat from the USA that was rich in Se. Now that UK bread is baked with UK wheat, usually deficient in Se (Adams *et al.* 2002), dietary intake of Se has declined and supplements are needed. Other issues of product quality in terms of trace element content and elemental balances are currently the subject of renewed interest. Elements such as zinc and copper can be deficient or present in toxic levels in soils, especially when contaminated wastes are applied to soils.

3. NUTRIENT DYNAMICS IN SOIL

Soil is a heterogeneous mixture of organic (plant debris, root exudates, decomposed residue of plants and animals often called humus) and inorganic (aluminosilicate clays, oxides, limestone, quartz, etc.) materials. It varies greatly in space and also in time: a single farmer's field may contain many identifiably different types of soil and the nutrient content, especially of nitrate, may vary from place to place and day to day (Clark *et al.* 2005) owing to the many processes that produce and consume nitrate (Addiscott & Whitmore 1987; Hatch *et al.* 2004; Milne *et al.* 2004). Other plant nutrients are also dynamic in time and space, but the degree of variation varies with their chemical and biological properties. Added to this, variation in the weather, specifically rainfall and temperature, and the changing nutrient requirements of crop plants as they grow (Barraclough 1986), makes matching the supply of nutrients from the soil to the needs of the crop a complex task. Achieving high NUE by manipulating inputs alone is difficult.

While much research has concentrated on understanding the chemistry of nutrient supply, e.g. by developing methods to extract the nutrients in soil available to crops and thus guide fertilizer requirements, relatively little has been done to link the physical structure of soil to NUE. Soil structure affects nutrient supply in two main ways. First, the tortuous nature of the network of pores in soil influences the transport of soluble nutrients. This can be advantageous in the case of highly soluble forms of nutrients such as nitrate-N, which is then less able to leach out of the rooting zone (e.g. Addiscott & Whitmore 1987). On the other hand, sufficient quantities of poorly soluble nutrients such as phosphate that diffuse only slowly as a result of a complex structure may not be available or accessible to plant roots (Barraclough 1986). Second, soil structure results from a complex relationship between organic matter and the mineral matrix, with a degree of physical protection from decomposition of SOM often being conferred by its adsorption onto mineral surfaces. SOM contains nutrients that, when decomposed by micro-organisms (mineralized), are transformed into mineral forms that are available to plants. However, the physical protection of SOM can cause the supply of N to plants to be smaller from clay soils, which protect SOM, than from sandy soils containing identical amounts of SOM (e.g. Hassink & Whitmore 1997). In addition, the very structure of the compounds mineralized confers a degree of protection by preventing decomposer organisms or their exoenzymes from accessing the nutrients in them. Certainly, some soil carbon, and by association probably some soil N, is centuries old (Jenkinson & Rayner 1977).

Soil structure can be altered by management: compaction by vehicles or ‘poaching’ by livestock can close pores and make nutrients less accessible to plants. Compacted soils are more prone to water-logging and hence to anaerobic conditions and the loss of N by denitrification. Conversely, ploughing loosens the soil and can improve the transport of nutrients, at the same time as ameliorating the physical condition of soil.

Soil structure also influences the fate of excess nutrients in soils. Thus, well-drained grassland soils, particularly if they are grazed, have a much higher propensity for excess nitrate to be lost by leaching (figure 3). Poorly drained soils, under most circumstances, have a lower leaching potential and N loss by denitrification is likely to be greater than by leaching. The provision of drainage in an inherently poorly drained soil also alters the pattern of phosphate loss (Haygarth *et al.* 1998*a*).

Consideration of how the biology of soil affects nutrient dynamics and NUE has been of concern to ‘organic’ farmers for many years, but it is now accepted as important in all farm systems (Abbott & Murphy 2003). SOM contains most of the N and much of the P and S contained in and eventually supplied to crops by soils. The soil microbial biomass (SMB), comprising all of the living micro-organisms in soil, plays a critical role by both mineralizing nutrients in SOM and immobilizing them in their bodies for later release and recycling (Powlson 1994). This mineralization–immobilization turnover (MIT) has been the subject of much recent research (e.g. Rees *et al.* 2000). Experiments using stable isotopes such as ^{13}C and ^{15}N (Murphy *et al.* 2003) have been used to develop mechanistic models of nutrient cycling through the SOM and SMB that focus on N but will eventually include S and P. Now stable isotope tracers are increasingly being coupled with molecular techniques to trace the flow of nutrients into the SMB in attempts to understand the role of soil micro-organisms in maintaining nutrient supply and in facilitating the wider aspects of soil function (Bol *et al.* 2003; Cookson *et al.* 2005). A vital question is whether a very diverse SMB is necessary to maintain a resilience of a soil function such as nutrient supply, and to resist stresses such as pollutant inputs and poor management (Davis *et al.* 2004).

4. BALANCED NUTRITION

As explained previously, developed countries have tended to focus on N as the main yield-controlling nutrient at the expense of P, K, S and trace elements (Aulakh & Malhi 2004). (This is not the case, however, in those soils which are inherently P-deficient, i.e. large tracts of Australia.) The efficient use of any nutrient depends on its balanced supply with other nutrients, i.e. all nutrients should be available at the right amount and time. The ‘Law of the Minimum’ emphasizes balanced nutrition (Claupein 1993; Lægrid *et al.* 1999), a good example of which was presented by Johnston *et al.* (2001) and is shown in table 3: at adequate levels of extractable (by Olsen’s method) soil P (above 19 mg kg^{-1}), the optimum N application for winter wheat yields of above 10 t ha^{-1} is 160 kg ha^{-1} in this experiment; at insufficient levels of extractable soil P, yield and the N optimum declines, and any N applied above the optimum is at risk of loss to the environment as well as being a waste of money. A similar interaction with implications for N loss has already been noted previously with respect to S supply to grassland (Brown *et al.* 2000).

Table 3. Yield of winter wheat (t ha^{-1}) given four different amounts of nitrogen fertilizer at four levels of available phosphorus (measured by Olsen’s method) in the soil. (Values underlined are the optimum N applications. Adapted from Johnston *et al.* (2001).)

available P (mg kg^{-1})	N applied (kg ha^{-1}) 80	120	160	200
30.4	9.32	9.64	10.12	10.25
19.0	9.37	9.83	10.25	10.30
10.3	8.46	9.14	9.10	9.34
5.0	7.75	7.88	7.85	8.08

Nutrient interactions can also be synergistic, i.e. benefits to yield and NUE are multiplicative, not just additive. Aulakh & Malhi (2004) described the synergistic response to N and P as being 13–89% of the response to N+P, depending on the yield potential, general level of soil fertility and nutrient application rates. They also note the possibility of reductions in yield if N is applied to soils with low P levels, an extension of the response ‘curve’ shown in table 3.

5. FARM SYSTEMS

When reviewing nutrient management in farm systems, it is useful to note the three main divisions of systems: intensive, integrated and extensive, the latter including organic management. Although this is a somewhat artificial separation and may not cover smallholder farms in developing countries very effectively, it summarizes the three main approaches to nutrient management in farming.

(a) *Intensive*

The intensive farm systems of developed countries seek to maximize yield through what is usually described as best management practice (BMP) that involves the efficient use of all inputs, including fertilizers and plant protection chemicals, crops and crop rotations, livestock breeding programmes and often precision agricultural techniques. Fertilizers have been central to this approach, which has resulted in a very rapid increase in productivity over that last 40 years. Yields from the Broadbalk wheat experiment, begun in 1843, are a good example of this (figure 1): the efficient use of fertilizers and lime, combined with new varieties of wheat and the effective use of crop protection chemicals, has increased grain yields on the experiment from 3 t ha^{-1} at best to approximately 10 t ha^{-1} today, with a maximum yield to date of 11.1 t ha^{-1}. Large increases in yield resulted from the introduction of short-strawed varieties of wheat and the development of herbicides and insecticides, i.e. effective pest and disease control. This has made it possible to introduce new, higher rates of N application. Earliest maximum rates were 144 kg N ha^{-1} but now 288 kg N ha^{-1} are being applied—typical of many of the most intensive production systems in the UK with target grain yields of 11–12 t ha^{-1}. In addition, farming in developed countries is under great pressure from the lower production costs of developing countries in South America, Asia, Eastern Europe and the Former Soviet Union. The adoption of market prices without any subsidy would increase the pressure to intensify, possibly making all but the biggest and most intensive production systems in developed countries unviable.

One possible approach to sustaining food supply to the rapidly increasing world population with a limited, indeed a declining, land area available for farming is to farm the best land as intensively as possible for maximum yields, allowing poorer land to be farmed more extensively or used for environmental good or amenity (Anonymous 1992). This would make best use of the most fertile soils and beneficial climates, but would result in large areas of relatively uniform landscape. In the UK at least, the income from tourism in rural areas is perhaps 10 times that from farming and similar to the whole of agriculture and the food chain (Roberts 2001; Thompson *et al.* 2002). Tourists want to see a 'patchwork quilt' of mixed and diverse land uses. Agricultural sustainability is dependent on more than efficient nutrient use and high yields where recreation and tourism dominate the economy.

(b) *Integrated*

The aim of integrated farming is to use fewer inputs, especially less fertilizer and pesticide, and accept slightly smaller yields and gross profit, but to maintain net profitability through the reduced costs of inputs. Minimum tillage and integrated pest management, using strategies other than chemical sprays, are often practised. Organizations such as LEAF (Linking Environment and Farming) in the UK (http://www.leafuk.org/leaf/) and EISA (European Initiative for Sustainable Development in Agriculture) in Europe (http://www.sustainable-agriculture.org/) promote integrated farming. Integrated farmers are strong advocates of nutrient management plans and auditing systems. Increasingly, however, the distinction between 'intensive' and 'integrated' is becoming unclear as intensive farmers adopt what they regard as useful integrated practices. Integrated systems have no specific mechanisms that optimize nutrient efficiency and minimize environmental impacts other than the careful and, perhaps, suboptimal use of inputs. As our description of the complexity of soil nutrient dynamics shows, suboptimal applications cannot guarantee better NUE: a graph of average losses of nitrate by leaching from the Broadbalk experiment (Goulding 2000) shows that these are reduced by applying suboptimal rates of N fertilizer, but so are yields. The skill of the land manager is critical, as explained in §5*e*.

(c) *Extensive and organic*

Extensive systems rely on low rates of inputs to attempt to balance offtakes in products. In some situations, for example upland livestock production, inputs can be minimal or even zero (Goulding *et al.* 2000). Increasingly, specialist local product/niche production uses more extensive systems that can provide added value either in terms of product quality or the delivery of environmental goods (e.g. less pollution, greater biodiversity), which may provide an economic advantage.

In some ways, organic farm systems can be considered an amalgam of integrated and extensive farming principles, i.e. minimizing and optimizing inputs, but with specialized and precisely defined requirements as to their origin. These are legally defined according to the rules of the accrediting body such as the Soil Association (http://www.soilassociation.org/web/sa/saweb.nsf?Open) in the UK and IFOAM (International Federation of Organic Agricultural Movements; http://www.ifoam.org/) across the world. The certifying bodies vary somewhat in their rules but, in the context of this article, all aim to use no refined, soluble fertilizers and to maintain as closed a nutrient cycle on farm as possible. However, off-farm exports of products are not returned in human waste and so the import of nutrients is essential. Nitrogen is obtained by biological fixation by legumes, P from unrefined rock phosphate and K from seaweed and various K-containing minerals. Recycling of animal manures and composted wastes is central to organic management systems; deep-rooting plants are used to recycle nutrients from subsoil to topsoil. Nutrient cycling on organic farms was discussed in detail by Goulding *et al.* (2000) and in a special issue of the journal *Soil Use and Management.* (Anonymous 2002).

(d) *Livestock production systems*

We have previously noted the poor efficiency of N conversion into product and the large amounts of N in animal diets that are converted into excreta. At best, the theoretical maximum efficiency of conversion of N into milk is 40–45% and in many circumstances it is less than 25% (Jarvis 1998). Incorporation of higher energy feeds such as maize silage is one means of reducing concentrate fed to intensively managed cattle and hence increasing N use efficiency. Much of the excess P in intensive livestock systems can be accounted for by the imported P in concentrates (Haygarth *et al.* 1998*b*), and there are opportunities to reduce this. As noted previously, the use of the manures and slurries generated in livestock managements increasingly becomes a key part of nutrient management.

(e) *Comparisons between systems*

Few full-scale studies of farm systems exist that permit the comparison of NUEs. However, Tinker (2000) compared conventional, integrated and organic farming systems for their effects on soils and plant nutrition, pests and diseases, animal husbandry, economics, biodiversity and environment, and food quality and health. The main conclusion with regard to nutrient management was the risk in organic systems of depleting soil nutrient reserves, especially of K, owing to a lack of sources approved for use in organic systems. This is supported by some but not all of the nutrient budgets calculated by Goulding *et al.* (2000). Soil fertility in organic systems has also been subject to a recent extensive review (Anonymous 2002). The main conclusion of this report was that, although nutrient management in organic systems is fundamentally different, the underlying nutrient pools and cycling processes are not (Stockdale *et al.* 2002). Thus, NUE can be assessed in the same way for all the three systems.

The authors have been involved in research assessing the losses of N from comparable conventional, integrated and organic farm systems in an area of similar soils in the Cotswold Hills of the UK. In common with all integrated farm systems, the LIFE (less intensive farming and the environment) system aims to maintain farm income by balancing reduced outputs against reduced inputs, and through the latter to reduce environmental impact; ultimately, its aim is to be environmentally benign (Jordan *et al.* 1997). On its original experimental site—a deep loam soil—nitrate loadings in drainage waters were 80% less than those from conventionally tilled land. In contrast, on a shallow (less than 30 cm deep) stony clay loam soil over limestone, losses of N were identical to those from a nearby conventional farm, and there was a reduction in gross margins. The *Organic farming study* measured N, P and K budgets, N losses and the economics and environmental benefits of this organically based farming system (Cobb *et al.* 1999). On average, nitrate leaching on the organic system was two-thirds that in the conventional system. A nutrient budget estimated the N efficiency to be 34%, about the same as that at a conventional, mixed farm on the same soil type, 20 km away.

The most comprehensive study of farm systems in the UK that the authors are aware of is *Focus on farming practice* (Leake 1996). On the integrated system, minimum tillage reduced autumn and winter nitrate concentrations by 25–50% and prevented soil erosion. Grass leys were an integral part of this, reducing leaching losses until ploughed, but then any gains were lost. Early drilling of autumn-sown crops and associated cultivation increased N uptake but also stimulated mineralization; later drilling reduced mineralization but the crop was much less able to use the N already present. Using mineral N measurements and a chlorophyll meter to calculate N requirements more precisely, and splitting N applications, prevented growth spurts and lodging without the need for growth regulators. The conclusion of the work was that the integrated system was more flexible and better able to meet the continually changing needs of farming than highly regulated organic systems, and that the expertise of the land manager is critical for effective NUE and sustainable farming.

It is important to compare these results, focusing on NUE in the context of environmental sustainability, with those in developing countries where economic and social needs dominate. Sanchez *et al.* (1997) suggested that the three main determinants for overcoming rural poverty in Africa were reversing soil fertility depletion, with fertilizers playing a key role, intensifying and diversifying land use with high-value products, and providing an enabling policy environment for the smallholder farming sector. They found that agroforestry could improve food production in a sustainable way by replenishing soil fertility: organic inputs were a source of biologically fixed nitrogen, and nitrate was captured by trees from depth.

6. BEST PRACTICE FOR NUTRIENT MANAGEMENT

Goulding (2000) summarized BMP for N management but the principles set out can be applied to all nutrients. For conventional (i.e. non-organic) systems for arable and horticultural crops,

- choose the highest-yielding variety appropriate to maximize the use of the available nutrients (bearing in mind quality, e.g. for bread-making wheat),
- maintain a green cover as much as is practicable to retain N, use a cover crop if necessary and drill autumn-sown crops early, but this must be balanced against the risk of carry-over of pests and diseases and the need for effective weed, pest and disease control,
- make regular soil analyses for pH, P, K and Mg and possibly trace elements,
- use lime to maintain the appropriate pH for optimum nutrient supply (6.5 for arable crops; 6.0 for grassland),
- calculate fertilizer requirements using a recommendation system such as the UK's RB209 (MAFF 2000); apply P, K and Mg to maintain recommended levels of these nutrients in soils,
- avoid unnecessary autumn and early spring applications of N; time applications to provide N when the crop is growing quickly,
- apply fertilizers and manures evenly, and well away from watercourses, with a properly calibrated spreader,
- use appropriate controls to minimize pest, disease and weed infestation, and
- irrigate carefully, i.e. only to support crop yield and using a scheduling system that takes account of the weather.

For grassland and livestock production systems, the same principles apply, although of necessity the relative importance of each of the options changes compared with tillage agriculture. The greater use of fertilizers and the specialization of farming systems often preclude the use of organic manures in arable farming systems and cause their accumulation and subsequent disposal problems for intensive livestock systems. However, there is a current re-evaluation of the need to use all nutrients from all sources in order to enhance their efficient use. Where animal manures and slurries are present, current advice (and, hopefully, practice) takes much more account of their potential for nutrient supply and also SOM status. Research at Karkendamm experimental farm in Northern Germany and the De Marke experimental farm in the Netherlands quantified nutrient flows and developed management strategies to reduce nutrient losses in grassland farming systems, producing a whole-farm nutrient model that integrated environmental and economic components (Rotz *et al.* 2005). The use of cover crops, low emission barns, covered manure storage and direct injection of manure into soil greatly reduced N losses, but at a net cost to the producer.

7. DECISION SUPPORT FOR NUTRIENT MANAGEMENT

Recommendation systems now include computer models and interactive, internet-based systems, with remote sensing, yield mapping and crop canopy measurements to fine-tune fertilizer applications (Kitchen & Goulding 2001). The complexities surrounding nutrient dynamics in soil suggest that computer-based systems are useful for marshalling the relevant information and presenting data in a fashion that is helpful to a farmer or adviser. Such decision support systems have taken various forms and differ in the level of sophistication. Most have been aimed at N owing to the importance and complexity of the dynamics of this element in soil. In the UK, the longest serving set of recommendations is the Defra-sponsored RB209 (MAFF 2000), now subsumed into the computer-based PLANET system (www.planet4-farmers.co.uk). PLANET and RB209 contain tables and recommendations for a range of nutrients.

Other decision support systems are more sophisticated, often being driven by computer simulation models, but usually deal with a single element such as N. SUNDIAL (Bradbury *et al.* 1993; Smith *et al.* 1996) has been released for farmers and advisers through the Rothamsted website (www.rothamsted.bbsrc.ac.uk/aen/sundial/sundial.htm). It differs from earlier recommendation systems in attempting to take explicit account of the weather following application of fertilizer, and thus the potential supply of N to the plant from soil mineralization during spring and summer. In this way, SUNDIAL tries to optimize the supply of N to the crop but minimizes the potential for loss. WELL_N (Goodlass *et al.* 1997) tries to do much the same for vegetable crops and NCYCLE is an N-balance model that compares inputs and outputs in grassland systems for beef and dairy production (Scholefield *et al.* 1991).

The animal–grassland system is a complex one, especially in dealing with slurry and manure produced. Some of this may be transferred to arable systems and MANNER (www.adas.co.uk/manner/) focuses on this need. Most of these decision support programmes supply information not only about the fertilizer need or value but also of the potential for losses (leaching and denitrification and, from MANNER, ammonia loss). The NGAUGE decision support system for grassland has been developed from the NCYCLE model by Brown *et al.* (2005). The underlying empirically based model simulates monthly N flows within and between the main components of the livestock production system according to user inputs describing site conditions and farm management characteristics. NGAUGE has a user interface that was produced in collaboration with livestock farmers to ensure availability of all required inputs. It relates production to environmental impact and is therefore potentially valuable to policy makers and researchers for identifying pollution mitigation strategies and blueprints for novel, more sustainable systems of livestock production.

Table 4. Nutrient audits for N, P and K on several organic farms in the UK (Adapted from Goulding *et al.* (2000)) to two significant figures.

	nutrient balance (kg ha^{-1} yr^{-1})		
farm	N	P	K
upland	+18	−0.2	+4.6
lowland dairy	+120	−3.8	+6.2
stockless	+96	+1.9	−20.0

Once decision support migrates to a computer-based environment, it becomes possible to integrate nutrient advice with support for pest, disease and weed control, scheduling, financial and general farm planning. This is the philosophy behind the UK Arable Decision Support (http://www.arableds.co.uk/home/).

8. NUTRIENT BUDGETS OR AUDITS

Nutrient budgets or audits have been compiled using a variety of scales and methodological approaches (Scoones & Toulmin 1998; Smil 1999*a*; Watson & Atkinson 1999). They measure or estimate the inputs and outputs of nutrients (usually N, P and K) to and from a field or farm system. Farm gate budgets are the most commonly used. They estimate the overall budget of nutrients into and out from a farm from measurements or farm records or both. They therefore indicate whether nutrients are exported off the farm, i.e. soil mining, or large surpluses are building through inefficient use or over-application of inputs as fertilizers, legumes, imported manures and residues or animal feeds. They do not usually include the necessarily very detailed measurements of losses, such as leaching, denitrification and ammonia volatilization, consider each field separately or measure transfers between fields. Nor do they provide information on soil processes, which are particularly important for N. They do, though, indicate overall efficiency and highlight problems. Goulding *et al.* (2000) used nutrient audits to indicate potential problems of nutrient supply on a range of organic farms in the UK (table 4). These suggest a surplus of N on the lowland dairy and stockless arable farms, and a deficit of K on the stockless arable farm. Conclusions are tentative, however, because the data are for a single year.

Leach *et al.* (2004) reported a comprehensive N budget compiled for each of 8 years on Coates Farm, a mixed dairy and arable farm in the Cotswold Hills of the UK. All the inputs and outputs were measured, calculated from farm records, or modelled, and a balance was achieved, i.e. all the N was accounted for. The budget showed an overall efficiency in N use for the mixed system of approximately 46%. Perhaps the most interesting result was that related to the move of the dairy herd from the farm to create a larger unit nearby that was economically more efficient. The N surplus on Coates Farm declined from 141 to 117 kg ha^{-1} yr^{-1} but on the specialized, enlarged dairy unit, it increased from 295 to 392 kg ha^{-1} yr^{-1}.

The MINAS nutrient accounting scheme in the Netherlands has been used to set targets for surpluses, with fines if targets are exceeded (Biewinga 2005). The UK is about to introduce a nutrient audit system into its PLANET fertilizer recommendation software, with benchmarks for most farm systems. Whole-farm nutrient audits were used very effectively by Koelsch (2005) to show that voluntary BMP on concentrated animal feeding operations (CAFOs or feedlots) in the USA was more effective (30–60% reduction in P accumulation) than mandatory nutrient management plans and buffer strips (5–7% reduction in P accumulation) in reducing nutrient surpluses.

The use of nutrient budgets to identify nutrient surpluses in developed countries should be contrasted with those calculated for SSA by Stoorvogel & Smaling (1990) and Smaling *et al.* (2002), showing the economic and socially unsustainable export of nutrients. Nutrient budgets are a powerful tool for raising awareness and stimulating action.

9. TARGETS FOR IMPROVING NUTRIENT MANAGEMENT

(a) *Strategic approaches*

The economic pressures and uncertainty experienced by farming have resulted in economic analyses of various nutrient management strategies. Gareau (2005) reported a ‘meta-analysis’ (i.e. a review of literature data) of the economics of conventional, fertilizer-based nutrient management systems against the alternatives of organic, cover-crop- and manure-based systems. The fertilizer-based system showed the larger profit for most grain crops, but the cover-crop- and manure-based systems showed promise as alternative strategies, especially if the manure did not have to be purchased or transported. With the increasing price of oil and, therefore, of fertilizers and need to effectively recycle manures, such alternative systems will become increasingly attractive.

(b) *Precision farming*

Direct measurement of the spatial variation in yield has been available since the early 1990s (Stafford *et al.* 1999). Knowing yield variation across a field offers the prospect of variable-rate N and other nutrient applications, but yield maps are confounded by many potential causes of yield variability as well as errors. Using yield maps alone to predict crop production for nutrient management without measuring other potential and often transient yield-limiting factors (e.g. pest incidence) may be a waste of effort and resource. However, variable-rate application maps can result in a 60% increase in the area correctly fertilized compared with a fixed-rate application (Ferguson *et al.* 1996). A recent review of the potential for the uptake of precision agricultural practices in Northern Europe (Sylvester-Bradley *et al.* 1999) concluded that the technology was most likely to be adopted where prior knowledge identified large heterogeneity and predicted treatment zones, but that the main obstacle was the lack of appropriate sensors. Murrell (2004) showed that variable N rates increased N use efficiency over fixed rates, but did not increase yield. Farmers are more likely to be convinced by practices that increase yields as well as NUE, such as good all-round agronomy (Murrell 2004; Olesen *et al.* 2004).

Precision-based methods have also not been widely adopted for grassland systems owing to the additional variability introduced by the impact of livestock and their excreta, which makes practical implementation of any greater locational precision very difficult. However, systems such as NGUAGE allow greater precision in being able to match inputs to requirements through improved timings and at differential rates in order to optimize dry matter production or to minimize environmental impact where this is a particular need.

(c) *Nitrification inhibitors*

Nitrification inhibitors (NIs) have often been suggested as a means of reducing N losses but they have not been extensively adopted. Prasad & Power (1995) pointed out that the need for a 0.3–0.5 t ha^{-1} increase in yield to cover the costs had prevented their adoption. Until recently, the low cost of N fertilizer and the high cost of NIs obviated their use for improving N efficiency. However, the recent rapid increase in N fertilizer costs and legislative moves to reduce N inputs, such as an N tax, could make them a viable and attractive option.

(d) *Knowledge transfer*

Nitrogen use efficiency on cereal farms is usually 20–50%, whereas on research plots it is 60–90% (Dobermann & Cassman 2004). The variation is caused by those factors over which we have some control—crop variety and rotation, tillage, pest, disease and weed management, irrigation and drainage—and those over which there is little or no control, especially the weather. There is clearly room for improvement in NUE, simply by improving knowledge transfer, but it should also be noted that the availability of skilled expertise, time and the application of resource is likely to be much higher in research centres than in farms, and it may not be possible to increase NUE on farms to the level obtained in experiments.

There are still opportunities to improve NUE simply by applying the necessary nutrients in the correct amounts at the correct times (Krupnik *et al.* 2004). Soil analysis should be seen as an essential aid to BMP for optimum NUE, including N in many cases, augmented by various techniques, such as chlorophyll meters and remote sensing in high-cost systems and colour charts in low-cost systems.

10. POLICY AND NUTRIENT MANAGEMENT

The recognition that good nutrient management is necessary for adequate security of food supplies and minimal environmental impact has resulted in the development of many government policies to direct practice. After the Second World War, when food supplies in Europe were scarce and famine was a reality, policies were introduced to direct nutrient, especially fertilizer, use to increase crop and animal yields. The Common Agricultural Policy of the EU was one such device that was very successful in increasing food supplies to the level of surpluses. The unintentional side effect of this success was environmental pollution and a view that manures were a waste product to be disposed of rather than to be used (Galloway *et al.* 2002).

An awareness of food mountains, wine lakes and adverse environmental impacts in the 1960s through to the 1980s has resulted in new policies and protocols to reduce surpluses (such as Set-aside in Europe), water (the Nitrates Directive and recent Water Framework Directive) and air pollution (UNECE protocols on ammonia emissions; Kyoto Protocol on greenhouse gases; De Clercq & Sinabell 2001). The Netherlands had, until recently, a compulsory MINAS nutrient accounting scheme, with fines if allowed surpluses were exceeded, and the UK has nitrate vulnerable zones in which there are limits to the amounts of manures that can be applied and restricted periods for application.

However, just as the earlier policies to drive food production caused unwanted, and probably unexpected pollution, so these later policies have had unwanted and unexpected consequences: rotational Set-aside is a prime cause of nitrate leaching (Goulding 2000) and whole-farm models that integrate all inputs to and outputs from farms suggest that practices to decrease one loss can increase others, e.g. practices that reduce nitrate leaching on arable farms, and those that reduce ammonia volatilization on livestock farms, can increase other environmental impacts such as denitrification and nitrous oxide emissions and P build-up in soils (Bergström & Goulding 2005). Research is needed to develop policies that stimulate 'Win-Win' management practices that deliver true sustainable farm systems.

11. RESEARCH REQUIREMENTS

(a) *More efficient plants versus more efficient management practices*

Giller *et al.* (2004) summed up the opportunities to improve N management as producing more efficient plants and more efficient management. Figure 4 shows their view of the progress that can be made in improving N use efficiency using both existing and probable new technologies.

Giller *et al.* (2004) thought that genetic manipulation (GM) technologies showed most promise for improving root architecture and were very sceptical about the likelihood of breeding for nitrogen fixation in cereals and other currently non-leguminous crops. Others are much more optimistic (Cocking 2005). Atkinson *et al.* (2005) also saw great potential in using the soil supply of nutrients by improved functioning of plant roots and thus of soil processes.

Plant breeding for NUE is not just about increasing yield or fixing N. Two of the principal causes of yield loss, and thus nutrient use inefficiency, are pests and diseases, and so breeding resistant varieties would have great benefits for NUE. There will also be benefits in breeding plants that can cope with predicted climate change and its interactions with changing rainfall patterns and nutrient supply and an ability to use extra CO_2, but this requires a better understanding of the link between C and other nutrient cycles (Metzlaff 2005). As far as grasses are concerned, it is considered that those bred for a high sugar content ('sugar' grasses) will, through improved N use in the animal gut, lead to reduced N contents of excreta and thus improved opportunity to reduce losses (Lee *et al.* 2002).

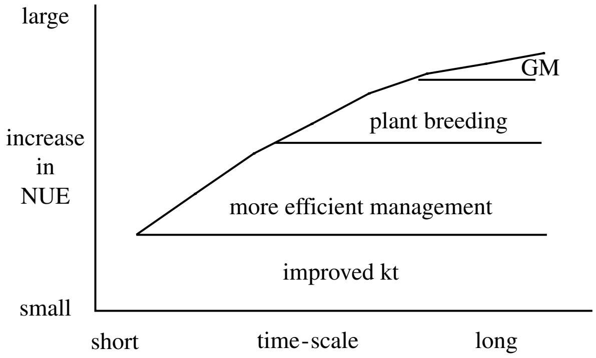

Figure 4. Giller *et al.*'s (2004) view of the probable benefits to nitrogen use efficiency (NUE) of existing and new technologies.

Current public concerns preclude the use of transgenic plants or animals in European agriculture. One area of concern is the possible impact of transgenic species on microbially mediated processes in soil. Motavalli *et al.* (2004) reviewed the research available and found no evidence of any impact of a transgenic plant on any nutrient cycling or related process in soil.

(b) *Nutrient availability from soils*

One of the most difficult tasks involved in calculating fertilizer requirements is calculating the release of nutrients, especially N, from soils. Research has developed simple N supply calculators as used in the UK's fertilizer recommendations system, RB209 (MAFF 2000) and decision supports such as the SUNDIAL model (Smith *et al.* 1996). However, a better understanding of MIT (see §3) and associated processes (nitrification and denitrification) would greatly assist in the development of better decision supports, as would soil-based sensors (Clark *et al.* 2005), but further research and development is needed before these become practicable.

(c) *Holistic approaches*

Some of the practices to improve NUE favoured by 'organic' or 'ecological' farming systems extend beyond science and so are outside the scope of this paper. However, other aspects are consistent with a scientific approach and merit research, in particular the efficient coupling of C with other nutrient cycles (Drinkwater 2004). This can be viewed in simple terms as the need to build, maintain and better manage SOM, especially the living part of that, the SMB. This is plain good practice for many aspects of soil quality as well as nutrient supply, including soil structure and minimizing energy use in tillage, and possibly pest and disease control. This may mean a return to more diverse crop rotations and the greater use of cover or catch crops. In research reported by Olesen *et al.* (2004), cover crops reduced fertilizer N requirement by 27 kg ha^{-1} and increased NUE from 42 to 52%; however, nitrate leaching increased by 14 kg ha^{-1}. Few changes in practice are truly Win–Win.

Research is needed to better understand and manage microbially mediated processes, e.g. the manipulation of MIT and dissimilatory nitrate reduction to ammonia to reduce denitrification and conserve N. There is good evidence that adding organic matter and fertilizers together improves NUE, as nutrients are held by the microbial biomass (Vanlauwe *et al.* 2004) and that the microbial biomass plays an important role in facilitating nutrient loss from soils in some situations (Turner & Haygarth 2001). Clearly, there is a need for more integrated studies of the interaction between the biology, chemistry and physics of soil nutrient dynamics if we are to manage soils for improved NUE (e.g. Whitmore 1999).

12. CONCLUSIONS

In the more affluent parts of the world, where consumers will pay more for what they regard as healthier food produced with minimal impact on the environment, more extensive production systems typified by 'organic farming' may prove to be sustainable, provided adequate and acceptable sources to replace exported nutrients can be found. Farmers in the EU may also have to farm in the future without the current system of subsidy payments. These are being moved from production subsidies to support for environmental goods as current priorities within sustainable agriculture change. A complete removal would focus even more attention on the effective recycling of nutrients in manures, composts and human wastes and drive the search for even more efficient use of fertilizers through a better understanding of nutrient cycling in soils and crop breeding, using GM technology or otherwise. Precision agriculture could help but, without subsidies, the cost of any input or technology will be critically assessed.

For most of the developed world, and in the developing world, an increasing population is demanding more food, especially more protein. It will be essential, therefore, to increase the efficiency of nutrient use in all management systems so that nutrients from all sources, i.e. those supplied through the mineralization of SOM, animal excreta and manures as well as fertilizers, are fully taken into account and used efficiently. Much progress can be made by better use of existing knowledge, but continued research and development will be necessary for more efficient plants and animals and nutrient management. There is still much to learn about nutrient cycling processes in soils, especially MIT and other microbially mediated processes. Sensors to measure real-time nutrient availability driving multi-nutrient decision support systems linked to precision application would improve nutrient use in conventional farming, and plant breeding for NUE, especially for better root distribution and nutrient uptake rather than just yield, would benefit all farm systems. In addition, the transfer of nutrients across different scales—field to field in residues, animal house to field in manures and across regional and intra- and international borders—will need to be accounted for.

Nutrient management on farms is under the control of the land manger, the most effective of whom will already use various decision supports for calculating rates of application to achieve various production targets. Increasingly, land managers will need to conform to good practice to achieve production targets and to conform to environmental targets if they are to achieve the objective of sustainable farm systems.

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