A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility.

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Abstract. On organic farms, where the importation of materials to build/maintain soil fertility is restricted, it is important that a balance between inputs and outputs of nutrients is achieved to ensure both short-term productivity and long-term sustainability. This paper considers different approaches to nutrient budgeting on organic farms and evaluates the sources of bias in the measurements and/or estimates of the nutrient inputs and outputs. The paper collates 88 nutrient budgets compiled at the farm scale in 9 temperate countries. All the nitrogen (N) budgets showed an N surplus (average 83.2 kg N ha^{-1} $year^{-1}$). The efficiency of N use, defined as outputs/inputs, was highest (0.9) and lowest (0.2) in arable and beef systems respectively. The phosphorus (P) and potassium (K) budgets showed both surpluses and deficits (average 3.6 kg P ha^{-1} $year^{-1}$, 14.2 kg K ha^{-1} $year^{-1}$) with horticultural systems showing large surpluses resulting from purchased manure. The estimation of N fixation and quantities of nutrients in purchased manures may introduce significant errors in nutrient budgets. Overall, the data illustrate the diversity of management systems in place on organic farms, and suggest that used together with soil analysis, nutrient budgets are a useful tool for improving the long-term sustainability of organic systems.

Keywords: nutrient budgets, organic farms, nutrient use efficiency, nutrient surplus

INTRODUCTION

In organic farming, the farm is considered as an integrated whole, recognising that complex relationships exist between resource flows on the farm and the many environmental factors that influence them. Organic farming systems emphasise reliance on ecological interactions and biological processes over direct intervention. As a result, the use of imported materials to build/maintain soil fertility is restricted. Achieving a balance between inputs and outputs of nutrients within the farm system is critical to ensure both short-term productivity and long-term sustainability. Nutrient management must be understood, planned and managed over periods of longer than a single crop or growing season (Watson *et al.* 2002).

Nutrient budgets are becoming increasingly accepted as a tool to describe nutrient flows within farming systems and to assist in the planning of the complex and coincident spatial and temporal nutrient management within rotational cropping and mixed farming systems (Watson & Stockdale 1997). In this paper, therefore, we consider different approaches to nutrient budgeting and evaluate the sources of bias in the measurements and/or estimates of the inputs and outputs used to compile budgets that are particularly pertinent to organic farming systems. Depending on the farm management and the balance of inputs and outputs of nutrients, N, P and K budgets have been shown to range from deficit to surplus in organic farming systems (e.g. Fagerberg *et al.* 1996; Nolte & Werner 1994; Wieser *et al.* 1996). We have brought together 88 nutrient budgets compiled at the farm scale from research and commercial organic farms of different types in nine countries with temperate climates. Our aim is to examine relationships between nutrient budgets and estimates of nutrient use efficiency derived from them, and management practices and/or farm type.

APPROACHES TO NUTRIENT BUDGETING

Methodology

Budgets are the outcome of a simple nutrient accounting process which detail all the inputs and outputs to a given, defined system over a fixed period of time. The underlying assumption of a nutrient budget is that of mass balance *i.e.* nutrient inputs to the system minus any nutrient exports from the system equal the change in storage within the system (Meisinger & Randall 1991). Although the nature and amounts of inputs and outputs vary among farming systems and even between fields, the mass balance concept provides a framework that can be applied systematically across a wide range of scales and farming systems (Committee on Long Range Soil and Water Conservation 1993). Nutrient budgets therefore have the potential to illustrate, both qualitatively and quantitatively, the flows of nutrients in to, out of, and within, a given system. Nutrient budgets are therefore of value to researchers, farmers, their advisors and for educational purposes (Watson & Stockdale 1999; Goodlass *et al.* 2002).

Nutrient budget methodology has recently been reviewed by a number of authors (e.g. Watson & Atkinson 1999; van Noordwijk 1999). There are a number of different budget types, which differ mainly in where the system boundary is drawn, whether internal flows are described and which inputs and outputs are included (Figure 1). Three main types of budgets are usually described, which are then applied at a variety of system levels (Jarvis 1999):

1) *Gate budgets* usually only record the flows of purchased or controlled nutrients entering and leaving the system. Uncontrollable inputs, such as biological fixation of N and atmospheric deposition, and losses are not included e.g. the MINAS nutrient accounting system used in the Netherlands describes flows at a farm level but excludes N fixation, due to difficulties in its accurate estimation (Munters

1997). This approach, therefore, is inappropriate for the compilation of nutrient budgets relevant to organic farms (Watson & Atkinson 1999). However, this type of nutrient budget has been used widely in policy analysis.

2) *Surface budgets* consider the difference between total inputs and removal in crop and/or animal offtake. These budgets include uncontrollable inputs but do not usually provide information on the fate or origin of any budget surplus *i.e.* whether it is lost from the system or 'stored' in the soil. Soil surface budgets are used to determine crop nutrient requirements (particularly P and K) from fertilisers and manures at a field scale (MAFF 2000).

3) *System budgets* give detailed information on inputs, outputs, losses and internal flows, usually for a number of compartments *e.g.* soil, crop, livestock, manures. Aarts *et al*. (1992) presented changes in storage, transfers and nutrient surpluses of dairy systems in the Netherlands using this approach. Such budgets need larger data inputs than 1) and 2) above but the increasing availability of relevant computer models can reduce the need for additional measurements.

There is no one correct approach to the compilation of nutrient budgets, instead appropriate methodology should be chosen depending on the purpose/question which is driving the compilation of the budget and the nutrient or nutrients being considered (Oenema & Heinen 1999).

System definition

The delineation of system boundaries in both space and time is a critical step in the compilation of nutrient budgets. In order to allow useful interpretation of the data, the definition of the system boundary also needs to be made explicit when the budget is presented.

Working within the horizontal dimension, including all the land within the farm boundary i.e. including woodland, tracks etc., provides a complete picture of the whole farm environment. More commonly only the managed land is included, so that for example, field margins are not included in estimates of field size. Another fundamental issue is the definition of boundaries in the vertical dimension; rooting depth is commonly used as the lower boundary.

Temporally, the question arises as to whether the budget should consider a single growing season, a calendar year (in which case where does it begin and end in relation to cropping pattern) or a complete crop rotation over several years? The decision will depend on the type of system and the purpose of the budget. For example, where P is applied once in 5 years on a rotational basis, budgets for a single year will not be either typical or useful. The use of data that describe complete rotations is critical for the compilation of nutrient budgets in organic farming systems, particularly where data is used to examine their likely environmental impact. For example, leaching losses have been shown to be large immediately following ploughing of leys but when averaged over whole farms and rotations losses are likely to be much lower (Philipps *et al.* 1998; Stopes *et al.* 2002). Occasionally longer-term records have been kept (Nolte & Werner 1994; Fagerberg *et al.* 1996), which allow the variation between years to be elucidated. This allows for climatic variation and its influence on crop establishment and yield, as illustrated for the stockless organic system at ADAS Terrington (Table 1). Budgets calculated across rotations can also reveal variation caused by farm management practices, such as batch rearing of animals, which do not match to an annual time step. For example, Kaffka & Koepf (1989) present farm-gate balances over the period 1952-81 for the biodynamic farm at Talhof as well as considering rotational means. In such cases, interpretation of the nutrient budgets is assisted by the availability of long-term data sets for soil chemical properties.

Presentation

Nutrient budgets are generally presented in tabular form for an annual time step on the basis of kg ha^{-1} $year^{-1}$ or kg $farm^{-1}$ $year^{-1}$, and many published studies present only annual means. There is of course no inherent reason why nutrient budgets should be calculated over any particular time step or presented in any particular way. The methodology (as described earlier) can apply to any system whose temporal boundaries can be much longer or shorter than a year. The methodology may also relate to a unit of livestock or the production of a given number of calories for human consumption rather than a farmed area (e.g. Watson & Atkinson 1999; Jarvis 1999). Nutrient budgets may also be presented as flow diagrams *e.g.* putting numbers on the arrows of Figure 1 for a specific farm or rotation. The presentation of nutrient budgets is often closely related to the purpose of the study, and in some cases, e.g. in education, diagrams which simply show the major nutrient flows can be as useful as actually putting numbers on all the arrows (Watson & Stockdale 1999).

QUANTIFICATION OF INPUTS AND OUTPUTS IN ORGANIC FARMING SYSTEMS

The major input and output flows for N, P and K in organic farming systems, where the spatial system boundary is defined as managed land on the farm considered to rooting depth are illustrated in Figure 2. This is the system for which we have compiled budgets from the literature and it can be described as a farm-scale surface budget. Oenema & Heinen (1999) have recently reviewed sources of bias in nutrient budgets. We will not repeat their analysis but highlight additional concerns particularly relevant for the measurement/estimation of each of these flows in organic farming systems.

Purchased inputs and sold outputs

Purchased inputs in feeds and supplementary fertilisers, *e.g.* rock phosphate, are permitted under organic standards (EC 2092/91). The nutrient imports in these materials are relatively easy to quantify from farm records of amounts purchased and manufacturers' information on product composition. Seed inputs are also relatively easy to quantify from quantity purchased and average percentage composition of seeds. At commonly used seed rates (Lampkin & Measures 1999), field beans (*Vicia faba*) could be expected to contribute 10 kg N ha^{-1}, cereals 3 kg N ha^{-1} and grass clover mix about 1 kg N ha^{-1}. In general seed contributes relatively little to the nutrient input on a whole farm basis, except for seed potatoes, which can import substantial quantities of K.

Many studies have relied on published standard/average values for the N, P and K contents of inputs, crop and animal products. Analytical data of this type is readily available for conventional systems e.g. Agricultural Research Council 1976; Fagerberg *et al*. 1993; Holland *et al.* 1991 *etc*. However, it may not be appropriate to use these values in organic agriculture. Indeed even within conventional systems the range in nutrient contents measured for any material due to season and site differences may be large (Jarvis *et al*. 1996) and may invalidate the use of simple average values for detailed nutrient management planning. Where measured values for an individual site are used in place of literature derived standard values, nutrient budgets can change substantially. For two different sites in NE Scotland, Table 2 illustrates the difference in the nutrient budget for a six-course rotation using literature and then measured values for the K content of straw, silage and grain. At one site the balance changes from a negative annual value to a positive one, potentially changing any management recommendations from this budgeting exercise.

Annual applications of manures or composts in organic systems are limited to the equivalent of 170 kg ha^{-1} $year^{-1}$ of N over the entire holding (Directive 91/676/EC). Application rates on individual areas of land as high as 250 kg ha^{-1} $year^{-1}$ are however permitted (as per the DEFRA Code of Good Agricultural Practice). Inputs from manure are difficult to quantify since accurate measurements of both quality and quantity are rarely available on commercial farms. The nutrient content varies greatly depending on the type of animal, its diet, the nature and amount of bedding material, the degree of separation of solids and liquids, dilution by rain water and storage conditions (Shepherd *et al.* 1999). Mean N contents of cattle FYM, 5 kg N t^{-1} on a fresh weight basis, (range of 2 to 10 kg N t^{-1}) and cattle slurry, 2.5 kg N m^{-3}, (range of 1.1 to 4.1 m^{-3}) collected in organic farming systems have been shown to be about 15% lower than manure from conventional systems (Dewes & Hunsche, 1998; Shepherd *et al.* 1999; Steineck *et al.* 1999). The differences are less clear for P and K, Dewes and Hunsche (1998) found that the K content of cattle manure was higher from organic farms but Steineck et al. (1999) found no significant differences between the P and K content of manures from the two systems. Composted municipal and green household waste is occasionally, but increasingly, used in organic farming systems. These typically contain 9 to 17 kg N t^{-1} dry weight and can also supply significant quantities of P and K (Berner *et al.* 1995; Rodrigues *et al.* 1995). However, like FYM, composts are variable in composition, depending not only on source but also on batch.

In general, nutrient data for organic crops and manures produced on organic farms is becoming available for use in simple nutrient budgeting exercises for organic systems. However, where the budgets are to be used to make detailed management recommendations, data should be collected on that farm and ideally over a number of seasons so that site and seasonal variability can be taken into account especially in relation to changes in soil nutrient status.

Deposition

Deposition of nutrients is rarely measured, even as part of detailed nutrient budgeting studies, instead data is usually taken from national figures. Figures for N deposition are increasingly available as maps of deposition, *e.g.* Stanners & Bourdeau (1995) and National Expert Group on Transboundary Air Pollution (2001). However, substantial local variation can occur due to the impact of ammonia volatilisation from housed livestock. Inputs of P and K from deposition are generally very low, except in systems receiving the influence of seas spray, where K inputs are increased (Review Group on Acid Rain 1997). While deposition is likely to represent a larger proportional nutrient input to organic than to conventional systems, there is little that can be done within organic systems to manage or adjust this input. In contrast, conventional farming systems might adjust fertilisation strategy – quantities and/or timing.

Nitrogen fixation

Nitrogen fixation represents a major input of N into organic farming systems. The amount of N fixed by leguminous crops is notoriously variable, being dependent on the climate, soil pH, available N, P and K, age of legume, species, cultivar and strain of symbiotic rhizobium (Cowling 1982; Ledgard & Steele 1992). White clover (*Trifolium repens*) is the most common legume in mixed organic systems in temperate regions, where it is usually grown with grass and utilised for grazing. Estimates of the amount of nitrogen fixed average 150 kg N ha^{-1} $year^{-1}$ (range 80 to 250 kg N ha^{-1} $year^{-1}$) and 85 kg N ha^{-1} $year^{-1}$ (range 50 to 130 kg N ha^{-1} $year^{-1}$) for 1-2 year old and older leys respectively (Kristensen *et al*. 1995). This decline in fixation is believed to be due to the build up of soil available N causing a decline in the proportion of clover (Crush 1987; Evans *et al*. 1995; Fisher 1996). Grazing has been shown to reduce fixation by 14-21% through the effect of higher soil N and greater grass competition (Eriksen *et al*. 1996). A sole crop of red clover (*Trifolium pratense*) is estimated to fix 240 kg N ha^{-1} $year^{-1}$ (Lampkin 1990; Schmidt *et al*. 1999). Other legumes grown in organic rotations, either as fodder or as green manures, include lucerne, vetches, lupins and trefoils. Estimates of N fixation range from 200 to 500kg ha^{-1} $year^{-1}$ for lucerne (Lampkin 1990) and 150 to 200kg ha^{-1} $year^{-1}$ for vetch (Nutman 1976; Sprent & Bradford 1977). However these species are often more difficult to manage and are less widely used, being confined to particular soil types or rotations.

Grain legumes obtain only 50% of their N from the atmosphere, compared with 90% by forage legumes. Nevertheless, the annual fixation by field beans has been estimated at between 150 and 280 kg N ha^{-1} (Nutman 1976; Kopke 1987), with peas fixing between 100 and 250 kg N ha^{-1} (Jensen 1989; Fisher 1996). However, much of the fixed N is removed when the grain is harvested. Sylvester-Bradley & Cross (1991) have estimated that the effect of the nitrogen residue from combined peas or beans is equivalent to only 20 to 25 kg N ha^{-1} $year^{-1}$ applied as fertiliser. There may even be a net removal of nitrogen by grain legumes under some conditions (Fisher 1996; Jensen 1989).

It is unlikely that farmers and/or their advisors will make direct measurements of N fixation to check the assumptions made within budgets (unlike measurements of nutrient contents of inputs etc.). However, a number of empirical relationships have been proposed for estimating N fixation by legumes (Barry *et al*. 1993; Kirchmann *et al*. 1988; Kristensen *et al*. 1995; Watson & Goss 1997; Haraldsen *et al*. 2000; Korsaeth & Eltun 2000). It is clear from the range of factors that these different authors included in their relationship (Table 3) that not all of them are suited to practical application using the type of information that is routinely available on farms. The use of grass-only reference crops or non-nodulating legumes for comparison will never be practical. Better quantification and record-keeping with regard to cutting and grazing management, *e.g.* yields of swards (both cut and grazed), and legume contents of swards, should however allow farmers and systems researchers to improve estimates of N fixation in combination with continued improvement and validation of practical models of N fixation.

NUTRIENT BUDGETS FOR ORGANIC FARMING SYSTEMS

Data sources

Following a literature search in refereed journals and English language conference proceedings, papers that detailed the compilation of nutrient budgets on biodynamic and organic farms were collated. Nitrogen, P and K budgets were included in this study where inputs and outputs of N, P or K were detailed separately on an annual basis Some additional budgets published in theses or unpublished reports have also been included. The literature sources are summarised in Table 4. Most farm types are represented but dairy farms dominate those studied, particularly due to the Swedish survey of 37 organic dairy farms. In total 88 farms were included and N budgets were the most commonly reported (88 farms) followed by P (71 farms) and K (70 farms). There are few published data on the use of other nutrients on organic farms although Mg, S and Zn budgets are reported by Nolte & Werner (1994), Nguyen *et al.* (1995) and Öborn *et al.* (2001) respectively.

Data manipulation and analysis

Nutrient budgets were compiled by considering all the inputs and outputs of nutrients as described in the papers (Table 4) to compile a surface budget at farm-scale (Figure 2). Inputs have been separated into purchased inputs excluding manure, purchased manure, fixation (N only) and deposition (N only) to allow the dependence of the farms on different input sources to be derived. Where no values were given for N in deposition, these have been obtained from national information (*e.g.* Stanners & Bourdeau 1995). In the published nutrient budgets surveyed here, only two papers made direct measurements of nitrogen fixation; Patriquin *et al.* (1981) used the acetylene reduction technique and Granstedt (1992) the difference method. Four of the studies did not include any estimate of N fixation (Kaffka & Koepf 1989; Fowler *et al*. 1993; Watson *et al.* 1994; Wieser *et al*. 1996), one was based on an estimated annual value (Nguyen *et al.* 1995) and the remainder were based on empirical relationships. Where no values were given for symbiotic N fixation, but information was provided on the areas growing leguminous and non-leguminous crops, an annual fixation value was derived from literature estimates (Whitehead 1995).

The resulting nutrient surplus or deficit (Δ nutrient) for each farm is the difference between nutrients sold in plant and animal produce and nutrient inputs in feed, seed, supplementary nutrients, fixation and deposition (N only). The value of Δ nutrient represents the amalgamation of any nutrient losses from the system and any change in the storage of nutrients within the system. Some of the budgets included had also made measurements/estimates to allocate the nutrient surplus between losses (volatilisation, leaching, denitrification) and 'storage'. However, to give the maximum data set for comparisons between farms, only surface budgets at the farm-scale are considered in this paper. Nutrient use efficiency was also calculated; it was defined as nutrients exported in sales divided by net nutrient imports.

Statistical analysis of the data was based on examination of correlations, scatter plots and multiple linear regression.

Results

All of the N budgets showed an N surplus. Averaging over all farm types the surplus was 86.2 kg N ha^{-1} $year^{-1}$ (Table 5). However, the efficiency of N use was relatively low (Table 5; average 0.3), except in the arable systems studied (where it was 0.8 and 1.0). The high efficiency of N use by the arable farms is intersting although it is difficult to draw conclusions from such a small data set. The data presented in Table 6 is from a subset of those dairy farms in Table 5 where a more detailed dataset was readily available. Across all the dairy farms studied in detail, N inputs averaged 118 kg N ha^{-1} $year^{-1}$ (SE 7.5; Table 6). On average, 62% of the N inputs were derived from N fixation (range 19-87%, SE 2.8) and 25% on average in purchased feed and bedding (range 0-65%, SE 2.7). Only 4 of the 47 farms studied imported any manure, these also had some crop production on the farm (dairy farms 14, 20, 33 and 47; Table 6). N outputs in products were also variable between farms (average 26 kg N ha^{-1} $year^{-1}$, SE 1.8; Table 6). However, across all dairy farms there was no significant increase in N in the products sold with increasing total N input

(Table 6) *i.e.* there was neither an increase in milk yield, crop outputs nor the N concentration in these products with increasing N input. Consequently there was a highly significant linear correlation between total N input and the N surplus (r^2=0.9455, n=47). Jarvis (1999) also found a highly significant correlation between N applied in fertiliser (the dominant N input in conventional farms) and the N surplus in conventional dairy farms. From farm-scale surface budgets the calculated N surplus is an indicator of the potential losses from the system. On dairy farms in the UK, it has been estimated that 75% of the surplus is lost, split roughly evenly between the processes of leaching, denitrification and volatilisation (Jarvis *et al.* 1996*)*. In other studies larger proportions of the surplus are assumed to be lost; Aarts *et al.* (1992) in the Netherlands suggested that most if not all (> 94%) of the N surplus would be lost from the system.

The P and K budgets calculated show both surpluses and deficits (Table 5, average 3.6 kg P ha^{-1} $year^{-1}$, 14.2 kg K ha^{-1} $year^{-1}$). The horticultural systems studied all imported significant quantities of manure to the system and showed the highest average P and K surplus. However these systems also showed the greatest range in the nutrient budgets due to differences in crop rotation, management and yields achieved (Table 5). Very high efficiency values were obtained for P and K in systems operating with very low to no inputs and showing nutrient budgets in deficit (Table 5). Inputs of P and K from accumulated reserves prior to conversion to organic farming and weathering of soil parent materials are excluded from the budgets as compiled, which may represent significant inputs to the system (*e.g.* Goulding & Loveland 1987). However, in many soils such high efficiencies coupled to negative nutrient budgets indicate that the system is not sustainable in the long-term. Greater attention should be paid to the long-term capacity of the soil to supply nutrients in the design of appropriate site-specific rotations in organic farming systems.

Across all the dairy farms studied, P and K inputs averaged 8 kg P ha^{-1} $year^{-1}$ and 26 kg K ha^{-1} $year^{-1}$ (SE 1.1 and 1.8 respectively; Table 6). Only 4 farms purchased manure, which made up 52 and 55 % of the P and K inputs respectively on those farms. Other purchased inputs *e.g.* in animal feed, bedding material and supplementary fertilisers made up 87 and 94% on average of the P and K inputs respectively. The level of P and K inputs were highly significantly correlated (r^2 = 0.6807, n=47). P and K outputs averaged 5 kg P ha^{-1} $year^{-1}$ and 7 kg K ha^{-1} $year^{-1}$ (SE 0.4 and 0.7 respectively; Table 6). There was a significant linear relationship between P output in products and P inputs for the dairy farms (r^2 = 0.4858; n=47) where the average efficiency calculated from the gradient of the relationship was 0.23. However, there was no significant relationship for K. Three farms (17,19,47) whose output had a significant component of crop products could be identified from the K:P ratio of the outputs (3.5 on average) whereas for all other farms the ratio was c 1.5 and within the ratio seen for milk (Holland *et al.* 1991). For both P and K there was a highly significant linear correlation between total input and the surplus (r^2=0.9127 and 0.9205 for P and K respectively, n=47).

CONCLUSIONS

The nutrient budgets shown (Tables 5 and 6) demonstrate the considerable range in nutrient budgets not only between farm types but also within any farm type. Future research needs to address the scope for increasing nutrient use efficiency through management practices. The data highlight the importance of balancing P and K offtake in organic produce with P and K inputs from organically acceptable sources.

This is particularly important for the long-term maintenance of soil fertility and yields. Farmgate budgets are unable to reveal whether surplus nutrients are accumulated in soil organic matter or lost to the environment. However, the large surpluses of N on some farms suggest that the effects of management practice on the environmental impact of organic farming warrants further investigation. The data presented here also suggest some cause for concern in relation to the sustainability of organic dairy systems because of their dependence on imported feedstuffs and bedding for P and K, and for N on the very variable fixation by legumes or imports of manure or compost. This is in agreement with the findings of Goulding *et al.* (2000). Longer-term studies, particularly those including the monitoring of soil nutrient pools, are critical if we are to increase our understanding of the sustainability of nutrient management in organic farming systems.

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TABLE HEADINGS

Table 1 Annual surface N budget for the period 1995-1999 for the stockless organic system at ADAS Terrington, UK. (Rotation comprises red clover, potatoes, winter wheat, winter beans, spring wheat).

Table 2 Surface K budgets calculated for ley/arable rotations at SAC Farms Tulloch and Woodside. The estimated budget uses standard literature values for the K content of crop products. The corrected budget uses analytical values for crop products.

Table 3 Parameters used in a number of empirical relationships to predict N fixation

Table 4 Data sources for the compilation of nutrient budgets at farm-scale for organic farms.

Table 5 Summary of farm-scale nutrient budgets by farm type

Table 6 Simplified nutrient budgets for 47 farms where dairy production is considered to be the major enterprise, but which also may have some cropping on farm (mixed) listed in order of increasing total N input to the farm system. n/a = information not available.

FIGURE HEADINGS

Figure 1. Simple diagrammatic representation of nutrient flows that may occur on a farm. Where the boundary of the system is drawn will determine which flows represent inputs, outputs and internal flows for that system.

-------- might represent the farm boundary, including cropped and uncropped land

_______ might represent the crop rotation boundary, including soil to rooting depth

Figure 2. Surface budget at the farm-scale used for the N, P and K budgets presented. The farm system boundaries are the cropped land to rooting depth. Δ nutrient (*i.e.* the budget surplus or deficit) calculated in this way represents the amalgamation of any nutrient losses from the system and any change in the storage of nutrients within the system.

Table 1

	1995	1996	1997	1998	1999
Deposition	30	30	30	30	30
Seed	4	4	4	4	4
Fixation (winter beans, red clover)	24	20	45	37	35
Inputs - total	**58**	**54**	**79**	**71**	**69**
Crop output	**92**	**110**	**71**	**81**	**89**
Balance	-34	-56	8	-10	-20

Table 2

	Woodside		Tulloch	
	Estimated[a]	Corrected	Estimated[a]	Corrected
INPUTS				
Deposition	2.1	2.1	2.1	2.1
Seed	3.2	3.2	0.7	0.7
Manure	50.5	50.5	53.1	53.1
Grazing	40.5	45.8	36.0	36.0
OUTPUTS				
Products	36.0	32.0	25.5	23.2
Straw	16.7	10.9	8.8	3.7
Silage	38.7	42.6	70.2	64.3
Liveweight gain	12.0	12.0	10.6	10.6
BALANCE	-7.0	4.1	-23.2	-10.0

[a] From Watson *et al.* (2000)

Table 3

Reference	Legumes studied	Variables									
		Yield of legume + grass	Yield of grass-only reference crop	% legume in mixture	Years after establishment	N content of legumes	N content of legume + grass	N content of grass-only reference crop	% legume N derived from fixation	Correction for stubble/root N	Sward management
Barry *et al.* (1993)	Alfalfa Soybean	√	√							√	
Haraldsen *et al.* (20000	Grass-clover	√		√		√			√		
Kirchmann *et al.* (1988)	Grass-clover	√	√			√	√	√	√	√	
Korsaeth & Eltun (2000)[a]	Grass-white clover Grass-red clover Grey peas Common vetch	√		√						√	
Kristensen *et al.* (1995)	Grass-clover (red and white mix)			√	√					√	
Watson & Goss (1997)	Grass-white clover	√	√	√						√	√

[a] Modified version of Hansen (1995)

Table 4

Country	Farm types	Years of data compiled	N	P	K	Reference
Austria	9 dairy	1	√[b]	√	√	Wieser *et al.* (1996)
Canada	1 arable, 1 dairy, 1 pig	1	√			Goss & Goorahoo (1995)
Canada	1 poultry	1	√[b]			Patriquin *et al.* (1981)
Germany	2 mixed	3	√			Bachinger & Stein-Bachinger (2000)
Germany	1 mixed[a]	1	√[b,c]	√	√	Kaffka & Koepf (1989)
Germany	1 mixed[a]	3	√	√	√	Nolte & Werner (1994)
Netherlands	1 dairy[a]	4	√	√	√	Vereijken (1986)
Netherlands	1 dairy, 1 arable	?	√	√	√	Nauta *et al.* (1999)
New Zealand	3 mixed	1	√[b]	√	√	Nguyen *et al.* (1995)
Norway	9 dairy 2 dairy[a] 1 sheep 1 mixed[a]	1-6	√	√	√	Ebbesvik (1998) Løes & Øgaard (1997)
Sweden	1 dairy	5	√[b]	√	√	Fagerberg *et al.* (1996)
Sweden	1 dairy	2	√	√	√	Björklund & Salomon (1995)
Sweden	37 dairy	1	√	√	√	Myrbeck (1999)
Sweden	1 dairy[a]	7	√			Granstedt (1992)
UK	2 dairy 3 beef	2 on two farms; 1 on 3 farms	√[b,c]	√	√	Fowler *et al.* (1993)
UK	1 dairy	3	√	√	√	Cuttle & Bowling (1997)
UK	2 horticultural	2 on one holding; 1 on one holding	√[b,c]	√	√	Watson *et al.* (1994)
UK	1 beef 1 dairy 1 horticulture	1	√	√	√	Goulding *et al.* (2000)
UK	1 beef	3	√	√	√	Watson & Atkinson (1999)

[a] Biodynamic [b] No deposition data [c] No fixation data

Table 5

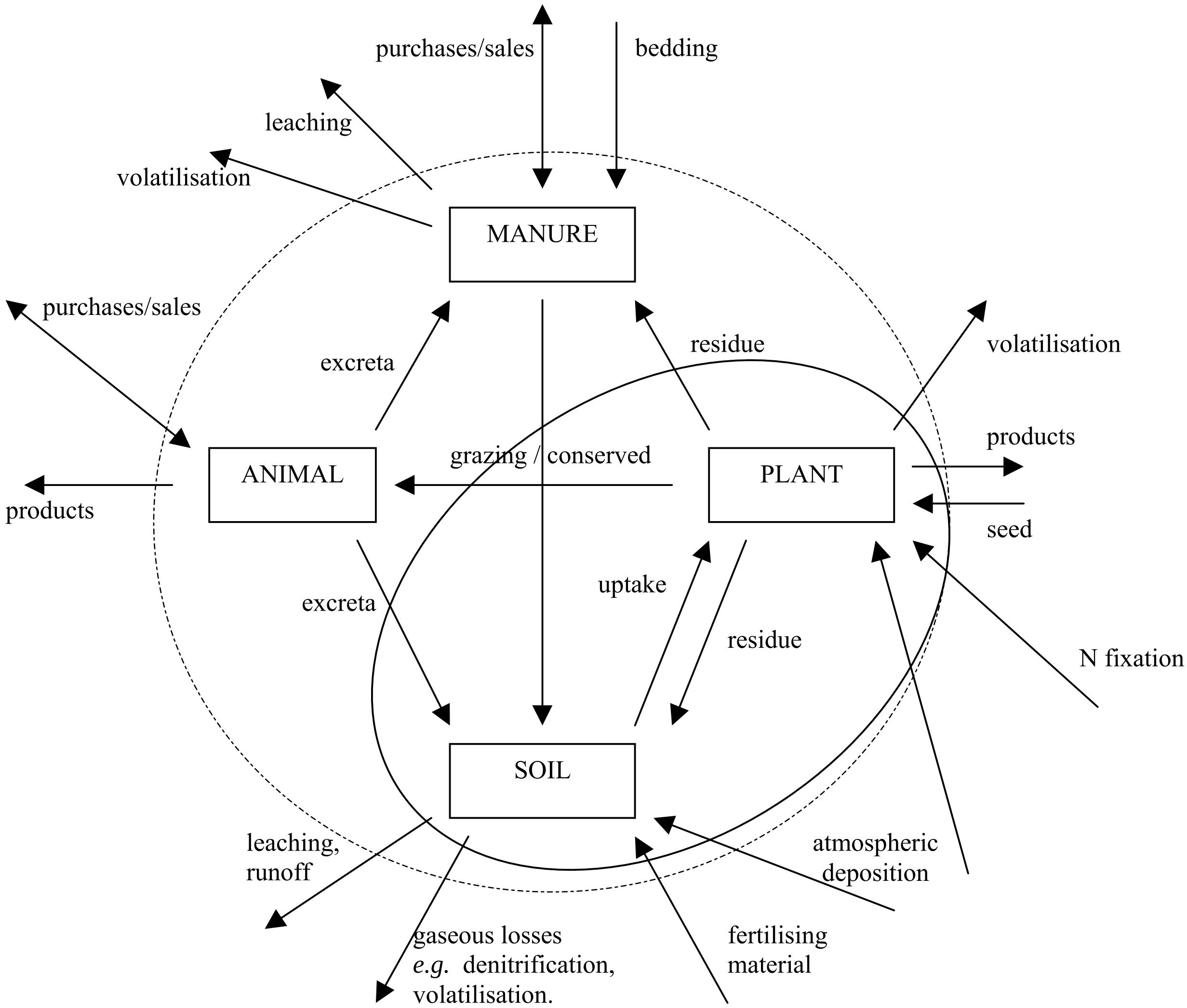
Farm type	n	Surplus (Input-Output) kg ha^{-1} year^{-1}			Efficiency (Output/Input)		
		Mean	SE	Range	Mean	SE	Range
N							
Arable	2	25.6	24.4	1.2- 50.0	0.9	0.1	0.8-1.0
Beef	5	112.0	25.6	18.4-164.0	0.2	0.03	0.1-0.2
Dairy	67	82.1	6.7	2.1-217.0	0.3	0.02	0.0-0.9
Horticulture	3	194.2	100.7	91.0-395.6	0.3	0.1	0.1-0.4
Mixed	8	54.6	8.6	21.0- 91.6	0.4	0.05	0.2-0.5
Mean		83.2					
P							
Arable	1	-6.0			1.3		
Beef	4	-1.8	1.4	-6 - 0	2.8	1.4	1.0- 7.0
Dairy	56	3.1	0.9	-6.5 - +36.0	2.1	1.2	0.3-66
Horticulture	3	38.9	26.0	1.7 - +89.0	0.4	0.2	0.1- 0.9
Mixed	6	-2.4	1.3	-6.9 - + 4.0	13.6	9.8	0.6-70
Mean		3.6					
K							
Arable	1	57.0			0.8		
Beef	4	3.0	3.4	-4.5 - + 12.0	2.8	2.4	0.2- 10
Dairy	58	9.6	2.0	-26.5 - + 58.0	5.3	4.6	0.1-266
Horticulture	3	122.0	88.0	-23.0 - +281.0	0.7	0.4	0.1- 1.6
Mixed	3	-2.2	1.2	-4.4 - - 0.3	1.6	0.3	1.1- 2.0
Mean		14.2					

Table 6

Country	Robust type	Farm size (ha)	Stocking rate (lu ha^{-1})[a]	Nutrient flows kg ha^{-1}									
				N fixation	Total N input	N in product sold	N surplus	Total P input	P in product sold	P surplus	Total K input	K in product sold	K surplus
1 Sweden	Mixed	55	0.49	26	36	34	2	1	1	-5	2	2	-7
2 Sweden	Mixed	33	n/a	21	37	22	15	2	5	-2	2	5	-3
3 Sweden	Mixed	101	0.57	18	39	13	26	2	3	-1	2	4	-2
4 Sweden	Mixed	180	n/a	22	42	15	27	2	3	-1	11	4	7
5 Sweden	Mixed	72	0.72	37	49	37	12	4	7	-4	7	10	-6
6 Sweden	Mixed	160	0.55	30	52	30	22	4	6	-2	5	8	-3
7 Sweden	Mixed	106	0.47	42	56	16	40	3	3	0	2	4	-2
8 Sweden	Mixed	132	0.66	44	64	22	42	4	5	-1	5	5	0
9 Sweden	Mixed	125	0.56	17	67	26	41	18	5	13	25	7	18
10 Sweden	Mixed	130	n/a	51	69	13	56	2	3	-1	7	4	3
11 Sweden	Mixed	64	0.48	40	73	20	53	7	4	3	32	5	27
12 Sweden	Mixed	67	1.03	45	73	31	42	10	6	4	11	6	5
13 Sweden	Mixed	185	n/a	35	75	24	51	5	5	0	11	6	5
14 Sweden	Mixed	71	n/a	47	78	15	64	3	3	0	5	5	0
15 Sweden	Mixed	44	1.07	64	85	20	64	3	4	-1	6	5	1
16 Sweden	Mixed	175	0.69	52	88	17	71	8	3	5	4	5	-1
17 Sweden	Mixed	83	0.87	33	89	38	51	8	6	2	12	18	-6
18 Norway	Dairy	14	n/a	52	97	35	62	9	7	2	53	10	43
19 Netherlands	Mixed	22	n/a	75	99	42	57	0	7	-7	0	27	-27
20 Sweden	Mixed	97	0.80	45	102	12	90	1	2	-1	2	3	-1
21 Sweden	Mixed	85	0.74	78	106	17	89	5	4	1	10	4	6
22 Sweden	Mixed	112	0.61	38	107	27	80	11	9	2	10	8	2
23 Norway	Dairy	9	n/a	46	107	34	73	19	7	12	62	23	39
24 Sweden	Mixed	129	n/a	76	108	18	90	5	4	1	5	6	-1
25 UK	Mixed	63	1.55	71	122	31	91	10	6	4	22	9	13
26 Sweden	Mixed	107	0.92	86	130	37	93	6	7	-1	10	10	0
27 Sweden	Mixed	30	0.80	80	131	18	113	6	3	3	15	5	10
28 Sweden	Mixed	60	0.68	111	135	17	117	3	3	0	4	4	0
29 Sweden	Mixed	25	1.38	69	137	33	104	20	7	13	50	9	41
30 Sweden	Mixed	59	0.47	65	142	41	101	15	9	6	24	11	13
31 Sweden	Mixed	83	0.34	33.7	144	28	116	21	6	15	66	8	58
32 Sweden	Mixed	60	1.25	113	147	18	128	3	4	-1	4	5	-1
33 Sweden	Mixed	137	0.77	27	147	31	117	18	6	12	31	8	23
34 UK	Mixed	99	1.90	123	157	24	133	7	5	2	10	5	5
35 UK	Dairy	56	n/a	117	159	37	122	3	7	-4	12	9	3
36 Netherlands	Dairy	52	n/a	80	160	49	111	11	10	1	43	16	27
37 Austria	Dairy	16	n/a	150	172	14	157	6	3	3	3	3	0
38 Austria	Dairy	30	n/a	150	173	15	158	2	4	-2	3	3	0
39 Austria	Dairy	20	n/a	150	177	21	156	4	5	-1	5	4	1
40 Austria	Dairy	13	n/a	150	179	23	156	3	5	-2	5	5	0
41 Austria	Dairy	32	n/a	150	180	18	162	2	3	-1	24	4	20
42 Austria	Dairy	52	n/a	150	181	14	167	4	3	1	19	5	14
43 Austria	Dairy	32	n/a	150	181	22	159	10	5	5	7	5	2
44 Austria	Dairy	37	n/a	150	183	8	175	3	2	1	5	2	3
45 Sweden	Mixed	37	1.19	57	186	69	117	29	13	16	30	11	19
46 Austria	Dairy	15	n/a	150	186	16	170	6	4	2	16	4	12
47 UK	Mixed	233	2.20	86	247	51	196	31	10	21	66	13	53

[a] lu=livestock units

Figure 1.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uptake
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N fixation
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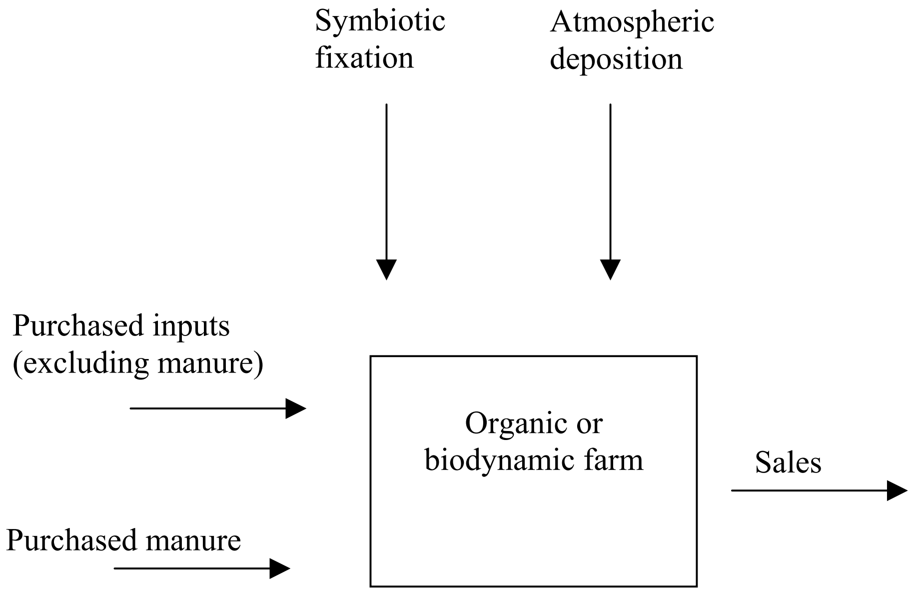
e.g. denitrification,
volatilisation.
fertilising
material

Figure 2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Organic or
biodynamic farm
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Purchased manure