DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS

CSG 15

Research and Development

Final Project Report

(Not to be used for LINK projects)

Two hard copies of this form should be returned to:
Research Policy and International Division, Final Reports Unit
DEFRA, Area 301
Cromwell House, Dean Stanley Street, London, SW1P 3JH.
An electronic version should be e-mailed to resreports@defra.gsi.gov.uk

Project title	Influence of level of self-sufficiency on the nutrient budgets of an organic dairy farm
DEFRA project code	**OF0180**
Contractor organisation and location	Institute of Grassland and Environmental Research Plas Gogerddan Aberystwyth
Total DEFRA project costs	£
Project start date	01/10/98
Project end date	30/09/02

Executive summary (maximum 2 sides A4)

In 1998, the organic dairy herd at Ty Gwyn, Trawsgoed was split into two herds to examine the physical and financial implications of adopting different feeding strategies and levels of feed self-sufficiency (DEFRA Project OF0146). A self-sufficient system (SS) in which cows were fed a high forage diet supplemented with home-grown cereals was compared with a system in which concentrate feeds were purchased from outside the farm (PC). The present study determined nutrient budgets for the two systems and used models to estimate the various forms of N loss. These studies were supported by field studies to provide additional information about areas of uncertainty identified in previous budget calculations.

Specific objectives were:

1. To determine whole-farm budgets and internal flows of N, P and K for the SS and PC organic dairy systems at Ty Gwyn.
2. To measure the effect of slurry applications on N fixation in grass/clover fields at Ty Gwyn and effects on the uptake of P, K and Mg.
3. To measure possible changes in the P and K content of soils in the SS and PC systems at Ty Gwyn and evaluate recommended laboratory tests as indicators of P and K deficiencies in these soils.

Nutrient budgets and losses. Annual whole-system budgets for N, P and K (April - March) were calculated for 1999/2000, 2000/01 and 2001/02 with additional determinations of N losses and internal flows for the final year. SS system budgets were influenced by continuing inputs of feed in the first two years. Differences between the two systems in the earlier years were therefore smaller than anticipated and it was only the final year that the SS system was fully representative of the intended self-sufficient management. The largest input of N was from biological fixation and in all three years was greater in the SS than in the PC system. This was due to higher clover yields in the SS system but did not appear to be related to differences in management. Purchased feed was also an important source of N except to the SS system in the final year. In this final year, the input of N in feed and bedding was reduced to 12% of that to the PC system. Outputs from the two systems were mainly as milk and in livestock. In the first year, the total output of N from the SS system was slightly greater than that from the PC system and then progressively declined relative to the PC system, reflecting the reduction in cow numbers in the SS system. Inputs of P and K were mainly dependent on purchased feed and bedding. There was therefore a marked difference between the inputs to the two systems in the final year but smaller differences in Years 1 and 2 when the SS system received significant inputs of feed. As with N, differences between outputs from the two systems were most marked in the final year.

There were appreciable surpluses of N for both systems in all years. In Year 1, the largest surplus was produced by the SS system but in subsequent years the PC surplus was the greater. However, when averaged over the whole field area, the surplus for the SS system was less than from the PC system in all three years (average 85 and 121 kg N/ha, respectively). When expressed per unit of milk production, the surplus was slightly higher for the SS system in Years 1 and 2 and markedly higher in Year 3 (19.1 g N/litre milk compared with 16.8 g/l for the PC system). Apart from a slightly higher value for the PC system in Year 1, the %N efficiency (output/input) of the two systems was between 25 and 26%. These estimates include the contribution of young stock to each herd; if they are excluded, efficiencies are increased to 29 - 33%.

There was a small deficit of P in the PC system in Year 1. With higher feeding rates in Years 2 and 3, P balances were positive. In contrast, balances for the SS system were negative in all years. The total deficit over the three years was equivalent to –12 kg P/ha when averaged over the whole system area, compared with a surplus of +5 kg/ha for the PC system. Potassium balances for the PC system were positive in all years whereas the reduced inputs to the SS system resulted in negative balances in Years 1 and 3. A quantity of dried lucerne was purchased in Year 2 to offset a shortage of silage in the SS system and this was sufficient to produce a positive balance in that year. The accumulated balance for the SS system over the three years was equivalent to –3 kg K/ha/year, compared with +31 kg/ha for the PC system. The deficits for the SS system were increased by the transfer of straw to the young stock in the PC system.

Modelling of N losses from the two systems in 2001/02 indicated that field losses were broadly similar for both systems when expressed on an area basis. There were additional large losses from the spreading of cattle slurry and farmyard manure: 19 - 23% of the total N supplied in slurry was lost as ammonia. There were also large losses of ammonia from cattle during housing in winter, with smaller emissions from slurry and manure stores. Together, all forms of loss were equivalent to 55 and 60 kg N/ha for the SS and PC systems, respectively. Ammonia volatilisation accounted for 52 and 61% of these totals. This was a higher proportion of the total loss than found for similar estimates of N losses from conventional dairy farms. The models indicated that soil N increased during the year, accounting for about 40% of the budget surplus in both systems at Ty Gwyn. The total loss plus increase in soil N was equivalent to 115 and 89% of the budget surplus calculated for the SS and PC systems, respectively. Estimates of internal transfers of P and K appeared to underestimate the quantities of K available in slurry.

Effects of slurry on N fixation. The effects of cattle slurry on N fixation were investigated in a field experiment in 1999 and 2000 by comparing fixation in untreated and slurry-treated plots in two fields at Ty Gwyn, using the ^{15}N isotope dilution method. In 1999, slurry applications to the experimental plots caused small but non-significant reductions in the percentage of clover-N derived from fixation (%Ndfa). Applications in 2000 were at a higher rate and produced significant reductions in %Ndfa which persisted for several harvests after the application. Estimates of the quantities of N fixed per unit area are shown in Table 8 for harvests following the first application in 2000. Slurry treatments in 1999 had little effect on either clover yield or %Ndfa and therefore little effect on the quantities of N fixed compared with plots that did not receive slurry. Applications in the following year had a greater effect: %Ndfa was reduced from 95 to 87% at the first harvest following a slurry application in May and from 84 to 58% after an application in July. However, these reductions appeared to be accompanied by corresponding increases in clover N yield which compensated for the reduction in the proportion of fixed N. As a result, the absolute quantity of N fixed was similar to that in the untreated control plots. Further investigations would be required to confirm this effect as the yield differences in the present study were not statistically significant. The measured value of the quantity of N fixed per tonne of clover dry matter in zero-slurry plots was 25% lower than the published value used to calculate N fixation for the current budgets.

Effects of slurry on soil P and K contents. Plots in Fields A and B were treated with different quantities of cattle slurry during the first three years of the project to provide soils with a range of P and K contents that could be used in the final year (in the absence of further slurry applications) to study the effects of P and K status on herbage production. Soils were collected from these plots at the start of the study and in the final year to determine contents of extractable P and K. For all treatments, offtakes of P and K during the period were greater than the quantities supplied in slurry and increased with increasing slurry inputs. Soil analyses showed a marked decline in soil-P and -K contents in all treatments between 1999 and 2002, approximately equivalent to one soil index point. The different slurry treatments during the first three years of the experiment resulted in only small differences between contents of extractable P and K in soils in the final year. All concentrations were low and equivalent to P and K indices 0 to 1. The only significant difference was a higher K content for the highest slurry treatment than in the zero slurry treatment in Field A. Application of potassium sulphate and calcined phosphate fertiliser in the final year produced a similar increase in soil-K but not P. Clover and grass yields in Field A in 2002 (in the absence of slurry applications) were significantly greater for the high-slurry than for the zero slurry treatment. Yields from the plots treated with mineral fertiliser were also greater than from the zero slurry plots. There were significant positive correlations between yields and soil-K but not with soil-P. Concentrations of P in clover were similar to or slightly less than the threshold considered adequate for the growth of clover in mixed swards; K contents were generally below the critical concentration.

P and K contents of field soils. Possible changes in soil P and K content in fields of the SS system were investigated by collecting soil samples from fixed points within each field in January/February of each year between 1999 and 2002. These were analysed separately to allow statistical analysis of trends in P and K contents over the 4-year period. Although contents of soil P and K varied between years, few fields exhibited consistent trends. However, the statistical analysis identified significant trends in a minority of fields. These ranged from +1.9 to -9.8 mg/kg per year for P and from +8.3 to -24.8 mg/kg per year for K. Most of the slopes indicated declining P and K contents but there were positive trends for P in one field and for K in one other. There was no significant change over the SS system as a whole.

Scientific report (maximum 20 sides A4)

1. Introduction

Organic farms are largely reliant on biological fixation to supply N and seek to minimise inputs of other nutrients by more effective recycling of materials within the farm. Whole-farm budgets, comparing nutrient inputs with the quantities recovered in agricultural products, are useful indicators of the efficiency and sustainability of these systems. Previous studies have included calculations of nutrient budgets for the organic dairy farm at Ty Gwyn, Trawsgoed. These indicated that there were considerable surpluses of N but only small surpluses of P and K, which approximately balanced the unavoidable losses by leaching. No P or K fertilisers have been applied at Ty Gwyn since the start of the conversion to organic production in 1992 and the positive balances have been largely due to the import of nutrients in purchased feed. In 1998, the herd was divided into two herds to examine the physical and financial implications of adopting different feeding strategies and levels of feed self-sufficiency (DEFRA Project OF0146). A self-sufficient system in which cows were fed a high forage diet supplemented with home-grown cereals was compared with a system in which concentrate feeds continued to be purchased from outside the farm. Introduction of the self-sufficient system was expected to have a major impact on nutrient budgets. Ending the import of purchased feed would remove the major source of P and K inputs and increase the risk of deficiencies. However, purchased feed also supplies N and the reduction in inputs was expected to have a beneficial effect of reducing N surpluses. The present study therefore supplemented OF0146 by determining nutrient budgets for the SS and PC systems at Ty Gwyn to compare the environmental impact and sustainability of the two systems. These whole-farm budgets were extended to include estimates of internal flows within the two systems and models were used to estimate the various forms of N loss.

The previous studies had identified areas of uncertainty in the budget calculations, some of which were examined in more detail in the present study. In particular, N applications in fertiliser or urine are known to inhibit N fixation by clover (e.g. Vinther & Aaes 1996) but there is little information about the extent to which N in slurry has a similar effect. In organic livestock systems, slurries and manures are the main form in which nutrients are recycled and any effect on N fixation could have a significant impact on the N budget of the farm. If slurry inhibits fixation and substitutes slurry-N for fixed-N, this may have a beneficial effect of reducing the overall N surplus. Field experiments were therefore carried out to determine the magnitude and duration of the effects of slurry applications on N-fixation.

Although N is generally the nutrient with the greatest immediate effect on herbage yields, clover survival and hence N-fixation is dependent upon adequate levels of P and K in the soil. These nutrients may therefore be equally important to the longer term productivity of organic systems. Calculation of nutrient budgets in previous contracts and the results of routine soil analyses provided no evidence of a downward trend in soil P and K levels at Ty Gwyn. However, it is difficult to reconcile these indications with the apparent need for regular applications of P and K fertilisers to conventional dairy farms. The risk of nutrient deficiencies is likely to have been exacerbated by the introduction of the self-sufficient system in 1998. The current project therefore included a more detailed investigation of possible changes in the P and K content of soils at Ty Gwyn, supported by field experiments to examine the effects of slurry on the availability of P and K supply.

2. Scientific objectives

1. To determine whole-farm budgets and internal flows of N, P and K for the self-sufficient and purchased concentrate organic dairy systems at Ty Gwyn.
2. To measure the effect of slurry applications on N fixation in grass/clover fields at Ty Gwyn and effects on the uptake of P, K and Mg.
3. To measure possible changes in the P and K content of soils in the self-sufficient and purchased concentrate systems at Ty Gwyn and evaluate recommended laboratory tests as indicators of P and K deficiencies in these soils.

3. Methods
3.1. Farm budgets

3.1.1 Whole-farm budgets

Whole-system budgets for N, P and K were calculated for the self-sufficient (SS) and purchased concentrate (PC) systems for the April - March period in 1999/2000, 2000/01 and 2001/02. Similar budgets were also calculated for the young stock, which were managed as a single separate unit within the farm. Inputs and outputs to the young stock were then apportioned to the SS and PC systems in the final analysis. Inputs included in the whole-farm budgets were biological N fixation, purchased feed, purchased bedding, livestock purchases and rainfall: outputs were in milk, livestock sales and straw. These do not include estimates of nutrient losses or changes in storage within the system. No fertilisers, other than lime, were applied to any field at Ty Gwyn during the monitoring period. All quantities refer to elemental P and K, not to P_2O_5 or K_2O.

Nitrogen fixation was calculated separately for each field from measured values of total herbage yield and the proportion of clover in the sward, assuming annual fixation rates of 40 kg N/ha per 1000 kg yield of red clover and 54 kg N/ha per 1000 kg of white clover (van der Werff *et al*., 1994). Fixation values were adjusted to allow for reduced N-fixation during grazing, using a correction factor derived from various sources in the literature. Estimates were not adjusted for possible reductions in N fixation following slurry applications. Quantities of nutrients in purchased feed were calculated from herd records of the weights of concentrates and other feed fed to the dairy cattle each month, combined with analyses of nutrient contents. Similarly, quantities of nutrients in bedding were estimated from the typical weekly use of sawdust for the dairy herds and straw to young stock multiplied by the concentrations of N, P and K measured in samples of these materials. Nutrients in livestock transfers were determined from farm records of numbers of animals transferred, typical empty body weights for cows, calves and heifers and published contents of N, P and K. The nutrient input in rainfall was measured directly from analysis of rainfall samples collected at Ty Gwyn. Outputs of nutrients in milk were calculated from monthly herd records of the volume of milk sold, multiplied by measured contents of N, P and K.

3.1.2. Internal transfers

Transfers of nutrients within the farm were only determined for 2001/02. Because of continuing inputs of feed to the self-sufficient system, the first two years of the study were less representative of the intended management. Estimates were made of outputs from the yard to fields in slurry and manure and the opposite transfer of nutrients from fields to the dairy in harvested crops. Quantities of nutrients applied in slurry and farmyard manure were calculated as the product of the weight of material applied and the measured nutrient content. Nutrient removals from fields in silage crops were estimated separately for each field from measured silage yields and corresponding grass and clover contents, including a factor of 0.9 to allow for a 10% loss at harvest. Nutrient contents of herbage samples were not analysed routinely and typical contents were therefore used, based on the limited number of samples that had been analysed and from results of the plot experiments conducted in the present study.

The more-detailed estimates of N losses were determined using a systems synthesis approach adapted from that described by Jarvis (1993). Losses from fields were determined using the NCYCLE model to estimate losses from grassland (Scholefield *et al*. 1991); SUNDIAL to estimate losses from arable crops (Smith *et al*. 1996) and MANNER to estimate losses following application of manures (Chambers *et al.* 1999). The NCYCLE model describes N losses from grass fields that are either cut or grazed whereas silage fields at Ty Gwyn are grazed after 1, 2 or 3 cuts. Losses for these mixed-use fields were calculated as weighted means of the NCYCLE estimates for cutting and grazing managements, using a separate weighting factor for 1-, 2- and 3-cut silage fields to allow for the proportion of time under each use. Other adjustments included reduction of the volatilisation factor in the model to provide values of ammonia loss during grazing similar to those described by Jarvis (1993). NCYCLE was designed to describe N flows in grassland receiving N fertiliser: to allow for the input from N fixation, the fertiliser rate in the model was set equal to the fixation value estimated from the clover yield (as determined for the budget calculations). Separate runs of the model were made for each field and soil type. NFIXCYCLE is a development of the NCYCLE model, specifically designed to describe fluxes in grass/clover swards. This model was therefore used to provide an alternative estimate of N losses. Losses from cereal fields in the self-sufficient system were determined with the SUNDIAL model using the standard parameters for the particular crop. It was not possible to use this model to satisfactorily describe N fluxes in the one field where cereal had been undersown with grass/clover and losses were therefore estimated using NCYCLE, describing the field as a cut, first-year grass sward. Estimates of field losses included a small additional component to represent the loss associated with sheep grazing the fields in early winter.

The MANNER model was used to estimate ammonia volatilisation and leaching losses following slurry and manure applications, again with separate estimates for all fields and soil types. The model does not include a prediction of denitrification losses arising from the application of organic manures and the study is therefore likely to underestimate this form of loss. As the model was developed to describe losses from arable fields, it will overestimate leaching from manures applied to grassland in autumn. To allow for this, drainage in the model was set to zero for applications in August or September. MANNER assumes that volatilisation losses are similar whatever date manures are applied. Volatilisation for summer applications was therefore calculated separately using a relationship based on typical values of the percentage of total N available to crops from slurry applications to grassland in summer (MAFF 2000). Losses from manures were added to the other field losses determined by NCYCLE and SUNDIAL. Volatilisation of ammonia from animals during housing and from slurry and manure stores was estimated from standard emission factors (Misselbrook 2001)

3.2. Effects of slurry on N fixation

Nitrogen fixation studies were carried out in 1999 and 2000. Plots were established during winter/early spring 1998 in two grass/clover fields; Ty Gwyn 1 and Palu bach B. Soils in Ty Gwyn 1 were typical brown earths of the Rheidol series (clay loam to sandy clay loam) whereas those in Palu bach was mapped as a typical alluvial gley of the Conway series (silty clay loam). Ty Gwyn 1 had been sown with a perennial ryegrass/white clover (cv. Alice & Menna) mixture in August 1993. Palu bach had been sown in July 1994 with a mixture of perennial ryegrass, timothy, white clover (cv. Alice & Menna) and herbs. Both fields had been strip-seeded with a Westerwolds ryegrass/Italian ryegrass mixture in October 1998 and had received a dressing of slurry in February 1999. The two areas were fenced to exclude stock. Plots (2.5 x 2.5 m^2) were established as a randomised blocks design with four replicates. The same plots were used to study the effects of slurry applications on P and K supply and the main treatments were determined by this experiment (Section 3.3).

The effects of cattle slurry on N fixation were investigated by comparing fixation in untreated and slurry-treated plots using the ^{15}N isotope dilution method. Measurements were made following slurry applications to plots in Ty Gwyn 1 and Palu bach on two dates in 1999 and in Ty Gwyn 1 on two dates in 2000. For each date and series of plots, measurements were made on four replicate slurry-treated plots and on four equivalent untreated control plots that had received the same treatments up to that date. The second series of measurements each year used plots that had not received slurry on the first occasion. Applications were made within 7 days after cutting the plots and used cattle slurry obtained from the slurry stores at Ty Gwyn farm.

Table 1. Application rates and properties of slurry applied to plots for the N fixation measurements in 1999 and 2000.

Application date	Slurry rate (l/m^2)	Dry matter content (%)	Total N content (mg/l)
1999 (Ty Gwyn 1 & Palu bach)			
20 May	4	4.3	1.49
23/24 July	4	6.3	1.77
2000 (Ty Gwyn 1)			
17 May	6	2.7	1.30
24 July	6	3.7	1.42

The ^{15}N measurements were made on two microplots (50 x 50 cm^2) within each main plot. These microplots were labelled with ^{15}N solution (equivalent of 20 kg N/ha) shortly before the slurry was applied. Slurry was applied uniformly to the plots, including the microplots, using a watering can fitted with a splash-plate to simulate a broadcast application. Similar microplots in the untreated control plots were labelled in the same way except that after applying the label, additional water was applied, equivalent to the volume of slurry applied to the treated plots. Details of the slurry applications are given in Table 1. Microplots were harvested at 4 - 6 week intervals at the same time as the main plots, for determination of grass and clover yields, N contents and ^{15}N enrichments. The proportion of N in clover derived from the atmosphere by N_2 fixation (%Ndfa) was calculated from the ^{15}N atom % excess in the clover and grass (Wood & McNeill 1993). These %Ndfa values were then combined with total quantities of clover-N measured in the main plots to determine the quantity of N fixed per unit area.

3.3. Effects of slurry on the P and K contents of soils and herbage

Plots were treated with different quantities of cattle slurry during the first three years of the project to provide soils with a range of P and K contents that could be used in the final year to study the effects of P and K availability on herbage production. The experiment was conducted on the same plots as the N-fixation measurements described in the previous section. Replicate plots (2.5 x 2.5 m^2) were either treated with no slurry or with different frequencies of slurry applications between 1999 and 2001, as shown in Table 2. Plots receiving two applications per year were treated with slurry in May and September/August: those with only a single application received slurry in July. Applications were made within 7 days after sampling and cutting the plots. For each application date, sufficient slurry for all plots was collected from the main slurry stores at Ty Gwyn and stored in a bulk tank in the field. The tank was stirred continuously during the applications to ensure consistency between the plots. Dry matter contents of the slurries used on the different occasions varied between 2.1 and 6.3% with nutrient contents of 0.8 – 2.0 mg N/l, 0.15 – 0.32 mg P/l and 0.8 – 2.2 mg K/l. The T5 plots (Table 2) were used to provide an additional treatment in 2002. They were treated with mineral fertilisers to examine whether pasture performance benefited from levels of P and K greater than those that could be achieved with slurry applications alone. Permission was obtained from the Soil Association to use potassium sulphate on these plots and this was applied as a split dressing in March and May 2002, supplying 66 and 83 kg K/ha, respectively. Phosphorus was applied to the same plots as an organically-approved calcined phosphate rock, supplying 39 kg P/ha in April and a further 22 kg/ha in May 2002. All plots were limed in April 2001 at 3.5 and 4.5 t/ha in Ty Gwyn 1 and Palu bach, respectively.

Plots were cut and sampled at 4 - 6 week intervals during the growing season between spring 1999 and August 2002 for determination of herbage yields and offtakes of P and K. Main comparisons between effects of soil P and K levels on pasture performance were confined to the final year when none of the plots received slurry. All samples in 2002 were separated into grass, clover and weed components. Soils were sampled (to 10-cm depth), air-dried and sieved (< 2mm) for determination of P and K contents. A bulk sample was collected from each area at the start of the study and from individual plots in May 2001 and September 2002. These were analysed using standard Olsen and ammonium nitrate extractants for available-P and -K, respectively (MAFF 1986). To provide a comparison between methods, P was also determined in selected soils using the 16-hour Olsen extraction procedure as used for the field soils (Section 3.4). To provide a more immediate measure of availability, additional samples were collected from the T1, T4 and T5 treatments in September 2002 and the fresh soils extracted as soon as possible afterwards using 0.01 M calcium chloride solution (within 4 hours of collection) for determination of soluble P and K.

Table 2. Slurry applications to plots in Ty Gwyn 1 and Palu bach (1999-2002)

Treatment	Slurry applications (litre/m^2)				
	1999	2000	2001	2002	Total
T1	4 + 4	6 + 4	6 + 6	0	30
T2	4 + 4	6 + 4	0	0	18
T3	4	6	0	0	10
T4	0	0	0	0	0
Additional plots - Ty Gwyn 1 only					
T5	4 + 4	6	0	0 *	14
T6	4 + 4	0	0	0	8

** mineral fertiliser applied in 2002*

3.4. Changes in the P and K content of field soils

Bulk samples of soils from all fields in the SS and PC systems were collected in February of alternate years as part of project OF0146. Contents of available P and K in the air-dried soils were determined using standard methods (Olsen-P and ammonium nitrate-extractable K). These were compared with contents measured in previous contracts to determine whether there were any consistent changes in P and K contents under the organic management.

More-detailed measurements of soil P and K content were carried out as part of the present project. These were confined to the SS system fields as the reduced inputs to this system were more likely to result in a depletion of soil nutrients. Soil samples were collected from ten fixed points within each field in January/February of each year between 1999 and 2002. These sampling positions were allocated at random along fixed transects but avoided physical features such as gateways and water troughs. Measuring along the transects allowed the same sampling points to be located each year. At each sampling point, 16 individual soil cores (0-20 cm depth) were collected from within a 2-m radius of the marked position and bulked together before air-drying. The air-dry soils were passed through a 2-mm sieve and stored in plastic pots. All soils were analysed together in the final year of the study in order to minimise analytical variability.

The choice of the most suitable methods for determining available P and K in these soils was based on findings from MAFF Project OF0114 *Optimisation of P and K management within organic farming systems*. Available-P was determined using a 16-hour Olsen extraction (sodium bicarbonate at pH 8.5) followed by determination of inorganic + organic P in the extract. Compared with the standard Olsen procedure used for the routine determination of soil P indices (MAFF 1986), this involves a longer extraction period and in addition, includes soluble forms of organic P in the final determination. Potassium was extracted using the standard ammonium nitrate procedure, as used for determining K indices (MAFF 1986).

Possible trends in soil nutrient content over the 4-year measurement period were examined by analysing the P and K data for each field using the statistical procedure described by Roberts (1992). Linear regression was used to fit straight lines to the four data points for each sampling position and to estimate the slopes of the fitted lines. The mean slope for the field was then calculated as the average of the individual slopes for the ten sampling positions and a *t*-test applied to test whether the mean slope differed significantly from zero.

4. Results

4.1. Farm budgets

The physical features and performance of the SS and PC systems between 1999 and 2002 are summarised in Table 3. The performance of the two herds is described in detail in the report of Project OF0146 (Weller *et al*. 2002). The two systems occupied a broadly similar forage area, with an additional area devoted to cereals in the SS system. Differences between the two systems in cow numbers, concentrate inputs and milk production generally increased between the introduction of the SS system in Year 1 and the final year.

Budgets for N, P and K in the self-sufficient and purchased concentrate systems are shown in Table 4. These incorporate the inputs and outputs to the young stock associated with each of the main systems. The main effect of including the young stock with the dairy herds is to reduce the inputs and outputs of nutrients in livestock compared with those where young stock are treated separately. As all young stock were fed purchased concentrates, their inclusion also adds to the feed inputs to the two systems. In the final year, this was responsible for most of the nutrient input in feed to the SS system. Straw from the cereal fields in the SS system was used by the young stock. As approximately half these animals belong to the the PC system, this portion of straw is treated as an output from the SS system (Table 4). Such a transfer is unlikely to occur outside of the current research context as organic farmers would wish to avoid unnecessary exports of nutrients from the farm.

4.1.1. Whole-system budgets

The largest input of N was from biological fixation and in all three years was greater in the SS than in the PC system. This can be explained by a higher forage area in 1999/2000 and higher clover yields in the SS system in all three years. However, there was little reason to suppose that the higher clover yields were a direct result of the self-sufficient management. Estimates from the earlier studies, before dividing the herd, indicated that fixation in fields subsequently allocated to the SS system was higher than in fields allocated to the PC system in two out of the six years and lower in one. Purchased feed was also an important source of N except to the SS system in the final year. The values for feed inputs in Table 4 also include nutrients in bedding; however, this generally represents only a small proportion of the total. In the first year, cows in the SS system were fed purchased cereals until the home-grown grain became available in October. As a result, differences between feed inputs to the two systems were less than anticipated. Because of this and the higher fixation, the total input to the SS system in 1999/2000 was greater than to the PC system. Feed inputs to the SS system in the second year were also higher than expected. Although the cows were fed home-grown grain, there was a shortage of silage during the winter and a quantity of dried lucerne had to be purchased to overcome this shortfall. This had a high N content and represented a significant input of N. However, cows in the PC system were fed a higher rate of concentrates than in the previous year so that the input in feed was appreciably greater than to the SS system. Only in the final year were inputs to the SS system representative of the intended self-sufficient management. In this year, the input of N in feed and bedding was reduced to 12% of that to the PC system. Outputs from the two systems were mainly as milk and in livestock. The output from the SS system in straw was greatest in 1999/2000 because part of that year's production was dumped outside of the farm, adding to the export from this system. The total output of N was slightly greater than from the PC system in this first year and then progressively declined relative to the PC system, reflecting the reduction in cow numbers in the SS system.

Table 3. Physical features and performance of the self-sufficient (SS) and purchased concentrate (PC) systems at Ty Gwyn: April - March 1999-2002.

	Self-sufficient system			Purchased concentrate system		
	1999/00	2000/01	2001/02	1999/00	2000/01	2001/02
Forage area (ha)	33.2	31.9	33.4	28.0	34.0	34.0
Grain area (ha)	8.4	9.6	8.1	0	0	0
Total area (ha) *	41.6	41.6	41.6	28.0	34.0	34.0
Number of cows	50.5	55.8	48.8	49.4	56.8	59.7
Cows/ha	1.22	1.34	1.18	1.45	1.67	1.75
Concentrates (t/cow)	0.79	0.30	0.39	0.95	1.53	1.42
Milk sales (m^3)	255	256	196	255	320	297
Total milk (l/cow)	5230	4711	4680	5360	5775	5681
** Area including young stock (ha)*	*50.0*	*50.9*	*50.1*	*36.3*	*43.6*	*44.4*

Inputs of P and K were mainly dependent on purchased feed and bedding. There was therefore a marked difference between the inputs to the two systems in the final year but smaller differences in Years 1 and 2 when the SS system received significant inputs of feed. This was particularly marked for K in Year 2 because of the high K content of the lucerne that was purchased that year. As with N, differences between outputs from the two systems were most marked in the final year. In Years 1 and 2, the largest output was from the SS system, mainly because of the export of K in straw.

Differences between total inputs and outputs are summarised in Table 5. As in previous studies, there were appreciable surpluses of N in all years. In Year 1, the SS system produced the largest surplus but in the subsequent years the surplus for the PC system was the greater. However, when averaged over the whole field area, the surplus for the SS system was less than from the PC system in all three years. When expressed per unit of milk production, the surplus was slightly higher for the SS system in Years 1 and 2 and markedly higher in Year 3. These results indicate that the SS system is less polluting on an area basis but that the N losses associated with the production of a particular volume of milk are likely to be less if the PC system is adopted. However, this is misleading at the wider, landscape scale as these estimates do not include the additional N losses that will occur wherever this purchased grain is grown.

An alternative measure of efficiency is the amount of N recovered in agricultural products expressed as a percentage of the total N input (Table 5). The PC system appeared to be the more efficient management in Year 1 but there was little difference between the % efficiency of the two systems in the following years. The efficiency of both systems is higher if young stock are excluded from the calculations, averaging 32.0 and

29.3% for the SS and PC systems, respectively. The calculated efficiencies are sensitive to relatively small changes in N inputs or outputs. For example, if the milk that was dumped during 2001/02 because of high cell counts had been included in the output, the efficiencies of both systems (including young stock) would have been increased to 28.9%.

Table 4. Nutrient budgets for the self-sufficient (SS) and purchased concentrate (PC) systems at Ty Gwyn (including young stock).

	Nitrogen (kg/year)		Phosphorus (kg/year)		Potassium (kg/year)	
	SS	PC	SS	PC	SS	PC
1999/2000						
N fixation	4918	4097	-	-	-	-
Feed & bedding	1053	1778	171	273	281	612
Livestock	83	81	25	25	6	6
Rain	267	194	2	1	95	69
Total input	6321	6150	198	299	382	687
Milk	1363	1390	242	243	382	383
Livestock	234	363	71	112	18	28
Straw	225	0	19	0	288	0
Total output	1821	1753	332	355	688	411
2000/01						
N fixation	4881	3652	-	-	-	-
Feed & bedding	1118	3610	128	559	679	993
Livestock	0	0	0	0	0	0
Rain	268	229	2	1	118	101
Total input	6267	7491	130	560	796	1094
Milk	1326	1685	243	304	384	480
Livestock	275	189	85	58	21	15
Straw	95	0	8	0	122	0
Total output	1695	1875	336	362	527	495
2001/02						
N fixation	4474	3781	-	-	-	-
Feed & bedding	333	2691	46	460	155	758
Livestock	0	14	0	4	0	1
Rain	300	266	2	2	93	82
Total input	5107	6752	48	466	247	841
Milk	1032	1563	186	282	294	445
Livestock	291	190	91	58	23	15
Straw	41	0	3	0	53	0
Total output	1365	1753	281	340	370	460

Although reduction of feed inputs was expected to reduce N surpluses, it will also increase the risk of P and K deficits. Even in the PC system, there was a small P deficit in Year 1. This was largely because of the relatively low rate at which concentrates were fed that year. With higher feeding rates in Years 2 and 3, P balances were positive. In contrast, balances for the SS system were negative in all years. The accumulated deficit over the three years was equivalent to –12 kg P/ha when averaged over the whole system area, compared with a surplus of +5 kg/ha for the PC system.

Potassium balances for the PC system were positive in all years and equivalent to 8 to 14 kg K/ha/year when averaged over the whole system area. To maintain K levels, these surpluses must be sufficient to balance the loss of K by leaching. Annual leaching losses measured in two grazing fields at Ty Gwyn were about 20 and 60 kg K/ha. However, the latter value and associated estimates of nitrate leaching are higher than expected and may indicate that these results are unreliable. The reduced inputs to the SS system resulted in negative balances in Years 1 and 3 but the high K content of the lucerne purchased in Year 2 was sufficient to produce a positive balance in that year. The cumulative balance for the SS system over the three years was equivalent to –3 kg K/ha/year, compared with +31 kg/ha for the PC system. Potassium budgets are affected more than those for N or P by whether young stock are included in the budget or treated separately. When included in the budget, the feed purchased for the young stock represents a significant input of K to the main systems. If young stock are excluded from the budgets, the accumulated deficit for the SS system is increased to -19 kg K/ha and the PC surplus reduced to 20 kg/ha. Budgets for the SS system are also affected by the export of straw to young stock (equivalent to 53 – 172 kg K/year).

Table 5. Difference between the nutrient input and output for the self-sufficient (SS) and purchased concentrate (PC) systems (a) including young stock; expressed as different measures of efficiency and (b) excluding young stock.

	Nitrogen		Phosphorus		Potassium	
	SS	PC	SS	PC	SS	PC
(a) Including young stock in SS and PC systems						
Input - output (kg/year)						
1999/00	4500	4397	-133	-56	-305	276
2000/01	4572	5616	-207	198	269	599
2001/02	3742	4999	-232	126	-122	381
Input – output (kg/ha)						
1999/00	90	121	-3	-2	-6	8
2000/01	90	129	-4	4	5	14
2001/02	75	113	-5	3	-2	9
Input – output (g/litre milk sold)						
1999/00	17.7	17.2	-0.5	-0.2	-1.2	1.1
2000/01	17.9	17.5	-0.8	0.6	1.1	1.9
2001/02	19.1	16.8	-1.2	0.4	-0.6	1.3
N efficiency (%)						
1999/00	25.3	28.5				
2000/01	25.5	25.0				
2001/02	25.9	26.0				
(b) Input – output (kg/ha): excluding young stock						
1999/00	95	135	-3	-2	-13	2
2000/01	86	138	-6	5	0	10
2001/02	34	52	-6	4	-6	8

4.1.2. Estimates of N losses

Results of the more detailed estimates of N losses for the two systems in 2001/02 (including young stock) are shown in Table 6. Field losses, as determined by the NCYCLE and SUNDIAL models, are broadly similar for both systems when expressed on an area basis. Leaching is the main form of field loss. However, there are additional large losses from the spreading of cattle slurry and farmyard manure, particularly through ammonia volatilisation. These are typical of the high losses of ammonia that occur where slurry is broadcast on the ground surface rather than injected or ploughed in. There was a higher loss from the PC system because a greater proportion of the slurry was spread in summer when volatilisation losses are particularly high. The MANNER estimates indicate that 19 - 23% of the total N supplied in slurry was lost as ammonia. There were additional large losses of ammonia from housed cattle during the winter. This accounts for about two thirds of the housing loss in Table 6. A further 14 – 17% was due to volatilisation from slurry and manure stores. The greater housing loss from the PC system reflects the higher number of cows than in the SS system. When averaged over the full field area, the total losses are equivalent to 55 and 60 kg N/ha for the SS and PC systems, respectively. Ammonia volatilisation accounted for 52 and 61% of these totals. This is a higher proportion of the total than has been found for similar estimates for conventional farms (Jarvis 1993; Cuttle 2002). Estimates of non-manure losses from the grass/clover fields at Ty Gwyn were low compared with those for the conventional farms and ammonia losses from spreading manures and during housing therefore assume a greater importance.

The models also provide estimates of changes in the total content of soil-N during the year. When the MANNER predictions of residual N from manure and slurry were added, the total amount of N in the soil increased by the equivalent of 35 and 41 kg N/ha for the SS and PC systems, respectively. The increase in soil N accounted for about 40% of the budget surplus. This demonstrates the extent to which losses may be overestimated if the surplus is taken as a measure of the N loss while neglecting that some of this N may be incorporated into soil organic matter. Ideally, the total N loss plus change in soil N should be equal to the N budget surplus. In the present study, the estimated loss and increase in soil N were equivalent to 115 and 89% of the surplus for the SS and PC systems, respectively (Table 6). Taken separately, the level of agreement is within the range observed in other studies; however, the more marked difference between the two systems suggests that the much-simplified farm model is not sufficiently responsive to differences in their management. For example, it takes no account of differences in the N content of the cows' diet, which might be expected to result in a higher N loss from housed animals in the PC system. An important consideration is that the models and ammonia emission factors were developed for conventional farms and may be less applicable to organic systems. On the basis of the difference in cow numbers, the volume of slurry from the PC herd in 2001/02 and its total nutrient content would be expected to be appreciably greater than from the SS system (Section 4.1.3). The actual slurry volumes and N contents measured in this year were less than from the SS system. The MANNER predictions of losses from spreading of manures, therefore either underestimate the loss from the PC system or overestimate the loss from the SS system. This is sufficient to explain much of the difference between the percentage of the budget accounted for in the two systems.

Table 6. Estimates of individual forms of N loss from the self-sufficient (SS) and purchased concentrate (PC) systems in 2001/02, including young stock: field losses are as determined by the NCYCLE model.

	SS		PC	
	kg N	(kg N/ha)	kg N	(kg N/ha)
Field losses				
- leaching	574	(12)	473	(11)
- volatilisation	219	(5)	225	(5)
- denitrification	365	(8)	244	(6)
Losses during spreading of manures				
- leaching	281	(6)	278	(6)
- volatilisation	589	(12)	704	(16)
Volatilisation during housing *	556	(12)	674	(15)
Total loss	2608	(55)	2623	(60)
Increase in soil N	1680	(35)	1803	(41)
Loss + increase in soil N as % of budget surplus	115		89	

* *including losses during milking in summer*

The NFIXCYCLE model was developed specifically to describe grass/clover systems, though not specifically for organic farms. Estimates of ammonia volatilisation using this model were 35 - 56% greater than those obtained with NCYCLE but leaching and denitrification losses were 40 - 50% smaller. It is possible that the model may underestimate these forms of loss by not taking adequate account of the high leaching and denitrification losses that occur from urine patches. The model's default values for the quantity of N supplied by N fixation were 56 and 92% greater than the estimated inputs to the SS and PC systems used for the 'fertiliser' input in NCYCLE. As these are mass-balance models, the higher input and lower losses resulted in a much higher predicted increase in soil-N than with NCYCLE and a less-close agreement between these estimates and the budget N surplus. Using NFIXCYCLE, the total loss plus change in soil N was equivalent to 129 and 114% of the surplus for the SS and PC systems, respectively.

4.1.3. Internal flows of P and K

Estimates of internal flows of P and K were confined to a comparison of the quantities of nutrients removed in silage and cereal crops in 2001/02 and the quantities returned to fields in organic manures. Estimates for the SS and PC systems, excluding young stock, are shown in Table 7. These do not include transfers of nutrients to and from fields during grazing. The input of P from manures appeared to approximately balance the offtake in crops whereas the K input was sufficient to replace only 89 and 77% of the crop offtake in the SS and PC systems, respectively. This conflicts with the results of the whole-farm budgets which indicate positive balances for K in the PC system. The slurry applied in 2001/02 represented only 85-86% of the total slurry production that year. The potential returns of nutrients are therefore about 15% greater than those in Table 7. This additional slurry would be sufficient to balance the apparent K deficit for the SS system but not in the PC system. Offtakes in silage crops were calculated using average nutrient contents and may therefore be subject to error. However, there also appears to be a discrepancy in the slurry estimates. There were 27% more cows in the PC than in SS system in 2001/02 which, together with the greater proportion of concentrates in their diet, would be expected to result in a greater quantity of nutrients in the slurry. The values in Table 7 indicate the opposite. Similarly, after allowing for the input of rain to the slurry stores, the volume of slurry from the PC system would be expected to be at least 20% greater than from the SS system. However, measurements of the slurry in stores and of the volumes applied indicate that 2470 m^3 of slurry was produced in the SS system in 2001/02, compared with 2340 m^3 in the PC system.

Table 7. Comparison of the quantities of nutrients removed from fields in silage crops and returned as slurry for the self-sufficient (SS) and purchased concentrate (PC) systems in 2001/02: excluding young stock fields.

	SS system			PC system		
	N (kg)	P (kg)	K (kg)	N (kg)	P (kg)	K (kg)
Offtake						
- in silage crops	3850	332	3061	4177	396	3536
- in arable crops	755	145	494	0	0	0
Total offtake	4605	477	3555	4177	396	3536
Slurry input	2792	448	3153	2356	391	2719

4.2. Effects of slurry on N fixation

Grass from slurry-treated plots was less enriched with ^{15}N than grass from plots that had not received slurry; typically containing 0.9 – 1.3 atom % excess compared with 1.2 – 1.6 atom % excess at the first harvest after the slurry application. This reflected the greater dilution of the ^{15}N label within the larger mineral-N pool of the slurry-treated soils. Enrichments declined rapidly with successive harvests but small differences between slurry-treated and control plots at the later harvests indicated that slurry continued to influence soil mineral-N contents up to the second and sometimes third harvest after the application. As clover plants obtained most of their N from the atmosphere rather than from the labelled mineral-N pool in the soil, enrichments were much lower than in grass; typically 0.1 – 0.3 atom % excess at the first harvest. Differences between slurry-treated and control plots in 1999 were generally non-significant but there were statistically significant differences between treatments in the following year. The percentages of clover-N derived from the atmosphere by fixation (%Ndfa), as calculated from these ^{15}N enrichments, are shown in Figure 1. In 1999, the slurry applications caused small but non-significant reductions in %Ndfa. Slurry was applied at a higher rate in 2000 and had a greater effect which persisted for several harvests after the application. This is in accord with the more persistent effect of slurry on soil-N, as indicated by the ^{15}N enrichments of the corresponding grass samples.

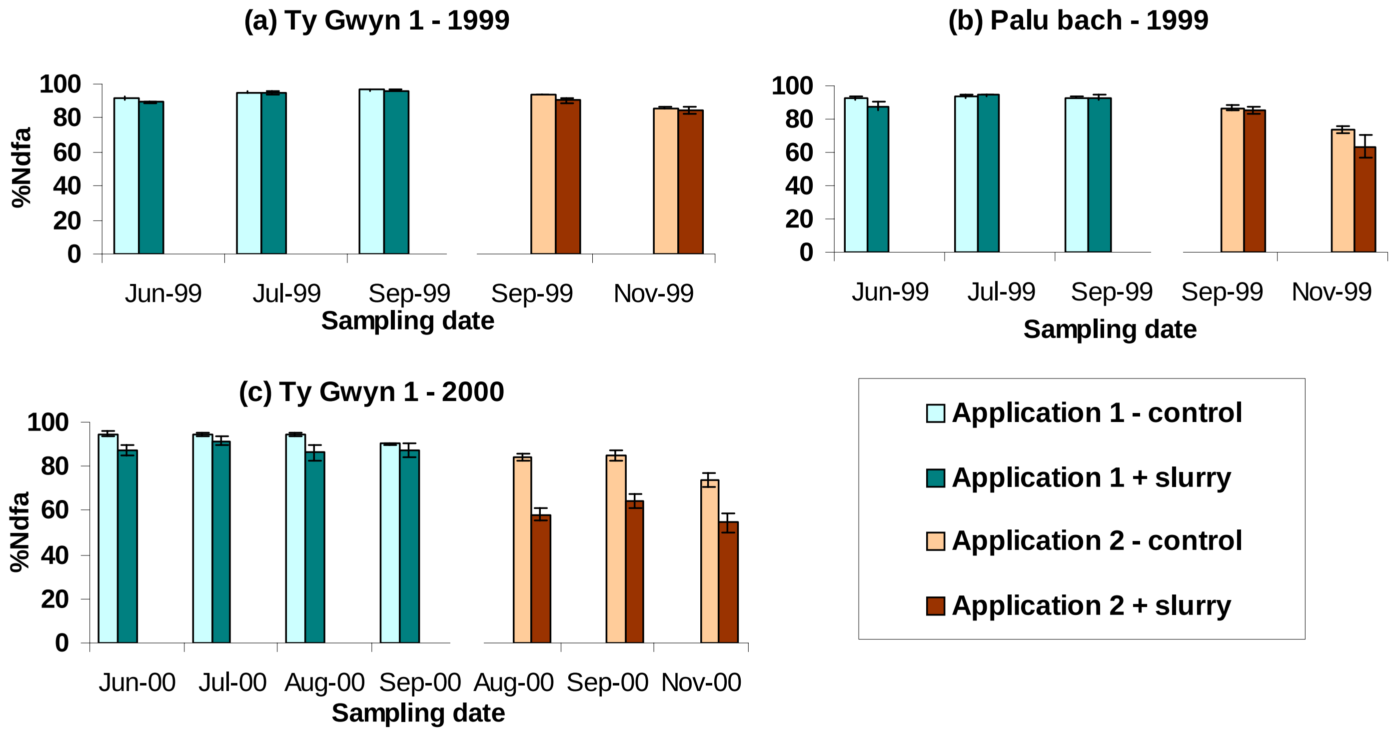
For practical purposes, the quantity of N fixed per unit area is more important than knowledge of the proportion of N obtained by fixation. This is calculated as the product of the total clover yield, N content and %Ndfa. Estimates of the quantities of N fixed per unit area are shown in Table 8 for harvests following the first application in 2000. Slurry treatments in 1999 had little effect on either clover yield or %Ndfa and therefore little effect on the quantities of N fixed compared with plots that did not receive slurry. Applications in the following year had a greater effect and significantly reduced %Ndfa compared with the control plots, particularly following the second application. However, these reductions were accompanied by corresponding increases in clover N yield which compensated for the reduction in the proportion of fixed N. As a result, the absolute quantity of N fixed was similar to that in the untreated control plots. This is contrary to what has been found in other studies where N has been applied to mixed swards. Applications of urine or N fertiliser generally reduced N fixation by reducing %Ndfa and the proportion of clover in the sward (e.g. Vinther & Aaes 1996; Laidlaw & Withers 1998). The apparent maintenance of a high level of N fixation in the present study is highly dependent on the increased clover yield in slurry-treated plots. However, the patchy distribution of clover resulted in high standard errors and none of these yield increases was statistically significant. Total herbage yields were significantly increased by the first and second slurry applications in 2000 but such increases have usually been accompanied by a reduction in clover yield in other studies. Baars (2000), however, found that slurry increased clover yields in conditions where soil K was limiting. In the present study, clover plants in slurry-treated plots had larger leaves and longer petioles but there was little additional evidence to help confirm these yield increases.

Table 8. Estimates of N fixation in untreated and slurry-treated plots at individual harvests from Ty Gwyn 1 after the slurry application on 17 May 2000: mean (standard error).

Harvest date	Clover yield (g/m^2)	Clover N (g/m^2)	Fixed N (g/m^2)	kg N fixed/t clover
Untreated plots				
22 June	20.3 *(7.35)*	0.82 *(0.285)*	0.77 *(0.270)*	38.9 *(0.66)*
21 July	25.8 *(5.85)*	0.98 *(0.223)*	0.93 *(0.210)*	36.1 *(0.18)*
21 August	32.1 *(4.59)*	1.54 *(0.227)*	1.45 *(0.214)*	45.1 *(0.38)*
25 September	27.6 *(2.32)*	1.33 *(0.103)*	1.20 *(0.093)*	43.7 *(1.03)*
Slurry-treated plots				
22 June	24.5 *(2.65)*	0.97 *(0.107)*	0.85 *(0.093)*	34.6 *(0.11)*
21 July	26.2 *(7.14)*	0.93 *(0.256)*	0.85 *(0.234)*	32.6 *(0.24)*
21 August	44.5 *(11.14)*	1.87 *(0.459)*	1.61 *(0.396)*	36.4 *(0.99)*
25 September	36.1 *(7.86)*	1.83 *(0.420)*	1.59 *(0.367)*	43.9 *(0.89)*

Estimates of N fixation for the N budgets in Section 4.1 were calculated from measured clover yields multiplied by the kg N fixed per tonne of clover dry matter. A value of 54 kg N/t has been used for the present budgets (van der Werff *et al*. 1994). In comparison, measurements in the present study on plots that had not received slurry indicate values of 32 - 41 and 36 - 45 kg N/t for clover at Ty Gwyn in 1999 and 2000. Similar fixation measurements in the previous project at Ty Gwyn (OF0113) indicated a value of 30 - 37 kg N fixed/t for white clover swards. Values for slurry-treated plots in the present study were 27 - 39 kg N/t in 1999 and 24 - 35 kg/t in 2000.

Figure 1. Percentage of the N in clover derived from fixation (%Ndfa) at individual harvests from slurry-treated and untreated plots in (a) Ty Gwyn 1 and (b) Palu bach in 1999 and (c) Ty Gwyn 1 in 2000.



4.3. Effects of slurry on the P and K contents of soils and herbage

4.3.1. P and K contents of soils

Total quantities of P and K added to the plots in slurry and removed in harvested herbage up to the final soil sampling are summarised in Table 9. For all treatments, offtakes of P and K during the period were greater than the quantities supplied in slurry. No slurry was applied in the final year but balances were still negative if restricted to the 1999-2001 period. Total offtakes were greatest for those plots that received the most slurry (T1). The greater offtake from slurry-treated plots was due both to greater yields and to increased contents of P and K in herbage. These negative balances suggest that soil P and K contents would have declined over the course of the study, even in those treatments receiving regular applications of slurry. However, the largest discrepancy between inputs and offtakes was with the zero slurry (T4) treatments. Balances for these plots (1999 -2002) were equivalent to -42 kg K and -8 kg P/ha for the plots in Ty Gwyn 1 and -59 kg K and -13 kg P/ha in Palu bach.

Table 9. Total P and K added to plots in slurry and removed in herbage (1999 - 2002).

Treatment	Added in slurry (kg/ha)		Removed in herbage (kg/ha) Mean (se)	
	P	K	P	K
Palu bach				
T1	6.8	51.5	14.7 (0.40)	89.1 (1.84)
T2	3.7	28.7	13.4 (0.26)	73.8 (2.15)
T3	2.7	16.1	12.6 (0.45)	60.0 (0.97)
T4	0	0	12.9 (0.23)	59.1 (5.25)
Ty Gwyn 1				
T1	6.8	52.4	11.3 (0.27)	92.1 (8.51)
T2	3.7	28.0	9.5 (0.33)	54.8 (2.30)
T3	2.8	16.4	9.6 (0.21)	59.4 (6.17)
T4	0	0	7.9 (0.42)	41.9 (4.22)
T5	3.1	20.9	10.0 (0.32)	67.5 (2.64)
T6	1.6	10.4	8.9 (0.39)	57.2 (1.74)

Soil P and K contents in 1999 and in 2002 (as determined by the standard Olsen and ammonium nitrate extraction methods) are summarised in Table 10. The most marked difference is between the contents measured at the start and end of the trial. Phosphorus contents in both sets of plots and K contents in the Palu plots were significantly greater at the start of the study. There were similar changes in the K content of soils in Ty Gwyn 1 but differences were not statistically significant because of the large difference between replicate samples in 1999. Concentrations in 2002 were equivalent to one soil index point lower than in 1999, except that K indices were two index points lower in those plots in Ty Gwyn 1 that had not received frequent applications of slurry. This rate of decline may have been exaggerated by abnormally high contents in 1999 due to the slurry applied in February of that year. However, there had been considerable growth on the plots prior to the initial soil sampling and this is likely to have removed much of the added P and K. Phosphorus and K contents of the soils collected in May 2001 were intermediate between those for 1999 and 2002.

Contrary to expectations, the different slurry treatments resulted in only small differences between contents of Olsen-P in soils at the end of the experiment (Table 10). There were no significant differences between the P contents of the different treatments in Palu bach: all treatment means were equivalent to P index 1. Nor were there significant differences between the contents of soil K in the Palu bach plots: these were equivalent to K index 0. There was more evidence of a limited effect of the slurry applications to the Ty Gwyn 1 plots. The P content of the high slurry treatment (T1) was significantly higher than the zero slurry (T4) treatment ($P < 0.01$), although both were equivalent to index 0. The mineral P fertiliser was claimed to be appreciably more soluble than rock phosphate; however, the application to the T5 plots in the final year had no significant effect on the extractable P content of soils sampled in September. In contrast, K contents from the T1 (high slurry) and T5 (potassium sulphate) treatments were both significantly higher than in the other plots ($P < 0.001$). Contents were equivalent to K index 1, compared with index 0 for the plots receiving less frequent or zero inputs of slurry.

Table 10. Soil P and K contents at the start of the experiment in 1999 and for individual treatments in September 2002 (1999 values are means of two bulk samples taken at random from the area immediately surrounding the plots).

	Olsen-P		Extractable-K	
	(mg/kg) Mean (se)	MAFF Index	(mg/kg) Mean (se)	MAFF Index
Palu bach				
1999 (bulk)	26.2 (1.04)	2	135 (0.2)	1
2002 P1	16.3 (0.55)	1	79 (3.2)	0
P2	15.3 (0.72)	1	78 (2.3)	0
P3	15.2 (0.62)	1	72 (3.3)	0
P4	15.6 (0.63)	1	74 (2.5)	0
Ty Gwyn 1				
1999 (bulk)	16.6 (0.02)	1	194 (57.3)	2-
2002 T1	13.5 (0.36)	0	120 (6.2)	1
T2	12.5 (0.48)	0	85 (3.0)	0
T3	12.0 (0.65)	0	88 (5.1)	0
T4	11.1 (0.54)	0	86 (2.8)	0
T5	12.2 (0.49)	0	128 (10.9)	1
T6	11.3 (0.48)	0	85 (3.1)	0

4.3.2. Comparison of soil extraction methods

In addition to the standard Olsen and ammonium nitrate procedures, selected soils were also analysed by alternative methods to allow comparisons with the transect soils and to examine whether extraction of fresh soils with a weak extractant such as calcium chloride solution provided a more sensitive measure of P and K availability. The high slurry (T1), mineral fertiliser (T5) and zero slurry (T4) treatments were selected to provide the greatest contrast. There were large differences in the quantities of P and K extracted by the different methods; however, relative values were similar to those with the standard extractants and the alternative methods appear to offer no advantages or indicate different relationships between the treatments. When the selected soils from both sets of plots were considered together, there was a close correlation between the quantity of P extracted by the standard Olsen and 16-hour Olsen procedures ($P < 0.001$). The quantities of P extracted by calcium chloride solution were not significantly correlated with the much higher quantities of Olsen P but there was a close correlation between quantities of K extracted by this reagent and by the standard K method ($P < 0.001$).

4.3.3. Effects of soil P and K on herbage properties

Total yields of herbage in 2002, up to the final harvest in August, are shown in Table 11, together with separated yields of grass and clover. As the final slurry applications were in August/September of the previous year, yields were assumed to be independent of the direct effects of slurry-N.

The plots in Palu bach contained too little clover to provide useful information about effects of slurry or P and K on clover growth. In spite of the low clover content, total herbage yields in 1999 -2001 were at least as great as those in Ty Gwyn 1. Yields of grass and of total herbage from the high slurry treatment (T1) in 2002 were not significantly different from the zero slurry plots (T4). There was a greater proportion of clover in the Ty Gwyn 1 plots. In this case, clover and grass yields in 2002 were both significantly greater from the high slurry (T1) than from the zero slurry (T4) treatment. There was also a much higher percentage of clover in the slurry-treated sward (30%) than in the controls (5%). Yields from the plots treated with mineral fertiliser (T5) were also greater than from the zero slurry plots. These higher yields correspond to those plots with significantly higher contents of soil P and K. There were significant positive correlations between yields and soil K but not with soil P. The mineral fertiliser treatment also indicated that the yield benefit was primarily due to K as the P fertiliser appeared not to increase levels of available P in the soil. The different slurry treatments had less effect on soil P and K contents in the Palu bach plots and yields of neither grass, clover or weeds were significantly correlated with either soil P or K. The only exception was a significant correlation between grass yield and soil K at harvest 2 ($P < 0.05$).

Table 11. Grass and clover yields from plots in Palu bach and Ty Gwyn 1 as the total of all harvests in 2002: treatment means (and standard errors).

	Dry matter yield (t/ha)					
	Grass		Clover		Total *	
	Mean	(se)	Mean	(se)	Mean	(se)
Palu bach						
T1	5.7	(0.26)	0.26	(0.148)	6.6	(0.25)
T2	5.6	(0.32)	0.03	(0.011)	6.3	(0.28)
T3	4.8	(0.33)	0.02	(0.015)	5.6	(0.43)
T4	5.1	(0.37)	0.14	(0.110)	6.3	(0.14)
Ty Gwyn 1						
T1	5.7	(0.10)	2.47	(0.33)	8.3	(0.35)
T2	4.9	(0.14)	0.27	(0.02)	5.7	(0.07)
T3	5.2	(0.25)	1.12	(0.36)	6.5	(0.44)
T4	4.4	(0.29)	0.28	(0.18)	5.5	(0.21)
T5	5.5	(0.10)	1.64	(0.46)	7.3	(0.45)
T6	5.0	(0.32)	0.59	(0.29)	6.1	(0.12)

** including weeds*

Table 12. Phosphorus and potassium content of grass and clover components of herbage from plots in Palu bach and Ty Gwyn 1: mean of harvests 1 – 3 in 2002.

	P content (mg/g)				K content (mg/g)			
	Grass		Clover		Grass		Clover	
	Mean	(se)	Mean	(se)	Mean	(se)	Mean	(se)
Palu bach								
T1	3.3	(0.07)	2.7	(0.16)	20.8	(0.19)	14.3	(0.19)
T2	3.3	(0.07)	2.5	(0.11)	17.6	(0.12)	12.1	(0.18)
T3	3.1	(0.08)	2.4	(0.02)	15.8	(0.51)	10.4	(0.09)
T4	3.3	(0.09)	2.9	(0.05)	16.8	(1.28)	13.2	(1.09)
Ty Gwyn 1								
T1	3.7	(0.12)	3.1	(0.14)	21.9	(1.54)	17.2	(1.63)
T2	3.5	(0.10)	3.1	(0.09)	14.7	(0.67)	11.5	(0.83)
T3	3.4	(0.08)	3.0	(0.10)	16.5	(0.97)	13.3	(0.33)
T4	3.5	(0.06)	2.9	(0.02)	15.0	(0.72)	11.0	(1.52)
T5	3.5	(0.09)	2.6	(0.11)	24.2	(0.42)	20.0	(0.57)
T6	3.4	(0.10)	3.0	(0.16)	17.5	(0.84)	13.2	(1.83)

Phosphorus contents in herbage were little affected by the slurry treatments (Table 12). In neither set of plots were there significant differences between P contents of either grass, clover or weeds from the zero slurry and high slurry treatments (T4 and T1) or the plots in Ty Gwyn 1 receiving mineral P fertiliser (T5). Potassium contents in herbage from the Palu bach plots tended to be highest for the high slurry treatment (T1), with more consistent differences for grass and weeds than for clover. Lowest concentrations of K in clover were found in samples from the intermediate slurry treatments, T3 and T2, rather than from the zero slurry treatment (T4). Treatment effects in Ty Gwyn 1 also tended to be more pronounced for grass and weeds than for clover, though all components showed higher contents for the high slurry (T1) than the zero slurry treatment (T4) at some harvests. At the second and third harvests in 2002, concentrations of K in herbage from the mineral fertiliser-treated plots (T5) were higher than those from the high slurry treatment.

In Palu bach, there were significant positive correlations between soil and plant P for grass at harvest 2 and for clover at harvest 3 ($P < 0.05$). The only significant correlations between plant and soil K contents were for grass at harvest 3 ($P < 0.05$) and for weeds at harvests 2 and 3 ($P < 0.01$). There were few significant correlations between soil and plant P in Ty Gwyn 1 but there were significant positive correlations between soil K and K in grass ($P < 0.001$), clover ($P < 0.01$) and weeds ($P < 0.01$) at all harvests. For both sets of plots, concentrations of P in clover were similar to or slightly less than the threshold of 3 – 4 mg P/g considered to be the minimum adequate concentration for clover grown in mixtures (Dunlop & Hart 1987), though above the threshold of 1 – 2.5 mg/g cited for clover monocultures. Potassium contents were generally below the critical concentration of 18 – 23 mg K/g for clover in mixtures (Dunlop & Hart 1987). Again, critical concentrations are lower (8 – 15 mg/g) for clover grown as a monoculture.

4.4. Changes in the P and K contents of field soils

Changes in soil P and K contents will be determined by the balance between nutrient offtakes and the quantities returned in slurry. Offtakes will increase with increasing number of silage cuts. Four fields (5,19, 25 and 32) were predominantly used for grazing and would be expected to have the lowest offtakes. Total quantities of slurry applied to the different fields over the four years ranged from 48 to 526 t/ha. In spite of the expected lower offtakes, most grazing fields received similar quantities of slurry to the silage fields.

The mean contents of extractable P and K in each field in the SS system are shown in Table 13. These are means of the values for the 10 sampling positions within each field, averaged over all four years. Although the ranges of contents were broadly similar, P and K contents were not significantly correlated, suggesting that different factors influenced their availability. There was an indication that levels of soil-K were influenced by whether fields were cut or grazed as the mean K content for grazing fields was significantly greater than that for silage fields ($P < 0.05$). This agrees with the observation above that cutting and grazing fields received similar rates of slurry in spite of the lower offtake from the latter. However, P contents of soils from cutting and grazing fields were not significantly different. Soil in Field 1 had the lowest P content, in spite of receiving considerably more slurry than all other fields.

Table 13. Mean concentrations of extractable P and K in soils from each field in the self-sufficient system at Ty Gwyn: mean values 1999-2002.

Field number	Phosphorus (mg P/kg OD soil)		Potassium (mg K/kg OD soil)	
	Mean	Coeff. of variation (%)	Mean	Coeff. of variation (%)
1	95	5	213	17
5	126	21	239	34
7	118	21	100	17
9	118	38	169	16
13	176	23	90	14
17	163	28	184	49
18	122	16	96	28
19	185	8	204	29
25	159	10	256	28
30	197	21	227	16
32	96	17	193	24
33	135	24	110	29
All fields	141	31	173	43

Although contents of soil P and K varied between years, few fields exhibited consistent trends. Fluctuations between years were generally greater for K than for P. For most fields, particularly for P, contents for the individual sampling positions within the field tended to fluctuate in a similar manner. However, it was not generally possible to relate these changes to any particular aspect of management. There were no consistent differences between the patterns of change in grazed or silage fields, between soil types or between soils with relatively high or low P and K contents. Similarly, there was no evidence that changes were due to cultivation: fluctuations were as great in soils from permanent pasture as in those which included periods of arable cropping.

The results of the statistical analysis of these fluctuations are summarised in Table 14. This shows the mean slope fitted to the P and K contents measured for each field between 1999 and 2002. Positive values indicate an increase in soil nutrient content over the four years whereas a negative slope indicates a decline. A number of the slopes for both P and K are statistically significant. These range from +1.9 to -9.8 mg/kg per year for P and from +8.3 to -24.8 mg/kg per year for K. Most of the significant slopes indicate declining P and K contents but there are positive trends for P in Field 19 and for K in Field 18. The apparent increase in P content in Field 19 is only significant at the 5% level but does not seem unreasonable: this was a predominantly grazed field with relatively low offtakes but received regular inputs of slurry. The slope for soil K was also positive but this was not statistically significant. The apparent increase in the K content of Field 18 is less readily explained as several silage cuts were taken from this field each year. The most marked declines in nutrient content were shown by Fields 30 and 33. Both were both recently converted fields, brought into the organic farm in 1998, and it is possible that the more pronounced changes in soil P and K contents may reflect their adjustment to a lower nutrient regime. Both received relatively little slurry over the 4-year period.

Table 14. Mean slope of the regression line fitted to the Year 1, 2, 3 and 4 data points for soil P and K contents in each field (mg/kg per year); asterisks indicate statistically significant trends.

Field number	Soil-P		Soil-K	
1	-0.02		16.8	
5	2.12		-1.4	
7	-2.37	*	-7.7	*
9	-2.41	*	-4.6	
13	-0.82		-5.0	**
17	-1.82		-24.8	*
18	-1.27		8.3	*
19	1.94	*	13.8	
25	-1.15		11.5	
30	-4.98	***	-22.0	***
32	-0.58		-21.8	*
33	-9.80	***	-21.9	**
All fields	-1.76		-4.9	

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

In practice, the change in nutrient status over the farm as a whole may be more important than the changes in individual fields. The overall status will reflect the farm's nutrient balance whereas the content of individual fields is determined more by management decisions and how the available slurry is allocated within the farm. The overall trend in soil P and K contents in the self-sufficient system at Ty Gwyn was examined by testing the significance of the average slope calculated over all sampling positions in all fields. This overall mean slope was not significantly different from zero. The associated standard errors indicate that the actual change would be less than ±2.8 and ±14.6 mg/kg per year for P and K, respectively ($P < 0.05$).

An additional benefit of the transect sampling is that it provides an indication of the variability within fields. This indicated that maximum and minimum K indices for individual positions generally ranged from one index point above and one below the field average. However, there was less variability in fields of low K status, so that in fields of average index 1, indices for individual positions generally did not fall below 1.

5. General Discussion

Comparisons between the nutrient budgets for the two systems are limited because of the time taken to fully establish the SS system. Only the budget for the final year of the study is representative of the intended management and differences between this and the PC system in earlier years are less than anticipated. Nevertheless, the results demonstrate that introduction of the SS system converted the previous small surpluses of P and K to small deficits of these nutrients. Changing to a more self-sufficient system did not have the expected effect of reducing N surpluses. It was expected that growing cereals to reduce the input of N in feed and to reduce the proportion of legume crops on the farm would reduce the farm N surplus compared with the PC system. Although the surplus was less than that for the PC system when expressed on an area basis, the SS system produced less milk and the surplus was greater per unit of milk production. There was little difference in the %N efficiency of the two systems (Table 5). At the start of the study, targets were set for the levels of efficiency expected to be achieved by the two systems: an average of 27% for the SS system and > 22% for the PC system. Although the target for the PC system was exceeded in all three years, the SS system only achieved an average of 27% if the straw that was transferred to the young stock was included with milk and livestock as an output in the calculations. The failure to achieve the expected level of efficiency could be explained by the low cereal yields and reduced milk output. The N efficiency of the PC system was relatively high compared with previous studies and this also contributed to the smaller than anticipated difference between the two systems.

The main component of the N budgets is the input of N by biological fixation. The ^{15}N studies at Ty Gwyn provided a measure of the actual quantities of N fixed in grass/clover fields to compare with the estimates used in the budgets. In particular, they provided measured values of the amount of N fixed per tonne of clover, as used to calculate N fixation. These values were typically 25% lower than the factor used to derive the present budgets. However, the present estimates do not include fixed N in roots and in stubble below cutting height, which may add a further 40% to the total fixation (Ledgard 2001). If this additional N is included, the factor is similar to the one currently being used.

The results of the studies to examine the effect of slurry on N fixation (Section 4.2) were inconclusive because of the high standard errors associated with the measured clover yields. The results suggest that though the proportion of N derived from fixation is reduced by slurry, this is balanced by a greater clover yield so that the total quantity fixed is similar to that in untreated plots. This is contrary to most studies where N is applied to mixed swards: the addition of N generally has an adverse effect on the growth of clover. Baars (2000), however, found that slurry increased clover yields in conditions where soil K was limiting. The measurements described in Section 4.3 indicate that K was also limiting in the plots at Ty Gwyn. Measurements on the same plots as those used for the N fixation studies demonstrated a positive response of clover yields to K fertiliser and a greater proportion of clover in plots previously treated with slurry. This provides support for the proposed interaction between N fixation and clover yield. If correct, these findings have two main implications for N budgets at Ty Gwyn and other organic farms. It was hypothesised that fixation would be reduced in slurry-treated fields, thus reducing the overall N surplus for the farm. If the absolute quantity of N fixed is unaffected by slurry, the benefits of the self-regulation of N fixation in response to increased soil N supply will be less than anticipated. Secondly, the findings add to the uncertainties about the current predictions of N surpluses. Fixation is calculated as the product of clover yield and a constant factor for kg N fixed/t clover. Our results suggest that where slurry increases the clover yield, a lower value should be used for this constant. In circumstances where slurry does not increase the yield, the change is necessary. The uncertainty arises because the routine measurements on the farm provide no information about the extent to which measured yields were increased by any particular slurry treatment and therefore what is the most appropriate constant to use. The contrasting responses to slurry in the two years of the present study show that such responses are unpredictable and may be determined by the level of soil K in the particular field. In these circumstances, using a constant factor to calculate fixation on fields where clover yields have been increased by slurry would overestimate the input of N. If our interpretation is incorrect and in reality there is no compensatory yield increase, it would still necessary to reduce the constant to allow for the reduced %Ndfa in slurry-treated swards. The plot experiments demonstrated that the reduction in %Ndfa is also unpredictable.

The plot and field measurements provided two sets of data to compare with the P and K deficits determined by the nutrient budgets for the SS system. The accumulated budget deficits between 1999 and 2002 (excluding young stock) were -15 and -19 kg/ha for P and K, respectively. In comparison, the statistical analysis of the results of the transect sampling of soils in the SS system indicated that the method would be able to detect changes greater than about 3 mg P and 15 mg K/kg per year over the system as a whole (less than this for some individual fields). These are equivalent to changes of about 20 kg P and 100 kg K/ha over three years (to a depth of 20 cm). Even if effects of soil buffering are ignored, the expected changes are not sufficient to have been detected by the sampling and analysis procedure that was employed, though if leaching losses are added the totals are likely to be close to these limits of detection. Changes in the P content of soils from the experimental plots cannot be compared because different extraction procedures were used; however, K contents are directly comparable. The change in soil K content in the plots between 1999 and 2002 was equivalent to a reduction of about 140 - 220 kg K/ha. Such a change would have been detectable if it had occurred in the field soils but was considerably larger than the reduction indicated by the nutrient budgets for this system. It was also larger than the deficit calculated for the plots themselves (equivalent to about -40 kg K and -7 kg P/ha over three years) but this again ignores the additional depletion through leaching.

It is difficult to reconcile the observed changes in soil P and K in the plots with changes in the main fields. There was little evidence of an overall decline of P and K contents in the field soils but a marked decline between 1999 and 2002 in the plots, even in those receiving slurry. The input of slurry to the high slurry treatment was similar to the average application to silage fields, although the offtake from the plots is likely to have been greater than from all but the 3-cut fields.

A further objective of the plot studies was to determine whether soil P and K contents were limiting herbage production and clover performance within the farm as a whole. The different slurry applications over three years did not produce the range of soil P and K contents that was expected. Final contents in the plots were less than in all but the lowest P and K status fields. Contents of P in soils from the plots were in the range 77 - 95 mg/kg compared with 95 - 197 mg/kg for the transect soils (16-h Olsen extracts). Similarly, plot soils contained 74 - 120 mg K/kg compared with 90 - 256 mg/kg for the field soils. However, the results from the plots in Ty Gwyn 1 indicated that at these low levels, total herbage yield and clover yield both responded positively to the K supplied in slurry or as mineral fertiliser. This suggests that K deficiency may be restricting clover growth in those fields at Ty Gwyn which have similar low levels of soil K. In these circumstances, clover survival may be dependent on regular applications of slurry to provide a readily available source of K throughout the growing season. The variability in nutrient content demonstrated by the transect sampling suggests that fields where the average K content appears to be adequate may also include areas where responses would occur.

6. Future Work

The extent to which nutrient deficiencies may be limiting clover growth at Ty Gwyn is an important issue, potentially affecting the overall performance of the farm and the more general advice given to visiting farmers. The plot experiment indicated a risk of K deficiency in those fields with the lowest soil K contents but, because of the limited range of soil K in the plots, we are unable to identify the threshold content at which effects occur. It is important that we examine responses to added K fertiliser in a range of fields at Ty Gwyn representing a wider range of soil nutrient contents.

The study identified a possible interaction between N fixation and soil K, via the effect of slurry on clover yield. This may be a particular characteristic of organic farms as grass/clover swards on conventional farms (and experimental plots) are more likely to receive regular dressings of K fertiliser. This interaction needs to be understood to make the most effective use of slurry to maximise N fixation and maintain contents of other soil nutrients. The N fixation experiment described above should be repeated on a more uniform sward and extended to identify the factors responsible for the unpredictable responses observed in the current study.

The budget calculations in the present study confirmed the importance of internal flows in determining the efficiency of nutrient use within the farm and also identified apparent discrepancies, particularly for K. Valuable information would be obtained from a more thorough analysis of the existing, extensive datasets collected during this and previous studies. This would develop a more time-based description of the systems to take full account of the carry-over of nutrients and materials from one season to another, which can have a marked effect on balances but has been inadequately addressed in previous studies.

7. References

Baars T. (2000) Effective use of manure and fertiliser in organically grown grass/clover swards. In K. Søegaard *et al*. (eds) *Grassland Science in Europe Vol. 5*. Proc. 18th General Meeting of the European Grassland Federation, Aalborg, Denmark, May 2000: 524-526.

Chambers B.J., Lord E.I., Nicholson F.A. & Smith K.A. (1999) Predicting nitrogen availability and losses following application of organic manure to arable land: MANNER. *Soil Use & Management*, **15**, 137-143.

Cuttle S.P. (2002) *Desk Studies which Use Models to Predict Losses from Farming Systems*. Project NT1842. Final Report to DEFRA .

Dunlop J. & Hart A.L. (1987) Mineral nutrition. In M.J. Baker & W.M. Williams (eds) *White Clover.* Wallingford, CAB International: 153-181.

Jarvis S. C. (1993) Nitrogen cycling and losses from dairy farms. *Soil Use & Management*, **9**, 99-105.

Laidlaw A.S. & Withers J.A. (1998) Changes in contribution of white clover to canopy structure in perennial ryegrass/white clover swards in response to N fertiliser. *Grass & Forage Science*, **53**, 287-291.

Ledgard S.F. (2001) Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant & Soil*, **228**, 43-59.

MAFF (1986) *The Analysis of Agricultural Materials*. Reference Book 427. London, Her Majesty's Stationery Office.

MAFF (2000) *Fertiliser Recommendations for Agricultural and Horticultural Crops (RB209)*. 7th edition. London, The Stationery Office.

Misselbrook T. (2001) *Updating the Ammonia Emissions Inventory for the UK for 1999*. Final Report to MAFF.

Roberts E.A. (1992) *Sequential Data in Biological Experiments*. London, Chapman & Hall.

Scholefield D., Lockyer D.R., Whitehead D.C. & Tyson K.C. (1991) *Plant & Soil*, **132**, 165-177.

Smith J.U., Bradbury N.J. & Addiscott T.M. (1996) SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land. *Agronomy Journal* **88**, 38-43.

Vinther F.P & Aaes O. (1996) Effects of urine on biological nitrogen fixation in a grass-clover pasture. *Transactions 9th Nitrogen Workshop*, Braunschweig, September 1996, 173-176.

Weller R.F., Jones E.L.. & Bowling P.J. (2002) *Comparison of the physical and financial performance of organic dairy farming systems 1998-2002. Part 1: Scientific Report*. Project OF0146. Final Report to DEFRA.

Wood M. & McNeill A.M. (1993) $^{15}N_2$ studies on nitrogen fixation by legumes and actinorhizals: theory and practice. *Plant & Soil*, **155/156**, 329-332.