Alternative Dairy Farming Systems to Reduce Pollution Impact of Nutrients - Phosphorus

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CONTENTS

EXECUTIVE SUMMARY

Inputs of phosphorus (P) above requirements for production on dairy farms leads to surplus P with increased risk of P transfer in land run-off to surface waters causing eutrophication. The impact of reducing surplus P inputs in purchased feeds and fertilizers on milk and forage production was investigated in three farm system comparisons on chalkland soils in southern England over a 3 year period. In accordance with current commercial practice, no attempt was made to regulate P inputs in system 1, which accumulated an average annual surplus of 23 kg ha^{-1}. In systems 2 and 3, total dietary P intake was reduced by 10 and 20%, respectively compared to system 1, and fertilizer P was largely ommitted altogether on system 3. These progressive reductions in purchased feed and/or fertilizer inputs into systems 2 and 3 decreased surplus P to 17 and 3 kg ha^{-1}, respectively without any apparent detrimental effects on milk production or herbage dry matter yields.

Milk P and protein concentrations were consistently and significantly increased on systems 2 and 3 which included maize in the diet. The composition of the diet and the stage of lactation were considered to have had more influence on milk P output than differences in dietary P intake within the range monitored. The reductions in dietary P intake in system 3 were estimated to have reduced faecal P output by 26% and improved the efficiency of utilisation of feed P by 8% compared to system 1. Surplus P was greatest in continuous maize fields receiving both dairy manure and starter P fertilizer.

Withholding P fertilizer on system 3 did not reduce Pofftake in cut herbage on soils of moderate P fertility. System field comparisons and replicated field experiments showed that starter P fertilizer did not benefit yields of continuous forage maize crops receiving manure on the shallow calcareous soils which dominated the site and increased the rate of soil P accumulation. However, starter P was beneficial to growth in one year on a non-calcareous soil, even after 4 years of continuous manure application.

Measured annual inputs of P from the atmosphere were 0.5 kg ha^{-1} and broadly equivalent to losses of P in land run-off, which were predominantly in particulate form. The results indicate there is scope to reduce surplus P on commercial dairy farms without sacrificing production targets and more precise identification of the need for P supplementation is required. Purchased feeds represent the largest P input on intensive dairy farms, yet these are rarely quantified on commercial holdings. The longer-term effects of reduced P inputs on herd health and fertility and forage production needs to be investigated.

1. INTRODUCTION

The cycling of phosphorus (P) within modern agricultural systems is of concern with respect to the eutrophication of surface waters. Inputs of P in fertilisers and feeds, their redistribution through crop and livestock production cycles and part accumulation in topsoil, increases the opportunity for the transfer of P in surface and sub-surface run-off from agricultural land to water (Foy and Withers, 1995; Sharpley and Rekolainen, 1997). The greatest risk of P loss occurs in catchments with erodible soils, where soil P has accumulated to unnecessarily high levels and where rain follows soon after fertilizer or manure applications to the soil surface. In particular, the increased potential for leaching of soluble P from soils which have become gradually saturated with surplus P associated with intensive livestock farming has become widely recognised as a serious, long-term eutrophication hazard (Breeuwsma *et al* 1995; Graetz and Nair, 1995).

A large proportion of the P in livestock diets is excreted and only relatively small amounts (20-30%) are removed in milk and meat products (Aarts *et al.* 1992). Consequently, livestock systems utilise P inputs inefficiently compared to crop systems and the manure generated during winter housing often requires disposal on a limited land area. As livestock systems have become more intensive with the need to maintain farm incomes there has been a trend for both a reduction in the land area available for recycling of excreted P and a greater reliance on purchased concentrates to maintain production (Lanyon, 1994). Both these factors have resulted in greater volumes of manure P loadings to the soil, a larger range of P surpluses on individual farms with increased risk of dissolved and particulate P transport in land runoff.

In the UK, dairy farms make a significant contribution to the national P surplus. In a desk study, Haygarth *et al.* (1998) estimated a P surplus of 26 kg ha^{-1} for a model intensive British dairy farm and similar values (8-34 kg ha^{-1}) have been obtained by others (Bacon *et al.*, 1990; Aarts *et al.*, 1992; Brouwer *et al.*, 1995). There is little information in the UK on the cycling of P within commercial dairy farms or of the impact of reducing surplus P inputs in feeds and/or fertilizers on production and profitability at the farm system scale. Initial system modelling studies in the Netherlands by Aarts *et al.* (1992) indicated that reductions in the P surplus on dairy farms could be achieved by better targeting of animal requirements and improved farm and manure management. Dietary manipulation experiments have also indicated there is scope to reduce faecal P output without affecting herd performance (Brodison *et al.*, 1989; Morse *et al.*, 1992; Brintrup *et al.*, 1993). Techniques for reducing P surplus therefore need to be examined within the context of whole systems of milk production which attempt to minimise losses whilst remaining commercially feasible. This project examined at the farm scale the feasability of reducing the P surplus in dairy farming systems and the resulting impact on farm production and profitability.

2. OBJECTIVES

To measure the inputs and outputs and fate of phosphorus in three different dairy farming systems designed to minimise nitrogen (N) loss.

To examine the sustainability of three milk production systems with differing phosphorus flows.

To provide data to enable models of phosphorus flow within profitable milk production systems to be devised.

3. MATERIALS AND METHODS

3.1 System Design

Three self-contained dairy farming systems were established at ADAS Bridgets experimental farm in 1994 to examine the agronomic, environmental and economic effects of implementing farm management practices aimed at reducing nitrogen (N) and P losses to the environment. As part of this study, the inputs, outputs and transfers of P were continuously monitored over a three year period. The site is located near Winchester in Southern England on predominantly free draining, shallow, calcareous silty clay loam soils developed over Upper Chalk and with a long term mean annual rainfall and excess winter rainfall of 787 mm and 260 mm, respectively. Soils typically have high concentrations of total P (*c.* 1000 mg kg^{-1}), low concentrations of water-soluble P (*c.* 2 mg kg-1) and adequate levels of Olsen-extractable P (*c.* 20 mg l^{-1} or ADAS Index 2, MAFF, 1994) for crop production. Grass grows well in spring and autumn at this site but is usually limited during summer by soil moisture deficits.

Each of the three systems was managed according to objectives which were primarily designed to reduce N loss (Appendices 1 and 2). System 1 adopted current commercial practice with the aim of maximising profitability whilst complying with UK Codes of Good Agricultural Practice (MAFF 1991). System 2 adopted techniques which were considered to reduce nutrient loss but without sacrificing production or profitability, whilst the objective of system 3 was to maximise use of recycled nutrients and achieve a major reduction in nutrient loss. Details of land areas and system management are summarised in Table 1.

Each system initially had 40 summer calving Holstein cows of similar age and performance and with a target milk production of 6000 litres per cow at 4.07% butterfat. In the second and third years this was reduced to 36 cows because the production of home-grown forage was less than expected. Cows failing to conceive or which became ill were culled and replaced according to the selection criteria. Land of similar soil type, soil fertility status, sward age and management history was allocated to each system as far as was practically possible. Systems 1 and 2 were each maintained on 19 ha whilst system 3 occupied a land area of 23 ha to allow for the anticipated lower grass production under the lower annual N inputs on this system (Table 1). These dedicated land areas provided all grazing and silage requirements and received the manure generated by each system. Replacement rates in the second and third lactation were comparatively high at 40% and 50%, respectively due to poor conception rates, especially following the hot dry summer weather in 1995 when cows suffered heat stress. Average calving date was the first week in July; the cows were usually fully housed during November and turned out to grass during March or April in each year, depending on day temperatures (Appendix 3).

Maize was substituted for a 2-year italian ryegrass (IRG) ley in systems 2 and 3 to provide a high energy feed which promotes good feed intake and nicely balances the higher protein levels in grass silage. The maize was cropped on the same areas continuously but undersown with IRG during June to help reduce winter leaching losses of N following harvest. In the first year, IRG did not establish in one field and winter cereals was drilled as a substitute cover crop. The IRG (and winter cereal) was dessicated the following February prior to manure application in March/April of each year. Manure storage facilities were increased to 3 and 5 months on systems 2 and 3 to allow for restrictions in manure applications during

September to November inclusive (system 2) and during September to January inclusive (system 3). Areas cut for silage varied for each system according to the availability of grass for grazing. Grazing swards were maintained at a height of 7 cm to maximise DM intake.

Table 1. *Land areas and management of each system*

	System 1	System 2	System 3
Objective	Commercial practice, high output	Reduced loss, high output	Minimal loss, reduced intensity
No. of cows[a]	36	36	36
Cropping areas			
Permanent grass	13	13	17
Italian ryegrass	6	-	-
Maize	-	6	6
Total area	19	19	23
Management			
Slurry storage	1 month	3 months	5 months
Slurry application			
Grass	Broadcast	Broadcast (diluted)	Injected (open slit)
Maize	-	Rapid incorporation	Rapid incorporation
Timing	No restriction	After 1 December	After 1 February
Fertilizer			
Nitrogen - grass	Economic optimum[b]	Tactical reduction[c]	Planned reduction[d]
- maize	-	Total 180 kg ha^{-1} [e]	Total 150 kg ha^{-1} [e]
Phosphorus	Recommended[b]	Recommended[b]	Nil
Feed	Least cost ration	ADAS MP system[f]	ADAS MP system[f]
Nitrogen	18% CP minimum	No surplus ERDP[f]	No surplus ERDP[f]
Phosphorus	High P	Moderate P	Low P
(target values)	(90 g cow^{-1} day^{-1})	(84 g cow^{-1} day^{-1})	(72 g cow^{-1} day^{-1})

[a] 40 cows in the first year [b] MAFF (1994) [c] depending on the results of soil mineral N analysis [d] 120 kg ha^{-1} for cutting and grazing [e] available soil N + available manure N + fertilizer N [f] AFRC (1993)

All cows were fed grass silage (system 1) or a 50:50 mixture of grass and maize silage (systems 2 and 3) to apatite plus parlour or pre-mix concentrate to match the Metabolisable Energy (ME) requirements for production (AFRC, 1993). System 1 received only parlour concentrate (12.9 MJ ME/kg DM, 18% crude protein) fed in the parlour twice a day in two equal feeds. Systems 2 and 3 diets were formulated to maximise the utilisation of effective rumen degradable protein (ERDP) using the UK Metabolisable Protein (MP) system plus a correction factor of +15% (AFRC, 1993). Diets for systems 2 and 3 were fed from a mixer wagon outside the parlour as a pre-mix containing rolled wheat, soda-treated wheat, soya bean meal, rapeseed meal, molassed sugar beet nuts, salts, vitamins and/or minerals. Quantities of supplementary feed (brewers grains and caustic-treated straw) were purchased when necessary to supplement grass growth in summer (usually from July). Total amounts of each feed type eaten in each system averaged over the experimental period are given in Appendix 4.

In system 1 no attempt was made to regulate P other than to follow current fertiliser recommendations (MAFF 1994). Fertiliser inputs therefore varied from field to field depending on soil P status, the anticipated requirements of the crop and the amount of P applied in slurry over the previous winter. In system 2, P inputs in feed were regulated to a level below that in system 1 but no deliberate attempt was made to reduce fertiliser P inputs. In system 3, feed P inputs were maintained at a low level whilst fertiliser P inputs were largely omitted altogether. Dietary P intakes in system 2 and 3 were regulated close to levels recommended by AFRC (1991) and ARC (1980), respectively by the use of dicalcium phosphate. Average annual P intakes in cut forage and purchased feedstuffs in groups 2 and 3 were 90% and 80%, respectively of those in group 1. All fertiliser P inputs were applied in water-soluble form either as NPK compounds (21:8:11, 24:4:11, 0:20:30, 12:62:0 and 18:46:0) or as straight triplesuperphosphate (20% P).

3.2 Monitoring of P inputs and outputs

Soil nutrient status at the start of the study was assessed by grid sampling at 50 m intervals to 30 cm depth. This is deeper than is advised for assessing P requirements in grassland but was necessary to assess soil mineral N status. Additional soil samples to 0.7.5 cm (PRG fields) and 15 cm (IRG, maize fields) taken in December 1994 showed satisfactory soil P fertility on all system fields (Appendix 5). Amounts of P from the atmosphere were monitored continuously from September 1994. Rainfall collected in a receiving dish of 152 mm diameter was measured at approximately fortnightly intervals and a sub-sample analysed for molybdate-reactive P (MRP) and total P. Annual P loads were estimated cumulatively as the product of rainfall during the monitoring period and the total P concentration measured in the rainwater.

Each batch of buffer and compound feedstuff delivered to the farm was sub-sampled for P content. Following tests on the uniformity of the feedstuffs, a single bulk sample was taken from each batch. The P content of the pre-mix formulation used in systems 2 and 3 was taken as the sum of the individual components. The content of P in each batch of grass and/or maize silage were similarly measured. Amounts of silage, buffer feed and concentrate given to the cows and the amounts that were not eaten (refusals) were accurately weighed each day for each system. Milk yields from each individual cow were recorded daily and milk samples from each cow at both evening and morning milkings were taken fortnightly for determination of fat, protein and lactose content. In the first year, milk P concentration was determined on an evening and morning sample from each cow on two occasions (November and January) during the lactation. Subsequently, P concentrations were determined on fortnightly bulked samples from each system and the cumulative milk P output (kg) calculated. Amounts of P consumed at grazing were not measured directly but were calculated from the difference in ME between consumption and the requirements for maintenance and milk production with allowances for changes in liveweight (AFRC, 1993). Liveweight was monitored on three occasions during the year; turn-out, at calving and at housing (Appendix 6). The cows were bedded on shavings with a P content of 0.4 g kg^{-1}. Output of P in sold calves was estimated assuming a P content of body liveweight of 7.4 g kg^{-1}.

Each individual load of slurry from each system's slurry store was weighed and sub-sampled for dry matter (DM) content just prior to spreading in order to match target N application rates. Similarly, each load of silage transported from the field was weighed and a sub-sample taken for determination of DM content prior to ensiling. Additional sub-samples of slurry and silage were bulked for determination of total N and P content. It was not possible to capture all the slurry during the housing period and estimated deficits (based on N) were made-up from alternative sources at ADAS Bridgets whenever these were available. The N:P ratios in these alternative sources varied widely. Internal transfers of slurry P were therefore estimated as the difference between total dietary P intake and output in milk and meat, and validated by a detailed P balance study on small groups of individual cows (Metcalf *et al.*, 1996). Annual P transfers within each system were calculated from April to March and included one growing season and one lactation. Individual field balance sheets took into account the carryover of slurry P during housing from one year to another.

3.3 Maize agronomy

Different combinations of starter N and/or P fertilizer for forage maize were tested in system 2 and 3 areas each year. In 1994, starter P fertilizer (as a 0:9:25 NPK compound) was incorporated into the seedbed and starter N fertilizer (ammonium nitrate) placed 5 cm to the side and 5 cm below the seed at drilling. In 1995 and 1997, starter N and P fertilizer were sub-surface placed in combination as diammonium phosphate (18% N, 20% P) and mono-ammonium phosphate (12% N, 23% P), respectively. In 1996, starter P as triplesuperphosphate (20% P) was sub-surface placed without starter N. Top-dressings of N applied at emergence to make up the targeted N rates for each system varied each year depending on the results of slurry N analysis. Average annual inputs of NPK in the slurry applied to the maize fields (Ohio and Pennsylvania) over the experimental period 1994-1997 were 164:37:131 kg ha^{-1} for system 2 and 127:26:90 kg ha^{-1} for system 3. Amounts of available N (NH_4-N) in the slurry averaged 71 and 53 kg ha^{-1} $annum^{-1}$ for each system, respectively. A summary of the N and P applied to each maize area is given in Table 2.

All areas were sown at the same time to the same variety in rows 75 cm apart at a seed rate of 38 kg ha^{-1} and received similar applications of pesticides each year. Sowing dates were 20 April, 27 April, 28 April and 14 April in each year, respectively. The variety was Eviva in 1994, Melody in 1995 and 1996 and Hussar in 1997. Crops were harvested at 30-35% DM content; each load transported from the field was weighed on a weighbridge to the nearest 10 kg and a sub-sample taken for determination of DM, N and P content (MAFF, 1986). Harvest dates were 5 October, 18 September, 21 October and 22 September in each year, respectively.

The response of forage maize to placed starter P fertilizers was also tested in replicated experiments in system 3 fields in 1994 (Ohio East), 1996 (Ohio East) and in 1997 (Pennsylvania North). These field areas had previously received slurry P but no inorganic P fertilizer (Table 2) and were adequately supplied with major nutrients. In 1994 (experiment

1), increasing rates of fertilizer P (30, 60, 90 and 120 kg ha^{-1}) were compared to a control plot receiving no P fertilizer. The fertilizer was broadcast as superphosphate onto the soil surface and incorporated just prior to drilling. Gypsum was applied to the experimental area to balance inputs of sulphur in the superphosphate. In 1996 (experiment 2), P application rates of nil, 17 or 32 kg P ha^{-1} were compared in the absence of any starter N fertilizer. As in system 2 fields in that year, the P was placed below the soil surface with the seed at drilling as triplesuperphosphate. In 1997 (experiment 3), two rates of starter N (N_1, N_2) and two rates of starter P (P_1, P_2) fertilizer, applied either alone as ammonium nitrate (N_1P_0, N_2P_0) or triplesuperphosphate (N_0P_1, N_0P_2), or in combination as mono-ammonium phosphate (N_1P_1, N_2P_2), were compared with a control receiving no fertilizer P or N (N_0P_0). The amounts of N supplied by N_1 and N_2 were 10 and 22-28 kg ha^{-1}, respectively and the amounts of P supplied by P_1 and P_2 were 18-20 and 40-41 kg ha^{-1}, respectively. There was no N_1P_2 or N_2P_1 treatment. All treatments were placed 5 cm to the side and 5 cm below the seed at drilling except for the N_1P_0 treatment, which was top-dressed directly after drilling because the seed drill could not be calibrated low enough to supply the amount required.

Experiments 1 and 2 were located on shallow (< 30 cm) calcareous soils and experiment 3 was located on a deeper (60 cm), non-calcareous soil. The experimental areas received the same inputs of N and P in cow slurry before the treatments were applied (Table 2), and were managed in exactly the same manner, as the rest of the system fields. The treatments were arranged in a randomised block design incorporating either 3 (experiment 3) or 4 (experiments 1 and 2) replicates with plots 10 m in length and 6 rows (4.5 m) wide. At harvest, two 5 m double rows were cut from the middle 4 rows of each plot and weighed. Six randomly selected, whole plants from each harvested area were finely chopped with a portable shredder and a sub-sample taken for determination of DM, N and P content (MAFF, 1986). Each experiment was monitored for signs of early crop growth response. In experiment 3, additional measurements of growth stage, plant height (stem base to bottom of the youngest leaf) and crop DM, N and P content were taken at approximately monthly intervals starting in mid-June when treatment effects on crop vigour were observed. At the mid-August sampling, the number of cobs on each of the six plants were also counted prior to shredding.

Table 2. *Inputs (kg ha^{-1}) of N and P in manure, starter fertilizer and in total[a] to forage maize in each system in each year.*

Year	N						P					
	System 2			System 3			System 2			System 3		
	Manure	Starter	Total	Manure	Starter	Total	Manure	Starter	Total	Manure	Starter	Total
1994	194	36	248	137	37	219	42	9	51	27	0	27
1995	196	20	228	146	32	176	48	20	68	27	0	27
1996	125	0	174	126	0	146	29	14	43	30	0	30
1997	140	10	159	100	14	114	29	19	48	18	0	18
Mean	164	16	202	127	21	164	37	16	53	26	0	26

[a] The total includes inputs in manures, starter inorganic fertilizer and top-dressed (N) fertilizer

3.4 Phosphorus losses

Teflon-coated porous suction cups were installed at a depth of 60 cm in the soil in selected fields to measure P losses by leaching over the winter drainage season. This technique is considered reliable for estimating nutrients in soil porewater (Zimmermann *et al.*, 1978; Webster *et al.*, 1993). A depth of 60 cm was chosen because of the marked spatial variability in the degree of fissuring in the chalk below this depth depending on chalk lithology, structure and hardness. One teflon-coated cup was placed at either end of a line of ceramic suction cups installed to measure N leaching losses. Each cup was spaced 2 m apart and at an angle of 30° to the vertical to avoid soil disturbance directly above the cup. A total of 90 teflon-coated cups were installed and perolating water was extracted following storm events. Leaching losses were calculated from the amounts of winter drainage estimated by a crop water use model (Bailey and Spackman, 1996) and the MRP concentration in the extracted leachate.

Losses of P in surface run-off and erosion were measured using run-off traps installed in selected fields cropped to either grass, maize stubble and/or winter cereal cover crop. Each trap collected the run-off from a 4 m^2 catchment area hydrologically isolated by corregated fencing. Two or three traps were installed on each field area monitored. After each storm event (defined as when >15 mm fell in 24 hours), the amount of run-off was measured and a sub-sample taken for determination of MRP, TDP and TP. Losses of each form of P were then calculated for each storm event. Additional spot samples of run-off from around the farm buildings were also taken during the 1996/97 winter and P forms determined (Appendix 7).

3.5 Analytical

Total P in crop, feedstuff, bedding and slurry samples was determined by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) following either aqua-regia digestion (mineral components) or Kjeldahl digestion (slurry). Liquid slurry samples (<100 g kg^{-1} DM) were analysed fresh but solid manure samples (>100 g kg^{-1} DM) were air-dried prior to analysis. MRP (<0.45μm) was determined colorimetrically according to the method of Murphy and Riley (1962). TDP (<0.45μm) was determined either directly by ICP-AES (turbid samples) or colorimetrically after persulphate digestion for non-turbid samples. TP (unfiltered) was determined by ICP-AES after aqua regia digestion (turbid samples) or colorimetrically after persulphate digestion for non-turbid samples. Particulate P (PP) was calculated as the difference between TDP and TP. All samples were stored at 4°C until analysed. MRP, TDP and TP determinations were carried out within 24-72 hours of collection.

3.6 Statistical analysis

Replication of each system was not possible because of the large land area and housing facilites needed. However, the effects of system and year on milk and first cut cut herbage data were assessed by analysis of variance (ANOVA) using daily milk yields summed for each half of each month and individual field DM yields, respectively as replicates in the ANOVA. Milk P concentrations measured, and milk P output calculated, for each half month during the second and third year were similarly analysed. Data for 1994/95 were not included because milk P concentrations were measured on only two occasions in that year. There were no significant ($P < 0.05$) interactions between system and year and their effects are therefore reported separately. For the replicated maize experiments, statistical differences in treatment mean values of measured parameters were examined by analysis of variance, which included a specific single degree of freedom comparison of the mean of the fertilizer treatments vs the control.

4. RESULTS

4.1 Weather and growing conditions

Average daily air temperatures and precipitation during the growing season in relation to the long-term average are shown in Figure 1. Daily air temperatures were generally close to or above normal, except for a cold February/March in 1996 which delayed grass growth. Summer months in 1995 were particularly hot and caused heat stress in the cows across all three systems. Rainfall patterns varied more widely. The first two grazing months (April/May 1994) were very wet and swards had to be periodically rested to avoid poaching damage. In contrast, very little rain fell after second cut silage in 1994 and buffer feeding with grass and/or maize silage had to commence from July onwards. In 1995, soil conditions were very dry throughout the main growing period; grass growth was generally poor and maize was harvested early and the crop matured early. However, a warm and wet September produced a flush of grass growth which was cut in November 1995. In 1996, June was extremely dry and areas allocated to second cut silage were reduced to provide adequate grazing but crop growth was boosted again by above-average rain in July.

4.2 Milk Production

4.2.1 Variation in milk phosphorus between individual cows

Sampling of individual cows in November 1994 (140-145 days in milk) and in January 1995 (203-208 days in milk) during the first lactation indicated a near two-fold variation in milk P concentration between individual cows in each system. The values ranged from 719-1190 mg l^{-1} in November and from 633-1100 mg l^{-1} in January and were normally distributed (Fig. 2). Concentrations of P were consistently lower in milk from cows sampled in January compared to the previous November, but there was no significant ($P < 0.05$) difference in concentrations between evening and morning milkings (Fig. 2).

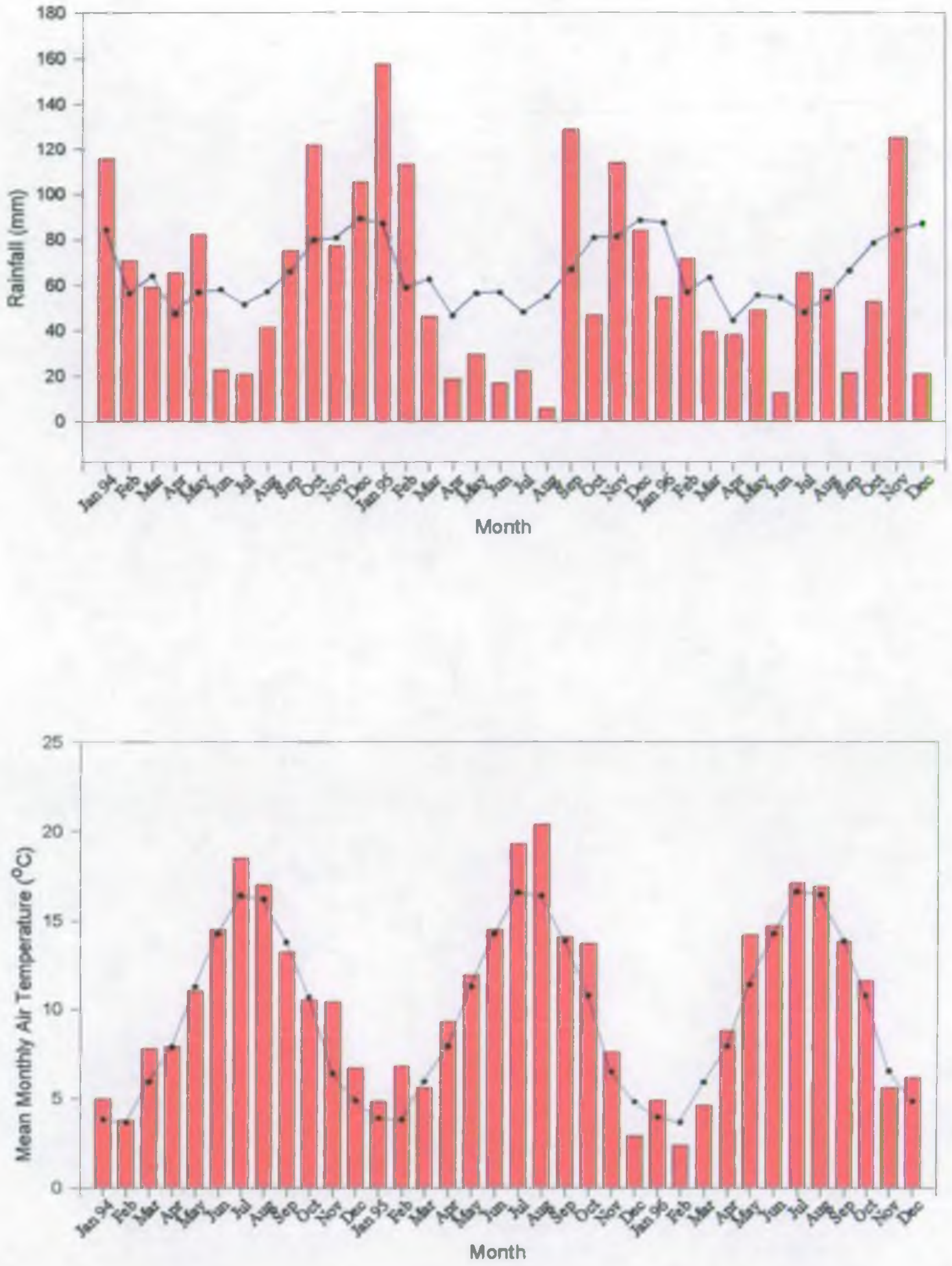


Figure 1. *Precipitation and mean daily air temperature over the monitoring period in relation to the 30-year mean.*

Variation in milk P could not be accounted for by differences in cow age or in milk yield. However, regression analysis indicated that milk P concentrations were significantly ($P < 0.001$) positively related to protein, fat and lactose concentrations (Table 3). Protein and lactose levels additively accounted for 57% of the variation in milk P but inclusion of milk fat did not improve the regression. On each sampling occasion, milk P concentrations were significantly ($P < 0.001$) different between the 3 groups of cows for both morning and evening

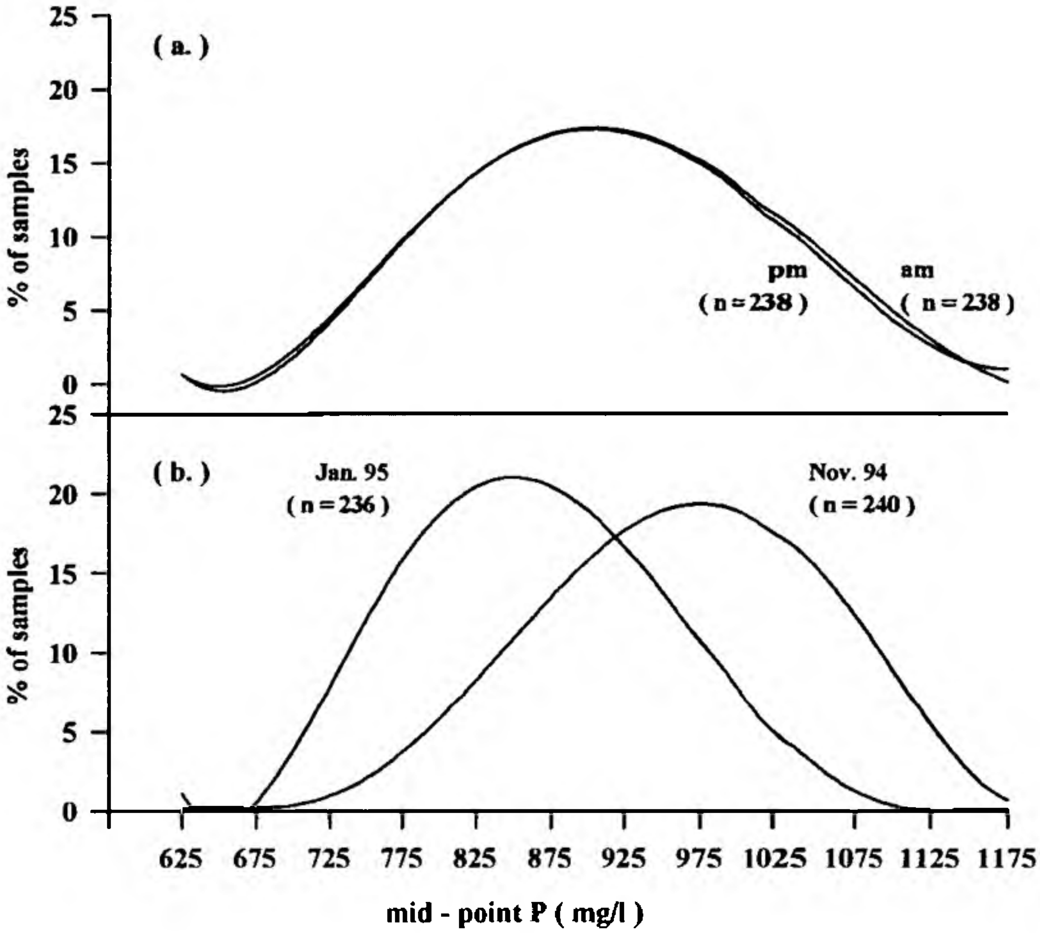


Figure 2. *Frequency distribution of milk P concentrations between (a) evening and morning milkings and (b) two sampling dates during the first lactation.*

milkings (Table 4); mean 24 hr yield-weighted values in groups 2 and 3 were significantly greater than those in group 1, and values in group 3 were significantly greater than those in group 2 on both sampling dates (Table 4).

Table 3. *Regression parameters for the relationship between milk P concentration (mg l^{-1}) and milk composition (%) on two sampling dates in the first lactation*

	November 1994				January 1995			
	Intercept	Gradient	Correlation coefficient r	Significance P	Intercept	Gradient	Correlation coefficient r	Significance P
Fat	586	94	0.56	<0.001	528	82	0.54	<0.001
Protein	135	253	0.69	<0.001	144	218	0.63	<0.001
Lactose	292	146	0.33	<0.001	403	103	0.35	<0.001

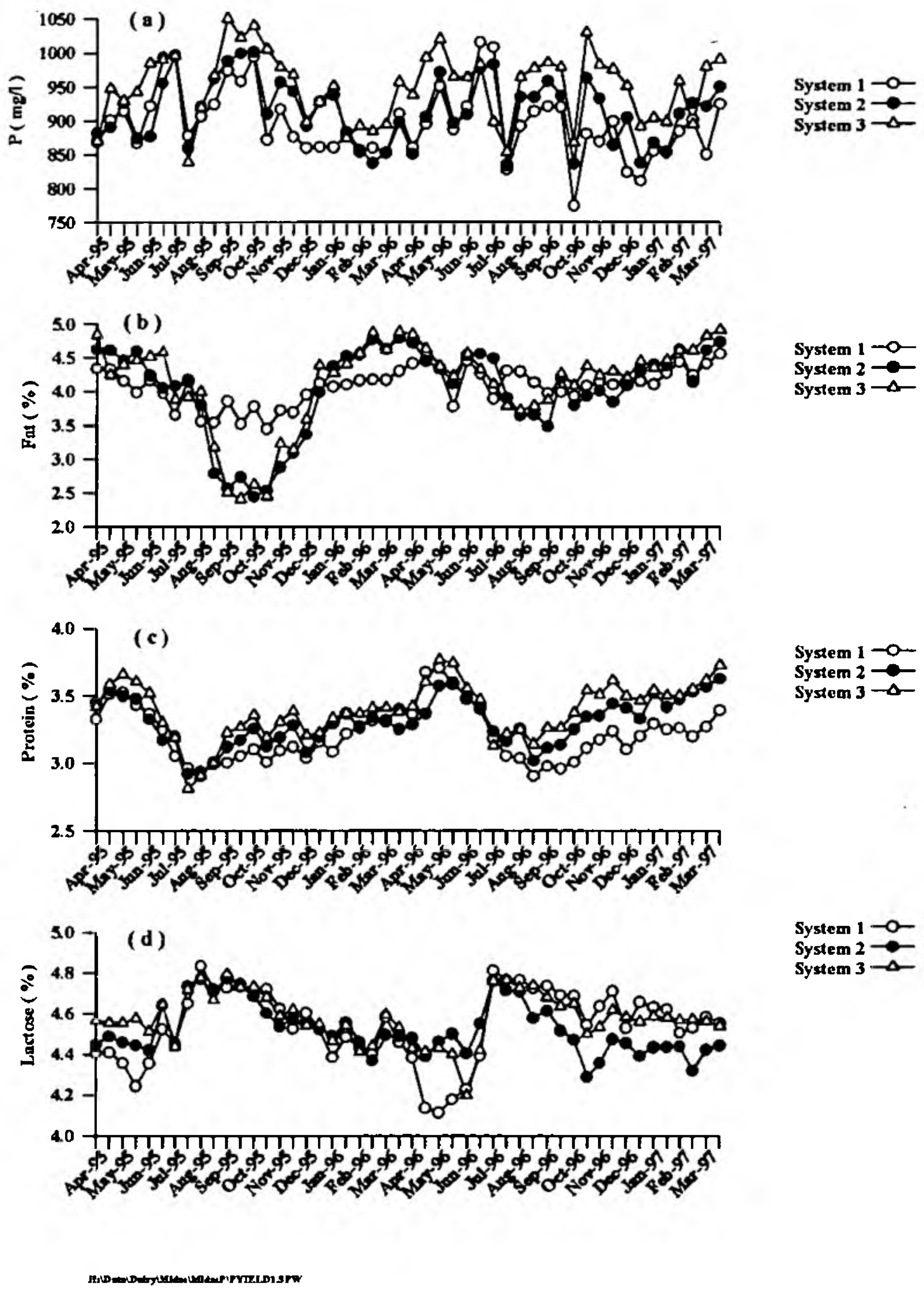


Figure 3. *Concentrations of (a) P (b) fat (c) protein and (d) lactose in milk sampled at fortnightly intervals over the second (1995/96) and third (1996/97) lactations.*

Table 4. *Average milk P concentrations (mg l^{-1}) in the evening and morning milk from each system on two sampling dates.*

System	November 1994			January 1995		
	PM	AM	Mean	PM	AM	Mean
1	928	902	912	831	839	837
2	965	981	976	854	851	853
3	1010	1013	1005	895	918	910
SE.			8.84			8.40
SE. (interaction)	12.5 (195 df)			11.9 (191 df)		

4.2.2 Variation in milk phosphorus during the lactation

System 3 cows continued to show consistently greater milk P concentrations than systems 1 and 2 throughout the second and third lactation despite their lower dietary P intake and the relatively high cow replacement rates (Fig. 3). The range in concentrations measured in the bulk samples was also considerable and similar to that measured for individual cows (760-1150 mg l^{-1}). The pattern of change in milk P during the lactation also showed some similarities between the two years. Concentrations decreased sharply within a month of calving, increased during August and September and decreased sharply again during October. Concentrations continued to fluctuate thereafter, decreasing again during December, although to a lesser degree in 1995/96. However, there was no difference in the average milk P concentration (920 mg l^{-1}) between the second and third lactations.

4.2.3 Variation in milk composition during the lactation

Changes in milk composition over the second and third lactations are also shown in Fig. 3. In the second lactation, milk fat levels were lowest during the August to November period when relatively large amounts of brewers grains were fed compared to other years and increased again when supplementary feeding ceased. However, the decline and milk fat in groups 2 and 3 during August to November and increase thereafter was much more pronounced than in group 1, such that towards the end of the lactation milk fat in groups 2 and 3 were higher than in group 1. Brewers grains were not fed during the third lactation because of better grass growth and fat concentrations remained more constant. However, groups 2 and 3 again

showed reduced milk fat compared to group 1, but the decline was slightly earlier and smaller than in the second lactation. This was reflected in a significant difference in average milk fat between years but there was no difference between the 3 systems in either year (Table 5).

As with milk P, milk protein concentrations were significantly different between the 3 groups, with group 3 showing consistantly greater protein levels than groups 1 and 2, especially in the third lactation (Fig. 3, Table 5). Protein levels were lowest after calving and generally increased during the lactation. Fluctuations in milk protein coincided exactly with those in milk P concentrations albeit less dramatically (Fig. 3). Milk protein levels were significantly greater in 1996/97 than in 1995/96, although the differences were small. In contrast, milk lactose concentrations were highest after calving and declined during the lactation, more so in group 2 cows during the third lactation. Lactose in group 1 cows tended to be lower than in group 2 and 3 cows during April to June when the majority of each group were dry (Fig. 3). There was no significant difference in milk lactose concentrations between the systems or between years (Table 5).

Table 5. *Average concentrations of P, fat, protein and lactose in milk from each system over the second and third lactation*

	Second lactation (1995/96)				Third lactation (1996/97)			
System	1	2	3	SE. (46 df)	1	2	3	SE. (46 df)
P (mg l^{-1})	904	917	947	5.00	889	910	951	6.23
Fat (%)	3.96	3.86	3.91	0.076	4.20	4.21	4.33	0.038
Protein (%)	3.19	3.24	3.31	0.013	3.24	3.37	3.47	0.018
Lactose (%)	4.54	4.56	4.59	0.011	4.55	4.48	4.56	0.021

SE. for comparing means between years (115 df) is 7.6, 0.074, 0.018 and 0.020 for milk P, fat, protein and lactose, respectively.

Average annual milk yields over the three lactations were slightly lower in groups 2 and 3 compared to group 1 in the first lactation but these differences disappeared in the second and third lactations (Table 6).

Table 6. *Annual milk yields and estimated P output from each system in each lactation*

System	Annual yield (l cow^{-1})			P output (kg cow^{-1})		
	First lactation	Second lactation	Third lactation	First lactation	Second lactation	Third lactation
1	6419	6979	6601	5.8	6.3	5.8
2	6026	6867	6226	5.7	6.3	5.7
3	6054	7192	6666	5.9	6.8	6.3
s.e.	76.1	71.9	80.8	(1)	0.09	0.08
P value	<0.001	0.009	<0.001		<0.001	<0.001

(1) Data not statistically analysed as milk P was measured on only two occasions in this year

The average annual output of P in the milk was consistantly greater in group 3 cows compared to the other two groups due to the higher concentration of P maintained in the milk (Table 6). Milk P output was slightly lower in the third lactation due to slightly lower milk yields. In relation to the total annual output of P in milk, differences between groups were very small. The estimated recoveries of P in the milk during a 3-month period when the cows were fully housed (December to February) were 22%, 22% and 30% in each group, respectively.

4.3 Maize agronomy

4.3.1 System comparisons

Dry matter yields were generally similar on system 2 and system 3 fields until 1997 when both system 3 areas yielded 1.7 t ha^{-1} less than system 2 areas (Table 7). Ohio East (system 3) also showed lower yield than Ohio West (system 2) in 1995 but this difference was not observed in Pennsylvania in that year and was reversed the following year. Crop N and P concentrations were very similar across all areas in all years falling within the narrow range of 13.4-15.9 g kg^{-1} for N and 1.5-1.9 g kg^{-1} for P. There were no appreciable differences in N and P offtake between system 2 and system 3 areas during the first 3 years; average values being 130 kg N ha^{-1} and 15 kg P ha^{-1} for both systems. In 1997, differences in offtake reflected differences in yield with 24 kg N ha^{-1} and 2.3 kg P ha^{-1} less offtake in system 3 than in system 2 areas (Table 7). DM yields and nutrient offtakes were greater in 1996 and 1997 than in 1994 and 1995 when crops suffered summer drought (Fig. 1); average DM yields in each year were 8.6, 7.9, 10.2 and 9.7, respectively.

Whilst the amounts of N supplied in the slurry were equal to (system 3) or slightly above (system 2) the offtake of N in the harvested crop, the amounts of slurry P applied were 67-135% greater than the offtake of P in the crop (Table 8). The additional P inputs in slurry and starter fertilizer to system 2 fields compared to system 3 fields did not significantly increase the cumulative crop P offtake but served only to increase the soil P loading. Surplus P represented a total P loading to the soil of 37 and 10 kg ha^{-1} $annum^{-1}$ for systems 2 and 3, respectively over the 4-year monitoring period. Starter P fertilizer applications to system 2 areas were only half those used commercially (Burnhill *et al.*, 1997) but still increased the surplus P in system 2 by 70% and accounted for 58% of the difference in P surplus between system 2 and system 3 fields

Table 7. *Field DM yields, N offtake and P offtake in manured forage maize grown with (System 2) or without (System 3) starter P fertilizer*

	System 2		System 3	
	Pennsylvania South (3.25 ha)	Ohio West (2.75 ha)	Pennsylvania North (3.25 ha)	Ohio East (2.75 ha)
DM yield (t ha^{-1})				
1994	8.7	8.3	8.3	9.1
1995	7.5	8.5	7.6	7.8
1996	10.9	9.2	10.1	10.7
1997	10.8	10.3	9.1	8.6
Mean	**9.3**		**8.9**	
N offtake (kg ha^{-1})				
1994	138	123	126	121
1995	103	115	113	112
1996	162	131	150	153
1997	146	149	124	124
Mean	**134**		**128**	
P offtake (kg ha^{-1})				
1994	16	13	14	14
1995	12	14	15	12
1996	19	15	17	18
1997	18	15	15	15
Mean	**16**		**15**	

Table 8. *Cumulative surpluses (kg ha^{-1}) of N and P in system 2 and system 3 fields*

	N		P	
	System 2	System 3	System 2	System 3
Input				
Slurry	655	509	148	102
Fertilizer	154	148	62	0
Total	809	657	210	102
Output	535	513	63	61
Surplus	274	144	147	41

4.3.2 Field experiments

Experiment 1

Maize yields from the replicated field experiment varied widely from 6.15 to 8.60 t DM ha^{-1} and there was no significant yield effect from any of the P fertilizer treatments compared to the control plot receiving no P fertilizer (Table 9). Yield variation was considered to be due to variation in soil depth between plots. Significantly lower concentrations of P were recorded in experimental plots compared to the field measurements in both years. This probably reflects differences in sampling method due to variation in the P content of the crop components.

Table 9. *The effect of increasing rates of placed starter P fertilizer on the total DM yield, crop P concentration and P offtake of forage maize at ADAS Bridgets in 1994 and 1996.*

	Treatment kg P ha^{-1}	DM yield t ha^{-1}	P concentration g kg^{-1}	P offtake kg ha^{-1}
1994	0	8.42	0.8	6.9
(Experiment 1)	30	8.60	0.9	8.0
	60	7.93	1.0	8.2
	90	6.15	0.9	5.5
	120	8.45	0.8	6.7
	SED	1.087	0.12	1.234
	P value	NS	NS	NS
1995	Nil	13.97	1.80	25.1
(Experiment 2)	17	14.13	1.78	25.1
	32	13.43	1.69	22.7
	SE (6 df)	0.325	0.028	0.424
	CV%	4.7	3.2	3.5

Experiment 2

There were no visible differences in crop growth between any of the treatments during the season and there was no effect of the lower rate of placed inorganic P on either DM yield, crop P concentration or crop P offtake at harvest (Table 9). In contrast, the application of the higher P rate slightly reduced DM yield and significantly (P 0.01) reduced the P content of the crop at harvest by 2.4 kg ha^{-1}.

Experiment 3

Plants established evenly and averaged 10 m^{-2} across all treatments. By mid-June, distinct visual differences in crop vigour and colour between the treatments were observed. Plants which had received N and P together (N_1P_1, N_2P_2) or P alone at the higher rate (N_0P_2) were significantly taller, contained higher DM, removed larger amounts of N and P from the soil and showed less purpling of leaf edges than plants which received either nil N and P, or N alone (Table 10). These three treatments had 6 fully expanded leaves whereas all other treatments had only 5 leaves. The N_0P_1 treatment also showed consistently better growth than the control or N only treatment but the differences were smaller. Plots receiving starter N only tended to be smaller with less DM accumulation than control plots, although not significantly so. Crop N and P concentrations were slightly diluted by the better growth on P or N and P plots but crop N concentrations were significantly increased on plots receiving N alone (Table 10).

Table 10. *Treatment differences in crop vigour, N and P concentrations and N and P uptake by forage maize in mid-June 1997 at ADAS Bridgets*

Treatment	Plant height (cm)	DM yield ($t\ ha^{-1}$)	N conc. ($g\ kg^{-1}$)	P conc. ($g\ kg^{-1}$)	N uptake ($kg\ ha^{-1}$)	P uptake ($kg\ ha^{-1}$)
N_0P_0	15.2	0.41	45.1	3.47	18.4	1.42
N_1P_0	14.4	0.35	47.3	3.57	16.8	1.27
N_2P_0	14.6	0.38	47.3	3.37	18.2	1.30
N_0P_1	15.7	0.49	44.0	3.50	21.8	1.73
N_0P_2	16.9	0.54	42.7	3.40	22.9	1.82
N_1P_1	18.0	0.70	43.6	3.43	30.5	2.40
N_2P_2	17.3	0.62	43.5	3.43	27.1	2.14
SE (12 df)	0.378	0.030	0.505	0.066	1.368	0.105
CV%	4.1	10.5	2.0	3.3	10.7	10.5

In mid-July, plots receiving N alone continued to show reduced plant height and associated DM accumulation and plots receiving either P alone or N and P together continued to show increased crop vigour compared to the control (Fig. 4). However, only differences between N_1, N_2 and P_1, P_2, N_1P_1, N_2P_2 were statistically significant ($P < 0.05$). Similar trends in P uptake were also not statistically significant compared to the control (Fig. 4). As in mid-June plots showing better growth showed slightly reduced tissue concentrations but not significantly so.

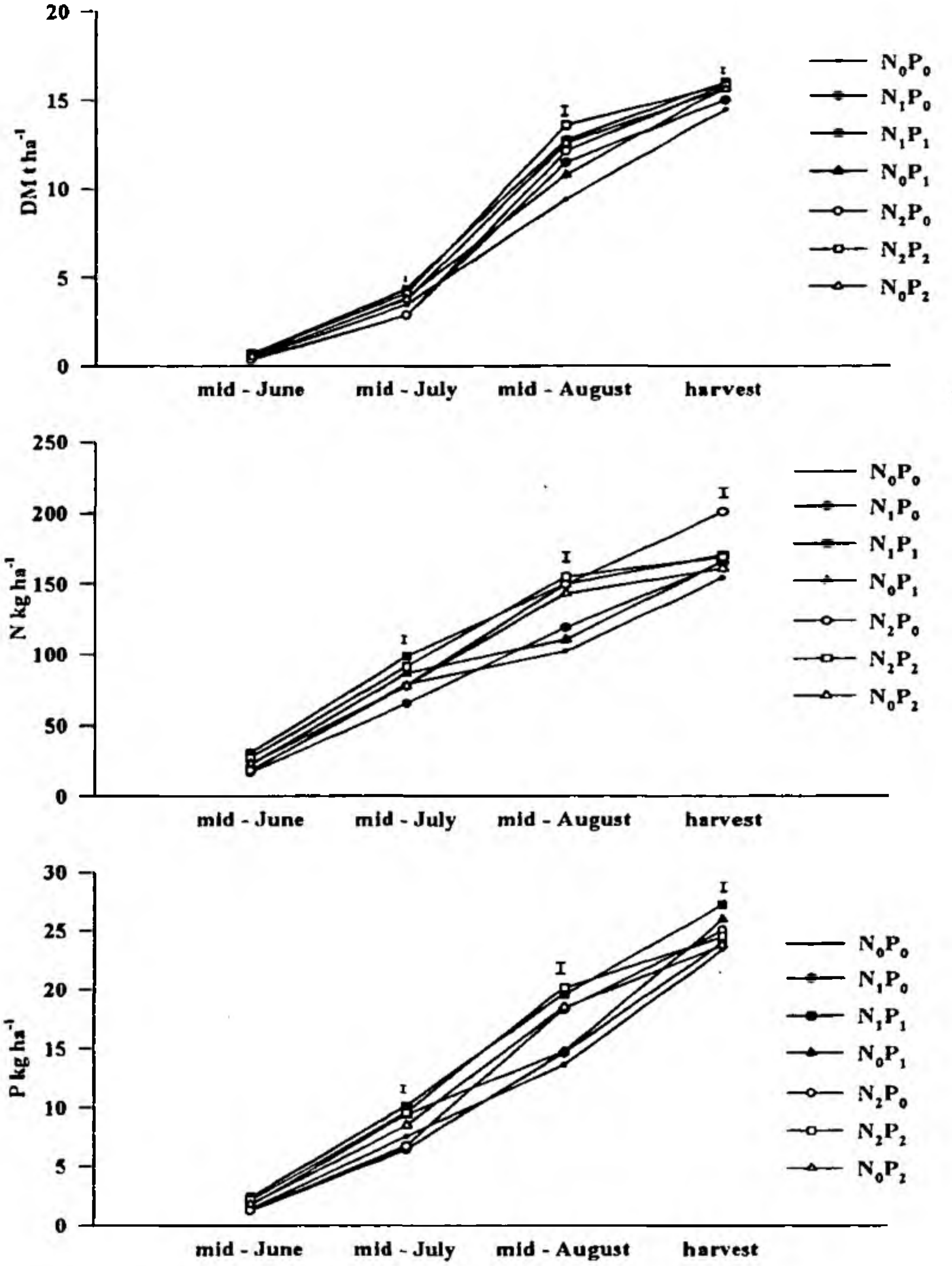


Figure 4. *Effect of starter N and/or P fertilizer on the pattern of DM accumulation, N offtake and P offtake in forage maize in 1997 (SE bars shown).*

In mid-august, all plots receiving fertilizer showed increased growth compared to the control although this was significant ($P < 0.05$) only for the N_0P_2, N_2P_0, N_1P_1 and N_2P_2 treatments (Fig. 4). For example, DM accumulation, N uptake and P uptake on plots receiving N and P together (mean N_1P_1 and N_2P_2) was 3.8 t ha^{-1}, 50 kg ha^{-1} and 6.2 kg ha^{-1}, respectively greater than on control plots receiving no fertilizer. Differences in N and P uptake between the rates of N alone or P alone were most apparent and significantly different at this stage of growth but there was no effect of rate when N and P were applied together (Fig. 4). In particular, N_2P_0 plots showed significantly higher concentrations of both N and P compared to N_1P_0 plots. All fertilizer treated plots had grown an extra leaf compared to the control but cob numbers per plant were unaffected. However, cob length was significantly increased by an average 2 cm on fertilized plots compared to unfertilized plots.

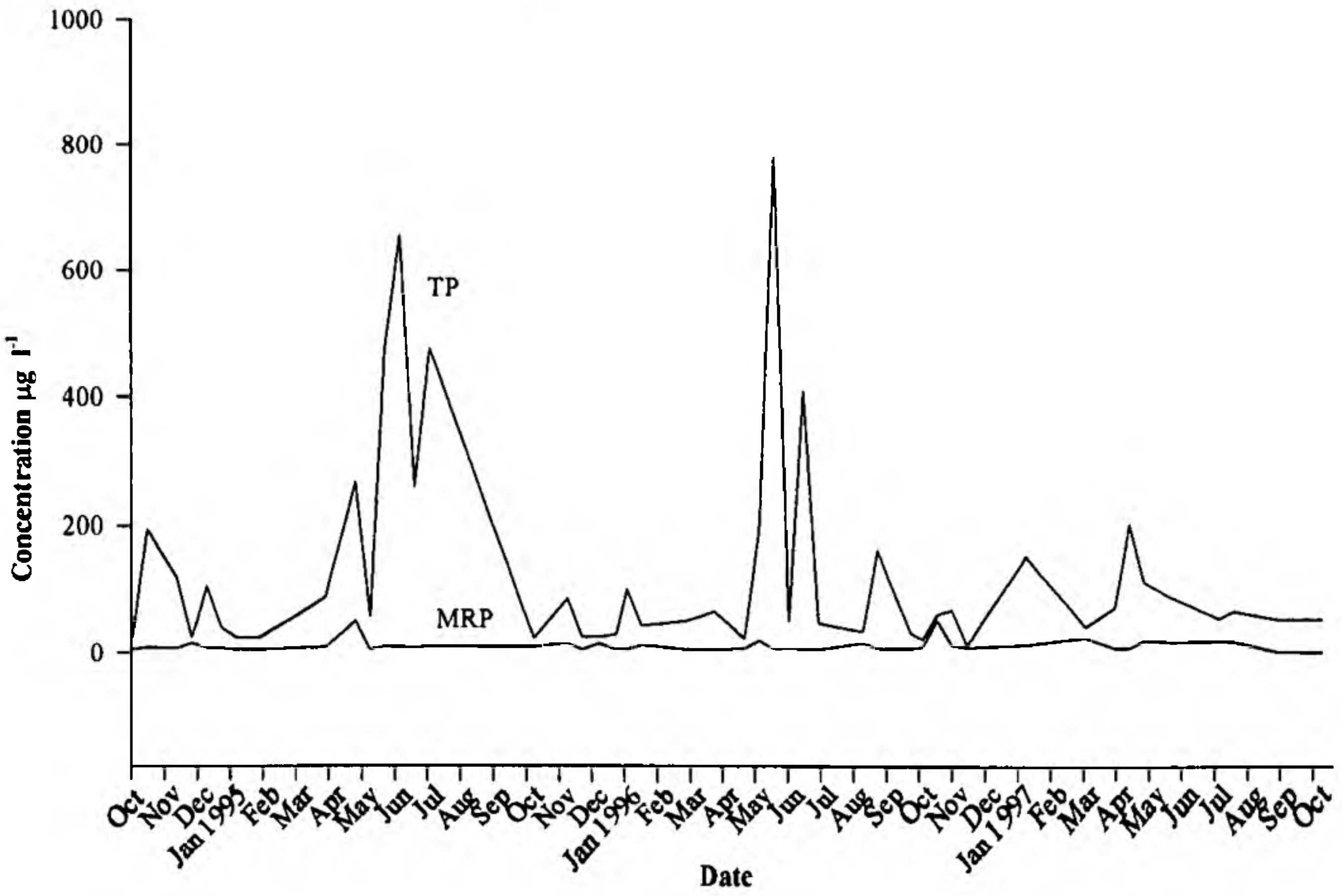
At harvest, there was a statistically significant treatment effect only between the mean of the fertilized plots and the control; there was no difference in DM yield between the plots receiving either N, P or NP fertilizer (Fig. 4). Only the plot which received broadcast N alone (N_1P_0) showed slightly lower yield than the other N and/or P treatments. The average yield response was 1.3 t ha^{-1} or 9%. There was also no overall statistical treatment effect on either the concentration or offtake of N and P, although the N_2P_0 treatment conspicuously showed elevated N content compared to other treatments (Fig. 4).

4.4 Phosphorus inputs and outputs

4.4.1Atmospheric inputs

Measured concentrations of MRP and TP in rainfall since September 1994 are shown in Fig. 5. MRP concentrations were relatively constant and generally below 50 $\mu g\ l^{-1}$ but TP concentrations were variable (up to 780 $\mu g\ l^{-1}$) with a tendency to increase sharply during summer months. Hence much of the P input occurred in particulate form, most probably as locally-derived soil particles disturbed by cultivations and transported by wind erosion in dry weather. To some extent atmospheric inputs might therefore be considered as recycled P rather than a true external input in these systems. Cumulative TP inputs in rainfall over the monitoring period amounted to 1.5 kg ha^{-1}, which is equivalent to 0.5 kg ha^{-1} annually. Annual MRP inputs were only 0.07 kg ha^{-1}. Gibson *et al* (1995) suggested a value of 0.22 kg

Figure 5. *Concentrations of molybdate-reactive P (MRP) and total P (TP) in rainfall over a 36 month period at ADAS Bridgets.*



TP ha^{-1} was appropiate for upland areas of the UK. These observations are therefore consistant with those of Loehr (1974) who observed that atmospheric inputs from cultivated areas are double those from non-cultivated areas.

4.4.2 Inputs in fertilisers and feeds

Total imports of fertilisers and feeds into each system are shown in Fig. 6. Inputs of inorganic P fertiliser in system 1 were higher than in system 2 due largely to the additional P required to establish the IRG in 1994 and again in 1996. Only two system 3 fields received any P fertiliser throughout the study period. Average fertiliser P inputs to each system were 258, 145 and 18 kg (14, 8 and 1 kg ha^{-1}), respectively. All systems received similar average amounts (*c.* 50 t DM) of concentrate feed (parlour cake or pre-mix) over the experimental period, although concentrate use tended to be greater in the first year in order to maintain milk production from the high proportion (40%) of first lactation heifers used to set up the systems. Also, the P content of the parlour concentrate delivered in 1996 was notably lower than in the previous years. This had a relatively large influence on system 1 P intakes due to their reliance on parlour concentrate, which was consequently lower than in system 2 in this year (Fig 3).

Only small quantities of supplementary feed (brewers grains and caustic-treated straw) were purchased in 1994, but much larger quantities, representing 31, 21 and 22% of the total P input in purchased feeds to each system, respectively, were required in 1995 due to the lack of rain during the April-August period reducing grass growth (Fig 3). No supplementary feed was considered necessary in 1996 due to the better grass growing conditions, although DM intake in each system ended up lower in this third year compared to earlier years. Total P inputs in purchased feeds were therefore greatest in the second year and lowest in the third year across all systems (Fig 3). Average annual P inputs in purchased feeds were 430, 405 and 293 kg (11, 11 and 8 kg cow^{-1}) for each system, respectively. Average dietary DM in cut forage and purchased feedstuffs in each system contained 4.7, 4.0 and 3. 4 g kg^{-1} P, respectively.

4.4.3 Outputs in milk and meat

Annual differences in milk production, mil P concentration and milk P otput between the three systems were presented in section 4.2. In the first year, the cows came into the systems already calved but annual outputs of P in calves and in net transfers of culled cows in the following

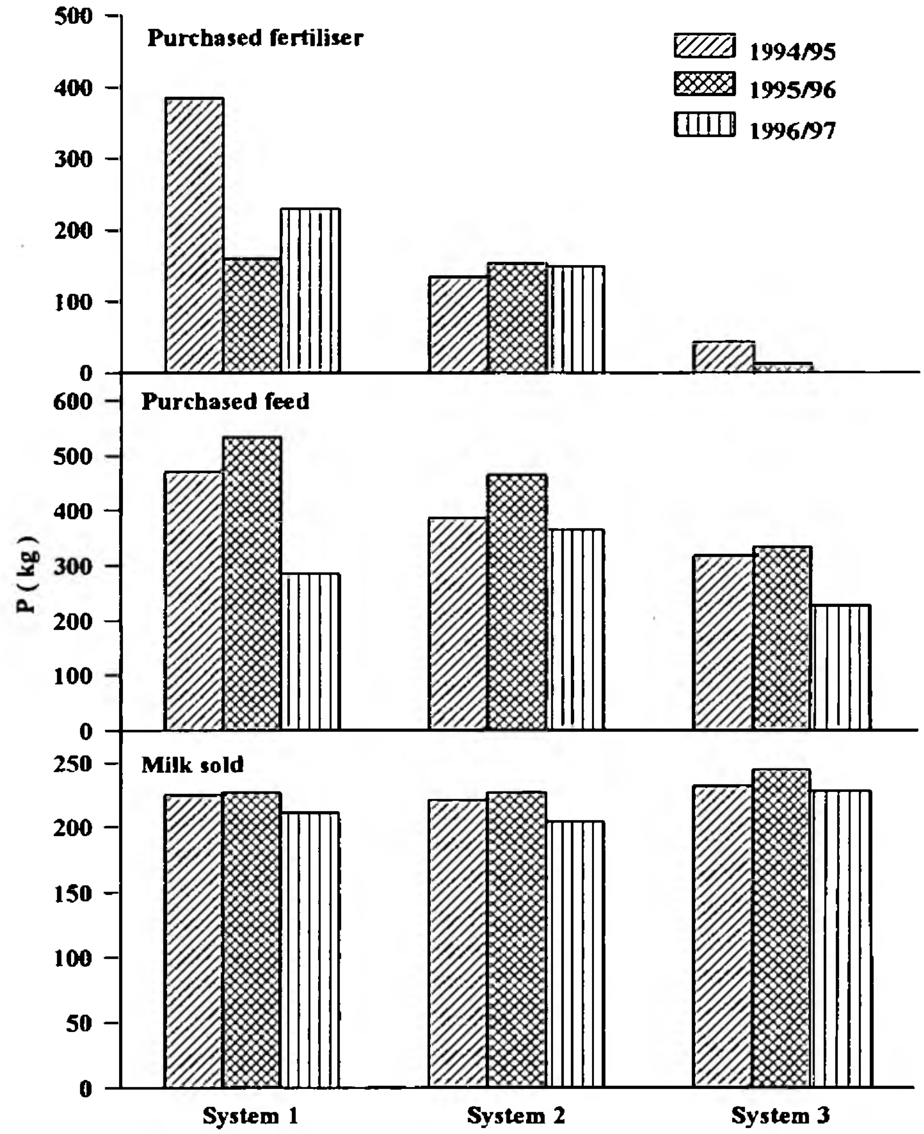


Figure 6. *Total inputs of P in fertilisers and feeds purchased and outputs of P in milk sold from each system in each year.*

two years averaged 25 kg across all systems. Similarly, small amounts of surplus silage accounted for *c.* 20 kg of P in each system. There was no indication that reducing or withholding fertilizer P inputs on system 3 was limiting cut herbage production of grass or maize (Fig 4). Actual data for each cut area in each system is given in Appendix 8.

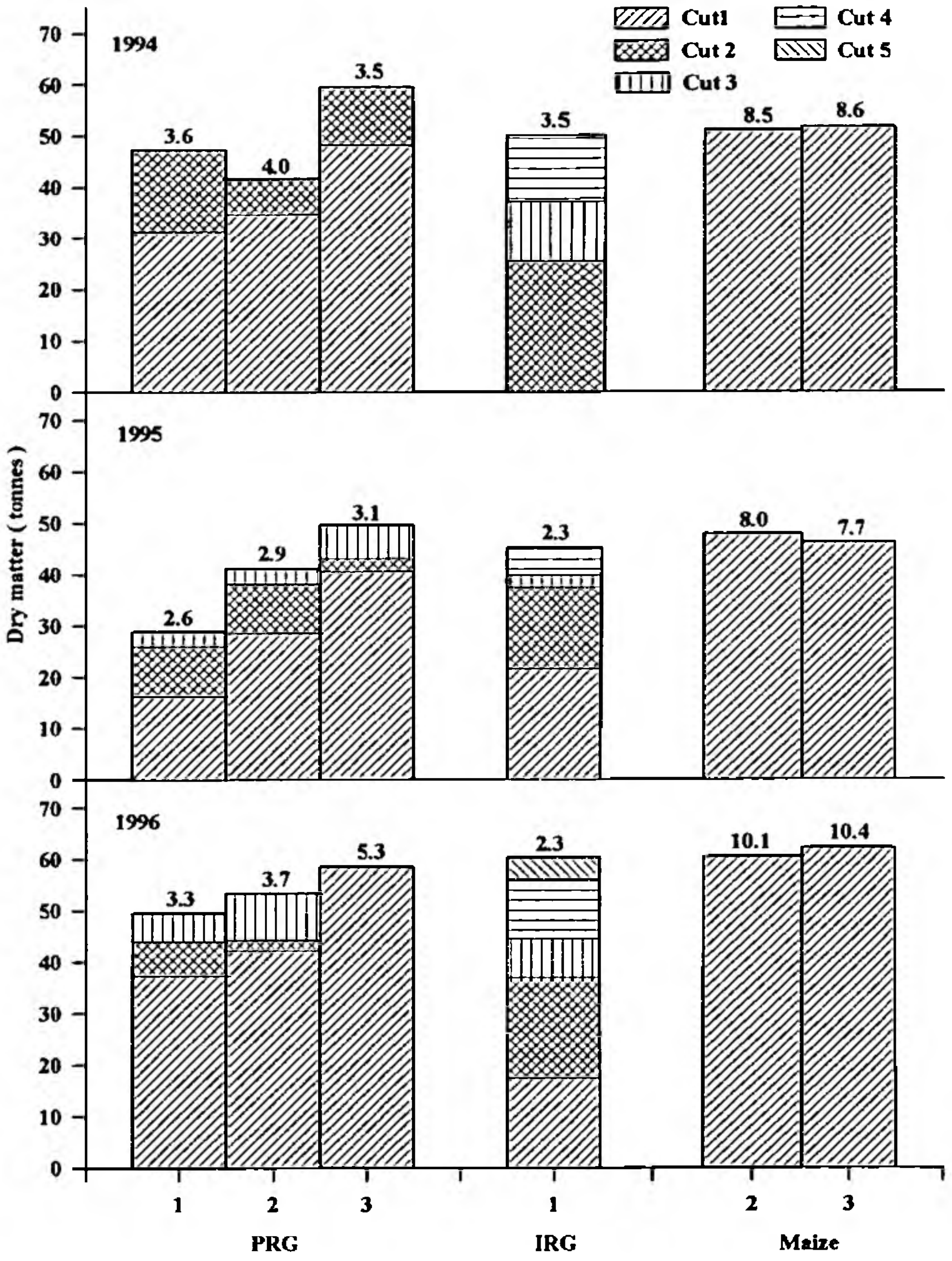


Figure 7. *Total DM production of cut forage from perennial ryegrass (PRG), italian ryegrass (IRG) and maize in each system in each year. (Values above the columns represent average production on a per hectare basis).*

Differences in total DM production (kg ha^{-1}) therefore reflected seasonal effects rather than system effects, being lowest in 1995, when very little rain fell during spring growth, and largest in 1996, when rainfall was more evenly distributed (Fig 1). Herbage yields recorded in system 1 fields in 1995 were particularly low, for reasons which are not clear. Total DM production from IRG areas in system 1 was very similar to that from maize areas in system 2 and 3 in all years (Fig 7). The limited statistical analysis indicated that DM yields were greater on systems 2 and 3 than on system 1 (Table 11).

Table 11. *Dry matter yields, herbage P concentrations and P offtake in first cut perennial ryegrass (PRG) for each system and in each year.*

	DM yield t ha^{-1}	P conc. g kg^{-1}	P offtake kg ha^{-1}
System 1	3.89	3.30	13.1
System 2	4.44	2.91	13.0
System 3	4.69	3.01	14.3
se	0.238	0.086	0.907
P value	0.016	NS	NS
1994	4.36	3.08	13.5
1995	3.62	2.77	9.9
1996	5.04	3.38	17.1
se	0.238	0.086	0.907
P value	0.003	<0.001	<0.001

The concentrations of P in cut herbage on systems 2 and 3 were slightly lower than in system 1, although this was not significant at the 5% level (Table 11). Since system 2 continued to receive P fertilizer, these differences are probably due to yield differences and/or soil P supply between fields. There were no differences in P offtakes between the systems, only between years (Table 11). Concentrations of P in second cut herbage were uniformly low across all three systems, with values close to 2 g kg^{-1} in most fields, but increased again to nearer 3 g kg^{-1} in autumn cut grass (Appendix 9). Concentrations of P in cut maize were all within the narrow range 1.5-1.9 mg kg^{-1}. Offtake of P in total cut forage from each system averaged 264, 216 and 259 kg (14, 11 and 11 kg ha^{-1}), respectively.

4.4.4 Phosphorus balance sheet

Inputs, outputs and estimated internal transfers of P (kg ha^{-1}) in each system averaged over the three years are given in Table 12 and Appendix 10. Values for system 3 are universally lower than for the other two systems because of the greater land area in system 3. Within the animal production part of the cycle, outputs of P in milk and meat were 28%, 31% and 36% of the dietary P inputs in each system, respectively. Purchased feeds were the major source of imported P onto the farm and when these were substantially reduced in system 3, there was a major reduction (26%) in the amounts of slurry P to be recycled. Estimated P intakes at grazing were comparatively low reflecting low DM intake (9-12 kg day^{-1}) by dry cows during spring and increased concentrate use (10-14 kg DM day^{-1}) in summer when cows calved and when availability of grass was reduced by soil moisture deficits.

The efficiency of P utilisation by the crop production part of the cycle was 49%, 53% and 87% in each system, respectively. Slight differences in total P output in cut forage and grazed areas between the systems reflected differences in the areas allocated each year. The annual surplus P in each system was 23, 17 and 3 kg ha^{-1} in systems 1, 2 and 3, respectively. Surplus P on individual fields ranged from +1 to +59 kg ha^{-1} in system 1, -2 to +121 kg ha^{-1} in system 2 and -19 to +47 kg ha^{-1} in system 3 (Appendix 11). Greatest P surpluses were recorded in fields continually cropped to maize in system 2, which received both dairy manure dressings and starter fertilizer.

4.5 Phosphorus losses

4.5.1 Surface run-off

Total amounts of P in surface run-off from fields in grass, maize stubble with IRG cover and winter barley over the monitoring periods in each year are shown in Table 13. There was large variation in run-off and in P concentrations between individual traps; for example total P typically varied between 0.5 and 10 mg l^{-1}, but with occasionally very high concentrations (up to 57 mg l^{-1}) measured during low flow. There were fewer storm events producing run-off in 1995/96 than in 1994/95 but the amounts collected were generally larger. Run-off from grassland fields occurred less frequently than from maize or barley fields. TP losses were consequently much lower from either permanent or reseeded grass as compared to those from maize or barley fields.

Table 12. *Inputs and outputs of P (kg ha^{-1}) for each system.*

	System 1 (19 ha)	System 2 (19 ha)	System 3 (23 ha)
Animal production			
Inputs			
Bedding	0.7	0.7	0.7
Purchased feeds	22.6	21.3	12.7
Home-grown silage	12.9	11.1	10.9
Grazing	8.5	7.6	6.5
Sub-total	44.7	40.7	30.8
Outputs			
Milk	11.6	11.4	10.2
Meat	0.8	0.9	0.7
Surplus silage	1.7	1.0	1.1
Sub-total	14.1	13.3	12.0
Animal balance	30.6	27.4	21.0
Crop production			
Inputs			
Atmosphere	0.5	0.5	0.5
Fertiliser	13.6	7.7	0.8
Slurry	31.6	27.7	19.2
Sub-total	45.7	35.9	20.5
Outputs			
Cut grass	13.9	11.4	11.3
Grazed grass	8.5	7.6	6.5
Sub-total	22.4	19.0	17.8
Crop balance = Surplus	23.3	16.9	2.7

Largest run-off volumes and P losses occurred from consolidated headland areas with little vegetative cover (Table 13). Differences in dissolved P (TDP and MRP) loads between fields were smaller reflecting the proportionally large (>95%) amount of partilculate P loss in soil erosion from maize stubble and barley fields. Run-off from grassland contained a higher proportion of soluble P compared to maize and barley fields, although particulate P was still dominant (Table 13). In all samples the TDP fraction was almost totally (> 90%) composed of molybdate-reactive P. Spot sampling of selected areas during the 1996/97 winter also showed a high proportion of TDP:TP loss from grassland puddles (30%) as compared to maize puddles or run-off (2%). Samples of cattle yard run-off from around the farm buildings in 1996/97 also showed a high proportion of TDP:TP loss (20%). Detailed reults are given in Appendix Since surface run-off represents only about 2% of the annual precipitation in chalk landscapes (Boorman *et al.*, 1996), annual TP losses from grass and maize/barley areas can be estimated at 0.1 and 0.6 kg ha^{-1}, respectively. With 6 ha of maize in the rotation, erosion losses from systems 2 and 3 were therefore slightly greater (0.25 kg ha^{-1}) than in system 1 (0.1 kg ha^{-1}), but still less than measured inputs from the atmosphere.

4.5.2 Leaching

Concentrations of MRP in the soil solution at 60 cm depth were uniformly low (<50 μg l^{-1}) in each drainage season with no difference between the three systems. The median value over the 238 pots which yielded was 10 μg l^{-1}. Rainfall over the 1995/96 and 1996/97 winters was well below average (Fig. 1) and the teflon-coated porous cups yielded leachate on only one occasion in each of these years. Cups tended to yield only after heavy rain confirming the observation of Williams and Lord (1997) that porous cups at this depth in the chalk parent material are able to pick up only water percolating through fissures at relatively low tensions (<15 kPa). Water moving much more slowly in the fine pores of the chalk matrix at much higher suctions may not therefore be recovered by this technique. In a comparison of two methods, Williams and Lord (1997) concluded that leaching losss of N might be underestimated by as much as 40%. Annual losses of MRP based on the long-term winter drainage volume of 260 mm are therefore estimated at 0.03-0.04 kg ha^{-1}. Concentrations of TP in selected samples taken in 1996/97 were on average 3 times greater than those of MRP indicating some movement of particulate P within the chalk fissures. Accounting for these factors, total losses of P in leaching are still no more than about 0.1 kg ha^{-1} and less than the amounts of P deposited from the atmosphere.

Table 13. *Loads of molybdate-reactive P (MRP), total dissolved P (TDP) and total P (TP) transported in surface run-off from selected areas averaged over two years, and the corresponding flow-weighted TP concentration.*

Land use	Monitoring period[a]	Number of trap events	Total run-off (mm)	P load MRP	P load TDP ($g\ ha^{-1}$)	P load TP	TDP:TP %	Flow-weighted TP concentration $mg\ l^{-1}$
Permanent grass	1	8	0.53	8.5	9.9	50.6	20	9.5
	2	1[b]	0.08	0.6	0.7	1.7	41	2.1
Reseeded IRG	2	3	0.38	7.2	8.8	25.4	35	6.6
Maize stubble + IRG	1	38	5.6	7.8	8.7	289.2	3	5.2
	2	22	21.1	26.6	29.9	669.2	4	3.2
Barley cover crop	1	17	2.7	5.1	5.5	109.4	5	4.0
Headlands	1	20	48.4	23.6	25.8	1216	2	2.5

[a] Period 1 - 16 January - 12 March 1995. Period 2 was 28 November 1995 - 26 February 1996.

[b] Installed late (14 February) and only one event was monitored.

5. DISCUSSION

5.1 Milk phosphorus

In previous studies, milk P concentrations have usually been averaged over the herd and consequently reported to be fairly constant. However, the data reported here indicates a near two-fold variation in milk P between individual cows, a significant proportion of which was explained by differences in milk protein content. Comparisons between the patterns of change in milk P and milk protein over the lactation also showed striking similarities which were absent for milk lactose and fat concentrations. This is not surprising since about half the P in milk is present in the colloidal casein protein fraction and the associated inorganic calcium phosphates which become precipitated onto the surfaces of casein micelles (Davies *et al.* 1983; Holt, 1985). The poorer correlation with milk lactose probably represents differences in the amount of soluble or diffusable ion complexes of P. Milk fat did not improve the regression equation because only negligible amounts of P occur in milk as phospholipids.

Not all of the variation in milk P could be accounted for by differences in milk composition. Since ruminants have a a self-regulating mechanism for maintaining homeostasis in P (Horst, 1986; AFRC, 1991), at least some of the unexplained variation may be genetically determined. About two-thirds of the 20 cows with the highest milk P concentrations in November 1994 showed the highest milk P in the January sampling, and about half of the 20 cows with the lowest milk P in November similarly showed lowest milk P in January. No investigations were carried out as to why some cows consistently showed lower or higher milk P concentrations than others; but reducing the numbers of cows in the herd with low milk P through breeding is likely to have only a small effect on maximising milk P output since only a proportion of the average herd will have low P. Hence, when averaged over each group, differences in milk P concentration and milk P output were relatively small and reductions in dietary P intake are clearly a more efficient means of reducing the farm P surplus.

The significantly greater P concentrations measured in milk from groups 2 and 3 compared to group 1 are therefore at least partly due to the higher protein levels in group 2 and 3 cows. The higher protein levels may be related to the introduction of maize starch into the diet despite similar total dietary ME supply between the 3 groups (Reynolds *et al.* 1997).

However, other factors must also be involved since milk protein and P concentrations in group 3 cows were also significantly greater than in group 2 cows yet they ate very similar amounts of maize silage. Protein levels are known to decrease after calving as the contribution from the colostrum declines (Davies *et al.* 1983), which probably explains the sharp drop in milk protein in July in both the second and third lactation. The fluctuations in milk protein and P over the remainder of the lactation observed across all 3 systems are more difficult to explain but probably relate to the introduction or cessation of different ingredients into the diet, differences in rumen degradable protein or the influx of new cows.

The greater P concentrations measured in milk from group 3 cows were obtained despite dietary P intakes which only marginally match P requirements (ARC, 1980). The lack of any direct effect of dietary P intake on milk P concentrations was also confirmed in a more controlled and replicated P balance study on two groups of cows at ADAS Bridgets which were fed group 1 and group 3 diets (Metcalf *et al.*, 1996). These data also support the conclusions from others that reductions in P intake within the range measured here do not affect milk production but increase the efficiency (+8%) with which P is removed in milk and decrease the faecal P output; in this study by 26%. There is a general lack of data on the long-term effects on animal health and fertility of reducing compound P inputs to minimum levels. Some allowance to insure against inadequate P levels in other constituents of the diet is inevitable. For example, measured concentrations of P in cut grass on the calcareous soils at ADAS Bridgets are >0.3% in the DM only in spring and commonly fall well below this during summer. However, these results give further support to the argument that the P content of commercially formulated compound feeds are unnecessarily high and that there is scope to reduce feed P inputs to dairy systems without unduly affecting cow performance.

No measurements of blood or of bone P were taken but a detailed P balance sheet undertaken on a small group of cows fed the system 3 diet suggested some slight mobilisation of body P reserves maybe occurring (Metcalf *et al.*, 1996). The length of time cows can be maintained on such a low P diet without inducing health or fertility problems is not known. Fertility problems have been associated with low P diets but evidence is sparse (Brodison *et al.*, 1989). Over the time period of this study, there was no indication of poorer health or fertility on system 3 cows compared to the other systems, although replacement rates were high in the second (40%) and third (50%) lactation. Poor conception rates were encountered on all 3 systems after the very hot summer weather experienced in 1995.

5.2 Maize agronomy

These results reported here lend support to the UK commercial experience of early growth benefits from placed NP fertilizer on non-calcareous soils and suggest that this benefit is largely due to the supply of P rather than of N. In experiment 3 in 1997, plots which did not receive placed fertilizer P clearly suffered from P shortage and showed poorer nutrient uptake and growth during June and July, an effect which was exaggerated when starter N was also applied. This response was obtained despite 4 years of continuous manuring with cow slurry and above average levels of Olsen-extractable P in the soil. Similarly small responses to starter P fertilizer in the prescence of broadcast manure were measured by Jokela (1992) and most recently by Schroder *et al.* (1997). Schroder *et al.* (1997) demonstrated that without P placement either in slurry or fertilizer, maize crops drilled at 75 cm spacings do not root quickly enough to utilise soil nutrient reserves efficiently. This is probably similar to the situation with lettuce crops whose roots grow so slowly that seed P reserves are depleted well before a broadcast fertilizer granule can be exploited (Costigan, 1987). Clearly broadcast manure P must be viewed as making a contribution to the total maintenance P requirement (MAFF, 1994) rather than providing a readily-available P source during early growth. Further work is required to identify the soil P level above which addition of starter P is not worthwhile under UK conditions (Touchton, 1988; Jokela, 1992).

Strict comparison between the system field yields is confounded by the lower N rates that were applied to system 3 fields. Hence it is not clear whether the lower yields on system 3 fields in 1997 is entirely due to lack of starter MAP or partly due to the relatively low amount of N the crop received in that year. In other years there was no indication of a reduction in DM yield by withholding starter P on calcareous soils and in experiment 1 in 1996 there was no benefit to placed P even at the higher rate of application. Commercial experience also indicates that forage maize crops on calcareous soils are not responsive to starter P (Huntseeds, 1995), despite the naturally low concentrations of P in the soil solution due to effective absorption by calcium carbonate (Frossard *et al.*, 1995). Forage maize does not grow particularly well on shallow calcareous soils and this may be a factor; for example the DM yields recorded at ADAS Bridgets (8-11 t ha^{-1}) are considered relatively low by commercial standards. Lack of soil moisture and nutrient transfer to roots can have an inhibitory effect on growth during critical periods and yields tend to be low without adequate summer rain, as occurred in 1994 and 1995.

Since the starter NP fertilizer is not combine drilled with the seed but only placed nearby, it is doubtful whether ammonia release from MAP or DAP is damaging under field conditions. There was no evidence from the system comparisons that placement of MAP or DAP to the highly calcareous soils in Ohio in 1995 and 1997 was deleterious to growth. Indeed, the only hint of a reduction in yield from application of placed P was in 1995 when TSP was applied without starter N, both in the system comparison (Ohio) and at the higher P rate (32 kg ha^{-1}) in experiment 1, presumably due to an antagonistic effect on uptake of other nutrients. Schroder *et al.* (1997) also noted the possibility of a negative response from placed P; in their experiments due to a combination of placed slurry (30 or 60 m^3 ha^{-1}) and placed starter P fertilizer (22 kg ha^{-1}) on sandy soils.

Acording to the British Survey of Fertilizer Practice (Burnhill *et al.* 1997), 64% of maize crops receive fertilizer P at an average rate of 72 kg P_2O_5 ha^{-1}. This commercial rate is nearly double that currently recommended (MAFF, 1994). In experiment 2 there was a clear growth benefit at the August sampling from application of the higher rate of P alone but not when N and P were applied together. However, these differences were not maintained through to harvest when all placed treatments gave slightly better yields. Hence these results suggest that the currently used high P rates may not be justified. Also, the small yield benefit at harvest was achieved with no apparent difference in N or P uptake indicating that the starter P was hardly utilised. In future, there may be a need locally to balance the small agronomic benefit gained from starter P applications with the potential adverse environmental effects of soil P accumulation. The system comparisons clearly showed the large surpluses that occur where manures and starter fertilisers are both applied. Eutrophication of surface waters is becoming increasingly recognised as a major environmental problem and farmers will increasingly need to become aware of the adverse effects of poor management of agricultural P inputs on the environment.

5.3 Phosphorus inputs and outputs

Although statistical comparisons between the systems were limited, mean values of milk yield, milk P concentration and composition indicated no consistent drop in milk yield and quality or P output in the milk. Similar comparisons for herbage yields meaned across field areas cut for silage indicated no drop in grass or maize DM output, although each system area was cut on slightly different dates. The lack of any effect of withholding P may be related to the lower N inputs on system 3 and consequently lower demand. Reductions in herbage DM output might have been expected under normal commercual N rates (Paynter and Dampney 1992).

System 1 represented current commercial practice and a P surplus of 23 kg ha-1 is very similar to those calculated for intensive dairy farms (Brouwer *et al.*, 1995; Haygarth *et al.*, 1998). How much variation in the P surplus occurs on UK dairy farms is not known. Puchased feeds are the major P input yet are rarely quantified on commercial holdings. Without declaring the P content of purchased feeds and without regular monitoring of herbage P concentrations, dairy producers are probably unaware of the level of P in their diets or of the need for P supplementation. As P is a relatively expensive ingredient of compound feeds, there maybe scope to reduce feed costs by regulating P intake more precisely. Methods to maximise the efficiency of herbage P content and reducing dependancy on purchased P inputs is the key to reducing P surpluses at the farm level.

Calcareous soils have a large capacity to bind P and it is not surprising that P leaching losses were negligible even in maize fields which continuously received cow slurry and inorganic P fertilizer. losses of P from the systems therfore occurred primarily in particulate form as eroding soil particles in surface run-off. Erosion is a significant problem on the more steeply sloping chalkland in Southern England (Boardman, 1990) but is rarely visible on the more gentle slopes (< 5°) at ADAS Bridgets. Nevertheless, these values are similar to those reported for chalkland catchments (Johnes *et al.*, 1997), suggesting that sheet erosion is an important P loss process and environmentally significant with respect to eutrophication.

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APPENDIX 1. *Details of systems.*

System 1 - `Good commercial practice´

Objective:	To achieve a high milk output and profitability per hectare using good commercial practice.
Production targets:	Milk quota >6000 l/cow Compound feed 1.4 t/cow Stocking rate 2.10 LU/ha (40 cows on 19 ha)
Environmental target:	To adhere to the Code of Good Agricultural Practice.
Land use:	Perennial ryegrass (13 ha) - Indiana South, Virginia South, Tennessee South Italian ryegrass (6 ha) - Parts of Minnesota and Rhode Island
Management:	Fertilizer: Optimum ADAS recommendations for N and P. Slurry: Limited (1 month) storage. Applied by conventional spreader onto silage areas during October-March and in July. Feeding: Conventional compound feed, formulated by least cost ration approach. Buffer feeding of silage only for short periods in spring and autumn, and in summer drought period if necessary. Estimated silage DM production of 96 tonnes. Target P intake of 96 g/cow/day

System 2 - `Reduced loss, high output'

Objective:	To reduce losses of N and P as far as possible, whilst achieving similar milk output and profitability per hectare as System 1.
Production targets:	Milk quota >6000 l/cow Compound feed 1.4 t/cow Stocking rate 2.10 LU/ha (40 cows on 19 ha)
Environmental target:	To adhere to CGAP, and comply with possible EC rules limiting stocking rate, timing and rate of manure/fertilizer application.
Land use:	Perennial ryegrass (13 ha) -Virginia North, Tennessee Middle, Carolina Middle Maize - 6 ha -Ohio West, Pennsylvania South
Management:	Fertilizer: ADAS recommendations for P but N reduced for grazing fields from June according to soil N status.
	Slurry: Diluted and spread by conventional spreader or shallow injection. Winter application after 1 December only.
Stored	manure to be covered. Ploughed the same day for maize.
	Feeding: Home-mix ration with mineral/vitamin supplement fed from forage box. Estimated silage DM production of 101 tonnes. Maize silage buffer fed to early lactation cows in July-September. Estimated P intake 84 g/cow/day.

System 3 - `Minimal loss, reduced intensity'

Objective:	To achieve the same milk yield per cow as System 1, and as high a profitability per hectare as possible, at a level of intensity targeted to achieve a major reduction in N losses, making maximum use of recycled nutrients.
Production targets:	Milk quota >6000 l/cow Compound feed 1.4 t/cow Stocking rate 1.74 LU/ha (40 cows on 23 ha)
Environmental target:	To adhere to CGAP. To comply with EC limit on nitrate leaching for Central England (max. 30 kg/ha at 270 mm excess rain, averaged over whole farm).
Land use:	Perennial ryegrass (17 ha) - Tennessee North, Illinois East, Carolina East Maize (6 ha) - Ohio East, Pennsylvania North
Management:	Fertilizer: No P fertilizer. For cutting, reduce fertilizer N by recycling manure N. For grazing, apply according to soil N. Estimated N input about half of recommended. Slurry: Stored covered from September-February. Spread by injection February-March, and after cut silage, maximum of 175 kg/ha total N. Ploughed the same day for maize. Feeding: As System 2, except P intake reduced to 72 g/cow/day by using home mixed ration supplemented by minerals/vitamins. Estimated silage DM production of 102 tonnes.

APPENDIX 2. *Decision rules to be used in managing the systems*

Objectives:	Management decisions within each system are based on the need to reduce nitrogen (N) losses to the environment. Decisions on phosphorus (P) management are secondary and must not compromise N objectives.
Land area:	The land allocated to forage production for each system is dedicated to that system for the whole period of the project.
Forage utilisation:	All cut forage is ensiled in a dedicated silo, or ensiled separately in Ag-Bag or bales. Any surplus silage which cannot be carried over to the following year is weighed and its feeding value and nutrient content measured. All grazing must be by system cows. If surplus herbage needs to be grazed in late autumn, a grazing record is kept and the weight of these cattle or sheep is estimated or measured. In the event of drought conditions, cows will be given access to silage when sward height falls below approximately 5cm (dry cows) or 7cm (early lactation cows).
Housing:	Cows on each system are housed as a separate group so that manure can be collected and stored separately. As far as possible time spent on communal holding/feeding areas is to be minimised.
Cow management:	Mean calving date is in July/August. Cows are culled strictly according to the standard health and welfare procedures and replaced by a cow as near as possible in terms of selection criteria. Cows failing to conceive within the specified period (c. 12 weeks) are replaced. Dry cows use only system dedicated areas.
Feeding:	Each system receives separate supplies of feed. Lactation requirements are assessed using the Metabolisable Protein System, and the ADAS Cow Feed programme which maximises the use of home-grown forage. If forage quantity becomes limiting, comparable forage is purchased.

APPENDIX 3. *Dates of turn-out and housing by day only (day) and night and day (night) in each year .*

	1994				1995				1996			
	Out		In		Out		In		Out		In	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
System 1	1/4	1/4	5/10	27/10	2/3	13/4	5/10	15/11	10/4	15/4	12/8	6/11
System 2	1/4	1/4	20/9	27/10	21/3	3/4	5/10	15/11	10/4	15/4	12/8	6/11
System 3	1/4	1/4	20/9	24/10	21/3	10/4	5/10	15/11	10/4	15/4	12/8	6/11

APPENDIX 4. *Average total dry matter and P intake in cut silage and purchased feedstuffs by each system*

	Dry matter intake (tonnes)			P intake (kg)		
	System 1	System 2	System 3	System 1	System 2	System 3
Grass silage	78	40	48	245	122	158
Maize silage	-	48	49	-	89	91
Brewers grains	11	11	3	64	32	21
Caustic-treated straw	6	5	10	3	6	5
Concentrate/pre-mix	50	51	50	363	367	267
Total	**145**	**155**	**160**	**675**	**616**	**542**

APPENDIX 5. *Soil pH and extractable concentrations of phosphorus (P), potassium (K) and magnesium (Mg) in system fields, sampled in December 1994..*

System	Field identification	pH	Extractable P (mg l^{-1})		
			Phosphorus	Potassium	Magnesium
1	Indiana South East	7.6	32 (3)	278 (3)	137 (3)
	Indiana South West	7.8	40 (3)	366 (3)	138 (3)
	Tennessee South East	7.8	35 (3)	228 (2)	126 (3)
	Tennessee South West	7.7	34 (3)	229 (2)	116 (3)
	Virginia South East	8.0	15 (1)	151 (2)	77 (2)
	Virginia South West	7.8	24 (2)	217 (2)	100 (2)
	Minnesota (Middle)	7.1	22 (2)	111 (1)	66 (2)
	Rhode Island Middle	7.7	40 (3)	338 (3)	101 (2)
2	Virginia North East	8.1	17 (2)	211 (2)	88 (2)
	Virginia North West	8.1	18 (2)	226 (2)	89 (2)
	Tennessee Middle East	8.0	34 (3)	203 (2)	129 (3)
	Tennessee Middle West	8.0	25 (2)	183 (2)	123 (3)
	Carolina Middle North	7.7	18 (2)	175 (2)	99 (2)
	Carolina Middle South	8.0	23 (2)	169 (2)	88 (2)
	Pennsylvania South	8.1	43(3)	256 (3)	83 (2)
	Ohio West	8.3	36 (3)	244 (3)	67 (2)
3	Tennessee North East	8.0	36 (3)	285 (3)	127 (3)
	Tennessee North West	7.8	41 (3)	258 (3)	185 (4)
	Illinois East North	8.0	25 (2)	243 (3)	113 (3)
	Illinois East South	8.0	25 (2)	203 (2)	120 (3)
	Carolina East North	8.0	24 (2)	201 (2)	101 (3)
	Carolina East South	8.0	35 (3)	222 (2)	97 (2)
	Pennsylvania North	7.9	40 (3)	233 (2)	86 (2)
	Ohio East	2.75	23 (2)	162 (2)	53 (2)

APPENDIX 6. *Average herd liveweight at turn-out, calving and at housing in each year.*

	Turn-out	Calving	Housing
		kg	
System 1			
1994	-	609	603
1995	658	622	620
1996	677	602	589
1997	607	-	-
System 2			
1994	-	589	605
1995	652	626	620
1996	641	630	613
1997	632	-	-
System 3			
1994	-	598	618
1995	653	621	616
1996	681	593	606
1997	664	-	-

APPENDIX 7. *Mean concentrations of MRP, TDP and TP in spot samples of yard run-off, field or road run-off and in standing puddles during the 1996/97 winter.*

Location	Date	TP $\mu g\ l^{-1}$	MRP $\mu g\ l^{-1}$	TDP $\mu g\ l^{-1}$	TDP/TP %
Pennsylvania (Running Water)	19/11/96	2860	53	53	2
Ohio/Road (Running Water)	19/11/96	3600	150	233	4
Cattle Yard (Running Water)	19/11/96	8160	1840	1850	23
Carolina N (Puddle)	19/11/96	3920	1207	1147	31
Ohio/Road (Puddle)	25/02/97	10993	136	136	1
Cattle Yard (Puddle)	25/02/97	4197	846	840	20

APPENDIX 8. *Areas and dry matter (DM) yields of herbage cut from perennial ryegrass (PRG), italian ryegrass (IRG) and maize fields in each system in each year.*

Crop	System 1		System 2		System 3	
	Area (ha)	DM Yield (tonnes)	Area (ha)	DM Yield (tonnes)	Area (ha)	DM Yield (tonnes)
			1994			
PRG - Cut 1	7.62	31.5	7.44	34.8	10.30	48.2
PRG - Cut2	5.40	15.9	3.00	6.8	6.55	11.3
PRG - All cuts		47.4		41.6		59.5
IRG - All cuts	6.00	49.9	-	-	-	-
Maize	-	-	6.00	50.9	6.00	51.7
Total		97.3		92.5		111.2
			1995			
PRG - Cut 1	6.00	16.3	7.50	28.6	9.20	40.6
PRG - Cut 2	3.00	9.7	3.50	9.6	2.00	2.6
PRG - Cut 3	2.00	2.9	3.06	2.8	5.12	6.4
PRG - All cuts		28.9		41.0		49.6
IRG - All cuts	6.00	45.1	-	-	-	-
Maize	-	-	6.00	47.8	6.00	46.2
Total		74.0		88.8		95.8
			1996			
PRG - Cut 1	8.27	37.5	8.22	42.3	11.1	58.6
PRG - Cut 2	2.80	6.7	1.03	2.1	0.0	0.0
PRG - Cut 3	4.00	5.4	5.36	9.0	0.0	0.0
PRG - All cuts		44.2		44.4		58.6
IRG - All cuts	6.00	51.9	-	-	-	-
Maize	-	-	6.00	60.6	6.00	62.3
Total		96.1		105.0		120.9

APPENDIX 9. *Average concentrations of P (g kg^{-1}) at cutting of grassland areas in each system.*

		System 1			System 2			System 3	
		1994	1995	1996	1994	1995	1996	1994	1995
PRG	Cut 1 (May)	3.5	2.9	3.5	2.8	2.7	3.2	2.9	2.7
	Cut 2 (July)	2.5	1.8	1.8	2.8	1.9	1.8	2.7	2.0
	Cut 3 (Aut)	-	3.2	2.9	-	2.4	2.6	-	2.0
IRG	Cut 1 (May)	3.0 [a]	2.9	3.1					
	Cut 2 (June)	2.3	2.2	2.9					
	Cut 3 (July)	-	1.9	2.2					
	Cut 4 (Aug)	-	-	2.7					
	Cut 5 (Nov)	2.1	2.2	2.9					
		3.2							

[a] Geogia North (not included in system 1 but used as a substitute field while the IRG was establishing)

APPENDIX 10. *Inputs and outputs of phosphorus in perennial ryegrass (PRG), italian ryegrass (IRG) and maize areas cut in each system in each year.*

System	Crop	P inputs			P outputs	Balance	
		Fertilizer (kg)	Slurry (kg)	Total (kg)	(kg)	Total (kg)	Load (kg ha^{-1})
				1994			
1	PRG	108.8	54.1	162.9	146.1	+16.8	+1.3
	IRG	220.5	52.9	273.4	126.2	+147.2	+24.5
	Total	329.3	107.0	436.3	272.3	+164.0	+8.6
2	PRG	49.2	89.7	138.9	119.7	+20.9	+1.6
	Maize	52.4	252.1	304.5	81.5	+223.0	+37.2
	Total	101.6	341.8	443.4	199.5	+243.9	+12.8
3	PRG	37.3	93.6	130.9	180.6	-49.7	-2.9
	Maize	0.0	160.6	160.6	82.9	+77.7	+13.0
	Total	37.3	254.2	291.5	263.5	+28.0	+1.2
				1995			
1	PRG	28.7	109.2	137.9	72.0	+65.9	+5.1
	IRG	130.3	127.3	257.6	100.7	+156.9	+26.1
	Total	159.0	236.5	395.5	172.7	+222.8	+11.7
2	PRG	31.2	153.6	184.8	99.1	+85.7	+6.6
	Maize	122.1	285.7	407.8	83.4	+324.4	+54.1
	Total	153.3	439.3	592.6	182.5	+410.1	+21.6
3	PRG	12.0	162.4	174.4	129.4	+45.0	+2.6
	Maize	0.0	159.4	159.4	85.6	+73.8	+12.3
	Total	12.0	333.1	345.1	215.0	+130.1	+5.7
				1996			
1	PRG	31.3	136.4	167.7	157.8	+10.0	+0.8
	IRG	112.3	89.2	201.5	175.1	+26.4	+4.4
	Total	143.6	225.6	369.2	332.9	+36.3	+1.9
2	PRG	14.2	73.6	87.8	161.5	-73.7	-5.7
	Maize	84.0	174.5	258.5	100.5	+158.0	+26.3
	Total	98.2	262.3	360.5	262.0	+98.5	+5.2
3	PRG	0.0	48.8	48.8	199.9	-151.1	-8.9
	Maize	0.0	181.8	181.8	105.8	+76.0	+12.7
	Total	0.0	230.6	230.6	305.7	-75.1	-3.3

APPENDIX 11. *Summary of P inputs and outputs for invidual system fields (excluding transfers at grazing) in system 1.*

Field	Area	P Inputs (kg)			P output	P balance
	(ha)	Fertilizer	Manure	Total	kg	kg ha^{-1}
System 1						
Indiana SE	2.00	24.2	134.1	158.3	79.5	+39.4
Indiana SW	3.54	23.9	42.8	66.7	29.7	+3.7
Tennessee SE	1.00	23.5	9.0	32.5	53.7	-21.2
Tennessee SW	1.08	5.8	7.1	11.7	0.0	+10.8
Virginia SE	3.00	105.0	148.2	253.2	178.5	+24.9
Virginia SE	2.38	47.3	11.0	58.3	36.5	+9.2
Minnesota M	2.37	70.6	27.0	97.6	94.4	+1.3
Minnesota W	2.37	117.1	61.9	179.0	76.2	+43.4
Rhode Island M	3.63	275.4	180.5	455.9	242.9	+58.7
Rhode Island W	3.63	80.3	49.2	129.5	0.0	+35.6
System 2						
Virginia NE	1.11	24.6	74.5	99.1	52.5	+41.9
Virginia NW	3.60	52.8	79.3	132.1	109.8	+6.2
Tennessee ME	1.00	21.3	28.2	49.5	43.9	+5.6
Tennessee MW	2.06	17.1	12.1	29.2	34.2	-2.4
Carolina M E	1.23	12.0	23.0	35.0	46.7	-9.5
Carolina M W	4.00	47.6	135.8	183.4	90.5	+23.2
Pennsylvania S	3.25	141.3	401.7	543.0	149.8	+121.0
Ohio W	2.75	119.4	310.7	430.1	121.4	+112.3
System 3						
Tennessee NE	2.00	0.0	87.7	87.7	97.3	-4.8
Tennessee NW	3.12	0.0	34.0	34.0	88.1	-17.3
Illinois East N	1.99	0.0	8.6	8.6	47.0	-19.3
Illinois East S	2.00	12.0	36.0	48.0	39.0	+4.5
Carolina East N	2.89	0.0	0.0	0.0	6.1	-2.1
Carolina east S	5.00	42.6	231.2	273.8	225.7	+9.6
Pennsylvania N	3.25	0.0	246.0	246.0	148.4	+30.0
Ohio E	2.75	0.0	255.8	255.8	126.1	+47.2

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