DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS **CSG 15**

Research and Development

Final Project Report

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Project title	**SOIL PHOSPHORUS AND HEAVY METAL CONTENTS ON THE NUTRIENT DEMONSTRATION FARMS**
DEFRA project code	**SP0505**
Contractor organisation and location	ADAS Gleadthorpe Research Centre, Meden Vale, Mansfield, Notts. NG20 9PF
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Executive summary (maximum 2 sides A4)

The overall objective of this study was to measure topsoil phosphorus (P) and heavy metal concentrations on three of the Nutrient Demonstration Farms set up under Defra project NT2001, and to assess the rate at which soil P and heavy metals were accumulating on all four of the Nutrient Demonstration Farms. In the UK, animal manure applications to agricultural land supply *c*.119,000 tonnes of P each year. The management of P within agricultural systems in an environmentally sound way is of key importance to the continued development of sustainable farming systems. In addition, concerns have been raised regarding the contamination of agricultural soils with heavy metals and the effects this may have on long-term soil fertility, and metal uptakes into the human food chain.

In February 2000, topsoil samples (0-15 cm) were taken from selected fields at three of the Nutrient Demonstration Farms. The soils were analysed for total and Olsen extractable P and total heavy metals (Zn, Cu, Ni, Cd, Cr, Pb). The degree of P saturation (DPS) was also measured on soil samples taken from Grange and Highlands Farms in order to assess the capacity of the soils to absorb further P inputs. At Grange Farm, 8 fields were selected with elevated soil P levels (ADAS Indices 4-8) and no further P inputs were made after autumn 1999. In autumns 2000 and 2001, topsoil (0-15 cm) samples were taken from these fields and analysed for total, Olsen extractable, calcium chloride ($CaCl_2$) extractable and water soluble P, to quantify any changes in soil P availability over time. Similarly, soil samples were taken from 4 fields at both Horsewold (Index 1-3) and Highlands Farms (Index 3-6), but these fields continued to receive manure additions as part of the normal farm manure management programme. The samples were taken within a 5 m radius of a permanent magnetically located sampling point that could be relocated accurately each year.

Heavy metal budgets were calculated for each of the four farms using farm data on feed inputs and crop outputs. Heavy metal surpluses were quantified and the rate at which soil P and heavy metal concentrations were likely to increase was estimated.

The implications of complying with the Defra 'Water Code' recommendation that "where organic manures are applied to fields at ADAS soil P Index 3 or above care should be taken to avoid total inputs of phosphate from organic manures and fertilisers exceeding the total amount of phosphate removed by crops" on farm manure management practices, was assessed on each farm.

Soil phosphorus

In February 2000, mean topsoil Olsen extractable P concentrations were 39 mg/l - Index 3 (range 19-66 mg/l) at Horsewold Farm, 70 mg/l - Index 4 (range 21-150 mg/l) at Highlands Farm and 105 mg/l - Index 6 (range 31-309 mg/l) at Grange Farm. The high values at Highlands and Grange Farms reflected the long history of poultry manure applications supplying P in excess of crop offtakes. At Grange Farm, topsoil total P concentrations (mean *c*.280 mg/kg) and extractable P concentrations (mean *c*.19 mg/l) showed a trend to decrease where manure applications were withheld between February 2000 and January 2002. At Highlands Farm, the continued layer manure applications (16 t/ha, 416 kg/ha P_2O_5) in autumns 2000 and 2001 showed a trend to increase topsoil total P concentrations by a mean of *c*.140 mg/kg (range 100-180 mg/kg). At Horsewold Farm, the pig slurry (15 m^3/ha, supplying 48 kg/ha P_2O_5) and duck manure (25 t/ha, supplying 319 kg/ha P_2O_5) applications in 2001 and 2002 had no measurable effects on topsoil total P or Olsen extractable P concentrations.

Across all the sites, Olsen extractable, water soluble and $CaCl_2$ extractable P concentrations were strongly related to total topsoil P concentrations ($P<0.001$), and were equivalent to *c*.8%, 6% and 0.5% of total P concentrations, respectively. The mean degree of phosphate saturation was 113% (15 fields; range 34-310%) at Grange Farm and 50% (12 fields; range 15-89%) at Highlands Farm, which was above the Dutch 25-40% threshold value where the soil's capacity to absorb P is exceeded and enhanced leaching and runoff P losses are likely to occur.

Farm P budget calculations identified annual surpluses of 23 kg P_2O_5/ha/yr at Highlands Farm, 30 kg P_2O_5/ha/yr at Grange Farm, 148 kg P_2O_5/ha/yr at Horsewold Farm and 31 kg P_2O_5/ha/yr at Berrowsfield Farm. At Grange Farm, the majority of the poultry manure was exported to neighbouring farms. If this was not the case (i.e. all the manure had to be applied on-farm), then the annual surplus would be over 1000 kg P_2O_5/ha/yr. If the phosphate surplus on each of the farms continued at the present rate it was estimated that all the fields would have an ADAS soil P Index of 3 or greater within 10-20 years. Hence, manures would have to be exported from each farm in order to comply with the recommendation in the Defra 'Water Code' on soils at ADAS P Index 3 or above that "total inputs of phosphate from organic manures and fertilisers should not exceed the total amount of phosphate removed by crops in the rotation".

Soil heavy metals

Soil analysis in February 2000 showed that topsoil heavy metal concentrations at Grange, Horsewold and Highlands Farms were similar to the median values in the National Soils Inventory. At all the farms, annual heavy metal inputs exceeded outputs leading to on-farm surpluses of 0.5-1.8 kg/ha Zn, 0.16-0.89 kg/ha Cu, 0.01-0.05 kg/ha Ni and *c*.0.07 kg/ha Pb. As with P, these surpluses would be 7-10 times greater at Betley if the poultry manure was recycled on farm. The most important sources of Zn and Cu were purchased livestock feeds (>50% of total inputs). Heavy metal loading rates were highest at Horsewold (which also had the highest soil metal concentrations) and Highlands Farms, reflecting the elevated heavy metal contents of the pig and laying hen feeds. The lowest loading rates were at Grange Farm (where the layer manures were exported) and at Berrowsfield Farm, reflecting the low metal contents of the dairy cow feeds. The time taken to reach the maximum permitted soil metal concentrations where sewage sludge is applied to agricultural land ranged for Zn from 196 years at Horsewold Farm to *c*.600 years at Grange and Berrowsfield Farms, and for Cu from 483 years at Horsewold Farm to 2,725 years at Berrowsfield Farm. For the other metals, the time taken to reach the soil limit values ranged from *c*.2,300 to >10,000 years.

The results of this work will assist Defra in achieving its policy objectives of quantifying and limiting P losses from agricultural systems, and in providing a sound scientific base to ensure that agricultural soils in England and Wales are not subject to long-term irreversible degradation as a result of heavy metal pollution from farm manure additions.

Scientific report (maximum 20 sides A4)

1. OBJECTIVES

The overall objective of the project was to measure topsoil phosphorus (P) and heavy metal concentrations on three of the Nutrient Demonstration Farms set up under Defra project NT2001, and to assess the rate at which soil P and heavy metals were accumulating on all four of the Nutrient Demonstration Farms.

More specifically the objectives of the project were:

- To determine topsoil phosphorus and heavy metal concentrations on three of the Nutrient Demonstration Farms.
- To quantify changes in soil extractable P levels over time where P inputs were withheld or continued to be made via farm manure additions.
- To establish the rate at which topsoil phosphorus and heavy metal levels were accumulating using farm budget calculations
- To assess the management practices required to recycle manures in accordance with the Defra Water Code phosphorus management guidelines.

2. EXTENT TO WHICH OBJECTIVES HAVE BEEN MET

The study has successfully quantified topsoil P and heavy metal contents, and heavy metal balances on the Nutrient Demonstration Farms. Mean Olsen extractable P levels were 39 mg/l - Index 3 at Horsewold Farm, 70 mg/l - Index 4 at Highlands Farm and 105 mg/l - Index 6 at Grange Farm. The high soil P levels at Highlands and Grange Farms reflected the long history of layer manure applications supplying P in excess of crop offtakes. At Grange Farm, there was some evidence that withholding manure applications for two harvest seasons reduced soil extractable P (mean *c*.19 mg/l) and total P concentrations (mean *c*.280 mg/kg). Farm P budget calculations identified annual surpluses on the farms of between 23 and 148 kg/ha P_2O_5 /year. If the phosphate surplus on each of the farms continued at the present rate it was estimated that all the fields would have an ADAS soil P Index of 3 or greater within 10-20 years, and that manures would have to be exported to comply with the Defra ‘Water Code’ recommendation on soils at ADAS P Index 3 or above “that total inputs of phosphate from organic manures and fertilisers should not exceed the total amount of phosphate removed by crops in the rotation”.

Topsoil heavy metal concentrations at Grange, Horsewold and Highlands Farms were similar to the median values the National Soils Inventory. Heavy metal surpluses ranged from 0.5-1.8 kg/ha Zn, 0.16-0.89 kg/ha Cu, 0.01-0.05 kg/ha Ni and *c*.0.07 kg/ha Pb. The time taken to reach the maximum permitted soil metal concentrations where sewage sludge is applied to agricultural land ranged for Zn from 196 years at Horsewold Farm to *c*.600 years at Grange and Berrowsfield Farms, and for Cu from 483 years at Horsewold Farm to 2,725 years at Berrowsfield Farm. For the other metals, the time taken to reach the soil limit values ranged from *c*.2,300 to >10,000 years.

The results of this work will assist Defra in achieving its policy objectives of quantifying and limiting P losses from agricultural systems, and in providing a sound scientific base to ensure that agricultural soils in England and Wales are not subject to long-term irreversible degradation as a result of heavy metal pollution from farm manure additions.

3. BACKGROUND

In recent years, concern has increased about the contribution of agriculture to phosphorus (P) losses to surface and groundwater systems, as P is the main cause of eutrophication in fresh water systems. Recent estimates by the Environment Agency suggest that agriculture is responsible for 43% of P inputs to surface water sources, compared with 24% from human and domestic waste in sewage, and 19% from detergents (Environment Agency, 2000). In the UK, animal manure applications to agricultural land supply *c*.119,000 tonnes of P each year Smith *et al*.(1998). The management of P within agricultural systems in an environmentally sound way is therefore of key importance to the continued development of sustainable farming systems. In addition, concerns have also been raised regarding the contamination of agricultural soils with heavy metals and the effects that this may have on long-term soil fertility, and metal uptakes into the human food chain. A study on the relative importance of different sources of metals to agricultural soils estimated that *c*.40% of Zn and Cu inputs were from animal manures, with pig and poultry manures of particular importance (Nicholson *et al*., 1998). Fertilisers and lime were estimated to contribute 34% of total Cd inputs to soils.

In 1997/98, four Nutrient Demonstration Farms (Figure 1) were established by Defra as part of the "Making the Most of Manure" campaign to promote the improved management of nutrient inputs to crops from manures and crop residues on commercial farms, and to minimise losses to the environment. Annual P budget calculations on these farms identified surpluses in the range 24-150 kg P_2O_5/ha per annum (Garwood and Chambers, 1999), which largely arose from the livestock enterprises (particularly pig and poultry production). The soil analyses undertaken in 1997 showed that at Grange Farm over 90% of the soils had an ADAS P Index of 3 or above (50% above Index 5), at Highlands Farm *c*.70%, and at Horsewold and Berrowsfield Farms *c*.30% were P Index 3 or above. The Code of Good Agricultural Practice for the Protection of Water (Defra, 1998) recommends that "where organic manures are applied to fields at ADAS soil P Index 3 or above care should be taken to avoid total inputs of phosphate from organic manures and fertilisers exceeding the total amount removed by crops in the rotation". The implications of witholding P additions on the extractable P status of soils with high P levels and the management practices required to recycle manures in accordance with the Defra 'Water Code' recommendation needed evaluation on the Nutrient Demonstration Farms (Defra project NT2001).

Figure 1. Location of Nutrient Demonstration Farms

Defra policies require information to quantify and limit P losses from agricultural systems. Also, the policies aim to ensure that agricultural soils in England and Wales are not subject to long-term irreversible degradation as a result of heavy metal pollution. The objective of this study was to measure topsoil P and heavy metal concentrations on three of the Nutrient Demonstration Farms, and to assess the rate at which topsoil P and heavy metal levels were accumulating on all four of the Nutrient Demonstration Farms.

3. MATERIALS AND METHODS

3.1. Farm details

(i) Horsewold Farm (Middleton on the Wolds, East Yorkshire)

A mixed farm with 182 ha of arable land on shallow soils above chalk (mainly Andover, Panholes and Burlingham Associations). Average annual rainfall is 700 mm. Around 65% of the land was used for winter cereal and oilseed rape production, 15% vining peas, 15% potatoes and 5% set-aside. The pig unit finished *c.* 8,000 bacon pigs (95 kg) per annum. The farm also had a duck growing unit with four sheds, each producing 6 crops of 9,000 birds per year (216,000 birds in total). Each year *c.*3,300 m^3 of pig slurry was produced, along with 1,500 tonnes of duck farmyard manure (FYM).

Figure 2. Redrock tanker and SAK trailing hose boom at Horsewold Farm

Slurry storage was in a 'tin tank' and below the slats in the pig houses, giving *c.*3 months capacity. At the start of project NT2001 (autumn 1998), the pig slurry was spread using a Tramspread boom attached to an 8 m^3 Malgar tanker. The Tramspread was capable of spreading pig slurry evenly (coefficient of variation < 25%) over a 12m bout width, but did not fit the 21m tramlines used at Horsewold Farm. Slurry topdressing in spring was not possible with this boom because of concerns about soil and crop damage. As a result, slurry was spread onto stubbles in the autumn (before cereals) and during winter (before vining peas and borage), and on to set-aside land in the spring and summer. In spring 1999, a 13.6 m^3 slurry tanker with a 21m SAK trailing hose boom (Figure 2) was purchased, which enabled the farm to topdress *c.*50% of the pig slurry produced to growing winter cereal and oilseed rape crops in spring, with spreader coefficients of variation measured at 16% and 21% (both below the acceptable 25% threshold suggested by Chambers *et al.,* 2001). The duck FYM was usually stored in field heaps before being spread on arable stubbles in the autumn, prior to the establishment of winter cereals or oilseed rape.

(ii) Grange Farm (Betley, Cheshire)

A mixed arable and grassland farm managed in 3 units, *c.*2 miles apart, covering approximately 200 ha of light (Wick Assocation) and medium/heavy textured soils (Clifton Association). Average annual rainfall is 750 mm. In the region of 17,000 m^3 of slurry from the 300 cow dairy herd and 5,500 tonnes of 'dry' layer manure from 450,000 laying hens was produced each year. The slurry was stored in a lagoon with a capacity of *c.*4 months and the layer manure stored under the stilt house giving *c.*12 months storage capacity.

At the start of the NT2001 project (1998), all the cattle slurry was spread using an umbilical system fitted with a splash-plate which could only access the fields at Grange Farm (85ha), with 30% of the cattle slurry applied in the autumn/winter to cereal stubbles and grassland, and 20% and 50% applied to grassland in spring and summer, respectively. The purchase of a 11 m^3 Joskin slurry tanker with a 12 m trailing hose boom in summer 2000, facilitated the transport of slurry from Grange Farm to the outlying blocks of arable land and grassland (spreader coefficient of variation measured at 26%). At the end of the project (2002) around 75% of the slurry was topdressed to arable and grassland crops in spring and summer, with *c.*10% spread in the autumn and 15% spread in winter (to prevent the lagoon from overflowing). Over 95% of the layer manure was exported and spread on neighbouring farms compared with less than 10% at the start of the project.

Figure 3. Joskin tanker and 12m trailing hose boom at Grange Farm

(iii) Berrowsfield Farm (Inkberrow, Worcestershire)

A mixed farm covering 160 ha (90 ha arable and 70 ha grassland) on heavy clay soils of the Denchworth Association. All the fields were underdrained, mostly with pipes at 60 m spacing and permeable fill to within 30 cm of the surface. Mole drains at 2 m spacing and 50 cm depth are renewed every 5 years. In the region of 6000 m^3 of separated slurry and dirty water from the 150 dairy cow herd were spread annually to grassland. At the start of the NT2001 project (1998), slurry was spread using a tractor mounted splash plate fed by a lay flat umbilical pipe and a Bauer pump. In summer 2000, the splashplate was replaced by a 6 m Veenhuis VMZ trailing shoe boom (Figure 4) and slurry was spread in early spring or to first cut silage aftermaths in late spring/early summer (spreader coefficient of variation measured at 20%). Approximately 1,300 tonnes of separated slurry solids and straw-based manure (FYM) from 150 young stock were spread on winter cereal land in autumn, and maize land in late winter /early spring.

Figure 4. Veenhuis 6m trailing shoe boom at Berrowsfield Farm

(iv) Highlands Farm (Rettendon, Essex)

An arable farm covering 420 ha on heavy clay soils of the Windsor Association, with 93,000 laying hens housed in 3 deep-pit buildings. Average annual rainfall is 600 mm. Piped field drainage (with moles) was present in most fields to control seasonal waterlogging. Approximately two-thirds of the farmed area fell within the Chelmer and Blackwater Nitrate Vulnerable Zone (designated in December 1998). In the region of 4,133 tonnes of layer manure were produced annually, with the deep pits under the houses providing up to 13 months storage. The pits were emptied throughout the year onto field storage sites. As the soils on the farm were heavy clays, the majority of the manure was spread in the autumn prior to cultivation for the next crop, when the land was trafficable. Around 65% was spread before winter wheat, 25% before winter oilseed rape and 10% before spring oilseed rape.

Figure 5. Bunnings Highlander manure spreader at Highlands Farm

The layer manure was spread using a Bunnings Highlander machine with moving bed and spinning discs (spreader coefficient of variation measured at 17%). In order to minimise odour nuisance, the agreement with the local District Council is that manure applications will be incorporated into the soil within 24 hours of application. At the start of the NT2001 project (1998), the manure was spread over one-third of the cropping area (129 ha), but changes to manure management practices by the end of the project meant that manure was spread over two-thirds of the cropping area (258 ha).

3.2. Soil and crop sampling and analysis

In February 2000, topsoil samples (0-15 cm) were taken from selected fields at three of the Nutrient Demonstration Farms (Table 1). At Grange and Highlands Farms, the majority of the fields had extractable P levels of ADAS Index 5 and above, so samples were also taken from lower P status soils on the farms to provide information on more ‘typical’ soil P and heavy metal levels. The soils were analysed for total and Olsen extractable P (along with pH, extractable K and Mg), and total heavy metals (Zn, Cu, Ni, Cd, Cr, Pb) using standard analytical techniques (Anon., 1986). The degree of P saturation (DPS) was also measured on the soil samples taken from Grange and Highlands Farms, in order to assess the capacity of the soils to absorb further P inputs using the Dutch soil P saturation method (Schoumans, pers. comm.). The soils at Horsewold Farm (calcareous silty clay loams over chalk at *c*.30cm) were excluded from this analysis, as the method is only appropriate for non-calcareous soils.

Table 1. Soil samples taken in February 2000 from the Nutrient Demonstration Farms

Farm	Total number of fields	Number of fields sampled (2000)	P status (1997)
Grange	34	16	Index 1-8
Horsewold	15	7	Index 1-3
Highlands	35	12	Index 2-6

At Grange Farm, 8 fields were selected with elevated soil P levels (ADAS Indices 4-8) and no further P inputs were made after autumn 1999. In autumns 2000 and 2001, topsoil (0-15 cm) samples were taken from these fields and analysed for total, Olsen extractable, calcium chloride extractable and water soluble P, to quantify any changes in soil P availability over time. Similarly, soil samples were taken from 4 fields at Horsewold Farm (Index 1-3) and 4 fields at Highlands Farm (Index 3-6), but these fields continued to receive manure additions as part of the normal farm manure management programme. Soil samples were taken within a 5m radius of a permanent magnetically located sampling point that could be relocated accurately each year.

Where wheat crops were grown, newest fully expanded leaf samples were collected between growth stages 32 and 39 to assess whether soil P supply was sufficient for plant growth. A total of 20-30 leaves were collected from plants within a 5m radius of the marked soil sampling point. At Highlands Farm, 7 fields were sampled in May 2000 and 4 in May 2001, at Horsewold Farm 3 fields were sampled in both June 2000 and 2001, and at Grange Farm 6 fields were sampled in May 2000 (samples were not taken in 2001 due to site access restrictions resulting from the Foot and Mouth disease outbreak).

3.3. Farm budgets

Farm heavy metal (Zn, Cu, Ni, Cr, Pb and Cd) budgets were calculated using data on the quantities of different materials entering or leaving the farm (Table 2), based on the data reported for 1997 by Garwood and Chambers (1999). Heavy metal concentrations were measured in compound feeds brought onto the farms (except at Inkberrow) and 'standard' figures used for all the other inputs (e.g. fertiliser inputs, atmospheric deposition rates, leaching losses). Manures that were recycled on farm were excluded from the budget calculations, although any manures leaving the farm (e.g. for use on neighbouring land) were treated as an output.

At each of the four Nutrient Demonstration Farms, the heavy metal 'surpluses' were quantified and using the previously completed P budgets (Garwood and Chambers, 1999), the rate at which soil P and heavy metal concentrations were likely to be increasing was estimated.

3.4. Defra 'Water Code' implications

The Defra 'Water Code' recommends that "where organic manures are applied to fields at ADAS soil P Index 3 or above care should be taken to avoid total inputs of phosphate from organic manures and fertilisers exceeding the total amount of phosphate removed by crops in the rotation" (Defra, 1998). Using results from the soil samples taken in 1997 and 2000 and the previous P budget calculations, the land area required to recycle the manures produced on the Nutrient Demonstration Farms in accordance with the Defra 'Water Code' recommendation was calculated.

Table 2. Summary of the inputs and outputs included in the heavy metal budget calculations

Inputs	Outputs
Inorganic fertilisers and lime	Crops sold
Seeds - brought in	Straw sold
Livestock feeds - brought in	Animal products sold: meat, milk, eggs
Bedding - brought in	Livestock manures - exported
Animals - brought in	Leaching
Drinking water	Soil erosion
Irrigation water	
Organic manures - brought in	
Atmospheric deposition	
Agrochemicals	

Data sources: Alloway *et al*. (1997); Chambers (1997); Chater & Williams (1974); Marks (1996); Nicholson *et al*. (1999).

4. RESULTS AND DISCUSSION

4.1. Topsoil P status of the Nutrient Demonstration Farms

Many of the fields on the Nutrient Demonstration Farms had a high P status as a result of repeated manure applications. In spring 2000, mean topsoil Olsen extractable P concentrations were on average 39 mg/l (ADAS Index 3) at Horsewold Farm, 70 mg/l (Index 4) at Highlands Farm and 105 mg/l (Index 6) at Grange Farm. Although the range of measured values was large (19-66 mg/l at Horsewold, 21-150 mg/l at Highlands and 31-309 mg/l at Grange Farm), with some very high concentrations (ADAS Index 9) measured at Grange Farm (Table 3).

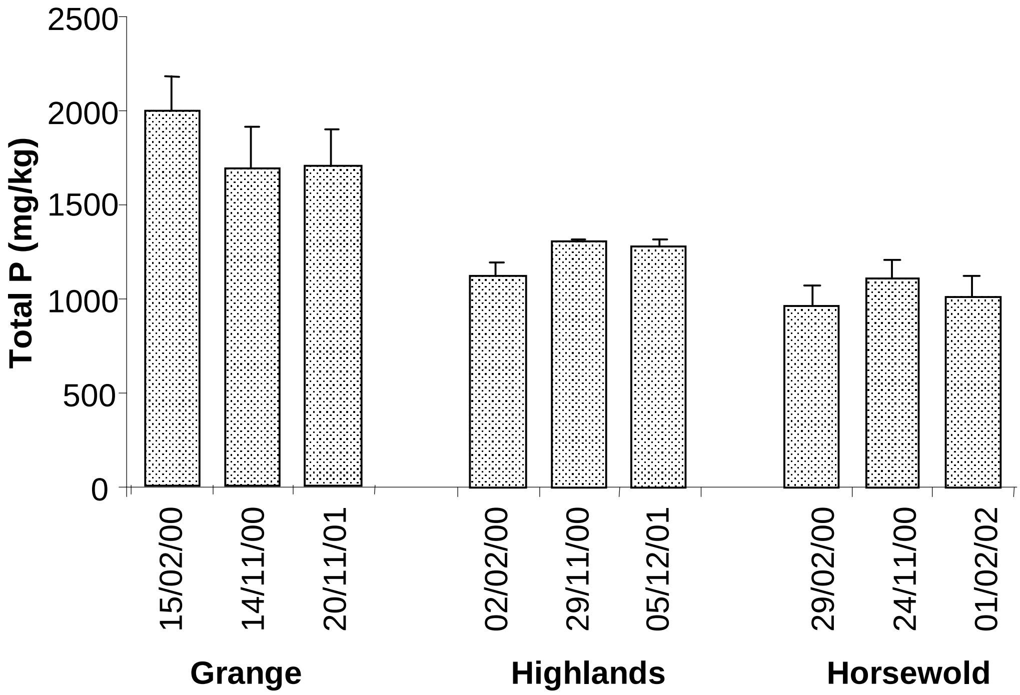
From autumn 1999 to January 2002, manure applications were withheld from the fields sampled at Grange Farm. During this period, topsoil total P concentrations showed a trend to decrease (mean of 278mg/kg; range 0-800 mg/kg), (Figure 1), but this could not be confirmed statistically (P>0.05). Olsen extractable P concentrations also showed a trend to decrease (mean 19 mg/l; range 0-67 mg/l) during this period (Figure 2), but again this decrease could not be confirmed statistically (P>0.05).

Table 3. Topsoil (0-15 cm) Olsen extractable P concentrations on the Nutrient Demonstration Farms (spring 2000)

Farm	Extractable P (mg/l)	Range (mg/l)
Grange	105 (Index 6)	31-309 (Index 3-9)
Highlands	70 (Index 4)	21-150 (Index 2-7)
Horsewold	39 (Index 3)	19-66 (Index 2-4)

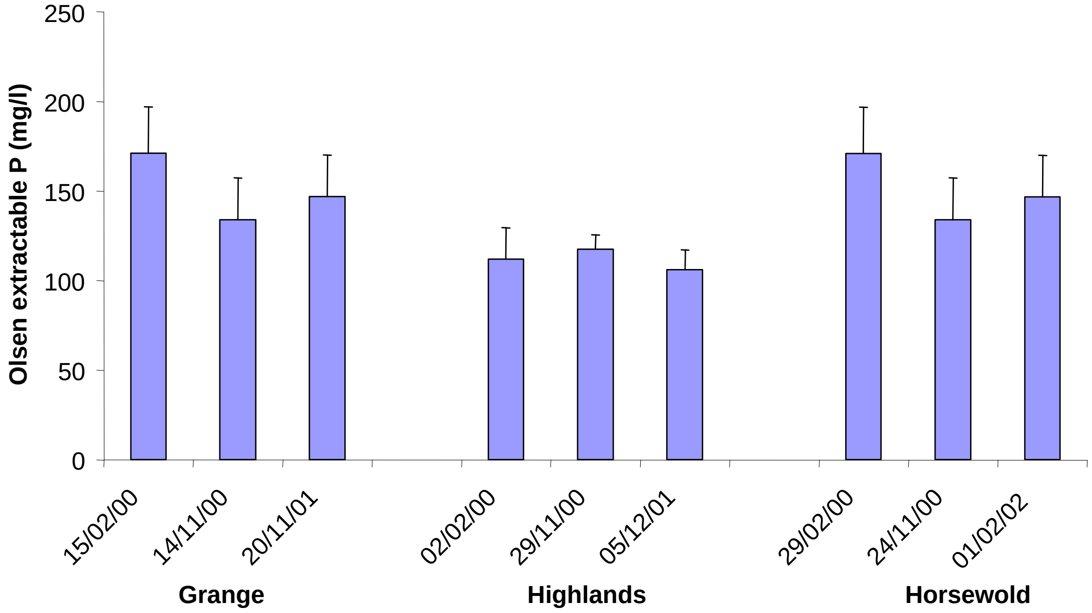
At Highlands Farm, two of the fields sampled received poultry manure in both 2000 and 2001. The layer manure was applied at *c*.16 t/ha and was estimated to contain 13 kg/t P_2O_5 (Anon., 2000), supplying a total of 416 kg/ha P_2O_5 (183 kg/ha total P) over the sampling period. A small increase (mean 140 mg/kg; range 100-180 mg/kg) in topsoil total P concentrations was measured on these fields between February 2000 and December 2001 (Figure 1).

Figure 1. Changes in topsoil total P concentrations at the Nutrient Demonstration Farms over a 2 year period



At Horsewold Farm, either pig slurry (*c*.15 m^3/ha, supplying an estimated 48 kg/ha P_2O_5 or 21 kg/ha total P) or duck manure (*c*.25 t/ha, supplying an estimated 319 kg/ha P_2O_5 or 140 kg/ha total P) was applied to 3 of the 4 fields sampled between February 2000 and 2002. During this period, there were no measurable changes (P>0.05) in topsoil total P (Figure 1) or Olsen extractable P concentrations (Figure 2).

Figure 2. Changes in topsoil extractable P concentrations at the Nutrient Demonstration Farms over a 2 year period



Olsen extractable, water soluble and $CaCl_2$ extractable P concentrations were strongly related (P<0.001) to total topsoil P concentrations across all of the sites (Figures 3-5), and were equivalent to *c*.8%, 6% and 0.5% of total P concentrations, respectively. Concentrations of $CaCl_2$ extractable P were <15 mg/kg in all of the soils sampled, except those at Index 7-9 at Grange Farm where concentrations were up to 25 mg/kg.

Figure 3. Relationship between topsoil total P and Olsen extractable P concentrations at the Nutrient Demonstration Farms (2000-2001)

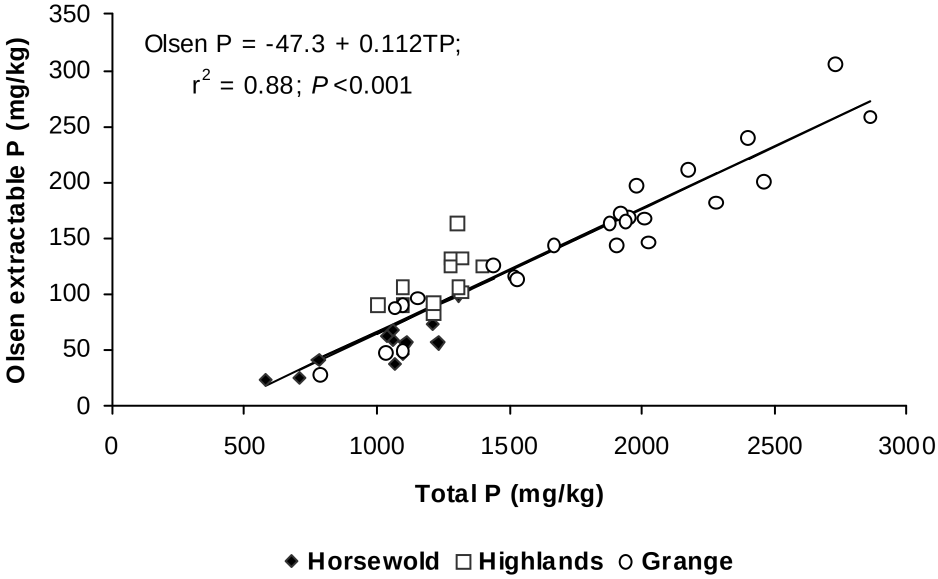


Figure 4. Relationship between topsoil total P and water soluble P concentrations at the Nutrient Demonstration Farms (2000-2001)

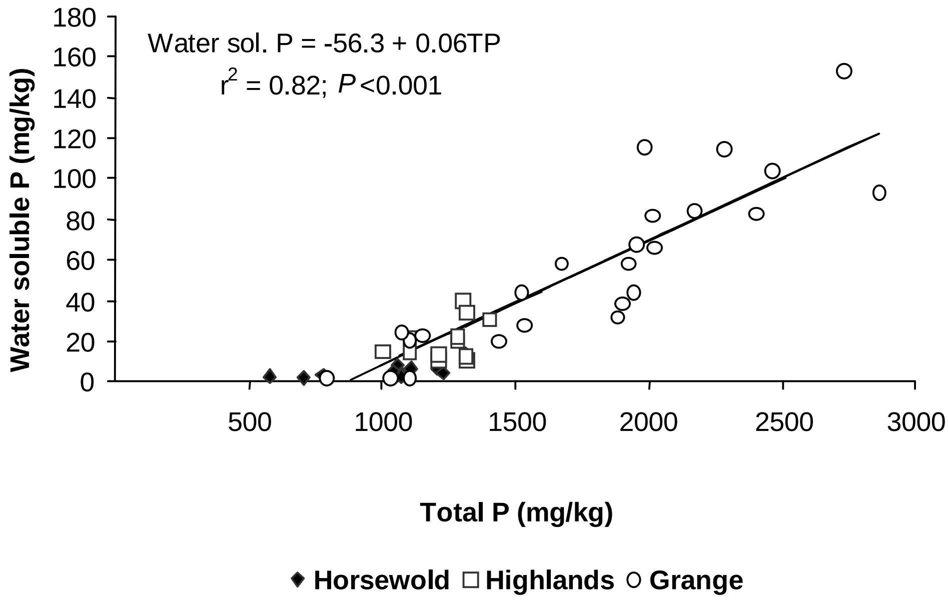
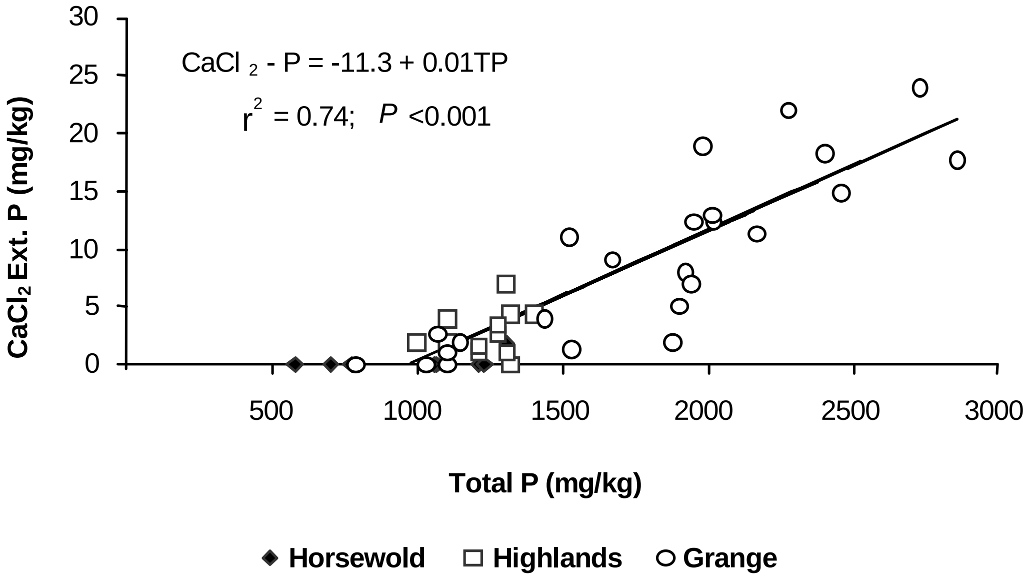


Figure 5. Relationship between topsoil total P and calcium chloride ($CaCl_2$) extractable P concentrations at the Nutrient Demonstration Farms (2000-2001)



4.1.1. Degree of phosphate saturation

The degree of phosphate saturation (DPS) has been used in the Netherlands as a simple index with which to quantify the eutrophication risk from P leaching, erosion or runoff from agricultural soils supporting livestock enterprises (Breeuwsma & Schoumans, 1987; Breeuwsma *et al*., 1995). DPS is the ratio between the amount of phosphate accumulated in a soil and the maximum phosphate sorption capacity of that soil. The phosphate sorption capacity (PSC) depends on a number of soil properties (clay, organic matter, iron and aluminium contents). In acid and neutral soils, P fixation takes place largely on iron (Fe) and aluminium (Al) hydroxides, which can be bound to organic matter. Measurement of the amount of Fe and Al hydroxides in soils therefore gives a measure of PSC (Schoumans *et al.,* 1986). DPS values of 25-40% have been suggested as a threshold for the release of soluble P from soils in runoff (Breeuwsma *et al.*, 1995).

DPS values at Grange Farm ranged from 34-310% (Table 4). The soils with a DPS >100% (5 fields) all had very high extractable P concentrations (>100 mg/l Olsen P, Index 6-9), whereas those at Indices of 3 and 4 (8 fields) had DPS values of *c*.50% (35-66%). However, there was only one field with a DPS less than the 40% threshold (containing 30 mg/l Olsen P, Index 3), suggesting that the risks of P leaching and runoff from the soils at Grange Farm was high.

Table 4. Degree of phosphate saturation (DPS) in the topsoils at Betley and Rettendon (mean & range)

Farm	DPS (%)
Grange (14 fields)	113 (34-310)
Highlands (12 fields)	50 (15-89)

At Highlands Farm, DPS values ranged from 15-89% (Table 4). Again, DPS values >60% (2 fields) were associated with soils containing >100 mg/l Olsen P (Index 6), whereas soils at Index 2-4 (<55 mg/l Olsen P) had DPS values in the range 15-54% (mean 33%). There were 4 fields with DPS values of less than 40% (Index 2-3).

These results suggest that non-calcareous soils at ADAS P Index ≥ 4 will have an elevated DPS (>40%) and associated high risks of P leaching and runoff.

4.1.2. Crop phosphorus concentrations

The analysis of P concentrations in plant material can be used to help diagnose if P is limiting crop growth. For winter wheat, the recommended test is based on %P in the dry matter of newest fully expanded leaf samples taken during stem extension (Bollons *et al.*, 1997). Critical %P concentrations needed for 95% of maximum grain yield range from 0.28-0.38% (HGCA, 1998).

Wheat leaf P concentrations were satisfactory (>0.28%) at Grange and Highlands Farms in both 2000 and 2001, indicating that soil P supply was adequate for crop growth (Table 5). However, at Horsewold Farm two of the three fields sampled in both 2000 and 2001 (i.e. 4 fields in total) had wheat leaf P concentrations of <0.28% (0.26-0.27%). Three of these fields had soil P concentrations between 19-21 mg/l (Index 2) despite recent manure applications (see Section 4.1), suggesting that the crop had 'borderline' P concentrations for maximum yield.

Table 5. Total P concentrations (%) in winter wheat leaves at Grange, Highlands and Horsewold Farms (median and ranges)

Farm	May/June 2000	May/June 2001
Grange (5 fields)	0.39 (0.32-0.45)	nd
Highlands (2000: 7 fields; 2001: 4 fields)	0.42 (0.36-0.55)	0.38 (0.32-0.43)
Horsewold (3 fields)	0.28 (0.26-0.32)	0.29 (0.26-0.35)

nd = no data

4.2. Soil heavy metal concentrations

Topsoil heavy metal concentrations at Grange, Highlands and Horsewold Farms were similar to the median values in the National Soils Inventory (McGrath & Loveland, 1992), Table 6. All the values were below the maximum permissible soil heavy metal concentrations where sewage sludge is applied to agricultural land (DoE, 1996)

Table 6. Topsoil total heavy metal concentrations (mg/kg dm) at the Nutrient Demonstration Farms (mean and ranges)

Site		Zn	Cu	Ni	Cr	Pb	Cd
Grange Farm	Mean	69	25	14	22	19	0.12
	Range	30-112	9-50	8-20	13-26	10-23	<0.10-0.24
Highlands Farm	Mean	79	35	19	45	28	0.20
	Range	65-93	18-58	15-24	32-60	23-34	0.10-0.27
Horsewold Farm	Mean	109	25	37	30	41	0.59
	Range	90-124	16-35	35-38	28-35	35-44	0.51-0.67
NSI[1]		82	18	23	39	40	0.7
Soil limit[2]		200	135	75	400	300	3

[1]Median value from the National Soils Inventory (McGrath & Loveland, 1992)
[2]Maximum permissible concentrations in soils where sewage sludge is applied to agricultural land (DoE, 1996)

Metal concentrations were generally lowest in the sandy soils at Grange Farm, with the silty clay loam soils at Horsewold Farm having the highest concentrations of Zn, Ni, Cd and Pb, and the clay soils at Highlands Farm the highest concentrations of Cu and Cr. These concentrations were principally a result of background soil type (i.e. clay soils tend to have higher metal concentrations than sandy soils) and manure metal loading inputs (pig and poultry manures are the most important sources of Zn and Cu).

4.3. Farm budgets

The farm heavy metal budgets were calculated using national figures for most inputs and outputs (Table 2), although feed samples were analysed at Grange, Highlands and Horsewold Farms to provide farm specific figures. Heavy metal concentrations measured in most of the feeds were within the range of values reported by Nicholson *et al.* (1999) for *c*.180 livestock feed samples (Table 7). On all the farms, annual inputs of heavy metals exceeded outputs leading to on-farm surpluses of 0.5-1.8 kg/ha Zn, 0.16-0.89 kg/ha Cu, 0.01-0.05 kg/ha Ni and *c*.0.07 kg/ha Pb (Table 7). Although, these surpluses would be 7-10 times greater at Grange Farm if the poultry manure was recycled on farm.

Table 7. Heavy metal and dry matter contents of livestock feeds from the Nutrient Demonstration Farms

Site	Feed type	Sample no.	Zn	Cu	Ni (mg/kg dry matter)	Cr	Pb	Cd	Dry matter (%)
Grange Farm	Layer	9	106	18.2	2.6	1.52	2.41	0.33	88.3
Highlands Farm	Layer	3	130	24.6	0.8	0.83	2.42	0.25	88.4
Horsewold Farm	Duck	3	117	23.4	2.7	1.59	0.77	<0.10	87.3
*Nicholson**	*Layer*	*4*	*94-311*	*11-56*	*1.3-5.2*	*0.3-1.3*	*<1-1.12*	*0.3-0.5*	*88.4-89.4*
Horsewold Farm	Pig	3	196	155	4.4	2.52	0.87	0.18	15.8
*Nicholson**	*Finisher pigs*	*7*	*173-986*	*90-183*	*1.2-4.3*	*<0.2-1.2*	*<1-1.5*	*<0.1-0.15*	*87.2-88.5*
Grange Farm	Cattle	6	64	23.5	2.0	1.19	1.59	0.08	37.5
*Nicholson**	*Dairy cake*	*15*	*39-289*	*11-77*	*0.6-7.2*	*0.6-3.9*	*<1-5.2*	*<0.1-0.4*	*84.5-87.9*

*From Nicholson *et al.* (1999)

The details of Highlands Farm were also entered into a European heavy metal budget for 'typical livestock farm types', as part of the AROMIS Concerted Action (AROMIS, 2000). The resulting budget (using European averages) was very similar to that calculated in Table 8 (using UK National figures and actual feed analyses), with Zn and Cu surpluses of 1.62 kg Zn/ha/yr and 0.25 kg Cu/ha/yr compared with 1.24 kg Zn/ha/yr and 0.26 kg Cu/ha/yr in Table 8.

The proportions of heavy metal inputs to each farm from livestock feeds, atmospheric deposition, fertilisers and lime, and other sources (seeds, bedding, water, etc.) are shown in Figure 6. The most important sources of Zn and Cu (>50% of total inputs) on all the farms were livestock feeds. In the cases of Ni and Pb, livestock feeds and atmospheric deposition were the most important sources.

Farm P budget calculations (Table 8) on the four Nutrient Demonstration Farms in 1997 identified annual surpluses of 23 kg P_2O_5/ha/yr at Highlands Farm, 30 kg P_2O_5/ha/yr at Grange Farm, 148 kg P_2O_5/ha/yr at Horsewold Farm and 31 kg P_2O_5/ha/yr at Berrowsfield Farm, based on the cropped areas of each farm (Garwood and Chambers, 1999). At Grange Farm, the majority of the poultry manure was exported to neighbouring farms (hence the high P output from this farm in Table 8). If this was not the case (i.e. all the manure was applied on farm) the annual surplus would be over 1000 kg P_2O_5/ha/yr.

Table 8. Annual heavy metal and P balances on the Nutrient Demonstration Farms

Farm		Zn	Cu	Ni	Cr	Pb	Cd	P
Grange (206ha)	Inputs (kg)	1,840	340	47.1	29.0	53.2	5.9	108,670
	Manure exported:							
	Outputs (kg)	1,663	285	40.6	24.3	37.7	5.2	104,673
	Surplus (kg)	176	55.4	6.5	4.6	15.3	0.7	2,699
	Surplus (kg/ha)	*0.85*	*0.27*	*0.03*	*0.02*	*0.07*	*0.003*	*13.1*
	Manures retained:							
	Outputs (kg)	104	7.0	1.5	1.0	2.8	0.2	18,016
	Surplus (kg)	1,735	333	45.6	28.0	50.2	5.7	90,654
	Surplus (kg/ha)	*8.42*	*1.62*	*0.22*	*0.14*	*0.24*	*0.03*	*440*
Highlands (411 ha)	Inputs (kg)	610	123	9.5	10.2	29.9	2.05	122,42
	Outputs (kg)	102	15	5.9	0.7	2.3	0.55	8,114
	Surplus (kg)	508	108	3.6	9.4	27.7	1.50	4,128
	Surplus (kg/ha)	*1.24*	*0.26*	*0.01*	*0.02*	*0.07*	*0.004*	*10.0*
Horsewold (182 ha)	Inputs (kg)	368	167	9.9	6.2	12.9	0.74	14,874
	Outputs (kg)	37	5.0	1.0	0.19	0.79	0.18	3,032
	Surplus (kg)	331	162	8.8	6.1	12.1	0.56	11,842
	Surplus (kg/ha)	*1.82*	*0.89*	*0.05*	*0.03*	*0.07*	*0.003*	*65.1*
Berrowsfield (171 ha)	Inputs (kg)	98	28	3.2	3.3	9.0	0.53	4,654
	Outputs (kg)	13	1.5	0.4	0.4	0.02	0.01	2,362
	Surplus (kg)	85	26.5	2.8	2.9	8.98	0.52	2,292
	Surplus (kg/ha)	*0.50*	*0.16*	*0.02*	*0.02*	*0.05*	*0.003*	*13.40*

4.4. Heavy metal loading rates

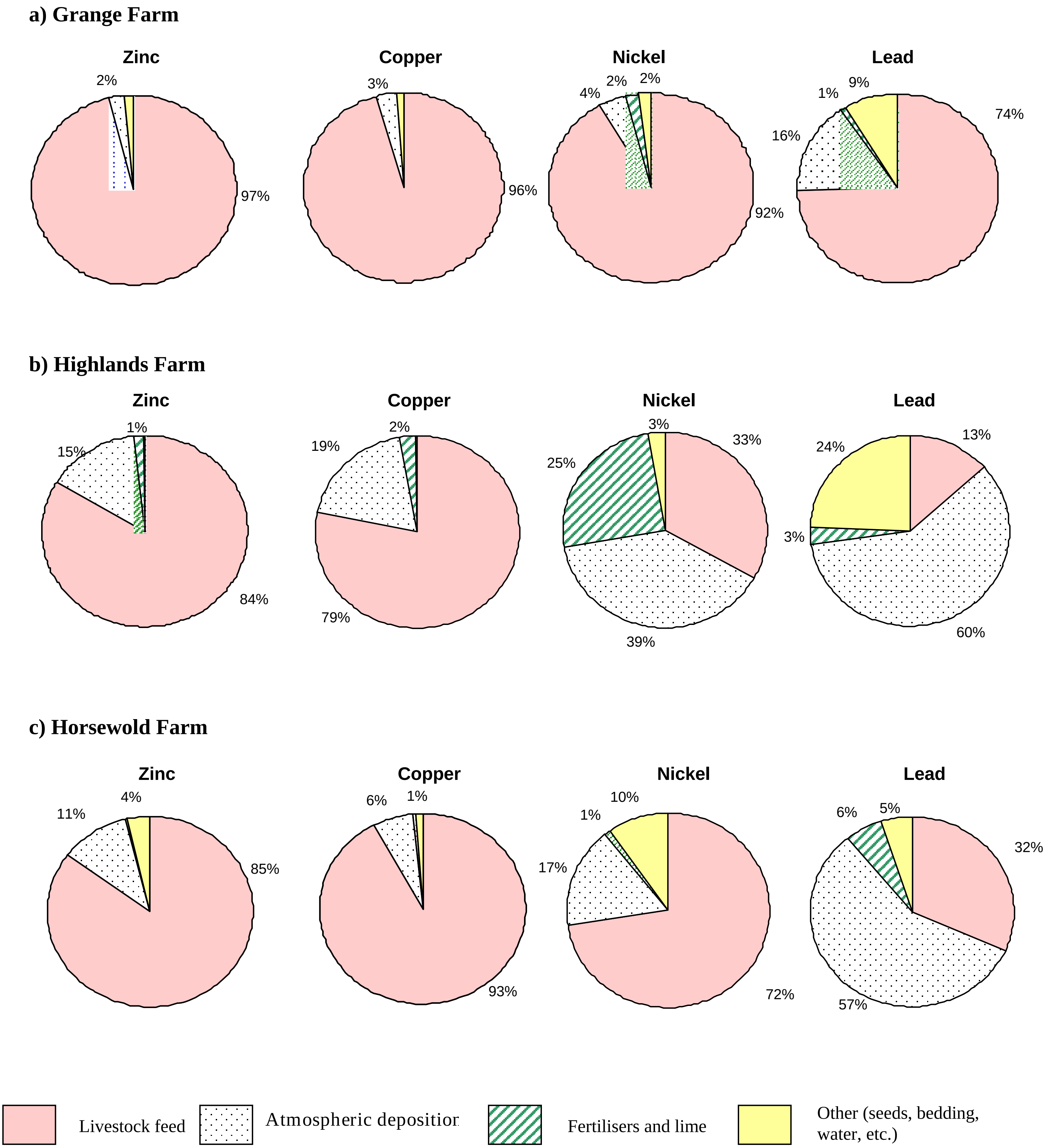
Annual heavy metal loading rates were calculated for each of the farms assuming the surplus (Table 8) was distributed across the whole of the farmed area. Zinc and copper had the highest loading rates on each farm ranging from 0.5-1.8 kg Zn/ha/yr and from 0.16-0.89 kg Cu/ha/yr, respectively, with loading rates from all the other metals less than 0.1 kg/ha/yr (Table 9).

Table 9. Heavy metal loading rates and time taken to reach soil metal concentration limits where sewage sludge is recycled to agricultural land (DoE, 1996)

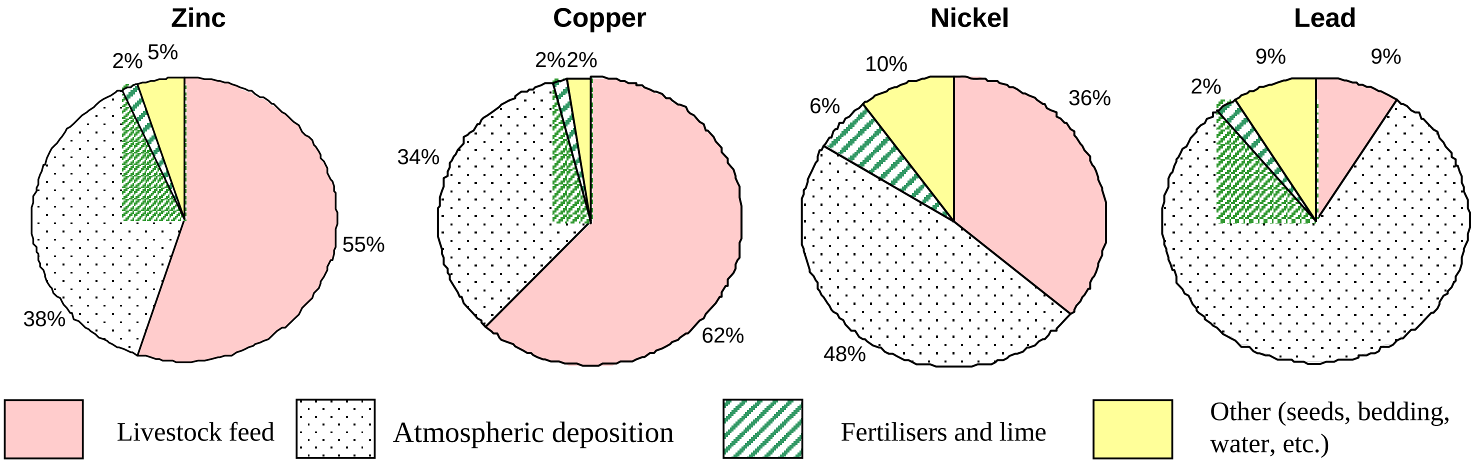
Farm		Zn	Cu	Ni	Cr	Pb	Cd
Grange *	Load (g/ha/yr)	853	269	31	23	74	3
	Time (years)	599	1,598	7,712	>10,000	>10,000	3,744
Highlands	Load (g/ha/yr)	1,235	263	9	23	67	4
	Time (years)	381	1,489	>10,000	>10,000	>10,000	2,730
Horsewold	Load (g/ha/yr)	1,820	892	49	33	67	3
	Time (years)	196	483	3,048	>10,000	>10,000	2,320
Berrowsfield	Load (g/ha/yr)	500	157	16	16	53	3
	Time (years)	614	2,725	>10,000	>10,000	>10,000	7,800

*Poultry manures exported

Figure 6. Proportion of heavy metal inputs from different sources at the Nutrient Demonstration Farms



d) Berrowsfield Farm



The heavy metal loading rates were used together with measured soil heavy metal concentrations (Table 6) to establish the length of time it would take for the soils to reach the limit concentrations (Table 9) in the Code of Practice for Agricultural Use of Sewage Sludge (DoE, 1996). Standard figures (McGrath and Loveland, 1992) for heavy metal concentrations in clay soils were used to estimate the metal contents of the soils at Berrowsfield Farm. Heavy metal loading rates were highest at Horsewold (which also had the highest soil metal concentrations) and Highlands Farms, reflecting the elevated heavy metal contents of the pig and laying hen feeds. The lowest loading rates were at Grange Farm (where the layer manures were exported) and Berrowsfield Farm, reflecting the low metal contents of the dairy cow feeds.

The time taken to reach the soil limits for Zn where sewage sludge is recycled to agricultural land ranged from 196 years at Horsewold Farm to *c*.600 years at Grange and Berrowsfield Farms, and for Cu from 483 years at Horsewold Farm to 2,725 years at Berrowsfield Farm. The Ni limit was estimated to be reached at Horsewold Farm after 3,048 years and at Highlands and Berrowsfield Farms after > 10,000 years. The Pb and Cr limits would be reached after > 10,000 years at all the farms, with the Cd limit value reached after 2,320 years at Highlands Farm and 7,800 years at Berrowsfield Farm.

4.5. Soil P loading rates

To increase soil extractable P by 10 mg/l will take an estimated 400-600 kg/ha of phosphate (P_2O_5) fertiliser (Anon., 2000). Therefore, based on the P surpluses identified in Table 8, it would take 3-4 years to raise topsoil extractable P concentrations by 10 mg/l at Horsewold Farm, 13-20 years at Berrowsfield Farm, 17-26 years at Highlands Farm and 13-20 years at Grange Farm (if all the poultry manure was exported). However, if all the poultry manure was applied to the farmed land at Grange Farm, the time taken would be *c*.1 year.

Fertiliser and organic manure applications should aim to raise soil extractable P to a target level for the rotation and then maintain this level within the soil. For grassland, combinable and forage crops the target is 16-25 mg/l Olsen extractable P, ADAS Index 2 (Anon., 2000). To reduce the risk of P loss the Defra 'Water Code' (Defra.,1998) advises that for fields at ADAS soil P Index 3 or above “care should be taken to avoid total inputs of phosphate from organic manures and fertilisers exceeding the total amount of phosphate removed by crops in the rotation".

Soil analysis in 1998 at Horsewold, Grange, Berrowsfield and Highlands Farms, indicated that 5 out of 15, 2 out of 34, 8 out of 22 and 8 out of 44 fields had soil P Indices of less than 3, respectively. The phosphate surpluses on each of the farms indicated that if manure applications continued at the present rate all the fields would have a P Index of 3 or more within 10-20 years. This indicates that in the near future, manure applications on the farms will be limited by annual crop P offtakes, if compliance with the recommendations in the Defra 'Water Code' is to be achieved.

4.6. Implications of the Defra 'Water Code'

A comparison of annual crop P offtakes using standard grain/grass P concentrations (Anon., 2000) and farmer estimates of crop yields and manure P inputs (from farm analysis and farmer estimates of manure production) was carried out for each farm, to assess the extent of manure management changes that would be required to meet the recommendations in the Defra 'Water Code'.

At Horsewold Farm, annual crop P offtakes (based on a rotation of 60% winter wheat, 16% vining peas, 12% borage and 12% oilseed rape) were estimated at 10,326 kg P_2O_5 per year. Manure phosphate applications were estimated at 13,179 kg P_2O_5 per year. These calculations indicate that *c*.3,000 kg of P_2O_5, which is equivalent to *c*.500 tonnes of duck FYM (assuming a duck FYM P_2O_5 content of 5.6 kg/t), would have to be exported.

At Grange Farm, annual crop P offtakes (based on a rotation of 50% grass, 30% winter cereal and 20% maize) were estimated at 11,720 kg P_2O_5 per year, compared with slurry phosphate applications of 17,510 kg P_2O_5 per year. These calculations indicate that *c*.5,800 kg of slurry P_2O_5 - equivalent to 5,600 m^3 of cattle slurry (assuming a cattle slurry analysis of 1.05 kg/m^3 P_2O_5) would have to be exported each year, in addition to all the layer manure currently exported from the farm.

At Highlands Farm, annual crop P offtakes (based on a rotation of 68% winter wheat, 24% oilseed rape and 8% spring barley) were estimated at 29,815 kg P_2O_5 per year, compared with manure phosphate applications of 53,664 kg P_2O_5 per year. These calculations indicate that *c*.24,000 kg of manure P_2O_5 - equivalent to *c*.1,800 tonnes of layer manure (assuming a layer manure analysis of 13 kg/t P_2O_5) would have to be exported each year.

At Berrowsfield Farm, annual crop P offtakes (based on a rotation of 53% grass, 40% cereals and 7% maize) were estimated at 8,510 kg P_2O_5 per year, compared with manure phosphate applications of 13,780 kg P_2O_5 per year. These calculations indicate that *c*.5,300 kg of manure P_2O_5 - equivalent to all 1,300 tonnes of solid manure (3,420 kg P_2O_5) and *c*.1,100 m^3 kg of cattle slurry (1,850 kg P_2O_5) would have to be exported each year.

5. CONCLUSIONS & RELEVANCE TO DEFRA POLICY

- Topsoil Olsen extractable P concentrations were on average 39 mg/l - ADAS Index 3 (range 19-66 mg/l) at Horsewold Farm, 70 mg/l - Index 4 (range 21-150 mg/l) at Highlands Farm and 105 mg/l - Index 6 (range 31-309 mg/l) at Grange Farm. The high values at Highlands and Grange Farms reflected the long history of poultry manure applications supplying P in excess of crop offtakes.

- At Grange Farm, there was some evidence that withholding manure applications led to reductions in topsoil P levels. Soil total P concentrations decreased by a mean of *c*.280 mg/kg (range 0-800 mg/kg) and Olsen extractable P concentrations by a mean of *c*.19 mg/l (range 0-67 mg/l) where manure applications had been withheld for 2 seasons. However, these reductions were not statistically significant ($P>0.05$), with longer timescales required to fully assess soil P concentration changes following the cessation of manure P additions.

- At Highlands Farm, the continued layer manure applications in autumns 2000 and 2001 supplying *c*.416 kg/ha P_2O_5/yr increased total topsoil P concentrations by a mean of 140 mg/kg (range 100-180 mg/kg), although it was not possible to prove these increases statistically ($P>0.05$). At Horsewold Farm, pig slurry and duck FYM applications (supplying 48 and 319 kg/ha P_2O_5, respectively) had no measureable effects on topsoil total P or Olsen extractable P concentrations.

- Across all the sites, Olsen extractable, water soluble and calcium chloride extractable soil P concentrations were strongly related to total topsoil P levels (P<0.001), and were equivalent to *c.* 8%, 6% and 0.5% of total P concentrations, respectively.

- The mean degree of phosphorus saturation (DPS) was 113% (15 fields; range 34-310%) at Grange Farm and 50% (12 fields; range 15-89%) at Highlands Farm, respectively. These data indicate that enhanced P leaching and runoff losses were likely from the soils on these farms as the values exceed the Dutch 25-40% saturation threshold for the release of soluble P.

- Farm P budget calculations identified annual surpluses of 23 kg P_2O_5/ha/yr at Highlands Farm, 30 kg P_2O_5/ha/yr at Grange Farm, 148 kg P_2O_5/ha/yr at Horsewold Farm and 31 kg P_2O_5/ha/yr at Berrowsfield Farm. Soil analysis data and estimated soil extractable P rate increases indicated that if the phosphate surplus on each of the farms continued at the present rate, then all fields would have a soil P Index of 3 or greater within 10-20 years. This would result in the farms having to export manure in order to comply with the recommendation in the Defra 'Water Code' that for fields at ADAS soil P Index 3 or above "care should be taken to avoid total inputs of phosphate from organic manures and fertilisers exceeding the total amount of phosphate removed by crops in the rotation".

- Soil analysis in 2000 showed that topsoil heavy metal concentrations at Grange, Horsewold and Highlands Farms were similar to median values in the National Soils Inventory. At all four farms, annual inputs of all heavy metals exceeded outputs leading to on-farm surpluses of 0.5-1.8 kg/ha Zn, 0.16-0.89 kg/ha Cu, 0.01-0.05 kg/ha Ni and *c*.0.07 kg/ha Pb.

- On all four farms, the most important sources of Zn and Cu were purchased livestock feeds (>50% of total inputs). Feeds were also important sources of the other heavy metals (e.g. Ni, Pb), particularly at Grange Farm, where *c*.19,000 tonnes of feed was purchased annually.

- Heavy metal loading rates were highest at Horsewold (which also had the highest soil metal concentrations) and Highlands Farms, reflecting the elevated heavy metal contents of the pig and laying hen feeds. The lowest loading rates were at Grange Farm (where the layer manures were exported) and at Berrowsfield Farm, reflecting the low metal contents of the dairy cow feeds.

- The time taken to reach the maximum permitted soil metal concentrations, where sewage sludge is applied to agricultural land, ranged for Zn from 196 years at Horsewold Farm to *c*.600 years at Grange and Berrowsfield Farms, and for Cu from 483 years at Horsewold Farm to 2,725 years at Berrowsfield Farm. For the other metals, the time taken to reach these soil limit values ranged from *c*.2,300 to >10,000 years.

6. KNOWLEDGE TRANSFER

Smith, K.A., Williams, J. R. and Chambers, B. J. (1999). Constraints on the beneficial recycling of organic solids in UK agriculture. Paper presented to the 3rd meeting of the ROSA (Recycling Organic Solids in Agriculture) EU Concerted Action Meeting at Silsoe, 1 October 1999.

Williams, J.R. (1999) Nutrient Demonstration Farms - utilising the value of farm manures. *ADAS Research Review*, 1998-1999, pp. 30-31.

Presentation to Environment Agency at Highlands Farm, October 2000

Results from this project were presented at 43 farmer meetings and 18 seminars for FACTS qualified agricultural consultants between spring 1999 and spring 2002.

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