Nutrient management on intensive dairy farms in the southwest of Ireland

End of Project Report

Project 5393

Authors:

James Humphreys, Mark Treacy and Kevin McNamara

Teagasc, Moorepark Dairy Production Research Centre, Moorepark, Fermoy, Co. Cork.

August 2006

Contents

1. Summary

Intensive grass-based dairy farming relies on high inputs of nutrients that are now regulated under SI 378, 2006 (Good Agricultural Practice for Protection of Waters). This project studied nutrient management practices on twenty-one intensive dairy farms in the south-west of Ireland between 2003 and 2006. Mean stocking rate was 202 kg organic-N/ha deposited by grazing livestock. Overall fertiliser-N use on the farms decreased from 266 to 223 kg N/ha/yr during the study, with the rate of fertiliser-N in the first application each year decreasing from 49 to 33 kg N/ha, while the rate of fertiliser-N applied for first cut silage production also fell from 106 to 96 kg N/ha. These decreases were partly achieved by applying more slurry in springtime and by the introduction of white clover on five of the farms. While the limits on fertiliser-N use under SI 378 were exceeded on ten farms in 2003, the limits were exceeded on only two farms in 2006. Fertiliser-P usage declined from 12.0 to 10.2 kg P/ha/yr, and complied with the limits of SI 378 on thirteen of the farms in 2006. Mean Morgan's extractable soil P concentration (STP) exceeded 10 mg/l on five farms, while the mean concentration exceeded 8 mg/l on ten farms. Phosphorus management, therefore, was close to that required by SI 378 on most farms. Slurry storage capacity met or exceeded the minimum requirements of SI 378 on eight farms; substantial investment in slurry storage facilities was necessary on thirteen farms. The mean N surplus on the farms declined from 277 to 232 kg N/ha/yr during the study due to a decline in total N input from 335 to 288 kg N/ha/yr over the same period. The mean efficiency of N-use increased from 17.9 to 20.2 %. The large variation in rates of fertiliser-N applied on farms with similar stocking rates suggests potential for further improvements in N use efficiency on some farms. Decreases in nutrient input levels can be partly attributed to increased farmer awareness, due to advice and record keeping from this study and the introduction of SI 378, and the increasing cost of nutrient inputs relative to output prices. In terms of fertiliser N and P use and soil P concentrations, complying with the limits in SI 378 does not require major changes in nutrient management practices on the majority of these intensive dairy farms.

2. Introduction

Agricultural land in Ireland is amongst the most expensive in Europe (FADN, 2007). The intensification of agriculture enables higher production to be achieved from a particular land area. Intensification has been favoured by many Irish dairy farmers to maximise returns from this expensive and limited resource. However, intensive grass-based dairy farming relies on high inputs of nutrients that are now regulated under Statutory Instrument (SI) 378, 2006 (Good Agricultural Practice for Protection of Waters).

As nutrients cycle though the farm system, unavoidable losses occur (Hilhorst *et al.,* 2001). Losses of nitrogen (N) occur by three major loss pathways; nitrate (NO_3^-) leaching, denitrification, and ammonia (NH_3) volatilisation (Whitehead, 1995). Nitrate leaching leads to the enrichment of surface and ground waters causing the eutrophication of rivers, lakes and estuaries (Watson, 2001). Nitrate enrichment of drinking water has been linked with possible human health problems such as 'blue-baby syndrome' and gastric cancer (Addiscott, 1996). Ammonia volatilisation results in NH_3 emission to the atmosphere which is subsequently returned to the land as 'acid rain', resulting in soil acidification, the eutrophication of water sources, and loss of biodiversity in sensitive ecosystems (Sutton *et al.,* 1998; Pain *et al.,* 1999; Krupa, 2003). Denitrification can lead to the emission of nitrous oxide (N_2O) to the atmosphere (Knowles, 1982). This contributes to global warming and the depletion of the ozone layer (Watson, 2001). Denitrification also leads to the emission of nitric oxide (NO) which contributes to 'acid rain' (Whitehead, 1995) and soil acidification (Watson, 2001). The control of N loss is complex as efforts to decrease N losses through one pathway often lead to increases in N loss through the other pathways (Watson and Foy, 2001). Therefore, N management requires careful planning (Jarvis *et al.*, 1996).

Phosphorus (P) loss results in the eutrophication of water bodies, and can occur by overland flow and to a lesser extent by leaching. Relatively small losses of P can be quite significant in terms of water quality (Jarvis and Aarts, 2000). Indeed, P loss to water is Ireland's greatest environmental concern (Toner *et al.*, 2005). Phosphorus loss is associated with high soil P levels and the inappropriate timing of fertiliser P applications, such as during periods of low crop demand or heavy rainfall.

Until recently there has been reluctance among farmers to curtail the use of artificial fertilisers. High application rates of artificial fertilisers have been economically justifiable due to the value of extra herbage produced relative to the cost of the fertiliser (Jarvis *et al*., 1996). Farmers are cautious about decreasing fertiliser rates as they fear that lower input levels will result in a decline in grass production, and ultimately farm output. In reality application rates have often been excessive and wasteful, resulting in large surpluses which have simply been lost from the system. While serious negative effects of nutrient loss on the environment are the main driver behind increasing legislation on nutrient usage, the loss of nutrients from the agricultural system is also a substantial financial cost. Therefore, increases in nutrient use efficiency provide farmers with an opportunity to counteract the negative financial effects of the continuing increase in the cost of agricultural inputs.

The objectives of this study were:

(i) To gain a better understanding of current nutrient management practices on intensive dairy farms in the south-west of Ireland.

(ii) To identify nutrient management practices which could potentially be improved to increase the efficiency of artificial fertiliser and animal manure usage on these farms.

(iii) To study farm-gate nutrient balances on these intensive dairy farms, and monitor the effects of changes in nutrient management practices, implemented by the farmers as a result of enhanced knowledge resulting from this study and subsequent economic decisions, on these balances.

3. Materials and Methods

3.1 Farm Selection

Twenty-one farms located in counties, Cork, Kilkenny, Limerick, Tipperary, and Waterford were selected for this study (Table 2). Grass-based, spring calving dairy systems were the main enterprise on each of the selected farms.

Table 2: Locations and major soil types of the farms studied.

Farm	County	Townsland	Major Soil Type
1	Cork	Kilworth	Sandy Loam
2	Waterford	Tallow	Loam
3	Cork	Rathcormac	Loam
4	Cork	Mitchelstown	Loam
5	Cork	Conna	Loam
6	Cork	Conna	Loam
7	Cork	Kilworth	Sandy Loam
8	Cork	Kilworth	Sandy Loam
9	Cork	Dunmanway	Loam
10	Cork	Mourneabbey	Loam
11	Cork	Mallow	Clay loam
12	Kilkenny	Urlingford	Loam
13	Kilkenny	Urlingford	Loam
14	Tipperary	Ballylooby	Loam
15	Tipperary	Golden	Loam
16	Cork	Charleville	Loam
17	Cork	Kildorrery	Sandy Loam
18	Limerick	Hospital	Clay Loam
19	Tipperary	Ardfinnan	Loam
20	Tipperary	Clogheen	Loam
21	Tipperary	Ardfinnan	Loam

Approximately 80 % of the farms were selected for having free-draining permeable soils, as this is the predominant soil type on which intensive dairying is carried out in Ireland. The remaining 20 % of farms have poorly drained impermeable soils. Under SI 378 (2006), all farms are located in Zone A, with the exception of farm 18 which is located in Zone B. These zones are stipulated under SI 378 (2006) based on the county in which the specific farm is located, and dictate the length of closed periods for nutrient application, and required storage periods for organic manures produced by housed livestock (SI 378, 2006).

All farms were previously involved in research programmes involving Teagasc, Moorepark, and had a history of accurate record keeping. As the emphasis of this project is nutrient management on intensive dairy farms, the majority of farms (17 of the 21) were selected with stocking rates of between 2 and 3 livestock unit (LU) per ha, where one LU is the equivalent of one dairy cow. These stocking rates are not typical of average Irish dairy farms, but are representative of intensive dairy units.

3.2 Data Collection

3.2.1 On-farm Recording

On-farm recording was carried out in 2004, 2005 and 2006. Purpose-built recording boards were designed and constructed to record all nutrient applications on each of the farms (Fig. 3). These boards were made of plywood and were mounted in the milking shed on each farm. The recording boards included a map of the farm, with each paddock individually numbered. The record sheet consisted of a large grid, with each column numbered corresponding to specific paddock numbers on the map. The record sheets were laminated, with special permanent ink pens provided for entering data on them. Calendars and cleaning cloths were also included.

Farmers recorded the date, nutrient type, and rate of every nutrient application on a field by field basis (Fig. 4). Data were collected from these boards during regular farm visits throughout each year. The recording sheets were cleaned with acetone after all information had been collected at the end of each year. The boards were reused the following year.

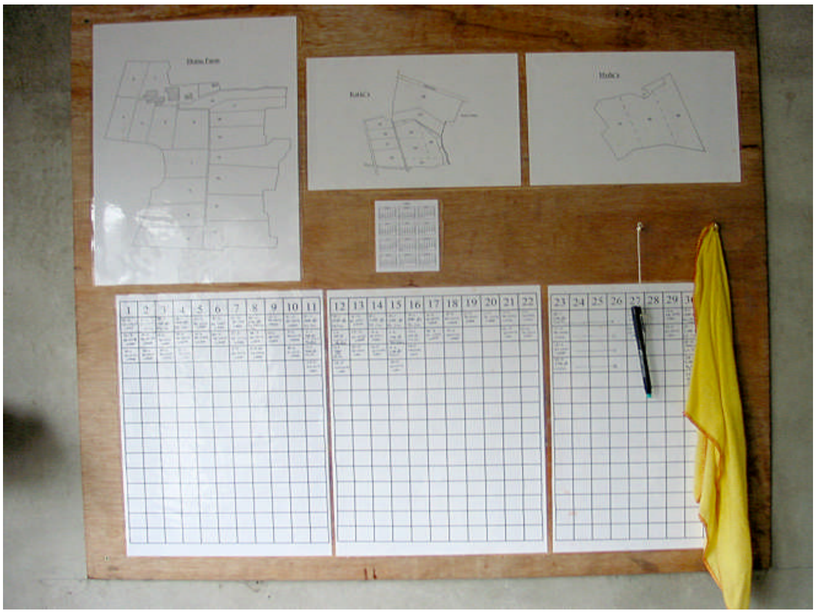

Figure 3: On-farm recording board.

Figure 4: Example of data entered on a recording board.

3.2.2 DAIRYMIS Records

DAIRYMIS is a computerised, data recording system run by Teagasc Moorepark, which monitors a large group of dairy farms in the south of Ireland (Crosse, 1991). All the farms selected for this study has data collected with this system. Data relating to livestock numbers, concentrate usage, and milk production and composition were extracted from the DAIRYMIS database for all years of the study. Annual fertiliser usage for 2003 was also extracted.

3.2.3 Grass Growth

Weekly grass growth data was measured using the methodology described by Corral and Fenlon (1978) at Moorepark Dairy Production Research Centre, Fermoy, Co. Cork (Latitude 55^{o}10’ N; Longitude 8^{o}16’ W). Four cut plots were fertilised similarly to the farm paddocks, with one plot cut per week, on a four week rotation .

3.2.4 Weather Data

Precipitation and soil temperature (measured at 100 mm soil depth) were recorded at the climatological station located at Moorepark Research Centre as described by Fitzgerald and Fitzgerald (2004).

3.3 Soil Analysis

A total of eight soil samples were taken on each of the farms during the study period (two samples taken during each of the four winter periods). Samples were taken using a standard soil corer, sampling to a depth of 100 mm. Each sample area was not greater than 4 ha, with sample areas evenly distributed across each of the farms. The sample areas were also carefully selected to ensure areas used for grazing and silage production were both represented. At least 50 soil cores were taken from each sample area, in a zig-zag pattern. Care was taken to avoid unusual spots in the sample area, such as old fences, ditches, and around gateways and feed troughs. Each sample was carefully mixed, before smaller representative samples were extracted and sent for analysis to Teagasc, Johnstown Castle, Co. Wexford. Samples were analysed for soil pH, Morgan's Soil P and K concentrations using the standard laboratory procedures for the Republic of Ireland, as described by Byrne (1979). Soil samples were dried for sixteen hours at 40 ^{o}C in a forced draught oven with moisture extraction. Soil pH was determined by mixing 10 ml of dried sieved (2mm) soil with 20 ml of H_2O and, after being allowed to stand for ten minutes, measuring the pH of the suspension using a digital pH meter with glass and calomel electrodes. For soil P and K concentrations, soil samples were extracted in a one part soil to five parts solution ratio with a 10 % sodium acetate solution buffered at pH 4.8 (Morgan's solution): 6 ml of dried soil was extracted using 30 ml of Morgan's solution using a Brunswick Gyratory shaker for 30 minutes at constant temperature (20°C). The suspension was then filtered using No.2 Whatman filter paper. Analysis for P and K content was then carried out on the clear extract by spectrophotometry and flamephotometry respectively.

3.4 Data Analysis

3.4.1 Stocking Rate

Farm stocking rates were expressed as kg organic N/ha. This was calculated by multiplying the average number of animals in each category of stock on the farm during the year by the annual N excretion of that category of animal according to standard values from SI 378, 2006 (Table 3), and dividing by the farm area.

Table 3: Annual nitrogen excretion rates for livestock (SI 378, 2006).

Livestock Type	kg N/year
Dairy Cow	85
Suckler Cow	65
Cattle (0-1 year old)	24
Cattle (1-2 years old)	57
Cattle (>2 years old)	65

3.4.2 Number of Days on which Fertiliser was Applied

The total number of days on which fertiliser was applied on each farm was recorded, regardless of the size of area fertilised.

3.4.3 Nitrogen Usage

Mean annual fertiliser N application rates were calculated on each farm by dividing the total quantity of fertiliser N applied during the given year by the total farm area, and was expressed as kg N/ha/yr.

The rate of fertiliser N applied in the first application of fertilisation was calculated by dividing the total quantity of fertiliser N applied in the first applications of fertiliser by the total area on which fertiliser N was applied in the first applications. Areas on which no fertiliser was applied in the first applications were not included in the calculation. Furthermore, applications made later than the first of March each year were not considered when calculating the first rotation rate, even if the area had not been previously fertilised in that year.

The rate of fertiliser N applied for the production of first cut silage was calculated by dividing the total quantity of fertiliser N applied on the area closed for silage production by the total area closed.

3.4.4 Phosphorus Usage

The total annual fertiliser P application was calculated by dividing the total quantity of fertiliser P applied during the year by the total farm area, and was expressed as kg P/ha/yr.

3.4.5 Slurry Storage and Usage

The weekly slurry storage requirements on each of the farms were calculated by multiplying the average number of stock in each animal category on the farm over the winter period of 2006 by the weekly storage requirements for each category of livestock (Table 4). Twenty of the farms were located in 'Zone A' and required 16 weeks winter storage capacity, while farm 18 was located in 'Zone B' and required 18 weeks winter storage capacity (SI 378, 2006).

The length, width and depth of all slurry tanks were measured on each farm. As defined in SI 378, available storage was calculated as the total volume of the tanks, less 200 mm of freeboard on covered tanks, or 300 mm of freeboard on uncovered tanks. In the case of uncovered tanks, an allowance for rainfall over the winter period, as stipulated under SI 378, was also calculated by multiplying the average net weekly rainfall for the area in which the farm was located (Table 5) by the number of weeks storage required, and deducted from the available capacity of the tanks.

The proportion of slurry applied during different periods of the year was calculated by dividing the total volume of slurry applied in the year (including imported slurry) into the volume of slurry applied in the specific period. Three periods were defined; (i) spring (January to April inclusive), (ii) May/June, and (iii) after June.

Table 4: Winter slurry storage capacity required for cattle (SI 378, 2006)

Livestock Type	m^3/week
Dairy Cow	0.33
Suckler Cow	0.29
Cattle >2 years	0.26
Cattle (18 to 24 months old)	0.26
Cattle (12 to 18 months old)	0.15
Cattle (6 to 12 months old)	0.15
Cattle (0 to 6 months old)	0.08

Table 5: Average weekly net rainfall during the winter period (SI 378, 2006)

County	mm/week
Cork	37
Kilkenny	23
Limerick	26
Tipperary	27
Waterford	31

3.4.6 Nitrogen Balances

Farm gate balances were calculated for each of the farms to show N imports and exports to and from the farm. All inputs and outputs of N were expressed as kg N/ha/yr.

Inputs

Fertiliser N imported was calculated as the total N fertiliser applied during the year. Nitrogen imported in concentrate feed was calculated by multiplying the total quantity of concentrate fed by its protein content and dividing by 6.25 (McDonald *et al.*, 1995). The N content of any pig slurry imported onto the farms was estimated as 4.2 kg N/m^3 (SI 378, 2006).

Outputs

Nitrogen exported in milk was calculated by firstly multiplying the quantity of milk sold (kg) by the protein content to give the total quantity of protein exported. This was then divided by 6.39, assuming that milk protein contains 15.6 % N (Smith *et al.*, 1995). Nitrogen exported in stock sold was calculated by estimating the total weight of stock sold and multiplying it by the N content. The N content of calves was taken as 0.029 kg N per kg liveweight, and of older stock as 0.024 kg N per kg liveweight (ARC, 1994). The estimated live-weights of the different categories of stock are presented in Table 6.

Nitrogen surplus (kg N/ha/yr) was calculated by subtracting total N exported from total N imported onto the farms, while % N use efficiency was calculated by dividing total exports by total imports, and multiplying by 100.

Table 6: Estimated animal liveweight.

Stock Category	**Liveweight (kg)**
Cow	625
Calf	50
Cattle (<1 year old)	250
Cattle (1 to 2 years old)	400
Cattle (> 2 years old)	600

3.4.7 Phosphorus Balances

Farm gate balances were calculated for each of the farms to show P imports and exports to and from the farm. All imports and exports of P were expressed as kg P/ha/yr.

Imports

Total P imported as fertiliser was calculated as the total quantity of fertiliser P applied in the year. The quantity of P imported in concentrate feed was calculated assuming 5 kg P per tonne of concentrate feed (SI 378, 2006). The quantity of P imported in pig slurry was estimated to be 0.8 kg P/m^3 (SI 378, 2006).

Exports

Phosphorus exported in milk sold was calculated assuming a P content in milk of 0.0009 kg P per kg of milk (McDonald *et al.*, 1995; Lynch and Caffrey, 1997). Phosphorus exported in stock sold was calculated by multiplying the total liveweight sold by the P content, estimated as 0.01 kg P per kg liveweight (McDonald *et al.*, 1995).

Surpluses and efficiencies were calculated in the same way as described for N.

3.5 Statistical Analysis

Statistical analyses were carried out using MSTAT-C (Freed *et al.*, 1991). Data were subjected to ANOVA to compare differences between years in factors such as stocking rates, fertiliser usage and nutrient surpluses. Each farm was included as a replication in the model.

The relationships between factors such as stocking rate and fertiliser N usage, nutrient inputs and outputs, and nutrient inputs and surpluses were examined using linear regression analysis.

4. Results

4.1 Weather Data

4.1.1 Precipitation

Mean annual precipitation recorded at Moorepark Research Centre, Co. Cork over the study period was 1009 mm (Table 7). Annual precipitation from 2003 to 2006 was 882.0, 1031.5, 1028.7, and 1094.3 mm respectively. The summer of 2006 was particularly dry, and was followed by an extremely wet late autumn/early winter period, during which 58 % of the annual precipitation was recorded.

Table 7: Annual precipitation at Moorepark Research Centre, Co.Cork (Jim Nash, Pers. Comm).

Month	**Rainfall (mm/month)**				
	2003	**2004**	**2005**	**2006**	**Mean**
January	63.9	102.5	119.8	68.6	88.7
February	71.0	56.8	34.8	26.2	47.2
March	61.2	112.4	79.4	124.5	94.4
April	101.0	64.5	82.8	27.8	69.0
May	101.3	42.9	75.7	127.1	86.8
June	104.7	89.3	82.4	13.2	72.4
July	86.6	46.6	66.9	26.2	56.6
August	3.5	171.1	47.8	39.5	65.5
September	40.9	79.0	104.6	201.3	106.5
October	31.7	170.4	153.4	133.6	122.3
November	125.2	27.2	105.6	150.6	102.2
December	91.0	68.8	75.5	155.7	97.8
Total (mm/year)	**882.0**	**1031.5**	**1028.7**	**1094.3**	**1009.1**

4.1.2 Soil Temperature

Average monthly soil temperatures (^oC), measured at a depth of 100 mm at Moorepark Research Centre, Co. Cork are presented in Table 8 (Jim Nash, Pers. Comm.). Mean annual soil temperatures from 2003 to 2006 were 10.8, 10.9, 11.5 and 11.2 ^oC respectively: mean annual soil temperature over the four year period was 11.1 ^oC.

Table 8: Average monthly soil temperatures (^{o}C) at Moorepark Research Centre, Co. Cork, from 2003 to 2006 (Jim Nash, Pers. Comm.).

Month	Average monthly soil temp. (^{o}C) (at 100mm depth)				
	2003	**2004**	**2005**	**2006**	**Mean**
January	5.0	5.6	7.1	5.9	5.9
February	5.2	5.8	5.8	5.3	5.5
March	7.2	6.5	7.8	6.1	7.0
April	9.8	9.5	9.5	9.4	9.6
May	12.0	12.7	12.6	12.8	12.5
June	16.0	15.9	16.8	16.7	16.3
July	16.9	15.9	17.9	18.4	17.3
August	17.5	17.0	17.2	16.6	17.1
September	14.6	15.3	15.5	15.7	15.2
October	10.7	10.4	12.6	12.5	11.5
November	8.4	9.4	8.7	7.8	8.6
December	6.8	7.6	7.0	6.8	7.0
Mean	**10.8**	**10.9**	**11.5**	**11.2**	**11.1**

4.2 Grass Growth

For the majority of 2006, weekly grass dry matter (DM) growth rates were lower than the rates recorded for the corresponding weeks of previous study years (Figure 5). These differences were greatest during the summer period. Spring growth rates were highest in 2003.

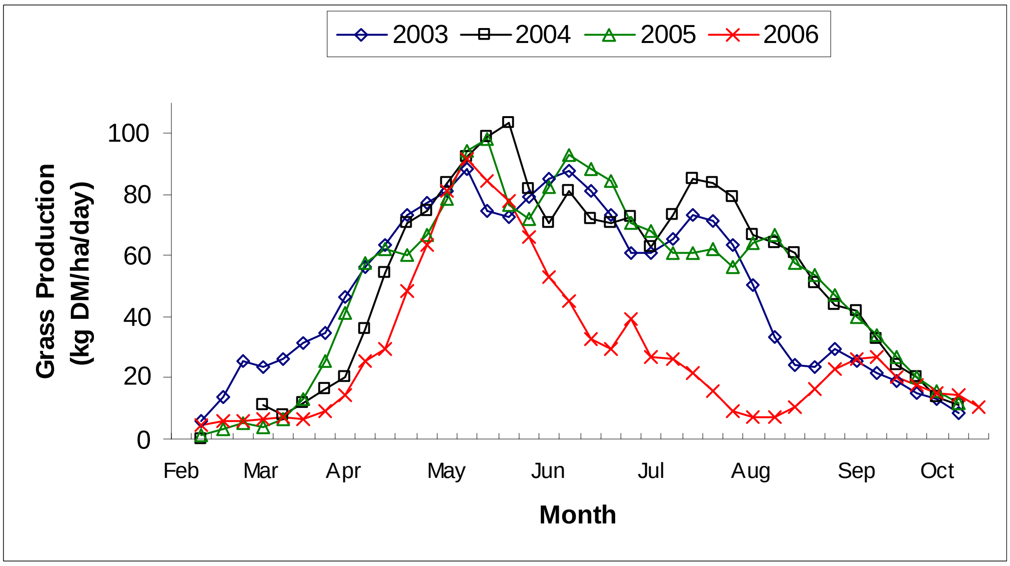

Figure 5: Mean weekly grass growth (kg DM/day) recorded at Teagasc, Moorepark, Co.Cork, 2003 to 2006.

4.3 Farm System Characteristics

4.3.1 Farm Area

Individual farm areas ranged from 24.92 to 130.31 ha during the study period (Table 9). Overall, the mean farm area did not change significantly during the study. The farm area of twelve farms remained unchanged during the study period. However, noteworthy decreases in farm area were observed on farms 6, 8, and 15, while increases were observed on the remaining six farms. The largest increases in farm area were observed on farm 3 (23 %) and farm 19 (26 %).

Table 9: Farm areas 2003 to 2006 (ha)

	Farm area (ha)				
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**
1	24.92	27.41	31.46	27.62	27.85
2	57.43	57.43	57.43	57.43	57.43
3	38.40	38.40	38.40	47.30	40.63
4	55.28	55.28	55.28	55.28	55.28
5	81.58	81.58	81.58	81.58	81.58
6	86.17	72.30	65.83	65.83	72.53
7	70.62	70.62	70.62	70.62	70.62
8	110.00	130.31	99.00	99.00	109.58
9	61.67	63.72	64.04	64.04	63.37
10	64.00	66.72	66.72	74.00	67.86
11	43.38	43.38	43.38	43.38	43.38
12	61.12	61.12	61.12	64.05	61.85
13	70.30	70.30	70.30	70.30	70.30
14	50.05	50.05	50.05	50.05	50.05
15	79.00	83.70	83.70	69.41	78.95
16	78.85	78.85	78.85	78.85	78.85
17	57.16	57.16	57.16	57.16	57.16
18	44.90	44.90	44.90	44.90	44.90
19	26.08	26.08	29.31	33.05	28.63
20	47.70	47.70	47.70	47.70	47.70
21	37.17	37.17	37.17	37.17	37.17
Mean	**59.32**	**60.20**	**58.76**	**58.99**	**59.32**
	Level of Significance (P-value)			s.e.m.	
Year	NS			0.984	

4.3.2 Stock Numbers

The mean stocking rate on the farms during the study period was 202 kg org. N/ha (Table 10). Significant ($P < 0.001$) differences were observed between the mean stocking rates of the individual farms, ranging from 162 kg org. N/ha on farm 7 to 246 kg org. N/ha on farm 19. Stocking rates increased by greater than 5 % on eight of the farms during the study period. There was little, or no change observed in stocking rates on six of the farms, while the stocking rates declined by at least 5 % on the remaining seven farms. The largest increases in stocking rates were observed on farms 1 (22%), 4 (40%) and 6 (24%), while the largest decreases were observed on farms 3 (32%), 13 (22%) and 17 (22%).

The mean number of dairy cows present on the farms during the study period was 89, ranging between 45 and 183 cows in 2003, while between 44 and 190 cows were present in 2006 (Table 10). The mean number of dairy cows increased significantly ($P < 0.001$) from 85 cows in 2003 to 93 cows in 2006. Increases of more than five cows were observed on eleven of the farms, with slight decreases in cow numbers observed on five farms. The largest decrease in cow numbers was observed on farm 3, with a 14 % decrease (14 cows) occurring over the study period. The largest increase in cow numbers was observed on farm 16 (39 cows), although farm 12 showed the largest proportional increase in cow numbers (21 cows, 37 %). However, the total stocking rates on farms 12 and 16 did not increase during the study period, as increases in dairy cow numbers were offset by decreases in the numbers of other stock (Table 10), particularly beef animals, on these farms.

Table 10: Stocking rate (kg N/ha), number of dairy cows, and other stock (Livestock Units) present on the pilot farms, 2003 to 2006.

	Stocking Rate (kg organic N/ha)					**Number of dairy cows/farm**					**Other Stock (LU/farm)**				
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**
1	197	211	213	241	216	45	46	51	44	47	13	22	28	34	24
2	211	200	208	218	209	73	73	75	75	74	69	62	66	72	67
3	271	254	251	184	240	100	101	100	86	97	22	14	13	17	17
4	168	192	206	235	201	62	63	66	70	65	47	62	68	83	65
5	166	164	175	174	170	120	119	124	128	123	39	39	44	39	40
6	188	200	220	233	210	107	107	129	137	120	83	63	41	44	58
7	163	159	161	166	162	79	78	77	85	80	56	54	57	53	55
8	205	153	195	204	189	183	182	178	190	183	82	53	49	48	58
9	174	173	180	187	178	96	96	100	100	98	30	33	35	41	35
10	233	206	222	196	214	84	83	83	87	84	91	79	91	84	86
11	203	166	186	219	194	71	72	73	72	72	33	13	22	40	27
12	197	200	235	196	207	56	66	77	77	69	86	78	92	71	81
13	193	179	162	151	171	81	81	79	82	81	79	67	55	43	61
14	229	245	248	245	242	102	102	100	127	108	33	42	46	17	35
15	215	192	212	249	217	112	112	122	118	116	88	77	86	85	84
16	198	162	165	187	178	111	111	121	150	123	73	39	32	23	42
17	224	194	194	175	197	60	61	64	55	60	91	70	67	62	72
18	243	220	230	226	230	81	81	91	90	86	47	35	30	29	36
19	250	254	239	241	246	56	57	59	54	57	21	21	24	40	26
20	162	158	161	172	163	49	50	67	66	58	42	39	24	30	34
21	230	206	190	204	208	61	62	56	58	59	40	28	27	31	32
Mean	**206**	**195**	**203**	**205**	**202**	**85**	**86**	**90**	**93**	**89**	**53**	**46**	**46**	**48**	**49**
	P-value		s.e.m.			P-value		s.e.m.			P-value		s.e.m.		
Farm	< 0.001		9.0			< 0.001		3.3			< 0.001		5.3		
Year	NS		3.9			< 0.001		1.4			< 0.05		2.3		

4.3.3 Milk Production

The volume of milk supplied from the individual farms ranged between 228,724 litre (farm 1, 2003) and 867,194 litre (farm 8, 2003) (Table 11). Overall, increases in production were observed on sixteen farms, with a significant ($P < 0.001$) increase in the mean volume of milk supplied from the twenty-one farms evident between 2003 and 2006.

The mean protein content of milk supplied from the farms ranged between 32.8 and 35.5 g/kg, with no significant change observed over the study period (Table 11). However, an increase ($P < 0.001$) in butterfat content was evident, increasing from 38.0 g/kg in 2003 to 39.1 g/kg in 2005, and 38.7 g/kg in 2006 (Table 11). During the study period milk butterfat ranged from 36.1 to 40.7 g/kg between individual farms ($P < 0.001$).

Table 11: Volume of milk sold (litres), milk protein content (g/kg) and milk butterfat content (g/kg), 2003 to 2006.

	Volume of milk sold (litres/year)					**Milk Protein (g/kg)**					**Milk Butterfat (g/kg)**				
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**
1	228,724	257,498	262,316	249,767	249,576	34.7	34.3	34.0	33.9	34.2	39.0	40.1	40.1	39.7	39.7
2	376,893	387,994	365,985	409,102	384,994	34.1	34.5	34.4	34.3	34.3	38.5	38.1	37.7	37.6	38.0
3	486,803	462,095	479,102	462,510	472,628	33.1	34.3	33.9	33.5	33.7	38.1	38.1	38.0	37.8	38.0
4	305,128	307,924	307,294	317,213	309,390	34.7	34.2	34.4	34.1	34.4	38.2	37.5	37.9	37.9	37.9
5	712,054	654,552	665,913	729,948	690,617	33.7	34.0	33.6	33.9	33.8	37.4	38.2	38.4	38.3	38.1
6	673,827	632,723	653,211	781,762	685,381	33.9	34.4	34.1	34.2	34.2	38.1	39.4	40.4	40.7	39.7
7	410,772	411,154	380,349	479,611	420,472	33.0	33.4	33.0	33.7	33.3	36.1	36.4	37.7	37.7	37.0
8	867,194	862,857	670,108	859,429	814,897	33.9	34.5	35.5	33.5	34.4	38.2	38.3	39.8	38.1	38.6
9	465,698	486,436	457,226	488,628	474,497	33.9	34.1	33.7	33.5	33.8	37.5	37.9	37.5	38.3	37.8
10	454,736	373,728	393,464	502,119	431,012	34.9	35.3	34.3	34.5	34.8	37.6	39.5	40.3	38.7	39.0
11	451,414	326,718	387,925	369,850	383,977	35.0	35.3	34.9	35.2	35.1	39.1	39.3	41.3	40.1	40.0
12	317,795	315,026	331,861	383,566	337,062	34.0	33.8	34.1	34.4	34.1	37.9	37.8	38.3	38.1	38.0
13	405,531	393,487	381,509	430,685	402,803	32.8	33.3	33.3	32.9	33.1	37.3	37.4	37.7	37.2	37.4
14	554,836	539,434	525,574	584,030	550,969	33.8	34.7	34.5	34.0	34.3	38.1	40.6	41.1	39.4	39.8
15	446,672	500,610	465,402	480,747	473,358	33.6	33.3	32.8	33.1	33.2	38.2	38.7	39.7	38.9	38.9
16	618,126	595,159	553,987	614,317	595,397	34.5	34.8	34.7	35.0	34.8	39.2	40.7	40.4	40.6	40.2
17	307,184	286,926	321,345	350,653	316,527	34.6	34.9	34.2	34.3	34.5	38.2	38.9	39.6	37.7	38.6
18	474,851	460,758	464,006	536,631	484,062	34.4	34.7	34.7	35.1	34.7	38.4	38.4	39.0	39.2	38.8
19	309,983	302,866	338,392	331,324	320,641	33.8	34.1	33.7	34.1	33.9	37.9	39.3	39.7	39.5	39.1
20	310,211	324,245	318,337	336,224	322,254	33.6	33.5	33.5	33.5	33.5	37.4	37.4	38.7	37.9	37.9
21	389,767	370,263	341,428	325,865	356,831	34.1	34.2	34.1	34.3	34.2	37.6	38.8	38.6	39.2	38.6
Mean	**455,629**	**440,593**	**431,654**	**477,332**	**451,302**	**34.0**	**34.3**	**34.1**	**34.1**	**34.1**	**38.0**	**38.6**	**39.1**	**38.7**	**38.6**
	P-value		s.e.m.			P-value		s.e.m.			P-value		s.e.m.		
Farm	< 0.001		16,660.1			< 0.001		0.16			< 0.001		0.28		
Year	< 0.001		7,271.0			NS		0.07			< 0.001		0.12		

4.3.4 Concentrate Usage

Concentrate usage on the farms ranged between 200 kg concentrate/cow (Farm 7, 2004) and 1470 kg concentrate/cow (Farm 1, 2006). Mean usage of concentrate in 2006 was significantly greater (P < 0.001) than the mean usage in other years (Table 12).

Table 12: Annual concentrate usage from 2003 to 2006 (kg concentrate/cow)

	Concentrate fed (kg concentrate/cow)				
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**
1	1040	955	720	1470	1046
2	780	630	605	678	673
3	1330	1170	860	1048	1102
4	560	415	500	790	566
5	755	770	710	883	780
6	700	820	550	990	765
7	585	200	455	940	545
8	625	330	580	840	594
9	410	350	298	526	396
10	1000	495	641	962	775
11	800	210	590	540	535
12	645	605	439	549	560
13	410	295	265	446	354
14	590	570	365	690	554
15	490	290	465	560	451
16	450	255	300	420	356
17	700	430	580	1160	718
18	475	280	205	710	418
19	745	815	949	1185	924
20	425	710	587	667	597
21	655	505	750	915	706
Mean	**675**	**529**	**544**	**808**	**639**
	Level of Significance (P-value)		s.e.m.		
Farm	< 0.001		71.5		
Year	< 0.001		31.2		

4.4 Fertiliser Usage

4.4.1 Number of Days on which Fertiliser was Applied

A large decrease in the number of days on which fertiliser was applied in each year was observed on eighteen of the twenty-one farms between 2004 and 2006 (Table 13). The mean number of days per year on which fertiliser was applied decreased significantly (P < 0.001) from 48 days in 2004 to 29 days in 2006. There was little or no change observed on farms 8 and 14, while an increase of 20 days was observed on farm 16. The maximum number of days in a year on which fertiliser was applied on an individual farm was 86 (farm 11, 2003), while the lowest number of days was observed on farm 13 in 2006, where fertiliser was applied on 9 days. The largest decrease was observed on farm 5, where the number of days on which fertiliser was applied decreased from 66 to 17 days.

Table 13: Number of days on which fertiliser N was applied, 2004 to 2006.

	Number of Days				
Farm	**2004**	**2005**	**2006**	**Mean**	**Change (%)**
1	36	33	17	29	-52
2	78	61	60	66	-23
3	60	50	39	50	-35
4	53	45	31	43	-42
5	66	32	17	38	-74
6	47	38	28	38	-40
7	45	43	29	39	-36
8	10	10	10	10	0
9	63	43	43	50	-32
10	65	48	43	52	-34
11	86	70	23	60	-73
12	28	25	16	23	-43
13	34	11	9	18	-74
14	44	41	43	43	-2
15	50	25	29	35	-42
16	31	34	51	39	+65
17	31	22	10	21	-68
18	41	30	19	30	-54
19	66	39	41	49	-38
20	18	19	12	16	-33
21	61	59	30	50	-51
Mean	**48**	**37**	**29**	**38**	**-39.6**

	P-value	s.e.m.
Farm	< 0.001	5.5
Year	< 0.001	2.1

4.4.2 Nitrogen Fertiliser Usage

Annual fertiliser N applications ranged from 107 kg N/ha/yr (Farm 20, 2005) to 389 kg N/ha/yr (Farm 3, 2005) during the study period (Table 14). Decreases of greater than 5% in annual N application rates were observed on fifteen farms, with the largest decreases in N usage observed on farms 7 (48 %), 17 (47 %), and 20 (46 %). Increases of greater than 5% were observed only on farms 6 and 16. The remaining four farms (farms 5, 8, 12, 13) showed changes of less than 5 % in fertiliser N usage between 2003 and 2006. Overall, mean fertiliser N usage decreased significantly (P < 0.001) from 266 to 223 kg N/ha/yr between 2003 and 2006.

Table 14: Annual fertiliser N applications (kg N/ha/yr), rate of fertiliser applied in the first annual N application (kg N/ha), and the rate of fertiliser N applied for the production of first cut silage (kg N/ha).

	Annual Fertiliser N Application (kg N/ha/yr)					**First Annual N Application (kg N/ha)**				**First Cut Silage N Rate (kg N/ha)**			
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**	**2004**	**2005**	**2006**	**Mean**	**2004**	**2005**	**2006**	**Mean**
1	267	256	270	253	262	61.6	40.6	37.0	46.4	106	100	111	106
2	287	258	249	256	263	56.6	44.3	46.7	49.2	98	98	99	98
3	328	287	389	268	318	53.2	41.1	25.5	39.9	125	90	114	110
4	296	254	215	236	250	56.6	42.9	37.0	45.5	80	99	80	86
5	271	270	268	263	268	33.8	34.0	33.3	33.7	100	105	99	101
6	270	243	313	308	284	56.6	30.9	37.0	41.5	89	115	80	95
7	273	198	175	141	197	46.8	37.5	37.0	40.4	89	103	94	95
8	142	129	170	140	145	44.8	0.0	0.0	14.9	66	100	57	74
9	280	243	231	231	246	50.6	30.6	34.6	38.6	106	111	106	108
10	306	280	273	252	278	61.5	31.5	31.5	41.5	115	100	86	100
11	263	221	268	212	241	0.0	68.0	28.4	32.1	118	133	108	120
12	266	231	287	265	262	28.7	34.5	42.6	35.3	99	85	101	95
13	140	201	115	141	149	43.8	28.4	33.4	35.2	118	89	98	102
14	315	325	317	274	308	70.9	39.5	28.4	46.3	125	133	93	117
15	256	204	189	211	215	49.4	28.4	28.4	35.4	113	118	116	116
16	204	147	137	216	176	39.5	25.1	31.6	32.1	115	100	76	97
17	244	200	169	128	185	51.5	46.7	29.6	42.6	130	124	92	115
18	308	206	215	245	244	46.1	34.0	28.4	36.2	119	119	86	108
19	325	301	281	248	289	61.0	38.9	40.2	46.7	87	67	108	87
20	202	139	107	109	139	56.6	31.2	37.0	41.6	113	128	107	116
21	337	311	237	283	292	56.6	29.0	50.7	45.4	118	121	105	115
Mean	**266**	**234**	**232**	**223**	**239**	**48.9**	**35.1**	**33.3**	**39.1**	**106**	**107**	**96**	**103**
		P-value		s.e.m.			P-value	s.e.m			P-value	s.e.m.	
Farm		< 0.001		14.5			NS	7.06			< 0.05	7.7	
Year		< 0.001		6.5			< 0.001	2.67			< 0.05	2.9	

A positive linear relationship ($R^2 = 0.37$, $P < 0.001$) was found between the stocking rates and the annual fertiliser N applications on the individual farms over the study period (Fig. 6). However, substantial variations in the rates of N applied on farms with similar stocking rates were evident. For example, farms 5 and 13 were both stocked at approximately 170 kg org. N/ha during the study (Table 11). However, the mean rate of N applied on farm 5 during the study period was 268 kg N/ha/yr, while only 149 kg N/ha/yr was applied, on average, on farm 13 during the study period (Table 14).

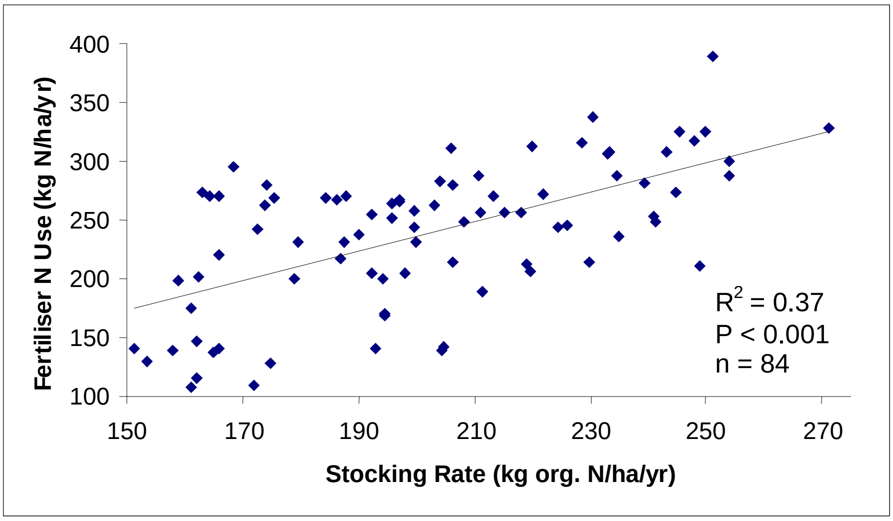

Figure 6: The relationship between stocking rates and annual fertiliser N applications on the pilot farms over the study period.

The rate of fertiliser N applied in the first application each year, as defined in section 3.4.3, ranged between 0.0 and 70.9 kg N/ha during the study period (Table 14). The maximum rate applied on an individual farm was 70.9 kg N/ha in 2004 (farm 14), and 50.7 kg N/ha in 2006 (farm 21). Overall, the mean rate of fertiliser N applied in the first application declined significantly ($P < 0.001$) from 48.9 to 33.3 kg N/ha between 2004 and 2006, a 32 % decrease. Decreases in the rate of N applied as the first application were observed on nineteen of the twenty-one farms, with the largest decrease occurring on farm 14 (from 70.9 kg N/ha in 2004 to 28.4 kg N/ha in 2006). An increase was observed on farm 12, while the rate of fertiliser applied in the first application on farm 5 showed little change between 2004 and 2006. However, a relatively low rate of fertiliser N was applied in the first application on this farm in 2004. Large quantities of pig slurry were applied on farm 8 instead of fertiliser N in the early spring periods of 2005 and 2006.

A 9 % decrease ($P < 0.05$) in the mean rate of fertiliser N applied for the production of first cut silage was observed between 2004 and 2006 (from 106 to 96 kg N/ha). Application rates for first cut silage production on individual farms in individual years ranged between 57 and 133 kg N/ha during the study period. In 2004, rates of 100 kg N/ha, or greater, were applied for the production of first cut silage on fourteen farms. However, in 2006, the number of farms applying rates exceeding this level declined to nine. Small (<5%) changes in the rates of N applied for the production of first cut silage each year were observed on six farms, while larger increases (>5%) in the rates of N applied for first cut silage production were observed on farms 1, 7, and 19. Decreases (>5%) in the rates applied were observed on the remaining twelve farms. The largest decrease was observed on farm 16, where the rate applied decreased by 34 % from 115 kg N/ha in 2004 to 76 kg N/ha in 2006.

Table 15: Types of N fertiliser used on the study farms in 2006.

Farm	Urea	CAN	Compounds
		% of total N used	
1	52.1	47.9	0.0
2	18.3	3.8	77.9
3	0.0	49.5	50.5
4	55.4	44.6	0.0
5	43.1	34.3	22.6
6	0.0	100.0	0.0
7	50.8	49.2	0.0
8	84.5	15.5	0.0
9	35.2	26.1	38.7
10	12.9	69.3	17.8
11	9.6	0.0	90.4
12	35.5	43.3	21.2
13	6.9	24.6	68.5
14	51.1	48.9	0.0
15	46.0	26.6	27.4
16	49.7	0.0	50.3
17	0.0	88.5	11.5
18	42.3	27.6	30.1
19	0.0	82.1	17.9
20	85.5	14.5	0.0
21	46.0	3.2	50.8
Mean	**34.5**	**38.1**	**27.4**
s.d.	26.4	29.0	28.0

Urea and Calcium Ammonium Nitrate (CAN) were the most commonly used forms of N fertiliser in 2006 (Table 15), accounting for 34.5 and 38.1 % of total N applied as fertiliser, respectively. Compound fertilisers of N, P, and K, such as 27:2.5:5 and 24:2.5:10, accounted for 27.4 %. Compound fertilisers were not applied on seven (33 %) of the farms, but accounted for over 90 % of the fertiliser N applied on farm 11. Approximately 95 % of the total urea used was applied before the end of May, with the remainder applied in late August and early September. No urea was applied on farms 3, 6, 17, or 19 in 2006.

4.4.3 Phosphorus Fertiliser

Table 16: Annual fertiliser P usage between 2003 and 2006 (kg P/ha/yr).

	Total fertiliser P applied (kg P/ha)				
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**
1	8.0	1.4	0.5	0.0	2.5
2	30.0	28.7	23.1	19.5	25.3
3	15.0	14.1	1.2	35.1	16.4
4	0.0	7.1	0.0	0.0	1.8
5	21.0	6.0	0.0	5.7	8.2
6	13.0	15.6	9.5	6.4	11.1
7	0.0	0.0	0.0	0.0	0.0
8	0.0	0.5	0.0	0.0	0.1
9	30.0	28.9	24.1	24.6	26.9
10	29.0	23.2	8.7	5.6	16.6
11	16.0	25.7	24.9	18.6	21.3
12	12.0	10.0	19.6	13.4	13.8
13	16.0	17.9	6.2	11.2	12.8
14	11.0	10.6	16.9	0.0	9.6
15	5.0	5.0	10.1	7.1	6.8
16	18.0	4.0	3.7	10.7	9.1
17	3.0	5.4	5.8	1.5	3.9
18	4.0	2.2	9.2	7.1	5.6
19	4.0	6.1	4.6	4.5	4.8
20	4.0	0.0	3.1	2.9	2.5
21	12.0	11.7	24.7	13.9	15.6
Mean	**12.0**	**10.7**	**9.3**	**8.9**	**10.2**

	Level of Significance (P-value)	**s.e.m.**
Farm	< 0.001	2.88
Year	NS	1.25

The mean annual application rate of fertiliser P decreased from 12.0 to 8.9 kg P/ha/yr during the study period, although this decrease was not significant (Table 16). However, significant differences ($P < 0.001$) in the mean application rates of P were observed between farms, while a high year to year variation in P usage was observed on many of the farms. Annual application rates ranged between 0.0 and 35.1 kg P/ha/yr during the study period, with little, or no, fertiliser P applied on farms 7 and 8. The highest mean rates of fertiliser P were applied on farms 2, 9, and 11, with greater than 20 kg P/ha/yr being applied on average on each of these farms during the study period (Table 16). Fertiliser P was generally applied as N, P and K compounds such as 27:2.5:5 and 24:2.5:10.

4.5 Slurry Management

4.5.1 Slurry Storage Capacity

The capacities of, and requirements for, slurry storage on the studied farms in 2006 are presented in Table 17. Under SI 378, twenty of the farms are located in 'Zone A' and require 16 weeks of storage over the winter period. Farm 18 is located in 'Zone B' and requires 18 weeks of storage. Winter storage requirements ranged between 416 and 1200 m^3 on individual farms, while the percentage of required storage available on individual farms ranged between 43 and 214 %. Existing slurry storage capacity met, or exceeded, the requirements on 38 % of the farms. However, on 2 farms (10 %), less than half of the required storage capacity was available, while 5 farms (24 %) had between 75 and 100 % of their required capacity.

Table 17: On-farm slurry storage capacity, and requirements.

Farm	Weekly storage requirement (m^3/week)	Required storage (weeks)	Winter storage requirement (m^3)	Available storage (m^3)	Available storage (weeks)	% of required storage available
1	26	16	416	186	7	45
2	43	16	688	424	10	61
3	35	16	560	1206	34	214
4	51	16	816	354	7	43
5	52	16	832	504	10	61
6	56	16	896	843	15	93
7	35	16	560	562	16	100
8	75	16	1200	2498	33	209
9	44	16	704	550	13	79
10	50	16	800	741	15	93
11	34	16	544	545	16	99
12	41	16	656	755	18	115
13	38	16	608	355	9	59
14	43	16	688	830	19	120
15	70	16	1120	1463	21	131
16	56	16	896	765	14	86
17	34	16	544	927	27	170
18	37	18	666	375	10	56
19	26	16	416	225	9	54
20	30	16	480	295	10	62
21	27	16	432	650	24	149
Min	26	16	416	186	7	45
Max	75	18	1200	2498	34	209
Mean	43.0		691.5	716.9	16.0	100.0
s.d.	13.4		214.9	517.0	8.0	50.5

4.5.2 Slurry Application

The percentage of slurry applied on the farms in the spring period ranged between 0 and 100 % during the study period. The mean proportion of slurry applied during spring period increased significantly (P < 0.05) from 50 to 65 % between 2004 and 2006. Over this same period, increases in the proportions of slurry applied in spring were observed on seventeen of the farms, with decreases evident on farms 3, 4, and 8. Overall, there was no change observed on farm 2, although less slurry was applied on this farm in the spring period of 2005 than in the other of the years studied. On farms 6, 13, and 19 in 2006, all the slurry was applied during the spring period.

Table 18: The proportion of slurry applied in spring, May/June, and after June.

	% of slurry applied											
	Spring				May/June				After June			
Farm	**2004**	**2005**	**2006**	**Mean**	**2004**	**2005**	**2006**	**Mean**	**2004**	**2005**	**2006**	**Mean**
1	79	45	86	70	21	55	14	30	0	0	0	0
2	65	44	65	58	0	13	0	4	35	43	35	38
3	54	55	36	48	43	25	1	23	3	19	63	28
4	68	45	59	57	32	28	37	32	0	27	4	10
5	29	36	38	34	71	36	36	48	0	27	26	18
6	56	77	100	78	24	23	0	16	20	0	0	7
7	53	47	63	54	19	13	15	16	28	39	22	30
8	47	63	35	48	20	19	8	16	33	18	57	36
9	36	0	80	39	37	31	0	23	26	69	20	38
10	46	43	58	49	48	36	34	39	6	20	8	11
11	30	62	54	49	70	36	46	51	0	2	0	1
12	28	76	50	51	28	0	23	17	44	24	26	31
13	31	59	100	63	56	31	0	29	13	10	0	8
14	66	52	38	52	23	26	0	16	11	22	62	32
15	70	68	73	70	18	0	12	10	12	32	15	20
16	53	51	60	55	28	39	40	36	19	10	0	10
17	39	52	68	53	41	48	32	40	20	0	0	7
18	60	54	68	61	32	17	32	27	8	29	0	12
19	76	67	100	81	24	11	0	12	0	23	0	8
20	57	65	81	68	20	35	0	18	22	0	19	14
21	11	40	47	33	29	17	53	33	60	43	0	34
Mean	**50**	**52**	**65**	**56**	**33**	**26**	**18**	**26**	**17**	**22**	**17**	**19**
	P-value	**s.e.m.**			**P-value**	**s.e.m.**			**P-value**	**s.e.m.**		
Farm	< 0.05	9.5			< 0.01	7.7			< 0.05	9.5		
Year	< 0.05	3.6			<0.05	2.9			NS	3.6		

The proportion of slurry applied during May and June decreased on sixteen of the farms between 2004 and 2006 (Table 18). Increases were observed on farms 4, 16 and 21, while no change was evident on farms 2 and 18. No slurry was applied on farm 2 during this period in 2004. However, in 2006, the number of farms on which no slurry was applied during May/June increased to seven (33 % of the farms). Overall there was a significant ($P < 0.05$) decrease in the mean proportion of slurry applied during May and June, from 33 % in 2004 to 18 % in 2006. The proportion of slurry applied in May and June on individual farms ranged between 0 and 71 % during the study.

The proportion of slurry applied on the farms after the end of June each year ranged between 0 and 63 %, with no significant differences evident in the mean proportions of slurry applied during this period each year (Table 18). No slurry was applied on farm 1 after the end of June in any of the studied years, while the number of farms on which no slurry was applied after the end of June increased from six (28 % of the farms) in 2004 to nine (43 % of the farms) in 2006. A large decrease in the proportion of slurry applied after the end of June was observed on farm 21, with a decrease from 60 % in 2004 to 0 % in 2006, while an increase from 3 to 63 % was observed on farm 3 during the same period.

Approximately 60 % of slurry was applied to areas used for the production of first cut silage in 2006, with the remainder applied on the grazing areas, generally at the beginning and end of the grazing season.

Slurry was spread by contractor on seven farms (although on three of these farms some slurry was also applied by the farmers), while the remaining fourteen farms used their own slurry equipment. Vacuum tankers were used on twenty of the farms, with an umbilical system used on farm 3. Low trajectory splash-plates were used to distribute the slurry on the majority of the farms. Injection was carried out on farm 14, while a band spreader was used on farm 8.

4.6 Soil pH and Nutrient Status

The mean pH of the soil samples taken during the study period (2 per farm taken each winter) was 6.0, ranging from 5.7 (farm 19) to 6.5 (farm 18) on individual farms (Table 19).

The mean Morgan's soil P concentration on the farms was 8.2 mg P/l, ranging from 4.2 to 17.5 mg P/l (Table 19). There was also considerable variation between individual samples, ranging between 1.6 and 26.2 mg P/l. The largest range in Morgan's soil P concentrations on an individual farm was observed on farm 13, where the values ranged from 3.5 to 26.1 mg P/l. The highest mean soil P was observed on farm 7 (17.5 mg P/l). All samples on this farm recorded high soil test phosphorus (STP), with 12.6 mg P/l being the lowest value recorded. The mean STP was found to be less than 5 mg P/l (the lower limit of soil index 3) on farms 15 and 16.

Table 19: Soil pH and nutrient status of the studied farms (mean of 8 samples per farm taken between 2003 and 2006).

Farm	pH			Soil P (mg/l)			Soil K		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1	5.8	5.4	6.3	9.2	5.9	11.5	153	101	274
2	6.1	5.5	6.5	10.5	6.4	16.9	148	51	237
3	5.8	5.3	6.2	9.0	3.6	14.8	137	106	166
4	5.8	5.5	6.5	10.0	4.5	26.2	113	57	234
5	6.0	5.4	6.4	8.5	5.5	12.6	105	56	156
6	6.4	5.9	6.9	7.4	3.7	11.8	111	54	166
7	6.0	5.6	6.4	17.5	12.6	25.7	163	59	303
8	5.9	5.4	6.5	6.9	2.9	10.5	111	47	169
9	6.1	5.4	6.8	10.2	4.1	26.0	108	46	181
10	6.0	5.5	6.4	8.3	4.1	13.7	209	62	299
11	6.1	5.7	6.5	9.9	4.2	19.6	175	65	299
12	6.2	5.7	7.0	5.8	2.7	13.5	128	58	169
13	6.4	5.9	7.2	10.1	3.5	26.1	120	62	187
14	5.9	5.3	6.8	7.0	3.8	9.7	90	48	135
15	6.2	6.0	6.7	4.4	3.3	5.4	107	63	165
16	5.9	5.4	6.5	4.2	1.6	8.4	84	46	135
17	6.0	5.5	6.7	7.1	4.7	10.8	156	87	268
18	6.5	6.1	6.9	6.6	2.9	13.9	107	52	243
19	5.7	5.4	6.3	7.6	4.6	12.6	157	121	205
20	5.8	4.9	6.3	6.4	2.9	13.4	135	36	173
21	5.9	5.1	6.4	5.5	4.4	8.6	129	31	248
Mean	**6.0**			**8.2**			**131**		
s.d.	**0.2**			**2.9**			**30**		

The recommended soil K concentration for grassland soils is between 101 and 150 mg K/l (Coulter, 2004). Mean soil K concentration ranged from 84 to 209 mg/l, with a mean concentration on the farms of 131 mg/l.

4.7 Farm-gate Nutrient Balances

4.7.1 Farm-gate Nitrogen Balances

Nitrogen inputs ranged between 130 and 462 kg N/ha/yr on the studied farms (Table 23). Fertiliser N was the largest input of N to the farms, accounting for nearly 80 % of the total N input during this study (Tables 20 to 23). Nitrogen contained in imported concentrate feed was the second largest source of N, with imported organic matter (OM) (pig slurry) also being a substantial source of N on some of the farms.

The mean total input of N decreased significantly ($P < 0.001$) by 14 %, from 335 kg N/ha in 2003 to 288 kg N/ha in 2006. Overall, the level of N input decreased on sixteen of the farms over the study period, while increases were observed on farms 6 and 16. Little or no change was observed on farms 5, 12, and 13. Decreases of greater than 25 % were observed on farms 3 (115 kg N/ha), 7 (131 kg N/ha), 8 (96 kg N/ha) and 17 (100 kg N/ha).

Nitrogen outputs from the farms ranged between 41 and 85 kg N/ha during the study period, with no significant change observed in the mean annual N output of the farms (Table 24). Nitrogen contained in milk sold from the farms was the largest N output, accounting for 78 % of the total N output (Tables 20 to 23). The remaining N output was accounted for by sales of calves, beef animals, old cows, and breeding replacements, as well as the export of livestock that died on the farms.

Nitrogen surpluses ranged between 87 kg N/ha (Farm 13, 2005) and 389 kg N/ha (Farm 7, 2003) during the study period, with a significant ($P < 0.001$) decrease, from 277 to 232 kg N/ha, observed in the mean N surplus of the farms. Nitrogen surpluses declined on seventeen (80 %) of the twenty-one farms during the study, while increases were observed on farms 6 and 16 (Table 24). Little change was observed in the N surpluses on farms 5 and 13. The maximum surplus observed in 2003 was 389 kg N/ha (Farm 7), while the maximum surplus observed in 2006 was 322 kg N/ha (Farm 19).

A substantial variation in the efficiency of N use was observed on the studied farms, ranging from 10.2 to 33.9 % during the study period (Table 24). This can be attributed to a large range in N output, obtained from a given level of N input (Fig. 7). Efficiency of N use increased on fifteen of the farms during the study, with decreases observed on the remaining six farms. On average, N was used least efficiently on farm 7 (12.9 %), while the most efficient usage was observed on farms 20 (26.5%) and 13 (26.4 %). While farm 7 was the least efficient farm in each of the first three years, efficiency of N use was improved substantially in 2006, when efficiency of N use increased from 10.2 % in 2003 to 16.3 % in 2006 due to a large decrease in fertiliser N input. Substantial increases in N use efficiency were also observed on farms 8 (from 15.0 to 23.4 %), and 17 (from 17.9 to 27.7 %) due to substantial decreases in N inputs to these farms.

Positive linear relationships were found between N input and N output ($R^2 = 0.32$, $P < 0.001$) (Fig. 7), and between N inputs and N surplus ($R^2 = 0.98$, $P < 0.001$) (Fig 8). A negative linear relationship was found between N input and N use efficiency ($R^2 = 0.45$, $P < 0.001$) (Fig. 9).

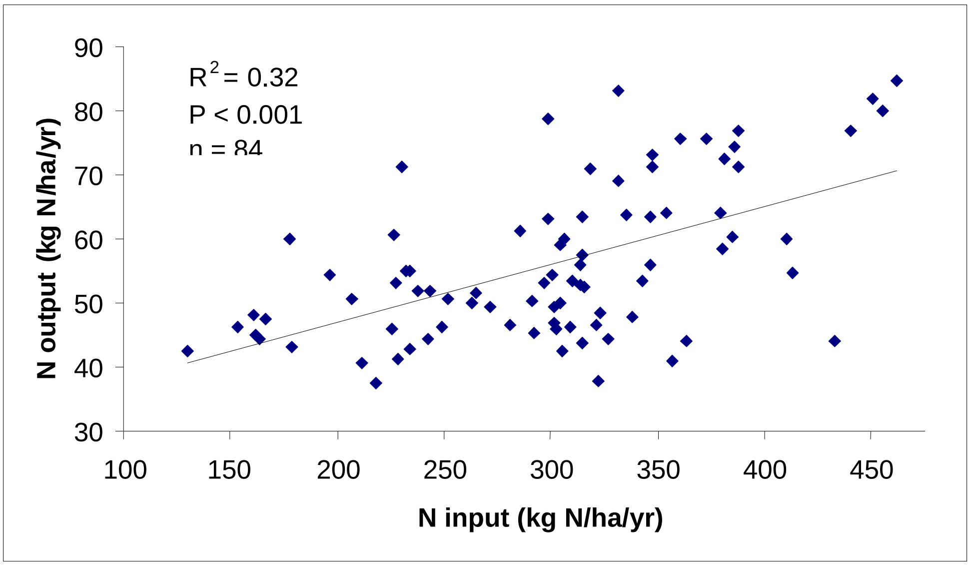

Figure 7: The relationship between N input and N output on the pilot farms.

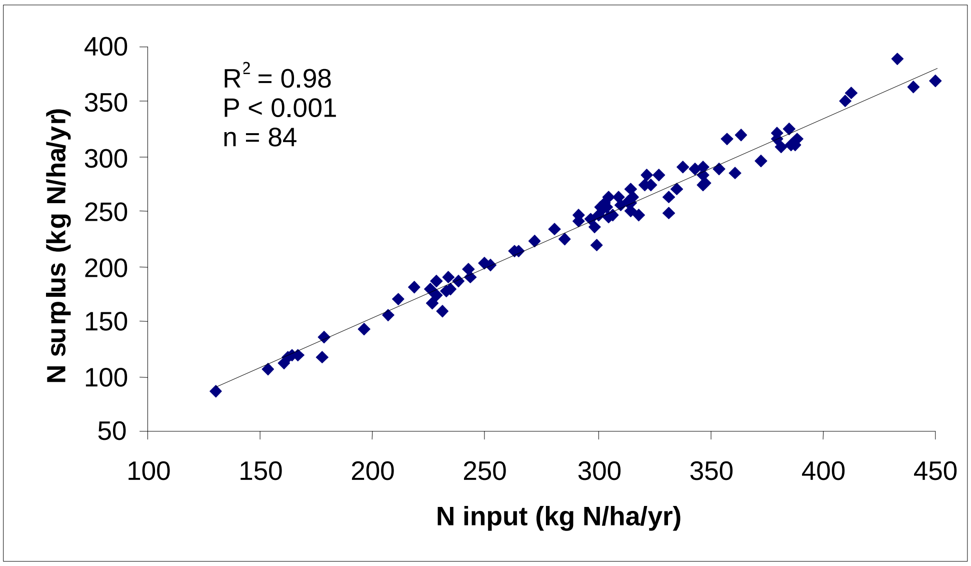

Figure 8: The relationship between N input and N surplus on the pilot farms.

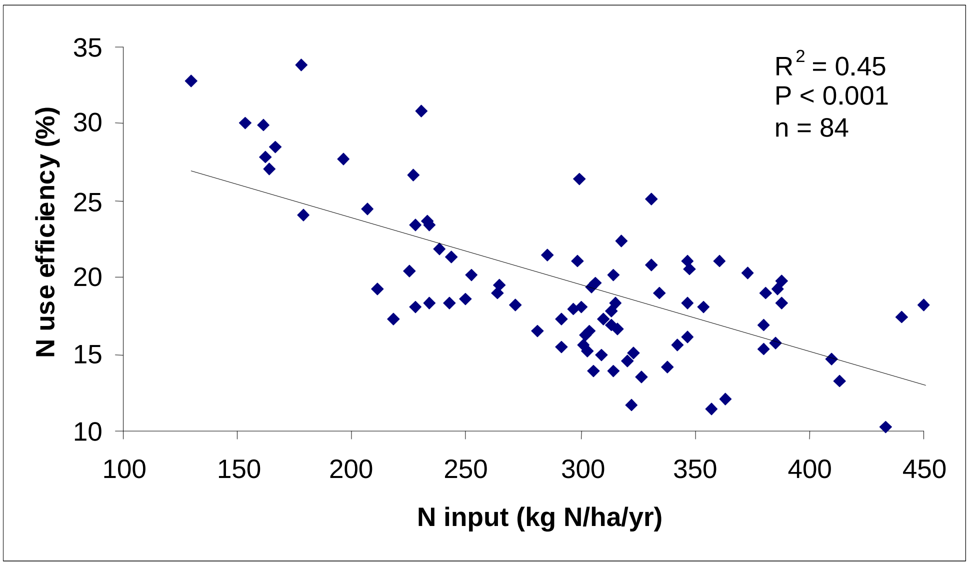

Figure 9: The relationship between N input and N use efficiency on the pilot farms.

Table 20: Farm-gate N balances, 2003 (kg N/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
											kg N/ha/yr											
Inputs																						
Fertiliser	267	287	328	296	271	270	273	142	280	306	263	266	140	315	256	204	244	308	325	202	337	266
Concentrate	69	56	122	32	42	45	32	43	24	79	55	43	27	46	36	30	53	39	63	23	51	48
Imported OM	73	0	0	35	0	0	128	138	0	0	0	0	0	0	11	0	0	0	67	0	0	22
Total	**410**	**343**	**450**	**363**	**313**	**315**	**433**	**324**	**304**	**385**	**318**	**309**	**167**	**361**	**303**	**234**	**297**	**347**	**455**	**225**	**388**	**335**
Outputs																						
Milk	47	36	68	31	47	51	31	36	40	38	59	29	31	60	29	44	30	59	65	35	58	44
Stock	13	17	14	13	8	13	13	12	10	22	12	18	17	15	17	11	23	15	15	11	14	15
Total	**60**	**53**	**82**	**44**	**56**	**63**	**44**	**49**	**50**	**60**	**71**	**46**	**48**	**76**	**46**	**55**	**53**	**73**	**80**	**46**	**71**	**58**
Surplus	**350**	**289**	**368**	**319**	**258**	**251**	**389**	**275**	**254**	**324**	**247**	**263**	**119**	**285**	**257**	**179**	**244**	**274**	**375**	**179**	**317**	**277**
Efficiency (%)	14.6	15.6	18.2	12.1	17.8	20.2	10.2	15.0	16.5	15.7	22.4	15.0	28.5	21.0	15.1	23.5	17.9	21.1	17.6	20.4	18.3	17.9

Table 21: Farm-gate N balances, 2004 (kg N/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
											kg N/ha/yr											
Inputs																						
Fertiliser	256	258	287	254	270	243	198	129	243	280	221	231	201	325	204	147	200	206	301	139	311	234
Concentrate	68	43	101	27	43	56	11	17	20	35	12	41	18	47	19	14	28	21	70	38	35	36
Imported OM	56	0	0	24	0	0	118	135	0	0	0	0	0	0	11	0	0	0	69	0	0	20
Total	**380**	**300**	**388**	**305**	**313**	**299**	**327**	**281**	**263**	**315**	**233**	**272**	**218**	**373**	**234**	**161**	**228**	**227**	**440**	**177**	**347**	**290**
Outputs																						
Milk	52	38	67	31	44	48	31	37	42	32	43	28	30	60	32	42	28	57	64	37	55	43
Stock	12	17	10	12	9	15	13	10	8	12	12	21	8	15	11	6	13	3	13	23	8	12
Total	**64**	**54**	**77**	**42**	**53**	**63**	**44**	**47**	**50**	**44**	**55**	**49**	**38**	**76**	**43**	**48**	**41**	**61**	**77**	**60**	**63**	**55**
Surplus	**316**	**246**	**311**	**263**	**260**	**236**	**282**	**234**	**213**	**271**	**178**	**222**	**181**	**297**	**191**	**113**	**187**	**166**	**363**	**117**	**283**	**235**
Efficiency (%)	16.9	18.1	19.8	13.9	16.9	21.1	13.6	16.6	19.0	13.9	23.6	18.2	17.2	20.3	18.4	29.9	18.1	26.7	17.5	33.9	18.3	19.6

Table 22: Farm-gate N balances, 2005 (kg N/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
											kg N/ha/yr											
Inputs																						
Fertiliser	270	249	389	215	268	313	175	170	231	273	268	287	115	317	189	137	169	215	281	107	237	232
Concentrate	52	43	73	35	42	41	25	38	18	48	37	35	15	31	22	17	38	16	65	28	48	37
Import OM	91	0	0	42	0	0	158	30	0	0	0	0	0	0	0	0	0	0	35	27	0	18
Total	**413**	**291**	**462**	**292**	**310**	**354**	**357**	**238**	**249**	**321**	**305**	**322**	**130**	**347**	**211**	**154**	**207**	**231**	**381**	**162**	**285**	**287**
Outputs																						
Milk	46	35	68	31	44	55	29	39	39	33	50	30	29	58	29	39	31	58	63	36	50	42
Stock	9	15	16	14	9	10	12	13	8	14	9	8	14	13	11	7	20	13	10	9	11	12
Total	**55**	**50**	**85**	**45**	**54**	**64**	**41**	**52**	**46**	**46**	**59**	**38**	**43**	**71**	**41**	**46**	**51**	**71**	**72**	**45**	**61**	**54**
Surplus	**358**	**241**	**378**	**247**	**257**	**290**	**316**	**186**	**203**	**274**	**246**	**284**	**87**	**276**	**171**	**107**	**156**	**159**	**309**	**117**	**224**	**233**
Efficiency (%)	13.2	17.3	18.3	15.5	17.2	18.1	11.5	21.8	18.6	14.5	19.3	11.7	32.8	20.5	19.2	30.1	24.5	30.8	19.0	27.8	21.4	20.2

Table 23: Farm-gate N balances, 2006 (kg N/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
											kg N/ha/yr											
Inputs																						
Fertiliser	253	256	268	236	263	308	141	140	231	252	212	265	141	274	211	216	128	245	248	109	283	223
Concentrate	78	50	67	63	52	78	53	58	33	64	40	36	23	57	31	27	69	54	97	32	63	54
Imported OM	0	0	0	40	0	0	108	30	0	0	0	0	0	0	0	0	0	0	35	38	0	12
Total	**331**	**307**	**335**	**338**	**315**	**386**	**302**	**228**	**265**	**316**	**252**	**301**	**164**	**331**	**242**	**243**	**197**	**299**	**380**	**179**	**346**	**288**
Outputs																						
Milk	49	39	53	32	49	65	37	47	41	38	48	33	33	64	37	44	34	68	55	38	49	45
Stock	20	21	11	16	9	9	12	6	10	15	2	14	12	19	7	8	21	11	3	5	7	11
Total	**69**	**60**	**64**	**48**	**58**	**74**	**49**	**53**	**52**	**52**	**51**	**47**	**44**	**83**	**44**	**52**	**54**	**79**	**58**	**43**	**56**	**57**
Surplus	**262**	**246**	**271**	**290**	**257**	**311**	**253**	**175**	**213**	**263**	**201**	**254**	**120**	**248**	**198**	**191**	**142**	**220**	**322**	**136**	**290**	**232**
Efficiency (%)	20.8	19.6	19.0	14.1	18.3	19.3	16.3	23.4	19.4	16.6	20.1	15.6	27.1	25.1	18.3	21.3	27.7	26.4	15.4	24.1	16.1	20.2

Table 24: Summary of annual total N inputs, outputs and surpluses (kg N/ha/yr), and efficiencies of N use on the studied farms from 2003 to 2006.

	Inputs (kg N/ha/yr)					Outputs (kg N/ha/yr)					Surpluses (kg N/ha/yr)					Efficiency (%)				
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**
1	410	380	413	331	384	60	64	55	69	62	350	316	358	262	322	14.6	16.9	13.2	20.8	16.4
2	343	300	291	307	310	53	54	50	60	54	289	246	241	246	256	15.6	18.1	17.3	19.6	17.7
3	450	388	462	335	409	82	77	85	64	77	368	311	378	271	332	18.2	19.8	18.3	19.0	18.8
4	363	305	292	338	325	44	42	45	48	45	319	263	247	290	280	12.1	13.9	15.5	14.1	13.9
5	313	313	310	315	313	56	53	54	58	55	258	260	257	257	258	17.8	16.9	17.2	18.3	17.6
6	315	299	354	386	339	63	63	64	74	66	251	236	290	311	272	20.2	21.1	18.1	19.3	19.7
7	433	327	357	302	355	44	44	41	49	45	389	282	316	253	310	10.2	13.6	11.5	16.3	12.9
8	324	281	238	228	268	49	47	52	53	50	275	234	186	175	218	15.0	16.6	21.8	23.4	19.2
9	304	263	249	265	270	50	50	46	52	50	254	213	203	213	221	16.5	19.0	18.6	19.4	18.4
10	385	315	321	316	334	60	44	46	52	51	324	271	274	263	283	15.7	13.9	14.5	16.6	15.2
11	318	233	305	252	277	71	55	59	51	59	247	178	246	201	218	22.4	23.6	19.3	20.1	21.4
12	309	272	322	301	301	46	49	38	47	45	263	222	284	254	256	15.0	18.2	11.7	15.6	15.1
13	167	218	130	164	170	48	38	43	44	43	119	181	87	120	127	28.5	17.2	32.8	27.1	26.4
14	361	373	347	331	353	76	76	71	83	77	285	297	276	248	277	21.0	20.3	20.5	25.1	21.7
15	303	234	211	242	248	46	43	41	44	44	257	191	171	198	204	15.1	18.4	19.2	18.3	17.8
16	234	161	154	243	198	55	48	46	52	50	179	113	107	191	148	23.5	29.9	30.1	21.3	26.2
17	297	228	207	197	232	53	41	51	54	50	244	187	156	142	182	17.9	18.1	24.5	27.7	22.1
18	347	227	231	299	276	73	61	71	79	71	274	166	159	220	205	21.1	26.7	30.8	26.4	26.3
19	455	440	381	380	414	80	77	72	58	72	375	363	309	322	342	17.6	17.5	19.0	15.4	17.4
20	225	177	162	179	186	46	60	45	43	49	179	117	117	136	137	20.4	33.9	27.8	24.1	26.6
21	388	347	285	346	342	71	63	61	56	63	317	283	224	290	279	18.3	18.3	21.4	16.1	18.5
Mean	**335**	**290**	**287**	**288**	**300**	**58**	**55**	**54**	**57**	**56**	**277**	**235**	**233**	**232**	**244**	**17.9**	**19.6**	**20.2**	**20.2**	**19.5**
	P-value		**s.e.m.**			**P-value**		**s.e.m.**			**P-value**		**s.e.m.**			**P-value**		**s.e.m.**		
Farm	< 0.001		15.9			< 0.001		2.8			< 0.001		15.5			< 0.001		1.52		
Year	< 0.001		6.9			NS		1.2			< 0.001		6.8			NS		0.66		

4.7.2 Farm-gate Phosphorus Balances

The input of P to the studied farms ranged between 5.8 and 46.7 kg P/ha/yr between 2003 and 2006 (Table 25). The mean input of P to the farms was 21.6 kg P/ha/yr. Fertiliser P accounted for 47 % of mean P input during the study, while P contained in concentrate feed purchased accounted for 35 % (Tables 26 to 29). The remainder of P input was due to the importation of pig slurry, although this only occurred on 7 farms during the study. While fertiliser P was the largest source of P input during the study, a greater level of P was imported in concentrate feed than as fertiliser in 2006 (Table 29). The lowest average level of P input over the study period was observed on farm 20 (10.8 kg P/ha/yr), while the largest mean P input was observed on farm 2 (33.6 kg P/ha/yr) (Table 25).

Phosphorus output from the farms ranged between 5.0 and 18.6 kg P/ha/yr during the study period, with the mean output of P declining ($P < 0.05$) from 13.2 kg P/ha/yr in 2003 to 12.1 kg P/ha/yr in 2006 (Table 25). The greatest export of P from the farms was due to the sale of milk, accounting for 60 % of total P output, with the remainder accounted for by the sale and deaths of livestock (Tables 26 to 29).

The mean P surplus on the farms decreased (although not significantly) from 11.2 to 9.2 kg P/ha/yr between 2003 and 2006, with the mean export of P during the study being 9.4 kg P/ha/yr (Table 25). Phosphorus surpluses ranged between -9.4 and 33.2 kg P/ha during the study period. Phosphorus deficits were observed on nine of the farms in at least one of the studied years, while a P deficit, or an extremely small P surplus, was observed on farms 17 and 18 in all of the study years. On average, the mean P surpluses over the study period were negative on farms 17, 18 and 20. The largest mean surpluses over the study period were observed on farms 7 (22.2 kg P/ha/yr) and 8 (21.8 kg P/ha/yr), with mean surpluses exceeding 20 kg P/ha/yr also observed on farms 2 and 9.

The efficiency of P use observed on the farms during the study period ranged from 14.9 to 242.4 %. The least efficient use of P over the study period was evident on farm 7 (23.7 %), while the most efficient use of P was observed on farm 17 (137.3 %).

Table 25: Summary of annual total phosphorus inputs, outputs, surpluses (kg P/ha/yr) and efficiencies of phosphorus use on the studied farms from 2003 to 2006.

	Inputs (kg P/ha/yr)					Outputs (kg P/ha/yr)					Surpluses (kg P/ha/yr)					Efficiencies (%)				
Farm	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**	**2003**	**2004**	**2005**	**2006**	**Mean**
1	33.7	23.6	26.5	13.5	24.3	13.0	13.8	11.4	16.5	13.7	20.7	9.9	15.1	-3.0	10.7	38.5	58.3	43.1	122.3	65.6
2	39.7	36.1	30.5	28.2	33.6	13.0	13.2	12.1	15.2	13.4	26.7	22.8	18.4	13.0	20.2	32.8	36.7	39.8	53.9	40.8
3	36.2	31.6	13.9	46.7	32.1	17.3	15.3	18.2	13.5	16.1	18.9	16.4	-4.3	33.2	16.1	47.7	48.3	131.2	28.9	64.0
4	12.1	16.2	13.9	18.3	15.1	10.4	10.1	11.1	12.0	10.9	1.7	6.2	2.8	6.3	4.3	85.6	62.0	80.0	65.8	73.4
5	28.4	13.5	7.3	14.7	16.0	11.3	11.1	11.3	11.8	11.4	17.0	2.3	-4.0	2.9	4.6	40.0	82.7	154.8	80.4	89.5
6	20.7	25.2	16.6	20.0	20.6	13.6	14.2	13.0	14.6	13.9	7.1	11.1	3.6	5.4	6.8	65.5	56.1	78.6	73.1	68.3
7	29.4	23.7	33.6	29.3	29.0	10.5	5.4	5.0	6.3	6.8	18.9	18.3	28.6	23.1	22.2	35.8	22.7	14.9	21.5	23.7
8	33.2	28.5	35.8	33.0	32.6	11.0	10.1	11.6	10.5	10.8	22.3	18.4	24.2	22.5	21.9	33.0	35.5	32.5	31.9	33.2
9	34.2	32.5	27.3	30.4	31.1	10.8	10.3	9.7	11.3	10.5	23.4	22.2	17.6	19.1	20.6	31.5	31.8	35.4	37.1	34.0
10	42.7	29.2	17.1	16.7	26.4	15.2	10.1	11.2	12.4	12.2	27.5	19.1	5.9	4.3	14.2	35.6	34.7	65.6	74.4	52.6
11	25.6	27.7	31.3	25.5	27.5	14.5	11.8	11.8	8.9	11.8	11.0	15.9	19.5	16.6	15.8	56.9	42.7	37.7	34.8	43.0
12	19.5	17.1	25.7	19.7	20.5	12.3	13.7	8.4	11.2	11.4	7.2	3.5	17.4	8.5	9.2	63.0	79.8	32.5	56.9	58.1
13	20.7	21.0	8.7	15.1	16.4	12.2	8.4	10.6	10.6	10.5	8.5	12.7	-1.9	4.5	6.0	59.0	39.7	122.0	70.2	72.7
14	18.9	18.8	22.3	9.9	17.5	16.4	16.3	15.0	18.6	16.6	2.6	2.5	7.3	-8.7	0.9	86.4	86.5	67.2	187.4	106.9
15	15.3	10.3	14.0	12.5	13.0	11.7	10.0	9.8	9.5	10.3	3.5	0.3	4.2	3.1	2.8	76.8	97.0	70.1	75.6	79.9
16	23.2	6.4	6.7	15.3	12.9	11.7	9.3	9.3	10.4	10.2	11.5	-2.9	-2.6	4.9	2.7	50.4	145.2	139.4	68.1	100.8
17	12.2	10.3	12.4	13.4	12.1	14.3	10.1	13.4	14.2	13.0	-2.1	0.2	-0.9	-0.8	-0.9	117.1	97.8	107.5	106.0	107.1
18	10.8	5.8	12.0	16.6	11.3	15.5	10.8	15.0	15.6	14.2	-4.7	-5.0	-3.0	0.9	-3.0	143.7	186.1	124.8	94.3	137.2
19	26.6	31.2	22.6	27.9	27.1	17.0	16.0	14.7	10.6	14.6	9.6	15.2	7.9	17.3	12.5	63.9	51.4	65.0	37.9	54.6
20	8.1	6.6	13.0	15.4	10.8	10.3	16.0	9.8	8.6	11.2	-2.2	-9.4	3.1	6.9	-0.4	127.3	242.4	76.0	55.4	125.3
21	20.9	17.8	33.1	24.9	24.2	15.0	12.6	12.9	11.1	12.9	5.8	5.2	20.2	13.8	11.3	72.1	71.0	39.0	44.8	56.7
Mean	**24.4**	**20.6**	**20.2**	**21.3**	**21.6**	**13.2**	**11.8**	**11.7**	**12.1**	**12.2**	**11.2**	**8.8**	**8.5**	**9.2**	**9.4**	**64.9**	**76.6**	**74.1**	**67.7**	**70.8**
	P–value		**s.e.m.**			**P–value**		**s.e.m.**			**P–value**		**s.e.m.**			**P–value**		**s.e.m.**		
Farm	< 0.001		3.04			< 0.001		0.88			< 0.001		3.37			< 0.001		16.67		
Year	NS		1.33			< 0.05		0.38			NS		1.47			NS		7.28		

Table 26: Farm-gate P balances, 2003 (kg P/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
												kg P/ha/yr										
Inputs																						
Fertiliser	8.0	30.0	15.0	0.0	21.0	13.0	0.0	0.0	30.0	29.0	16.0	12.0	16.0	11.0	5.0	18.0	3.0	4.0	4.0	4.0	12.0	12.0
Concentrate	12.1	9.7	21.2	5.5	7.4	7.7	5.6	7.5	4.2	13.7	9.6	7.5	4.7	7.9	6.2	5.2	9.2	6.8	11.0	4.1	8.9	8.4
OM imports	13.7	0.0	0.0	6.6	0.0	0.0	23.8	25.7	0.0	0.0	0.0	0.0	0.0	0.0	4.1	0.0	0.0	0.0	11.7	0.0	0.0	4.1
Total	**33.7**	**39.7**	**36.2**	**12.1**	**28.4**	**20.7**	**29.4**	**33.2**	**34.2**	**42.7**	**25.6**	**19.5**	**20.7**	**18.9**	**15.3**	**23.2**	**12.2**	**10.8**	**26.6**	**8.1**	**20.9**	**24.4**
Outputs																						
Milk	7.7	6.1	11.8	5.1	8.1	8.6	5.4	6.2	6.8	6.3	9.6	4.8	5.3	10.3	4.9	7.3	5.0	9.8	11.0	6.0	9.7	7.4
Stock	5.3	6.9	5.5	5.2	3.2	4.9	5.1	4.8	4.0	8.9	4.9	7.5	6.8	6.1	6.8	4.5	9.3	5.7	6.0	4.2	5.3	5.8
Total	**13.0**	**13.0**	**17.3**	**10.4**	**11.3**	**13.6**	**10.5**	**11.0**	**10.8**	**15.2**	**14.5**	**12.3**	**12.2**	**16.4**	**11.7**	**11.7**	**14.3**	**15.5**	**17.0**	**10.3**	**15.0**	**13.2**
Surplus	**20.7**	**26.7**	**18.9**	**1.7**	**17.0**	**7.1**	**18.9**	**22.3**	**23.4**	**27.5**	**11.0**	**7.2**	**8.5**	**2.6**	**3.5**	**11.5**	**-2.1**	**-4.7**	**9.6**	**-2.2**	**5.8**	**11.2**
Efficiency(%)	38.5	32.8	47.7	85.6	40.0	65.5	35.8	33.0	31.5	35.6	56.9	63.0	59.0	86.4	76.8	50.4	117.1	143.7	63.9	127.3	72.1	64.9

Table 27: Farm-gate P balances, 2004 (kg P/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
												kg P/ha/yr										
Inputs																						
Fertiliser	1.4	28.7	14.1	7.1	6.0	15.6	0.0	0.5	28.9	23.2	25.7	10.0	17.9	10.6	5.0	4.0	5.4	2.2	6.1	0.0	11.7	10.7
Concentrate	11.9	7.4	17.5	4.7	7.4	9.6	1.9	3.0	3.6	6.0	2.0	7.1	3.1	8.2	3.3	2.4	4.9	3.6	12.2	6.6	6.1	6.3
OM Imports	10.3	0.0	0.0	4.4	0.0	0.0	21.9	25.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	12.9	0.0	0.0	3.6
Total	**23.6**	**36.1**	**31.6**	**16.2**	**13.5**	**25.2**	**23.7**	**28.5**	**32.5**	**29.2**	**27.7**	**17.1**	**21.0**	**18.8**	**10.3**	**6.4**	**10.3**	**5.8**	**31.2**	**6.6**	**17.8**	**20.6**
Outputs																						
Milk	8.7	6.3	11.2	5.2	7.4	8.1	5.4	6.1	7.1	5.2	7.0	4.8	5.2	10.0	5.5	7.0	4.7	9.5	10.8	6.3	9.2	7.2
Stock	5.1	7.0	4.1	4.9	3.7	6.0	0.0	4.0	3.2	4.9	4.8	8.9	3.2	6.3	4.5	2.3	5.5	1.3	5.3	9.7	3.4	4.7
Total	**13.8**	**13.2**	**15.3**	**10.1**	**11.1**	**14.2**	**5.4**	**10.1**	**10.3**	**10.1**	**11.8**	**13.7**	**8.4**	**16.3**	**10.0**	**9.3**	**10.1**	**10.8**	**16.0**	**16.0**	**12.6**	**11.8**
Surplus	**9.9**	**22.8**	**16.4**	**6.2**	**2.3**	**11.1**	**18.3**	**18.4**	**22.2**	**19.1**	**15.9**	**3.5**	**12.7**	**2.5**	**0.3**	**-2.9**	**0.2**	**-5.0**	**15.2**	**-9.4**	**5.2**	**8.8**
Efficiency(%)	58.3	36.7	48.3	62.0	82.7	56.1	22.7	35.5	31.8	34.7	42.7	79.8	39.7	86.5	97.0	145.2	97.8	186.1	51.4	242.4	71.0	76.6

Table 28: Farm-gate P balances, 2005 (kg P/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
												kg P/ha/yr										
Inputs																						
Fertiliser	0.5	23.1	1.2	0.0	0.0	9.5	0.0	0.0	24.1	8.7	24.9	19.6	6.2	16.9	10.1	3.7	5.8	9.2	4.6	3.1	24.7	9.3
Concentrate	9.0	7.4	12.7	6.1	7.3	7.1	4.3	6.6	3.1	8.4	6.5	6.1	2.5	5.3	3.9	2.9	6.6	2.8	11.3	4.9	8.4	6.3
OM Imports	17.0	0.0	0.0	7.9	0.0	0.0	29.3	29.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.6	5.0	0.0	4.5
Total	**26.5**	**30.5**	**13.9**	**13.9**	**7.3**	**16.6**	**33.6**	**35.8**	**27.3**	**17.1**	**31.3**	**25.7**	**8.7**	**22.3**	**14.0**	**6.7**	**12.4**	**12.0**	**22.6**	**13.0**	**33.1**	**20.2**
Outputs																						
Milk	7.7	5.9	11.6	5.2	7.6	9.2	5.0	6.3	6.6	5.5	8.3	5.0	5.0	9.7	5.2	6.5	5.2	9.6	10.7	6.2	8.5	7.2
Stock	3.7	6.2	6.6	6.0	3.8	3.8	0.0	5.4	3.0	5.8	3.5	3.3	5.6	5.2	4.7	2.8	8.2	5.4	3.9	3.7	4.4	4.5
Total	**11.4**	**12.1**	**18.2**	**11.1**	**11.3**	**13.0**	**5.0**	**11.6**	**9.7**	**11.2**	**11.8**	**8.4**	**10.6**	**15.0**	**9.8**	**9.3**	**13.4**	**15.0**	**14.7**	**9.8**	**12.9**	**11.7**
Surplus	**15.1**	**18.4**	**-4.3**	**2.8**	**-4.0**	**3.6**	**28.6**	**24.2**	**17.6**	**5.9**	**19.5**	**17.4**	**-1.9**	**7.3**	**4.2**	**-2.6**	**-0.9**	**-3.0**	**7.9**	**3.1**	**20.2**	**8.5**
Efficiency(%)	43.1	39.8	131.2	80.0	154.8	78.6	14.9	32.5	35.4	65.6	37.7	32.5	122.0	67.2	70.1	139.4	107.5	124.8	65.0	76.0	39.0	74.1

Table 29: Farm-gate P balances, 2006 (kg P/ha/yr).

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Mean
												kg P/ha/yr										
Inputs																						
Fertiliser	0.0	19.5	35.1	0.0	5.7	6.4	0.0	0.0	24.6	5.6	18.6	13.4	11.2	0.0	7.1	10.7	1.5	7.1	4.5	2.9	13.9	8.9
Concentrate	13.5	8.7	11.6	10.9	9.0	13.6	9.2	10.1	5.8	11.1	6.9	6.3	4.0	9.9	5.4	4.6	11.9	9.4	16.8	5.5	11.0	9.3
OM Imports	0.0	0.0	0.0	7.4	0.0	0.0	20.2	22.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.6	7.1	0.0	3.1
Total	**13.5**	**28.2**	**46.7**	**18.3**	**14.7**	**20.0**	**29.3**	**33.0**	**30.4**	**16.7**	**25.5**	**19.7**	**15.1**	**9.9**	**12.5**	**15.3**	**13.4**	**16.6**	**27.9**	**15.4**	**24.9**	**21.3**
Outputs																						
Milk	8.4	6.6	9.1	5.3	8.3	11.0	6.3	8.0	7.1	6.3	7.9	5.6	5.7	10.8	6.4	7.2	5.7	11.1	9.3	6.5	8.1	7.7
Stock	8.2	8.6	4.4	6.7	3.6	3.6	0.0	2.5	4.2	6.1	1.0	5.7	4.9	7.8	3.1	3.2	8.5	4.5	1.3	2.0	3.0	4.4
Total	**16.5**	**15.2**	**13.5**	**12.0**	**11.8**	**14.6**	**6.3**	**10.5**	**11.3**	**12.4**	**8.9**	**11.2**	**10.6**	**18.6**	**9.5**	**10.4**	**14.2**	**15.6**	**10.6**	**8.6**	**11.1**	**12.1**
Surplus	**-3.0**	**13.0**	**33.2**	**6.3**	**2.9**	**5.4**	**23.1**	**22.5**	**19.1**	**4.3**	**16.6**	**8.5**	**4.5**	**-8.7**	**3.1**	**4.9**	**-0.8**	**0.9**	**17.3**	**6.9**	**13.8**	**9.2**
Efficiency(%)	122	53.9	28.9	65.8	80.4	73.1	21.5	31.9	37.1	74.4	34.8	56.9	70.2	187	75.6	68.1	106	94.3	37.9	55.4	44.8	67.7

A strong positive linear relationship (R^2 = 0.92, P < 0.001) was observed between P input and P surplus (Fig. 10), while a weaker positive relationship (R^2 = 0.32, P < 0.01) was found between the mean P surpluses and STP levels on the farms (Fig. 11).

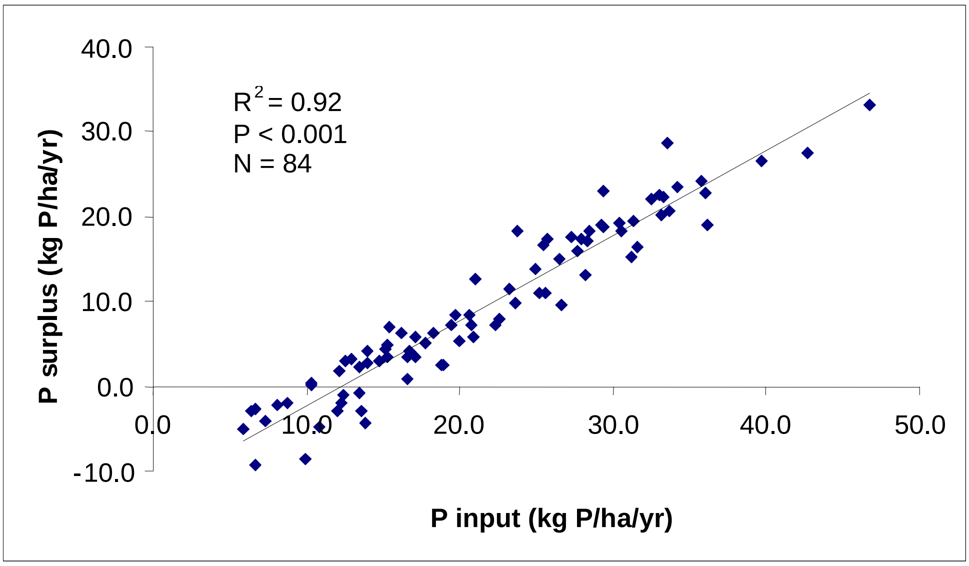

Figure 10: The relationship between P input and P surplus on the pilot farms.

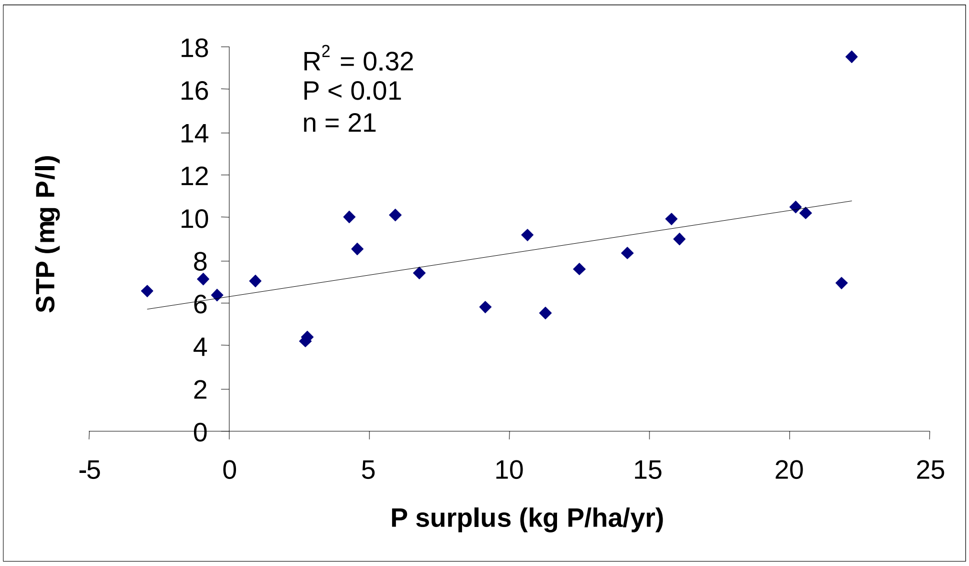

Figure 11: The relationship between Soil Test Phosphorus (mg P/l) and Phosphorus surpluses on the pilot farms.

5. Discussion

5.1 Objectives

The main objectives of this project were:

(i) To develop a better understanding of current nutrient management practices on intensive dairy farms in the south-west of Ireland.

(ii) To identify nutrient management practices which could potentially be improved to increase the efficiency of artificial fertiliser and animal manure usage on these farms.

(iii) To study farm-gate nutrient balances of intensive dairy farms, and monitor the effects of changes in nutrient management practices, implemented due to economic decisions of the farmers, on these balances.

5.2 Nitrogen

Fertiliser N was the main N input to the farms selected for this study, accounting for nearly 80 % of total N input during the study period (section 4.7.1), while N contained in purchased concentrate was the second most important N input. During the first three years of the study, concentrate feed accounted for approximately 13 % of the total imports of N (Tables 20 to 22, Section 4.7.1). However, due to the higher levels of concentrate feed used in 2006 (Table 12, Section 4.3.4), concentrate feed accounted for nearly 19 % of the N imported onto the farms in 2006 (Table 23, Section 4.7.1). The increase in concentrate feed use in 2006 can be attributed to below average grass growth during the summer period (Fig. 5, Section 4.2), caused by a prolonged period of extremely dry weather (Table 7, Section 4.1.1). The importation of pig slurry also resulted in a substantial input of N on a number of the farms during the study, particularly on farms 1, 4, 7, 8 and 19 (Tables 20 to 23, Section 4.7.1).

The main output of N from the farms was in milk sold from the farms. This is not surprising as spring calving dairy herds are the main enterprises on each of the farms selected for this study. Output of N from the farms did not change significantly during the study, even though total N input decreased (Tables 20 to 23). This resulted in an increase in the mean efficiency of N use on the farms, from 17.9 % in 2003 to 20.2 % in 2006. These efficiencies are slightly higher than the mean efficiency (17 %) found in a study of twelve Irish dairy farms in 1997 (Mounsey *et al.*, 1998), but lower than the mean efficiency of 30 % observed by Ledgard *et al.* (1997) on a group of dairy farms in New Zealand. However, there was large variation in the efficiencies observed on individual farms in the present study, which ranged between 10.2 and 33.9 %. This large variation can be largely attributed to variations observed in the level of fertiliser N input on farms with similar stocking rates (Fig. 6, Section 4.4.2). Farms on which clover was being used to supply part of the N requirements of the grass sward tended to be among the most efficient in the group. White clover was introduced to farms 13 and 17 during the study period. These were the most efficient farms in 2006, with the efficiency of N use exceeding 27 % on both farms (Table 24, section 4.7.1). The establishment of white clover was also encouraged on farm 20. On average, this was the most efficient farm during the study. However, although farm 7 also had clover pastures, efficiency of N use was relatively low on this farm throughout the study (Table 24, section 4.7.1). This was due to large inputs of N which resulted from the importation of large quantities of pig slurry.

As the input of N decreased during this study it was not surprising that the mean N surplus also decreased. There was a very strong positive linear relationship between N input and N surplus on the dairy farms (Fig. 8, Section 4.7.1), in agreement with other studies (Oenema *et al*., 1998; Jarvis, 1999). As N fertiliser use has been declining on Irish farms at national level since 2000 (CSO, 2007), it is likely that the national N surplus has also been decreasing over the same time period. Overall, the level of N input measured during the study period was found to account for 32 % of the observed N output on the studied farms ($P < 0.001$) (Fig. 7, Section 4.7.1). There was a marked decrease ($P < 0.001$) in N efficiency with increasing N input (Fig. 9, Section 4.7.1), indicating that very high N inputs cannot be justified.

The decrease in N input was mainly due to a decrease in mean fertiliser N input on the farms, from 266 kg N/ha/yr in 2003 to 223 kg N/ha/yr in 2006 (Table 14, section 4.4.2). This was largely the result of decreases in the rate of fertiliser N applied in the first annual application, and for the production of first cut silage (Table 14, section 4.4.2). These decreases were partly achieved by increasing the proportion of slurry applied on the farms during the spring period (section 5.4), while the introduction of white clover on five farms (7, 13, 15, 17, and 20) also resulted in a substantial decrease in fertiliser N use on these farms (section 5.2.1).

O'Connell *et al.* (2004) showed that the recovery of N by the grass sward generally increased the later the fertiliser N was applied in spring. Therefore, fertiliser N application rates should be kept relatively low early in the season. In 2006, seven of the twenty-one farmers applied less than 30 kg N/ha at the first application. On four farms (2, 12, 19 and 21) applied rates exceeded 40 kg N/ha. A rate of 29 kg N/ha is recommended as the first annual fertiliser N application (Mc

Namara, Per. Comm.; Humphreys *et al.*, 2002; Humphreys *et al.*, 2007). There is clearly potential to further decrease the first annual fertiliser N application rate on many of the farms in this study.

The rate of fertiliser N applied for the production of first cut silage is also an area where there is potential to decrease fertiliser N use on many of the studied farms. Over the study period, the mean rate of fertiliser N applied for the production of first cut silage decreased ($P < 0.05$) from 106 to 96 kg N/ha (Table 14, section 4.4.2). This decrease was partly achieved by substituting some fertiliser N with slurry N, and by taking the nutrient value of slurry into account when fertilising for the silage crop, as discussed further in section 5.4. However, the rate of fertiliser N applied for the production of first cut silage in 2006 exceeded 100 kg N/ha on nine farms. Therefore, it is likely that further decreases in N use are possible on these farms.

In general, the rate of fertiliser N applied increased as the stocking rate increased (Fig. 6, Section 4.4.2). However, a large variation between the rates of fertiliser N applied on individual farms was observed, even where stocking rates were similar. Although part of this variation could be attributed to differences in levels of background soil N (O'Connell *et al.*, 2003), and the use of white clover on some farms, the results suggest there is potential for a decrease in N usage on many intensive dairy farms in Ireland. The greatest variations in the rates of fertiliser N applied in the study were observed on the less intensively stocked farms, therefore, it appears that the largest potentials to reduce fertiliser N applications will be found on the less intensive dairy farms.

For example, farms 5 and 13 were both stocked at approximately 170 kg org. N/ha during the study period. However, annual fertiliser N usage varied substantially between the farms, with an average rate of 268 kg N/ha/yr being applied on farm 5, while an average of 149 kg N/ha/yr was applied on farm 13 (Table 14, Section 4.4.2). Concentrate feed usage was also higher on farm 5 (Table 12, Section 4.3.4). These results suggest a potential to decrease the level of fertiliser N applied on farm 5. It should be noted, however, that white clover had been introduced to some of the pastures on farm 13, although the actual area was relatively small, and certainly not substantial enough to explain the differences in N input. While the rate of N applied on farm 5 in 2006 was below the maximum permitted rate of 286 kg fertiliser-N/ha/yr (Farm stocking rate between 171 and 210 kg org. N/ha) under SI 378, 2006, it exceeded the rate recommended as sufficient for crop requirements at this stocking level (Humphreys *et al.*, 2007). Indeed, in 2006, less fertiliser N was applied on farms 1 and 19, which were both stocked at 241 kg org. N/ha, than was applied on farm 5.

The rates of fertiliser N applied in 2006 on farms 6 (308 kg N/ha/yr) and 14 (274 kg N/ha/yr) exceeded the maximum limits permissible under SI 378, 2006 (Table 14, section 4.4.2). These farms were both stocked at greater than 210 kg org. N/ha (Table 10, section 4.3.2) and were permitted to apply 256 kg fertiliser-N/ha/yr. While farms which are highly stocked appear to have the greatest difficulties in complying with SI 378, 2006, the results from the majority of the farms in this study which were stocked at greater than 210 kg org. N/ha, demonstrate that the limits are workable.

The mean number of days on which fertiliser was applied each year decreased from 48 days in 2004 to 29 days in 2006 (Table 13, section 4.4.1). Milk production on the farms was not negatively affected (Table 10, section 4.3.2). While it has been traditionally recommended that fertiliser N is applied after each grazing, Mc Namara *et al.* (2006) found no negative effects on grass production when a once per month application strategy was adopted during the spring period, while they recommended a twice per month application strategy for the remainder of the year. Decreasing the number of days per year on which fertiliser is applied can lower time and labour requirements associated with fertiliser application, particularly where spreading equipment must be attached to a tractor on each occasion, as well as simplifying record keeping. While the majority of farms in this study reduced the number of days on which fertiliser was applied over the study period, the number of days increased on farm 16 (Table 13, section 4.4.1). Fertiliser was applied regularly on this farm as a spreader remained on a tractor dedicated to the task for the whole year.

Fertiliser N was generally applied as either urea or CAN, while N, P, K compound fertilisers accounted for 27.4 % of fertiliser N applied (Table 15, Section 4.4.2). The use of urea in spring-time is recommended as it is a cheaper source of N than CAN (Humphreys *et al.*, 2007), while also being less susceptible to immediate loss after application than CAN (Addiscott, 1996). However, N losses through NH_3 volatilisation are associated with the application of urea fertiliser in warm, dry conditions (Pain *et al.*, 1999). For this reason its use is not recommended during the summer period (Watson *et al.*, 1990; Humphreys *et al.*, 2004a). This advice appears to be well accepted by farmers. Ninety-five percent of the urea applied on the studied farms in 2006 was applied before the end of May, with the remainder applied in late August and early September.

5.2.1 Case Study – Three White Clover Farms (7, 17 and 20)

White clover was introduced on five of the farms (7, 13, 15, 17, and 20) during the study period, generally using the over-sowing method, as described by Healy *et al.* (2005). This resulted in a 35 % decrease in the mean N usage on these farms during the study. However, substantial areas of clover were only established on farms 7, 17 and 20 by the end of the study period. A 47 % decrease in mean fertiliser N usage was observed on these three farms during the study.

The farm area on these three farms (7, 17 and 20) remained unchanged during the study period. Mean milk production increased from 342,722 litres in 2003 to 388,829 litres in 2006. The average stocking rate on the three farms declined from 183 kg org. N/ha in 2003 to 171 kg org. N/ha in 2006, although the mean number of dairy cows present on the farms increased from 63 cows in 2003 to 69 cows in 2006. However, the number of other stock present on the three farms decreased from a mean of 63 LU in 2003 to a mean of 48 LU in 2006. Concentrate feed usage remained largely unchanged on the farms during the initial three years of the study. However, concentrate feed usage increased during 2006. This was due to the extremely dry weather conditions experienced in the summer of 2006.

The use of fertiliser N declined substantially on farms 7, 17 & 20, from an average of 240 kg N/ha/yr in 2003 to 126 kg N/ha/yr in 2006. This decrease (47 %) was substantially higher than the decrease observed in the mean fertiliser N usage of the twenty-one farms in the study (16 %). The mean rate of fertiliser N applied in the first application on these three farms declined from 51 kg N/ha in 2004 to 34 kg N/ha in 2006, while the mean rate of fertiliser N applied for the production of first cut silage decreased from 111 kg N/ha in 2004 to 98 kg N/ha in 2006. These decreases are similar to the mean decreases in fertiliser N applications recorded on all twenty-one farms in the study (Table 14, section 4.4.2).

While white clover was an important factor in achieving the observed decreases in fertiliser N use, improved slurry management was also evident on the three farms, with the mean percentage of slurry applied in the spring period increasing from 50 % in 2004 to 71 % in 2006 (Table 18, section 4.5.2).

The decrease in fertiliser N use observed on these three farms resulted in decreased N surpluses and increased N use efficiency. On average, mean total N input to the farms decreased from 318 kg N/ha/yr in 2003 to 226 kg N/ha/yr in 2006, while the mean N output remained unchanged. This resulted in a decrease in the mean N surplus of the farms, from 271 kg N/ha/yr in 2003 to

177 kg N/ha/yr in 2006, while the mean N use efficiency on these farms increased from 16.2 % in 2003 to 22.7 % in 2006.

According to Humphreys and Lawless (2006), stocking rates of up to 170 kg org. N/ha can be supported on clover swards receiving 90 kg fertiliser N/ha/yr. Although many of the farms studied were stocked at a level too high to consider a white clover system, there is potential for decreased N inputs on the less intensively stocked farms in this study through the use of white clover. Nationally, a large proportion of dairy farms are stocked at less than 170 kg org. N/ha (Connolly *et al.*, 2007) and consequently there appears to be potential for large decreases in fertiliser N usage on many farms through the introduction and management of white clover pastures.

5.2.2 Similar Studies

In a study of dairy farms in Ireland stocked at greater than 210 kg org. N/ha, McQuinn *et al.* (2002) found the average fertiliser N use to be 268 kg N/ha/yr, while Humphreys *et al.* (2003a) found the average use of fertiliser N on a group of 32 intensive Irish dairy farms to be a little over 300 kg N/ha/yr between 1993 and 2001. While the rate of fertiliser N used on the farms in this study was slightly lower than in earlier studies, it is not surprising, as nationally fertiliser N use has been decreasing during the last decade (CSO, 2007). However, it should be noted that the farms in the earlier studies were stocked at a slightly higher level than that observed in the current study.

Mounsey *et al.* (1998) carried out a study of twelve intensive Irish dairy farms in 1997. The mean stocking rate was 219 kg org. N/ha. They found a mean N surplus of 304 kg N/ha/yr, with surpluses ranging between 198 and 408 kg N/ha/yr on the individual farms. These surpluses exceed those found in the current study, although the stocking rate of the current study is also lower. Nitrogen use efficiency was 19 %. Similar to the current study, fertiliser N was the most important N input, accounting for 88 % of total N input, while milk sales accounted for the largest export of N. The rate of fertiliser N applied in the first annual application observed by Mounsey *et al.* (1998) greatly exceeded the rate applied on the farms in the current study, with a mean application of 60.1 kg N/ha being applied. The lowest rate applied was 57.5 kg N/ha, approximately twice the rate now being recommended (Humphreys *et al.*, 2007). When compared to the results of the current study, it appears that the rate of N used in the first annual application has been decreasing on intensive Irish dairy farms over the past decade. This is to be expected as the recommended rate has been halved during this period.

A recent study by Raison *et al.* (2006) studied nutrient management on 139 pilot farms in nine regions of the Atlantic seaboard of Europe over a three year period. There was a large variation observed between farming systems in the different regions, and this had distinct effects on the observed nutrient balances. Farms in the northern regions, including Ireland, were based on grazing, and harvested grass was stored and used in winter. The stocking rates varied between 136 kg org. N/ha and 187 kg org. N/ha, and fertiliser N use was generally greater than 200 kg N/ha/yr. Fertiliser N use decreased during their study, but still remains relatively high in comparison to other regions. Concentrate usage was relatively low, particularly in Ireland where the mean concentrate usage was 580 kg/cow during the study.

The farm systems in the southern regions, such as Northern Portugal, were very intensive, with stocking rates as high as 510 kg org. N/ha. These systems produced very high yields of milk per ha, but also required high levels of maize and concentrate feeding. The use of fertiliser N was also relatively high at approximately 200 kg N/ha/yr. Nitrogen surpluses on these farms exceeded 500 kg N/ha/yr. However, it should be noted that the farms in the study were not representative of the area, and were selected as being potentially problematic to the environment.

In the regions located in west France, such as Brittany and Pays de Loire, inputs of concentrate feed and fertiliser N were relatively low. This resulted in low N surpluses, close to 100 kg N/ha/yr. However, regulation on N input is strict in these regions as water quality is poor, and stocking rates were low, at approximately 115 kg org. N/ha.

The large difference in surpluses observed between regions by Raison *et al.* (2006) is in agreement with the findings of a number of previous studies. Dutch dairy farms can have N surpluses over 450 kg N/ha/yr (Van der Meer and van Uum-van Lohuyzen, 1986; Ledgard *et al.*, 1997), while Ledgard *et al.* (1997) found much lower surpluses (mean 131 kg N/ha/yr) on a group of dairy farms in New Zealand, when biological fixation was included as an N input.

“Blanket” approaches to environmental policy appear too simple (Wade *et al.*, 2005). In the study of Raison *et al.* (2006), Brittany was the region with the worst water quality, despite the fact that the dairy farms in this region showed the lowest N surpluses. This demonstrates the major differences in the fate of N surpluses in different regions and systems. The cultivation of soil for the production of maize, as is common in Brittany, is likely to cause a release of N through the process of mineralisation (Shepherd *et al.*, 1999), leading to large N losses to ground water through NO_3^- leaching (Neill, 1989; Whitehead, 1995). Therefore, grass-based systems such as in Ireland appear to have an environmental advantage (Pflimlin *et al.*, 2006). Indeed in areas with soil types from which there is a high risk of N leaching, permanent pastures are recommended (Bossuet *et al.*, 2006). Permanent grassland acts as a store for N, as indicated by its high OM content (Brogan, 1966; McGrath and Zhang, 2003; O'Connell *et al.*, 2003), lowering the risk of loss to water. It is also possible that much of the N surpluses observed on grass-based farms in northern Europe are lost to the environment through the process of denitrification (Smith *et al.*, 1995), resulting in a large proportion of the N being released as N_2O and N_2 to the atmosphere. However, it is important to bear in mind that improvements in water quality are relatively slow and, therefore, the effects of low N surpluses on dairy farms in Brittany may not become apparent for a number of years. Intensive poultry and pig units may also be counteracting the positive effects of low N fertiliser use on the dairy farms (Andre Le Gall, Pers. Comm.).

5.3 Phosphorus

Phosphorus loss to water is one of Ireland's greatest environmental concerns (Toner *et al.*, 2005). Therefore, the management of P on intensive Irish dairy farms requires careful consideration. The management of P on the farms in this study was generally close to recommended practice (Section 2.3.1.1;, with very high (>15 mg P/l) STP values uncommon. The mean STP concentration on the farms was 8.2 mg P/l. This is lower than a mean STP concentration of 11.7 mg P/l found on twelve intensive Irish dairy farms in 1997 (Mounsey *et al.*, 1998), but is comparable with the mean STP concentration (8.3 mg P/l) of all soil samples received from commercial farms for analysis by Teagasc, Johnstown Castle between 2003 and 2006 (Fig. 2, Section 2.3.3). The mean STP concentration exceeded 10 mg P/l on five of the studied farms. This was the upper limit of soil index 3, the target index prior to the implementation of SI 378, 2006. However, as discussed in section 2.3.1.1, the upper limit of index 3 was lowered to 8 mg P/l under SI 378, 2006. The mean STP concentration exceeded 8 mg P/l on ten of the studied farms.

The use of fertiliser P decreased (although not significantly) from 12.0 to 8.9 kg P/ha/yr during the study. However, there was substantial variation in the rates of fertiliser P applied, with annual applications ranging between 0.0 to 35.1 kg P/ha/yr during the study period. Fertiliser P accounted for 47 % of the P input to the farms. This is lower than the findings of Mounsey *et al.*

(1998) who found fertiliser P contributed 67 % of total P input to the dairy farms in their study. However, as fertiliser P use has declined on Irish dairy farms during the interim period (Fig. 2, section 2.2.3), it is not surprising that the fertiliser P accounted for a lower proportion of total P input in the current study.

The mean input of P from imported pig slurry also decreased, from 4.1 kg P/ha/yr in 2003 to 3.1 kg P/ha/yr in 2006. On farms where pig slurry was imported, P in the slurry accounted for the largest proportion of total P input on these farms. Fertiliser P usage was generally low on these farms. Purchases of concentrate feed accounted for 32 % of the P input to the farms during the first three years of the study. However, in 2006, almost 44 % of P input was due to concentrate feed usage, slightly greater than the proportion of P imported as fertiliser. Phosphorus exported in milk sold from the farms accounted for 60 % of P output, slightly lower than the 75 % calculated by Mounsey *et al.* (1998) in their study. The export of P in animals which died, or were sold, from the farms accounted for the rest of the P output.

The mean P surplus during the study period was 9.4 kg P/ha/yr. This is lower than the findings of Tunney and Culleton (1995) who found a P surplus of 18 kg P/ha/yr on an Irish grass-based dairy farm. Tunney and Culleton observed an input of 26 kg P/ha/yr due to fertiliser P use. This greatly exceeds the mean fertiliser P use on the farms in this study (10.2 kg P/ha/yr) (Table 16, Section 4.4.3). However, this difference would be expected as fertiliser P usage has declined during the interim period (Fig 2, Section 2.3.3). In a European context it appears that the P surpluses observed in the current study are relatively low; eg. Raison *et al.* (2006) found a range of mean surpluses between 8 and 71 kg P/ha/yr on dairy farms across a number of regions along the Atlantic seaboard of Europe. Dairy farms in the northern regions tended to have the lowest P surpluses as they were grass-based systems using relatively low levels of concentrate feed. The largest surpluses were observed on the very intensive dairy farms in the southern regions due to large P inputs resulting from very high levels of concentrate feed usage.

Substantial variation in the P surpluses of the individual farms was observed during the current study. These ranged between -9.4 and 33.2 kg P/ha/yr, with the surplus of P very strongly related (R^2 = 0.92, $P < 0.001$) to the total input of P to the individual farms (Fig. 10, Section 4.7.2). However, unlike N surpluses which are seen as an economic waste, and potential environmental problem, P surpluses may be necessary on certain farms if an increase in STP is required (Culleton *et al.*, 1999). It is therefore important to consider the results of soil sampling when looking at the P balances on the farms.

It is evident that farms 15 and 16 had low mean STP concentrations of 4.4 and 4.2 mg P/l, respectively. The maximum STP concentration recorded on farm 15 was 5.4 mg P/l, and, therefore, this farm in particular needs a surplus P balance if it is to achieve a mean STP concentration in index 3, the target index. In the final three years of the study, both farms 15 and 16 displayed low P surpluses, with a deficit displayed on farm 16 in two of the years. Therefore, it is unlikely that soil P concentrations will increase by a substantial level on these farms unless P input is increased.

At the other extreme, farm 7 recorded the highest mean STP concentration (17.5 mg P/l) of all farms in the study, with individual soil samples from the farm having STP concentrations between 12.6 and 25.7 mg P/l (Table 19, Section 4.6). This farm also had the highest mean P surplus of the studied farms (Table 25, section 4.7.2). This was the result of large applications of imported pig slurry on this farm which accounted for 82 % of the total P input over the study period. However, no fertiliser P was applied on farm 7 during the study period. Considering the high STP values observed in all soil samples analysed from this farm, it is likely that the volume of pig slurry being applied to this farm in future years will have to be reduced to reduce the risk of P pollution from this farm.

The second largest mean P surplus was observed on farm 8. This farm also received large volumes of imported pig slurry, accounting for almost 79 % of total P input over the study period. The mean STP concentration on farm 8 was 6.9 mg P/l, and is in the target index. It should be noted, however, that there was a large variation in the STP concentrations of the individual soil samples taken on this farm, ranging between 2.9 and 10.5 mg P/l. This is likely due to the uneven application of pig slurry, with some fields receiving larger volumes of pig slurry than others during past years. Therefore, the results of soil sampling should be carefully considered when deciding where to apply imported pig slurry on this farm.

The three farms (2, 9, and 11) which received the highest levels of fertiliser P all had STP concentrations close to, or exceeding 10 mg/l. As these STP concentrations are now considered excessive, and due to the constraints on fertiliser P application under SI 378 (2006) fertiliser P applications will have to be lowered substantially on these farms in future years. In order to avoid imbalances in STP concentrations due to the restriction of fertiliser P use, the careful distribution of slurry over the farm area is very important (Tunney, 1990; Watson and Foy, 2001) (Section 2.3.4).

5.4 Slurry Management

The proper collection, storage, and disposal of slurry, is a substantial cost on Irish dairy farms. However, there is a growing realisation that slurry is a valuable resource, containing a large reservoir of nutrients, and with proper management has the potential to substantially lower the requirements for artificial fertiliser usage (Swensson, 2003). As the cost of artificial fertilisers increases and as regulatory limits on their usage are imposed, efficient slurry management is becoming increasingly important (Lalor and Hoekstra, 2006; SI 378, 2006; Humphreys, 2008).

Thirty-three percent of slurry applied on the pilot farms in the initial year of the study was applied in the May/June period, coinciding with the period immediately after the harvest of first cut silage. This has been the traditional management practice on Irish grassland farms as ground conditions are generally good at this time of year, and the slurry replaces a large proportion the P and K removed in the silage crop (Schulte and Herlihy, 2007). However, as already discussed in section 2.2.4.1, the application of slurry at this time of year generally results in poor utilisation of the N fraction of the slurry, due to large losses of NH_3 in dry, warm conditions (Sommer *et al.*, 1991). Although the use of low trajectory splash plates, dribble bars and trailing shoe methods of application decrease NH_3 losses (section 2.2.4.1), it is preferable to apply slurry in spring (Thompson and Pain, 1989; Pain, 2000).

Humphreys *et al.* (2007) recommended applying at least 70 % of slurry during the spring period. An increase in the mean proportion of slurry applied in the spring period, from 50 to 65 %, was observed on the pilot farms in the course of the study period, while the proportion of slurry applied in the May/June period decreased from 33 to 18 %, with little change in the proportion applied after the end of June each year (Table 18, Section 4.5.2). The increases in the volumes of slurry applied in springtime were partly achieved by substituting some fertiliser N with slurry on part of the grazing area in the first round of fertilisation of the year. However, the greatest potential to increase the volume of slurry applied in springtime was realised by applying slurry on the areas closed for the production of first cut silage, at the beginning of April. It was recommended by Teagasc that farmers applied 90 kg N/ha in addition to 33 m^3/ha of slurry. In certain cases, slurry was already being used on the silage area, but its N content was not taken into account when calculating the required rate of fertiliser N. It was possible for the mean rate of fertiliser N applied for the production of first cut silage to be lowered from 106 kg N/ha in 2004 to 96 kg N/ha in 2006 (Table 14, section 4.4.2). These results suggest that there is considerable scope to increase the proportion of slurry applied early in the year on commercial Irish dairy farms, and hence an opportunity to decrease N fertiliser usage through the more efficient use of slurry N.

The application of slurry and fertiliser N to the same areas with little or no interval between applications was observed on a number of farms at the start of the project. As discussed in section 2.2.2.3, this can lead to losses of N through the process of denitrification, and should be avoided (Clayton *et al.*, 1997; Dittert *et al.*, 2005). It was recommended to the farmers (by Teagasc staff) that a one week interval was allowed between applications (Humphreys *et al.*, 2007). The application of diluted slurry has also been shown to increase the efficiency of N utilisation due to increased infiltration rates, decreasing the potential for losses through NH_3 volatilisation (Frost, 1994; Pain *et al.*, 1999; Chambers *et al.*, 1999). The diversion of dirty water into slurry tanks, rather than separate storage tanks was recommended (by Teagasc staff) during the spring period of each year to dilute slurry being applied after the cutting of first cut silage. However, this practice is not recommended during the closed winter period (Humphreys *et al.*, 2007) due to the increased storage facilities which would have to be provided.

Under SI 378 (2006) periods during which the land spreading of slurry is prohibited have been established. This has created a legal obligation on farmers to provide slurry storage facilities for all slurry and dirty water produced during these closed periods. It is evident from Table 17 (Section 4.5.1) that substantial investment will be necessary on many of the farms in this study to comply with these regulations. Only 38 % of the farms in this study already had sufficient slurry storage facilities, while 10 % of the farms had less than half of their required storage capacities. According to Raison *et al.* (2006), insufficient storage capacities limit the use of organic manures and, therefore, the lowering of fertiliser N use in grass-based dairy systems in northern Europe, including Ireland, as sometimes slurry must be spread due to necessity (as storage facilities are full) rather than being applied at times when conditions resulting in optimum nutrient utilisation are present. However, of the eight farms in this study which had adequate slurry storage facilities, only two achieved the target of applying 65 % of their slurry in spring (Table 18, section 4.5.2). In certain cases, farmers with limited storage applied slurry in springtime by necessity, as tanks were full to capacity before the end of the wintering period. On farms where this was not a problem, slurry application may have been delayed until ground conditions improved, or when more time was available after the busy calving season, as two-thirds of the farmers applied slurry using there own equipment.

6. Conclusions

From this study it was clear that fertiliser N is the main N input on intensive Irish dairy farms. Fertiliser N use tended to increase with stocking rate, but substantial variation was observed between farms stocked at similar levels (Fig. 6, section 4.4.2). The variation was greatest between the farms with relatively low stocking rates. Therefore, there is potential to decrease N use on some less intensively stocked farms in this study. There is less scope for decreases on the higher stocked farms, as fertiliser N usage is generally already close to Teagasc recommendations, while stocking rates are too high for white clover systems to be successfully adopted. However, decreases in fertiliser N use will be necessary on farms 6 and 14 to comply with the limits of SI 378, 2006.

The use of white clover in the grazing sward allowed fertiliser N rates to be decreased substantially on three farms (7, 17 and 20) (Table 14, section 4.4.2) with little change in output observed on these farms (Table 24, section 4.7.1). This system has the potential to substantially reduce fertiliser N use on many Irish dairy farms. As a very strong linear relationship was observed between N input and N surplus on the farms (Fig. 8, section 4.5.3) a decrease in N input should lead to a decrease in N surplus. Decreases in N input will be expected to also lead to an increase in N use efficiency (Fig. 9, section 4.5.3).

It is also clear that decreasing the number of days per year on which fertiliser was applied was possible without negatively affecting the productivity of the studied farms. Decreasing the number of days on which fertiliser is applied saves labour and simplifies record keeping of fertiliser application on farms.

Rates of fertiliser P used on the farms varied substantially. Farms which imported large volumes of pig slurry applied little or no fertiliser P. High P surpluses were associated with elevated STP (Fig. 11, section 4.5.4). High P surpluses are the result of high levels of P input (Fig. 10, section 4.5.4). As farms with elevated levels of soil P require the lowest input of P, careful examination of P management is required on the farms. Soil P concentrations were generally close to recommended levels. However, the lowering of the upper limit of soil index 3 under SI 378 (2006) has resulted in an increase in the number of soil samples now being categorised as index 4. This resulted in the mean soil P concentrations on five of the farms in this study, previously classified as index 3, being reclassified as index 4. Phosphorus contained in purchased concentrate feed fed on the farms accounted for a large proportion of the P input of the farms (ranging from 13.4 to 67.5 % on individual farms). Unavoidable increases in concentrate feed use as a result of factors outside farmers' control, such as poor grass growth caused by drought, can increase the P balance of a farm in a given year.

Increasing the proportion of slurry applied in springtime allowed fertiliser N use to be decreased on the studied farms. However, there is scope to further increase the proportion of slurry applied in springtime on many of the farms. In order to comply with SI 378 (2006) substantial investment in slurry storage facilities was required on almost two-thirds of the studied farms.

7. References

Aarts, H.F.M. (2003) Strategies to meet requirements of EU-Nitrate Directive on intensive dairy farms. *Proceedings No. 518, International Fertiliser Society*, York, UK, pages 2-26.

Aarts, H.F.M., Habekotte, B., Hilhorst, G.J. and Koskamp, G.J. (1999) Efficient resource management in dairy farming on sandy soil. *Netherlands Journal of Agricultural Science*, 47:153-167.

Addiscott, T.M. (1996) Fertilizers and nitrate leaching. *In:* Hester, R.E. and Harrison, R.M. (eds.): *Agricultural Chemicals and the Environment, Issues in Environmental Science and Technology*. Royal Society of Chemistry, London, UK, pages 1-26.

Allen, A.G., Harrison, R.M., and Wake, M.T. (1998) A meso-scale study of the behaviour of atmospheric ammonia and ammonium. *Atmospheric Environment*, 22:1347-1353.

ARC (1994) *The Nutrient Requirements of Ruminant Livestock*. Technical Review by an Agricultural Research Council Working Party. CAB International, Wallingford, UK, 351 pages.

Asman, W.A.H., Sutton, M.A. and Schjorring, J.K. (1998) Ammonia: emission, atmospheric transport and deposition. *New Phytologist*, 139:27-48

Aulakh, M.S., Doran, J.W. and Mosier, A.R. (1992) Soil denitrification – significance, measurement, and effects of management. *Advances in Soil Science*, 18:2-57.

Bailey, L.D. (1976) Effects of temperature and root on denitrification in a soil. *Canadian Journal of Soil Science*, 56:79-87.

Beever, D.E., Offer, N. and Gill, M. (2000) The feeding value of grass and grass products. *In:* Hopkins, A. (ed.): *Grass: It's Production and Utilisation* (3rd edition), Blackwell Science, Oxford, pages 140-195.

Benoit, M., and Simon, J.C. (2004) Grassland and water resources: recent findings and challenges in Europe. *In:* Luscher, A., Jeangros, B., Kessler, W., Huguenin, O., Lobsiger, M., Millar, N. and Suter, D. (eds.) *Proceeding of the 20th General Meeting of the European Grassland Federation*. Vdf Hochschulverlag AG, Zurich, pages117-128.

Bijay-Singh, Ryden J.C. and Whitehead, D.C. (1989) Denitrification potential and actual rates of denitrification in soils under long-term grassland and arable cropping. *Soil Biology and Biochemistry*, 21:897-901.

Black, A.S., Sherlock, R.R. and Smith, N.P. (1987) Effect of timing of simulated rainfall on ammonia volatilization from urea, applied to soil of varying moisture content. *Journal of Soil Science*, 38:679-687

Bossuet, I., Chambaut, H., Le Gall, A. and Raison, C. (2006) Study of the distribution of nitrogen surplus in experimental dairy farms of the Atlantic Area. *In: Proceedings of the Green Dairy Project Final Seminar,* Rennes, December 2006. Institut de L'Elevage, Rennes, France, pages 67-92.

Bouwmeester, R.J.B., Vlek, P.L.G. and Stumpe, J.M. (1985) Effect of environmental factors on ammonia volatilization from a urea-fertilized soil. *Soil Science Society of America Journal,* 49:376-381.

Braam , C.R., Ketelaars, J.J.M.H. and Smits, M.C.J. (1997a) Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. *Netherlands Journal of Agricultural Science,* 45:49-64.

Braam, C.R., Smits, M.C.J., Gunnink, H. and Swierstra, D. (1997b) Ammonia emission from a double-sloped solid floor in a cubicle house for dairy cows. *Journal of Agricultural Engineering Research,* 68(4):375-386.

Brentrup, F., Kusters, J., Lammel, J. and Kuhlmann, H. (2000) Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. *International Journal of Life Cycle Assessment,* 5:349-357.

Brogan, J.C. (1966) Organic carbon in Irish pasture soils. *Irish Journal of Agricultural Research,* 5:169-176.

Brookes, P.C., Heckrath, G., De Smet, J., Hofman, G., and Vanderdeelen, J. (1997) Losses of phosphorus in drainage water. *In:* Tunney, H., Carton, O.T., Brookes, P.C., and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, UK, pages 253-271.

Brouwer, F.M., Godeschalk, F.E., Hellegers, P.J.G.J. and Kelholt, H.J. (1995) Mineral balances at farm levels in the European Union. *Onderzoekverslag,* 137:141.

Byrne, E. (1979) *Chemical Analysis of Agricultural Materials*. Teagasc, Johnstown Castle, Wexford. 194 pages.

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

Clark, D.A. (1997) How much nitrogen is enough? 'Focus on Profitability', *Ruakura Dairy Farmers Conference,* 49:92-99. DairyNZ, Hamilton, New Zealand.

Clayton, H., Mc Taggart, I.P., Parker, J., Swan, L. and Smith, K.A. (1997) Nitrous oxide emissions from fertilised grassland: A 2-year study of the effects of N fertiliser form and environmental conditions. *Biology and Fertility of Soils,* 25:252-260.

Connolly, L., Burke, T., and Roche, M. (2001) Teagasc National Farm Survey 2000, Teagasc, Dublin, 13 pages (www.teagasc.ie, downloaded 13/05/06).

Connolly, L., Kinsella, A., Quinlan, G., and Moran, B. (2007) National Farm Survey 2006. Teagasc, Farm Surveys Department, Athenry. 39 pages.

Corral, A.J. and Fenlon, J.S. (1978) A comparative method for describing the seasonal distribution of production from grasses. *Journal of Agricultural Science, Cambridge*, 91:61-67.

Coulter, B.S. (ed.) (2004) *Nutrient and Trace Element Advice for Grassland, Tillage, Vegetable and Fruit Crops*. 2nd edition. Teagasc Publications, Dublin, 95 pages.

Coulter, B.S., McDonald, E., MacNaeidhe, F.S., Parle, P.J., Blagden, P.A., Fleming, G.A. and Gately, T.F. (1999) Nutrient and Trace Element Status in Grassland and Tillage Soils. End of Project Report ARMIS No. 4109, Teagasc Publications, Dublin, 46 pages.

Crosse, S. (1991) Development and implementation of a computerised management information system (DAIRYMIS II) of Irish dairy farmers. *Computers and Electronics in Agriculture,* 6:157-173.

CSO (2007) *Principal Statistics in Relation to Agriculture.* Central Statistics Office, Cork (downloaded 13/12/07, www.cso.ie)

Culleton, N., Murphy, J. and Murphy, W.E. (1999) The Evaluation of Environmental, Agronomic and Economic Implications of High and Low Input Dairy Systems- Investigations to Determine the Minimum Phosphorus that is Required to Ensure Optimum Production, *Rural Environment Series No. 22,* Teagasc Publications, Dublin, 23 pages.

Cuttle, S.P. and Bourne, P.C. (1993) Uptake and leaching of nitrogen from artificial urine applied to grassland on different dates during the growing season. *Plant and Soil,* 150:77-86

Cuttle, S.P., Scurlock, R.V. and Davies, B.M.S. (2001) Comparison of fertilizer strategies for reducing nitrate leaching from grazed grassland, with particular reference to the contribution of urine patches. *Journal of Agricultural Science, Cambridge,* 136:221-230

Daniel, T.C., Carton, O.T. and Magette, W.L. (1997) Nutrient-management planning. *In:* Tunney, H., Carton, O.T., Brookes, P.C., and Johnston, A.E. (eds): *Phosphorus Loss from Soil to Water.* CAB International, Wallingford, UK, pages 297-309.

Davies, D.A. and Hopkins, A. (1996) Production benefits of legumes in grassland. *In:* Younie, D. (ed.): *Legumes in Sustainable Farming Systems, Occasional Symposium No. 30*, British Grassland Society, Craibstone, UK, 2-4th September 1996, pages 234-246.

De Klein, C.A.M. and Van Logtestijn, R.S.P. (1996) Denitrification in grassland soils in The Netherlands in relation to irrigation, N-application rate, soil water content and soil temperature. *Soil Biology and Biochemistry,* 28:231-237.

De Klein, C.A.M., Sherlock, R.R., Cameron, K.C. and Van der Weerden, T.J. (2001) Nitrous oxide emissions from agricultural soils in New Zealand- a review of current knowledge and directions for future research. *Journal of the Royal Society of New Zealand,* 31:543-574.

Deletic, A. (1999) Sediment behaviour in grass filter strips. *Water Science and Technology,* 39:129-136.

De Vos, J.A. (1997) *Water flow and nutrient transport in a layered silt loam soil.* Dissertation No. 2331, Wageningen University, The Netherlands, Unpublished.

Diamond, J. and Shanley, T. (1998) Infiltration rate assessment of some major soils, End of Project Report, ARMIS 4102, Teagasc Publications, Dublin, 14 pages.

Dittert, K., Lampe, C., Gasche, R., Butterbach-Bahl, K., Wachendorf, M., Papen, H., Sattelmacher, B. and Taube, F. (2005) Short-term effects of single or combined application of mineral N fertilizer and cattle slurry on the fluxes of radioactively active trace gases from grassland soil. *Soil Biology and Biochemistry,* 37:1665-1674.

Dobbie, K.E. and Smith, K.A. (2003) Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. *Global Change Biology,* 9:204-218.

FADN (2007) *Farm Accountancy Data Network (FADN) Public Database*. Brussels. Downloaded 16/10/07, (http://ec.europa.eu/agriculture/rica/database/database.cfm)

Firestone, M.K. (1982) Biological denitrification. *In: Nitrogen in Agricultural Soils*. Agronomy Monograph no.22, ASA-CSSA-SSSA, Madison, USA, pages 289- 326.

Fitzgerald, D.A. and Fitzgerald, D.L. (2004) Meteorological measurements. *In:* Keane, T. and Collins, J.F. (eds.) *Climate, Weather and Irish Agriculture.* Met Eireann, Dublin, pages 9-26.

Foy, R.H., Smith, R.V., Jordan, C. and Lennox, S.D. (1995) Upward trend in soluble phosphorus loadings to Lough Neagh despite phosphorus reduction at sewage treatment works. *Water Research,* 29:1051-1063.

Foy, R.H., Tunney, H., Carroll, M.J., Byrne, E., Gately, T., Bailey, J.S. and Lennox, S.D. (1997) A comparison of Olsen and Morgan soil phosphorus test results from the cross-border region of Ireland. *Irish Journal of Agricultural and Food Research,* 36:185-193.

Foy, R.H., Bailey, J.S. and Lennox, S.D. (2002) Mineral balances for the use of phosphorus and other nutrients by agriculture in Northern Ireland from 1925 to 2000- methodology, trends and impacts of losses to water. *Irish Journal of Agricultural and Food Research,* 41:247-263.

Fraser, A.I., Harrod, T.R. and Haygarth, P.M. (1999) The effect of rainfall intensity on soil erosion and particulate phosphorus transfer from arable soils. *Water Science and Technology,* 39(12):41-45.

Freed, R., Einsensmith, S.P., Goetz, S., Reiscosky, D., Smail, V.W. and Wolberg, P. (1991) *User's Guide to MSTAT-C: A Software Programme for the Design, Management, and Analysis of Agronomic Research Experiments.* Michigan State University, Michigan, USA.

Frost, J.P. (1994) Effect of spreading method, application rate and dilution on ammonia volatilization from cattle slurry. *Grass and Forage Science,* 49:391-400.

Frost, J.P., Stevens, R.J. and Laughlin, R.J. (1990) Effect of separation and acidification of cattle slurry on ammonia volatilization and on the efficiency of slurry nitrogen for herbage production. *Journal of Agricultural Science, Cambridge,* 115:49-56

Gardiner, M.J. and Radford, T. (1980) *Soil Associations of Ireland and their Land Use potential*. Soil Survey Bulletin No. 36. Teagasc, Dublin, 142 pages.

Garwood, E.A. and Ryden, J.C. (1986) Nitrate loss through leaching and surface runoff from grassland: effects of water supply, soil type and management. *In:* Van der Meer, H.G., Ryden, J.C. and Ennik, G.C. (eds.): *Nitrogen Fluxes in Intensive Grassland Systems*. Martinus Nijhoff Publishers, Dordrecht, The Netherlands, pages 99-113.

Gibson, C.E. (1997) The dynamics of phosphorus in freshwater and marine environments. *In:* Tunney, H., Carton, O.T., Brookes, P.C. and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water.* CAB International, Wallingford, UK, pages 119-135.

Grignani, C. and Laidlaw, A.S. (2002) Nitrogen economy in grasslands and annual forage crops: control of environmental impact. *In:* Durand, J-L., Emile, J-C., Huyghe, C. and Lemaire, G. (eds.): *Multi Function Grasslands- Quality Forages, Animal Products and Landscapes,* Proceedings of the 19th General Meeting of the European Grassland Federation, La Rochelle, France, 27-30th May, 2002, pages 625-633.

Guckert, A. and Hay, R.K.M. (2001) The overwintering, spring growth, and yield in mixed species swards of white clover in Europe. *Annals of Botany,* 88:667-668.

Hack-ten Broeke, M.J.D. and Van der Putten, A.H.J. (1997) Nitrate leaching affected by management options with respect to urine-affected areas and groundwater levels for grazed grassland. *Agriculture, Ecosystems, and Environment,* 66:197-210.

Hanegraaf, M.C. and Den Boer, D.J. (2003) Perspectives and limitations of the Dutch minerals accounting system (MINAS). *European Journal of Agronomy,* 20:25-31.

Hassink, J. (1995) Effect of the non-fertilizer N supply of grassland soils on the response of herbage to N fertilization under mowing conditions. *Plant and Soil,* 175:159-166.

Hatch, D.J., Jarvis, S.C. and Dollard, G.J. (1990) Measurements of ammonia emission from grazed grassland. *Environmental Pollution,* 65:333-346.

Haygarth, P.M., Chapman, P.J., Jarvis, S.C. and Smith, R.V. (1998) Phosphorus budgets for two contrasting grassland farming systems in the UK. *Soil Use and Management,* 14:160-167.

Healy, M., Humphreys, J., Lawless, A., and Keane, G.P. (2005) Over-sowing white clover into permanent grassland. *In: Proceedings of the Agricultural Research Forum, Tullamore, 14th & 15th March 2005, page 21.*

Heathwaite, A.L. (1997) Sources and pathways of phosphorus loss from agriculture. *In:* Tunney, H., Carton, O.T., Brookes, P.C. and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water.* CAB International, Wallingford, UK, pages 205-223.

Heathwaite, A.L. and Dils, R.M. (2000) Characterising phosphorus loss in surface and subsurface hydrological pathways. *The Science of the Total Environment,* 252:523-538.

Hennessy, T. (2004) Farm level adjustment in Ireland following decoupling. *Annual Meeting of the British Farm Management Association, Bedford, England, November 2004,* 8 pages. (Downloaded 25/09/07 www.tnet.teagasc.ie/fapri/downloads/pubs2004/bedfordpaper.pdf)

Herlihy, M., McCarthy, J., Breen, J. and Moles, R. (2004) Effects over time of fertiliser P and soil series on P balance, soil-test P and herbage production. *Irish Journal of Agricultural and Food Research,* 49:131-151.

Hilhorst, G.J., Oenema, J. and Van Keulen, H. (2001) Nitrogen management on experimental farm 'De Marke'; farming system, objectives and results. *Netherlands Journal of Agricultural Science,* 49:131-151.

Humphreys J. (2008) Nutrient issues on Irish farms and solutions to lower losses. *International Journal of Dairy Technology,* 61 (1) 36-42.

Humphreys, J., Ryan, M., O'Connell, K. and Lawless, A. (2002) Nitrogen input systems-implications. *In: Countdown to Reform;* Proceedings of the Teagasc National Dairy Conference, November 2002, Killarney, pages 82-106. Teagasc, Dublin.

Humphreys, J., Casey, I.A. and Carton, O.T. (2003a) Meeting environmental objectives and potential constraint on dairy production in Ireland. *In:* Bos, J., Aarts, F., Vertes, F., and Pflimlin, A. (eds.): *Nutrient Management at Farm Scale: How to Attain Policy Objectives in Regions with Intensive Dairy Farming?* Wageningen Academic Publishers, The Netherlands, pages 145-164.

Humphreys, J., O'Connell, K. and Watson, C.J. (2003b) Effect of nitrate legislation on fertiliser nitrogen management for grassland. *In: Proceedings No. 517,* The International Fertiliser Society, pages 1-33.

Humphreys, J., O'Connell, K., Lawless, A. and McNamara, K. (2004a) Strategic use of nitrogen in a new environment. *Annual Journal of the Irish Grassland Association,* 38:13-31.

Humphreys, J., O'Connell, K., Lawless, A., McNamara, K. and Boland, A. (2004b) Improving nutrient use efficiency on dairy farms. *In: Proceedings of the National Dairy Conference 2004,* Teagasc, Carlow, pages 68-99.

Humphreys, J. and Lawless, A. (2006) *A Guide to Management of White Clover in Grassland*, Teagasc Publications, Moorepark, Cork, 80 pages.

Humphreys, J., Boland, A., and Lalor, S. (2007) Cutting fertiliser N costs on farms. *In:* Buckley, F. (ed.): *Irish Dairying- Winning on a World Stage.* Teagasc, Dairy Production Research Centre, Cork, pages 83-89.

Husted, S., Jensen, L.S. and Storgaard Jorgensen, S. (1991) Reducing ammonia loss from cattle slurry by the use of acidifying additives: the role of buffer system. *Journal of the Science of Food and Agriculture*, 57:335-349.

Hyde, B.P., Carton, O.T., O'Toole, P. and Misselbrook, T.H. (2003) A new inventory of ammonia emissions from agriculture. *Atmospheric Environment,* 37:55-62.

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

Jarvis, S.C. (1998) Nitrogen management and sustainability. *In:* Cherney, J.H., and Cherney, D.J.R. (eds.): *Grass for Dairy Cattle*. CAB International, Wallingford, UK, pages 161- 192.

Jarvis, S.C. (1999) Accounting for nutrients in grassland: Challenges and needs. *In:* Corrall, A. (ed.): *Accounting for Nutrients- A Challenge for Grassland Farmers in the 21st Century*, British Grassland Society Occasional Symposium No.33, pages 3-12.

Jarvis, S.C., Hatch, D.J. and Roberts, D.H. (1989a) The effects of grassland management on nitrogen losses from grazed swards through ammonia volatilisation; the relationship to excretal N returns from cattle. *Journal of Agricultural Science, Cambridge,* 112:205-216.

Jarvis, S.C., Pain, B.F., Hatch, D.J. and Thompson, R.B. (1989b) Ammonia volatilisation and loss from grassland systems. *Proceedings of the XVI International Grassland Congress,* Nice, France. The French Grassland Society, Nice, France, pages 157-158.

Jarvis, S.C., Barraclough, D., Williams, J. and Rook, A.J. (1991) Patterns of denitrification loss from grazed grassland: Effects of N fertilizer inputs at different sites. *Plant and Soil,* 131:77-88.

Jarvis, S.C. and Hatch, D.J. (1994) Potential for denitrification at depth below long-term grass swards. *Soil Biology and Biochemistry,* 26:1629-1636.

Jarvis, S.C., Scholefield, D. and Pain, B.F. (1995) Nitrogen cycling in grazing systems. *In:* Bacon, P.E. (ed.) *Nitrogen Fertilisation in the Environment,* Marcel Dekker, New York, pages 381-419.

Jarvis, S.C., Wilkins, R.J. and Pain, B.F. (1996) Opportunities for reducing the environmental impact of dairy farming managements: a systems approach. *Grass and Forage Science,* 51:21-31.

Jarvis, S.C. and Aarts, H.F.M. (2000) Nutrient management from a farming systems perspective. *In:* Soegaard, K., Ohlsson, C., Sehested, J., Hutching, N.J., and Kristensen, T. (eds.): *Grassland Farming- Balancing Environmental and Economic Demands*, Proceedings of the 18th General Meeting of the European Grassland Federation, Aalborg, Denmark, 22-25th May 2000, pages 363-373.

Jarvis, S.C., and Ledgard, S. (2002) Ammonia emissions from intensive dairying: a comparison of contrasting systems in the United Kingdom and New Zealand. *Agriculture, Ecosystems, and Environment,* 92(1):83-92.

Jarvis, S.C. and Menzi, H. (2004) Optimising best practice for N management in livestock systems: meeting production and environmental targets. *In:* Luscher, A., Jeangros, B., Kessler, W., Huguenin, O., Lobsiger, M., Millar, N., and Suter, D. (eds.): *Land Use Systems in Grassland Dominated Regions.* Proceedings of the 20th General Meeting of the European Grassland Federation, Luzern, Switzerland, 21-24th June 2004, pages 361-372.

Johnston, A.E., Tunney, H. and Foy, R.H. (1997) Phosphorus loss from agriculture to water: synthesis and summary. *In:* Tunney, H., Carton, O.T., Brookes, P.C. and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water.* CAB International, Wallingford, UK, pages 455-461.

Jordan, C. (1989) The effect of fertiliser type and application rate on denitrification losses from cut grassland in Northern Ireland. *Fertilizer Research,* 19:45-55.

Jordan, C. (1997) Mapping of rainfall chemistry in Ireland 1972-94. *Biology and Environment: Proceedings of the Royal Irish Academy* 1(97B):53-73.

Jordan, C. and Smith, R.V. (1985) Factors affecting leaching of nutrients from intensively managed grassland in County Antrim, Northern Ireland. *Journal of Environmental Management,* 20:1-15.

Jordan, C., McGuckin, S.O. and Smith, R.V. (2000) Increased predicted losses of phosphorus to surface waters from soils with high Olsen-P concentrations. *Soil Use and Management,* 16:27-35.

Jordan, P., Menary, W., Daly, K., Kiely, G., Morgan, G., Byrne, P. and Moles, R. (2005) Patterns and processes of phosphorus transfer from Irish grassland soils to rivers- integration of laboratory and catchment studies. *Journal of Hydrology,* 304:20-34.

Keane, T. and Collins, J.F. (2004) *Climate, Weather and Irish Agriculture.* Met Eireann, Dublin.

Kesik, M., Blagodatsky, S., Papen, H. and Butterbach-Bahl, K. (2006) Effect of pH, temperature and substrate on N_2O, NO, and CO_2 production by *Alcaligenes faecalis p. Journal of Applied Microbiology,* 101:655-667.

Klasink, A., Steffens, G. and Kowalewsky, H.-H. (1991) Odour and ammonia emissions from grassland and arable land. *In:* Nielsen, V.C., Voorburg, J.H., and L'Hermite, P. (eds.): *Odour and Emissions from Livestock Farming*. Elsevier, London, pages 170-176.

Knowles, R. (1981) Denitrification. *In:* Paul, E.A., and Ladd, J. (eds.) *Soil Biochemistry,* Vol. 5. Marcel Dekker, New York, pages 323-369.

Knowles, R. (1982) Denitrification. *Microbiological Reviews,* 46:43-70.

Kroodsma, W., Huis in 't Veld, J.W.H. and Scholtens, R. (1993) Ammonia emission and its reduction from cubicle houses by flushing. *Livestock Production Science,* 35:293-302.

Krupa, S.V. (2003) Effects of atmospheric ammonia (NH3) on terrestrial vegetation: a review. *Environmental Pollution,* 124:179-221.

Kuipers, A. and Mandersloot, F. (1999) Reducing nutrient losses on dairy farms in The Netherlands. *Livestock Production Science,* 61:139-144.

Kurz, I., Coxon, C., Tunney, H. and Ryan, D. (2005) Effects of grassland management practices and environmental conditions on nutrient concentrations in overland flow. *Journal of Hydrology,* 304:35-50.

Kurz, I., O'Reilly, C.D. and Tunney, H. (2006) Impact of cattle on soil physical properties and nutrient concentrations in overland flow from pastures in Ireland. *Agriculture, Ecosystems, and Environment,* 113:378-390.

Lally, B. and Riordan, B. (2001) *Economic Impact on Irish Dairy Farms of Strategies to Reduce Nitrogen Applications.* Teagasc Publications, Dublin, 26 pages.

Lalor, S. and Hoekstra, N. (2006) Technology for recycling of manure and organic residues in a whole farm perspective: applicability to Irish farming systems. *Tearmann: Irish Journal of Agri-Environmental Research,* 5:43-54.

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

Ledgard, S.F., Penno, J.W. and Sprosen, M.S. (1997) Nitrogen balances and losses on intensive dairy farms. *Proceedings of the New Zealand Grassland Association,* No. 59. New Zealand Grassland Association, Dunedin, New Zealand, pages 49-53.

Ledgard, S.F., Crush, J.R. and Penno, J.W. (1998a) Environmental impacts of different nitrogen inputs on dairy farms and implications for the Resource Management Act of New Zealand. *Environmental Pollution,* 102(S1):515-519.

Ledgard, S.F., Jarvis, S.C. and Hatch, D.J. (1998b) Short-term nitrogen fluxes in grassland soils under different long-term nitrogen management regimes. *Soil Biology and Biochemistry,* 30:1233-1241.

Ledgard, S.F., Penno, J.W. and Sprosen, M.S. (1999) Nitrogen inputs and losses from clover/grass pastures grazed by dairy cows, as affected by nitrogen fertilizer application. *Journal of Agricultural Science, Cambridge,* 132:215-225.

Lockyer, D.R. and Whitehead, D.C. (1990) Volatilization of ammonia from cattle urine applied to grassland. *Soil Biology and Biochemistry,* 22:1137-1142.

Lucey, J. (2006) *Water Quality in Ireland 2005: Key Indicators of the Aquatic Environment.* Environmental Protection Agency, Wexford, Ireland.

Lynch, P.B. and Caffrey, P.J. (1997) Phosphorus requirements for animal production. *In:* Tunney, H., Carton, O.T., Brookes, P.C. and Johnston, A.E. (eds): *Phosphorus Loss from Soil to Water.* CAB International, Wallingford, UK, pages 283-296.

Marks, M.J., Peel, S. and Unwin, R. (1999) The control of nutrient losses to the environment from grassland farming. *In:* Corrall, A. (ed.): *Accounting for Nutrients- A Challenge for Grassland Farmers in the 21st Century*. British Grassland Society Occasional Symposium No.33, pages 99-104.

McCrory, D.F. and Hobbs, P.J. (2001) Additives to reduce ammonia and odor emissions from livestock wastes: A review. *Journal of Environmental Quality,* 30:345-355.

McDonald, P., Edwards, R.A., Greenhalgh, J.F.D. and Morgan, C.A. (1995) *Animal Nutrition* (5th edition). Prentice Hall, Harlow, England.

McGarrigle, M., Bowman, J., Clabby, K., Lucey, J., Cunningham, P., MacCarthaigh, M., Keegan, M., Cantrell, B., Lehane, M., Clenaghan, C. and Toner, P. (2002) *Water Quality in Ireland 1998-2000*. Environmental Protection Agency, Wexford, Ireland.

McGrath, D. and Zhang, C. (2003) Spatial distribution of soil organic carbon concentrations in grassland of Ireland. *Applied Geochemistry*, 18:1629-1639.

Mc Namara, K.A., Humphreys, J. and Watson, C.J. (2006) Fertilizer nitrogen strategies and grass production. *Proceedings of the Agricultural Research Forum 2006.* Irish Grassland and Animal Production Association, Dublin, p.46.

McQuinn, K., Riordan, B. and Lally, B. (2002) Prospective impact of environmental regulations, and other policies on fertiliser use in Ireland. *Proceedings of the Fertiliser Association of Ireland,* Dublin, 39:12-33.

Meyer, R.D. and Jarvis, S.C. (1989) The effects of fertiliser/urine interactions on NH_3 –N losses from grassland soils. *Proceedings of the XVI International Grassland Congress.* International Grassland Society, Nice, France, pages 155-156.

Monaghan, R.M., Paton, R.J., Smith, L.C. and Binet, C. (2000) Nutrient losses in drainage and surface runoff from cattle-grazed pasture in Southland. *Proceedings of the New Zealand Grassland Association.* New Zealand Grassland Association, Invercargill, pages 99-104.

Morgan, M.F. (1941) *Chemical Soil Diagnosis by the Universal Testing System.* Connecticut Agricultural Experimental Station Bulletin, No. 450.

Morgan, M.A. (1997) The behaviour of soil and fertiliser phosphorus. *In:* Tunney, H., Carton, O.T., Brookes, P.C. and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, UK, pages 137-149.

Morse, D., Head, H.H., Wilcox, C.J., Van Horn, H.H., Hissem, C.D. and Harris Jr., B. (1992) Effects of concentration of dietary phosphorus on amount and route of excretion. *Journal of Dairy Science,* 75:3039-3049.

Mounsey, J., Sheehy, J., Carton, O.T. and O'Toole, P. (1998) *Nutrient Management Planning on Irish Dairy Farms*. End of Project Report, ARMIS 4347, Teagasc, Dublin.

Mulqueen, J., Rodgers, M. and Scally, P. (2004) Phosphorus transfer from soil to surface waters. *Agricultural Water Management*, 68:545-547.

Murray, P.J., Hatch, D.J., Dixon, E.R., Stevens, R.J., Laughlin, R.J. and Jarvis, S.C. (2004) Denitrification potential in a grassland subsoil: effect of carbon substrates. *Soil Biology and Biochemistry,* 36:545-547.

Neill, M. (1989) Nitrate concentrations in river waters in the south-east of Ireland and their relationship with agricultural practice. *Water Research*, 23:1339-1355.

Nguyen, M.L., Haynes, R.J. and Goh, K.M. (1995) Nutrient budgets and status in three pairs of conventional and alternative mixed cropping farms in Canterbury, New Zealand. *Agriculture, Ecosystems and Environment*, 52:149-162.

Nguyen, M.L., Sheath, G.W., Smith, C.M. and Cooper, A.B. (1998) Impact of cattle treading on hill land. 2. Soil physical properties and contaminant runoff. *New Zealand Journal of Agricultural Research*, 41:279-290.

O'Connell, K., Humphreys, J. and Watson, C.J. (2003) Quantification of nitrogen sources for grassland. *Proceedings of the Fertiliser Association of Ireland*, No. 40:15-29, Dublin.

O'Connell, K., Humphreys, J. and Watson, C.J. (2004) Apparent recovery of fertilizer nitrogen by pasture. *Proceeding of the Agricultural Research Forum 2004.* Irish Grassland and Animal Production Association, Dublin, page 18.

O'Donovan, M., Delaby, L., Stakelum, G. and Dillon, P. (2004) Effect of autumn/spring nitrogen application date on level of dry matter production and nitrogen efficiency in perennial ryegrass swards. *Irish Journal of Agricultural and Food Research*, 43:31-41.

Oenema, O., Boers, P.C.M., Van Eerdt, M.M., Fraters, B., Van der Meer, H.G., Roest, C.W.J., Schroder, J.J. and Willems, W.J. (1998) Leaching of nitrate from agriculture to groundwater: the effect of policies and measures in The Netherlands. *Environmental Pollution*, 102:471-478.

Oenema, O. and van den Pol-van Dasselaar, A. (1999) Managing nutrient budgets of grassland farming systems: Options and perspectives. *In:* Corrall, A. (ed.): *Accounting for Nutrients- A Challenge for Grassland Farmers in the 21st Century.* British Grassland Society Occasional Symposium No.33, pages 107-116.

Oenema, O., Kros, H. and de Vries, W. (2003) Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. *European Journal of Agronomy*, 20:3-16.

Oenema, O., Vellinga, T.V. and Van Keulen, H. (2006) Nutrient management under grazing. *In:* Elgersma, A., Dijkstra, J., and Tamminga, S. (eds.): *Fresh Herbage for Dairy Cattle*. Springer, New York, USA, pages 63-83.

Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. (1954) *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*. United States Department of Agriculture, Washington D.C., Circular No. 939, 19 pages.

Pain, B.F. (2000) Control and utilization of livestock manures. *In:* Hopkins, A. (ed.): *Grass- It's Production and Utilization*. Blackwell Science Ltd, Oxford, UK, pages 343-364.

Pain, B.F., van der Weerden, T.J., Chambers, B.J., Phillips, V.R. and Jarvis, S.C. (1998) A new inventory for ammonia emissions from U.K. agriculture. *Atmospheric Environment*, 32:309-313.

Pain, B.F., Misselbrook, T.H. and Chadwick, D.R. (1999) Controlling losses of nitrogen as ammonia from manures. *In:* Corrall, A. (ed.): *Accounting for Nutrients- A Challenge for Grassland Farmers in the 21st Century*. British Grassland Society Occasional Symposium No.33, pages 93-98.

Parkin, T.B., Sexstone, A.J. and Tiedje, J.M. (1985) Adaption of denitrifying populations to low soil pH. *Applied and Environmental Microbiology*, 49:1053-1056.

Parsons, A.J. and Chapman, D.F. (2000) The principles of pasture growth and utilization. *In:* Hopkins, A. (ed.): *Grass- It's Production and Utilization*. Blackwell Science Ltd, Oxford, UK, pages 31-89.

Petersen, S.O., Sommer, S.G., Aaes, O. and Soegaard, K. (1998) Ammonia losses from urine and dung of grazing cattle: effect of N intake. *Atmospheric Environment*, 32:295-300.

Pflimlin, A., Irle, A. and Mirabal, Y. (2006) Contribution of the dairy herd to nitrogen and phosphorus surplus at regional scale and risks for water quality. *Proceedings of the Green Dairy Project Final Seminar,* Rennes, December 2006. Institut de L'Elevage, Rennes, France, pages 97-112.

Phillips, V.R., Cowell, D.A., Sneath, R.W., Cumby, T.R., Williams, A.G., Demmers, T.G.M. and Sandars, D.L. (1999) An assessment of ways to abate ammonia emissions from UK livestock buildings and waste stores. Part 1: Ranking exercise. *Bioresource Technology,* 70:143-155.

Pommel, B. and Dorioz, J.M. (1997) Movement of phosphorus from agricultural soil to water. *In:* Tunney, H., Carton, O.T., Brookes, P.C. and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, Uk, pages 243-251.

Raison, C., Pflimlin, A. and le Gall, A. (2006) Optimisation of environmental practices in a network of dairy farms of the Atlantic area. *Proceedings of the Green Dairy Project Final Seminar,* Rennes, December 2006. Institut de L'Elevage, Rennes, France, pages 43-65.

Rees, Y.J., Pain, B.F., Phillips, V.R. and Misselbrook, T.H. (1993) The influence of surface and sub-surface application methods for pig slurry on herbage yields and nitrogen recovery. *Grass and Forage Science,* 48:38-44.

Ross, C.A. and Jarvis, S.C. (2001) Measurement of emission and deposition patterns of ammonia from urine in grass swards. *Atmospheric Environment,* 35:867-875.

Rotz, C.A. (2004) Management to reduce nitrogen losses in animal production. *Journal of Animal Science,* 82:E119-E137.

Rotz, C.A., Sharpley, A.N., Satter, L.D., Gburek, W.J. and Sanderson, M.A. (2002) Production and feeding strategies for phosphorus management on dairy farms. *Journal of Dairy Science,* 85:3142-3153.

Ruz-Jerez, B.E., White, R.E. and Balls, P.R. (1994) Long-term measurement of denitrification in three contrasting pastures grazed by sheep. *Soil Biology and Biochemistry,* 26:29-39.

Ryan, M., Noonan, D. and Fanning, A. (1998) Relative denitrification rates in surface and subsurface layers of a mineral soil. *Irish Journal of Agricultural and Food Research,* 37:141-157.

Ryan, M., Brophy, C., Connolly, J., McNamara, K. and Carton, O.T. (2006) Monitoring of nitrogen leaching on a dairy farm during four drainage seasons. *Irish Journal of Agricultural and Food Research,* 45:115-134.

Ryden, J.C., Whitehead, D.C., Lockyer, D.R., Thompson, R.B., Skinner, J.H. and Garwood, E.A. (1987) Ammonia emission from grassland and livestock production systems in the UK. *Environmental Pollution,* 48:173-184.

Scholefield, D., Tyson, K.C., Garwood, E.A., Armstrong, A.C., Hawkins, J. and Stone, A.C. (1993) Nitrate leaching from grazed grassland lysimeters: effects of fertilizer input, field drainage, age of sward and weather patterns. *Journal of Soil Science,* 44:601-613.

Scholefield, D., Lord, E.I., Rodda, H.J.E. and Webb, B. (1996) Estimating peak nitrate concentrations from annual nitrate loads. *Journal of Hydrology,* 186:355-373.

Scholefield, D. and Fisher, G.E.J. (2000) Nutrient cycling in grazing systems. *In:* Rook, A.J., and Penning, P.D. (eds.): *The Principles and Practice of Grazing, for Profit and Environmental Gain, within Temperate Grassland Systems*. Occasional symposium No. 34, British Grassland Society, Harrogate, pages 119-128.

Schroder, J.J., Aarts, H.F.M., ten Berge, H.F.M., van Keulen, H. and Neeteson, J.J. (2003) An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. *European Journal of Agronomy,* 20:33-34.

Schroder, J.J., Vertes, F., Chadwick, D.R. and Sillebak Kristensen, I. (2005) How to compare the nutrient use efficiency of dairy farms? *Proceedings of the European Grassland Federation Working Group Workshop in Maastricht, 23rd October 2005,* 13 pages.

Schulte, R.P.O. and Herlihy, M. (2007) Quantifying responses to phosphorus in Irish grasslands: Interactions of soil and fertiliser with yield and P concentration. *European Journal of Agronomy,* 26:144-153.

Sharpley, A.N. and Rekolainen, S. (1997) Phosphorus in agriculture and its environmental implications. *In:* Tunney, H., Carton, O.T., Brookes, P.C. and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, UK, pages 1-53.

Shepherd, M.A., Hatch, D.J., Bhogal, A. and Jarvis, S.C. (1999) Soil nitrogen supply under grassland swards: Measurement and prediction. *In:* Corrall, A. (ed.): *Accounting for Nutrients-A Challenge for Grassland Farmers in the 21st Century*. British Grassland Society Occasional Symposium No.33, pages 23-28.

SI 378 (2006) European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2006, Government Publications Office, Dublin, 49 pages.

Simek, M. and Cooper, J.E. (2002) The influence of soil pH on denitrification: progress towards the understanding of this interaction over the last 50 years. *European Journal of Soil Science,* 53:345-354.

Skiba, U.M., Sheppard, L.J., MacDonald, J. and Fowler, D. (1998) Some key environmental variables controlling nitrous oxide emissions from agricultural and semi-natural soils in Scotland. *Atmospheric Environment,* 32:3311-3320.

Smil, V. (2000) *Cycles of Life*. Scientific American Library, New York.

Smith, R.V., Lennox, S.D., Meek, R. and Smyth, D.R. (1995) The use of utilised metabolizable energy for grazing livestock to model the flux of nitrogen through Northern Ireland grassland. *Journal of Environmental Management,* 43:375-387.

Smith, K.A., Thomson, P.E., Clayton, H., McTaggart, I.P. and Conen, F. (1998) Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils. *Atmospheric Environment,* 32:3301-3309.

Smits, M.C.J., Valk, H., Elzing, A. and Keen, A. (1995) Effect of protein nutrition on ammonia emission from a cubicle house for dairy cattle. *Livestock Production Science,* 44:147-156.

Sommer, S.G., Olesen, J.E. and Christensen, B.T. (1991) Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry. *Journal of Agricultural Science,* 117:91-100.

Sommer, S.G., Christensen, B.T., Nielsen, N.E. and Schjorring, J.K. (1993) Ammonia volatilization during storage of cattle and pig slurry: effect of surface cover. *Journal of Agricultural Science,* 121:63-71.

Sommer, S.G., Hansen, M.N. and Sogaard, H.T. (2004) Infiltration of slurry and ammonia volatilisation. *Biosystems Engineering,* 88:359-367.

Sommer, D.G., Jensen, L.S., Clausen, S.B. and Sogaard, H.T. (2006) Ammonia volatilization from surface-applied livestock slurry as affected by slurry composition and slurry infiltration depth. *Journal of Agricultural Science,* 117:91-100.

Steenvoorden, J.H.A.M., Fonck, H. and Oosterom, H.P. (1986) Losses of nitrogen from intensive grassland systems by leaching and surface runoff. *In:* Van der Meer, H.G., Ryden, J.C. and Ennik, G.C. (eds.): *Nitrogen Fluxes in Intensive Grassland Systems*. Martinus Nijhoff Publishers, Dordrecht, pages 85-97.

Stevens, R.J. (1999) Losses to water and air. *In:* Corrall, A. (ed.): *Accounting for Nutrients - A Challenge for Grassland Farmers in the 21st Century.* British Grassland Society Occasional Symposium No.33, pages 77-86.

Stevens, R.J., Gracey, H.I., Kilpatrick, D.J., Camlin, M.S., O'Neill, D.G. and McLaughlan, W. (1989) Effect of date of application and form of nitrogen on herbage production in spring. *Journal of Agricultural Science, Cambridge,* 112:329-337.

Stevens, R.J., Laughlin, R.J., O'Bric, C.J., Carton, O.T. and Lenehan, J.J. (1997) The efficiency of the nitrogen in cattle slurry acidified with nitric acid for grass production. *Journal of Agricultural Science,Cambridge,*129:335-342.

Styles, D., Donohue, I., Coxon, C. and Irvine, K. (2006) Linking soil phosphorus to water quality in the Mask catchment of western Ireland through the analysis of moist soil samples. *Agriculture, Ecosystems, and Environment,* 112:300-312.

Sutton, M.A., Lee, D.S., Dollard, G.J. and Fowler, D. (1998) Atmospheric ammonia: Emission, deposition and environmental impacts. *Atmospheric Environment,* 32:269-271.

Swensson, C. (2003) Analyses of mineral element balances between 1997 and 1999 from dairy farms in the south of Sweden. *European Journal of Agronomy,* 20:63-69.

Tamminga, S. (1992) Nutrition management of dairy cows as a contribution to pollution control. *Journal of Dairy Science*, 75:345-357.

Thompson, R.B. (1989) Denitrification in slurry-treated soil: Occurrence at low temperatures, relationship with soil nitrate and reduction by nitrification inhibitors. *Soil Biology and Biochemistry,* 21:875-882.

Thompson, R.B. and Pain, B.F. (1989) Denitrification from cattle slurry applied to grassland. *In:* Hansen, J.A., and Hendriksen, K. (eds.): *Nitrogen in Organic Wastes Applied to Soils*. Academic Press, London, pages 247-260.

Thompson, R.B., Pain, B.F. and Lockyer, D.R. (1990a) Ammonia volatilization from cattle slurry following surface application to grassland. I. Influence of mechanical separation, changes in chemical composition during volatilization and presence of the grass sward. *Plant and Soil,* 125:109-117.

Thompson, R.B., Pain, B.F. and Rees, Y.J. (1990b) Ammonia volatilization from cattle slurry following surface application to grassland. II. Influence of application rate, wind speed and applying slurry in narrow bands. *Plant and Soil,* 125:119-128.

Toner, P., Bowman, J., Clabby, K., Lucey, J., McGarrigle, M., Concannon, C., Clenaghan, C., Cunningham, P., Delaney, J., O'Boyle, S., MacCarthaigh, M., Craig, M. and Quinn, R. (2005) *Water Quality in Ireland 2001-2003*. Environmental Protection Agency, Wexford, Ireland.

Toor, G.S., Sims, J.T. and Dou, Z. (2005) Reducing phosphorus in dairy diets improves farm nutrient balances and decreases the risk of nonpoint pollution of surface and ground waters. *Agriculture, Ecosystems and Environment,* 105:401-411.

Tunney, H. (1990) A note on a balance sheet approach to estimating the phosphorus fertiliser needs of agriculture. *Irish Journal of Agricultural Research,* 29:149-154.

Tunney, H. and Culleton, N. (1995) Phosphorus balance on a dairy farm in Ireland. *Irish Journal of Agricultural and Food Research,* 34:76-77.

Tunney, H., Breeuwsma, A., Withers, P.J.A. and Ehlert, P.A.I. (1997) Phosphorus fertiliser strategies: present and future. *In:* Tunney, H., Carton, O.T., Brookes, P.C., and Johnston, A.E. (eds.): *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, pages 177-203.

Tunney, H., Carton, O., O'Donnell, T. and Fanning, A. (1998) *Phosphorus Loss from Soil to Water.* End of Project Report, ARMIS 4022, Teagasc Publications, Dublin,11 pages.

Turtola, E. and Paajanen, A. (1995) Influence of improved subsurface drainage on phosphorus losses and nitrogen leaching from a heavy clay soil. *Agricultural Water Management,* 28:295-310.

Ulen, B. and Jakobsson, C. (2005) Critical evaluation of measures to mitigate phosphorus losses from agricultural land to surface waters in Sweden. *Science of the Total Environment,* 344:37-50.

USEPA (2002) *Inventory of United States Greenhouse Gases and Sinks: 1990-2000.* United States Environmental Agency, Washington D.C., USA.

Valk, H. and van Vuuren, A.M. (1996) Implications of environmental constraints on livestock production. *In:* Keane, M.G. and O'Riordan, E.G. (eds.): *Pasture Ecology and Animal Intake-Potential for and Consequences of Extensification of Beef and Sheep Production on the Grasslands of the EC.* Teagasc Publications, Dublin, pages 45-56.

Van der Eerden, L., de Vries, W. and van Dobben, H. (1998) Effects of ammonia deposition on forests in The Netherlands. *Atmospheric Environment,* 32:525-532.

Van der Meer, H.G. and van Uum-van Lohuyzen, M.G. (1986) The relationship between inputs and outputs of nitrogen in intensive grassland systems. *In:* Van der Meer, H.G., Ryden, J.C. and Ennik, G.C. (eds.): *Nitrogen Fluxes in Intensive Grassland Systems*. Martinus Nijhoff Publishers, Dordrecht, pages 1-18.

Verbruggen, I, Nevens, F., Mulier, A., Meul, M., Reheul, D., Salomez, J., Hofman, G., Declercq, P., Bries, J., Herelixka, E., ver Elst, P. and Vogels, N. (2003) Flanders. *In:* Bos, J., Pflimlin, A,, Aarts, F. and Vertes, F. (eds.): *Nutrient Management at Farm Scale: How to Attain Policy Objectives in Regions with Intensive Dairy Farming?* Wageningen Academic Publishers, The Netherlands, pages 165-183.

Wade, A.J., Neal, C., Whitehead, P.G. and Flynn, N.J. (2005) Modelling nitrogen fluxes from the land to coastal zone in European systems: a perspective from the INCA project. *Journal of Hydrology,* 304:413-429.

Watson, C.A. and Stockdale, E.A. (1999) Whole-farm nutrient budgets: What do they tell us? *In:* Corrall, A. (ed.): *Accounting for Nutrients- A Challenge for Grassland Farmers in the 21st Century*. British Grassland Society Occasional Symposium No.33, pages 35-40.

Watson, C.J. (2001) Nitrogen cycling in grassland systems. *Proceedings No. 462,* International Fertiliser Society, York, UK, pages 1-36.

Watson, C.J., Stevens, R.J., Garrett, M.K. and McMurray, C.H. (1990) Efficiency and future potential of urea for temperate grassland. *Nutrient Cycling in Agroecosystems,* 26:341-357.

Watson, C.J., Jordan, C., Taggart, P.J., Laidlaw, A.S., Garrett, M.K. and Steen, R.W.J. (1992) The leaky N-cycle on grazed grassland. *Aspects of Applied Biology,* 30:215-222.

Watson, C.J. and Mills, C.L. (1998) Gross nitrogen transformations in grassland soils affected by previous management intensity. *Soil Biology and Biochemistry,* 30:743-753.

Watson, C.J., Jordan, C., Lennox, S.D., Smith, R.V. and Steen, R.W.J. (2000) Inorganic nitrogen in drainage water from grazed grassland in Northern Ireland. *Journal of Environmental Quality,* 29:225-232.

Watson, C.J. and Foy, R.H. (2001) Environmental impacts of nitrogen and phosphorus cycling in grassland systems. *Outlook on Agriculture,* 30:117-127.

Webb, J., Menzi, H., Pain, B.F., Misselbrook, T.H., Dammgen, U., Hendriks, H. and Dohler, H. (2005) Managing ammonia emissions from livestock production in Europe. *Environmental Pollution,* 135:399-406.

Weier, K.L., Doran, J.W., Power, J.F. and Walters, D.T. (1993) Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. *Soil Science Society of America Journal,* 57:66-72.

Whitehead, D.C. (1986) Sources and transformation of organic nitrogen in intensively managed grassland soils. *In:* Van der Meer H.G., Ryden J.C. and Ennik G.C. (eds.): *Nitrogen Fluxes in Intensive Grassland Systems.* Martinus Nijhoff Publishers, Dordrecht, pages 47-58.

Whitehead, D.C. (1995) *Grassland Nitrogen.* CAB International, Wallingford, UK, 397 pages.

Whitmore, A.P., Bradbury, N.J. and Johnson, P.A. (1992) Potential contribution of ploughed grassland to nitrate leaching. *Agriculture, Ecosystems and the Environment,* 39:221-233.

Wu, Z., Satter, D. and Sojo, R. (2000) Milk production, reproductive performance, and faecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. *Journal of Dairy Science,* 83:1028-1041.

8. Publications from this project

Treacy M. (2008) Nutrient management on intensive dairy farms in the southwest of Ireland Masters (M.Phil) Thesis. School of Biological Sciences, Queens University Belfast, May 2008, 145 pages.

Treacy M. Humphreys J. Mc Namara K. Browne R. and Watson C.J. (2008) Farm-Gate Nitrogen Balances on Intensive Dairy Farms in the South-West of Ireland. *Irish Journal of Agricultural and Food Research*, (in press).

Humphreys J. Treacy M. Mc Namara K. Browne R. and Watson C.J. (2008) Farm-Gate Phosphorus Balances on Intensive Dairy Farms in the South-West of Ireland. *Irish Journal of Agricultural and Food Research*, (in preparation).

Humphreys J. LeGall A. Aarts F. and Pflimlin A. (2008) Sustainable options for grassland agriculture in Europe. International conference: Sustainable grassland production in Europe and the Water Framework Directive. Johnstown Castle Research Centre in November 2008.
This paper will be published as a peer reviewed publication in *Tearman*.

Humphreys J. (2007) Cutting back on fertilizer for grassland in 2007**.** *Proceedings of the Fertilizer Association of Ireland 2007,* 43. 2-35. www.fertilizer-assoc.ie/publications.htm

Treacy M. Humphreys J. McNamara K. and Watson C.J. (2007) Nutrient management on intensive dairy farms in the south-west of Ireland. *Agricultural Research Forum*, 7.

Humphreys, J. (2008) Cutting fertilizer costs on grassland farms. *Forage and Nutrition Guide 2008*, 6-9.

Humphreys, J. (2008) White clover to lower fertilizer N costs. *Today's Farm*, March/April 2008, 22-23.

Humphreys J. (2008) Cutting fertilizer costs on grassland farms. *Irish Independent – Farming Supplement*, 19 February 2008, 12-14.

Humphreys J. (2008) Spend less on nitrogen without cutting output. *Today's Farm,* January/February 2008, 20.

Humphreys J. (2008) Cutting expenditure on fertilizer N. *Irish Farmers Journal – Fertilizer Supplement*, 16 February 2008, 7.

Humphreys J. (2007) White Clover to cut the rising cost of fertilizer N. *Forage and Nutrition Guide*, 2007, 10-13.

Humphreys J. (2007) Fertilizer N for grassland. *Farming Independent*, 20 February 2007, 11-13