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Farm-gate nitrogen balances on intensive dairy farms in the south west of Ireland

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Nitrogen management and farm-gate N balances were evaluated on 21 intensive dairy farms in the south west of Ireland for each of four years (2003 to 2006). The mean annual stocking density was equivalent to 202 kg/ha (s.d. 29.6) of N excreted by livestock on the farm. The mean annual farm-gate N surplus (imports – exports) declined between 2003 and 2006 (277 to 232 kg/ha, s.e. 6.8; $P < 0.001$) due to a decline in annual N imports (fertilizer, feed and imported manures; 335 to 288 kg/ha, s.e. 6.9; $P < 0.001$). Overall annual fertilizer N use on the farms decreased during the study period (266 to 223 kg/ha, s.e. 6.5; $P < 0.001$) mainly due to lower inputs for the first application in spring and for the production of first-cut silage. These decreases were partly offset by applying more slurry in spring for early grazing and for first-cut silage. The introduction of white clover resulted in lower N imports on four farms. Export of N from farms was unaffected by reductions in N imports. The mean efficiency of N use tended to increase over time (0.18 in 2003 to 0.20 in 2006). The large variation in quantities of fertilizer N applied on farms with similar stocking densities suggests potential for further improvements in the efficiency of N use. In terms of fertilizer N use, complying with S.I. No. 378 of 2006 did not require major changes in the N management practices on 19 of the farms.

Keywords: dairy farms; farm-gate nitrogen balance; nitrogen surplus; nitrogen use efficiency

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Introduction

Intensive grass-based dairy farming relies on large inputs of fertilizer N to produce sufficient dry matter (DM) to sustain high milk output per hectare. There is growing concern that excessive losses of N are damaging the environment. Agriculture in Ireland is estimated to be the origin of 82% of N in Irish inland surface waters (Toner *et al.*, 2005) and to be the source of 97% of ammonia and 81% of nitrous oxide emissions to air (DAF, 2007; DEHLG, 2007). Hence, the use of N fertilizers is regulated under S.I. No. 378 of 2006. The cost of fertilizer N has increased substantially in recent years (CSO, 2007) and its inefficient use in agricultural production is an unnecessary cost.

The difference between N imported onto farms in fertilizers, feeds, manures or in other materials and N exported from farms in products such as milk and meat usually shows a surplus of N generated by the production system (Aarts *et al.*, 1988; Ledgard, Penno and Sprosen, 1997; Aarts, Habekotté and Van Keulen, 1999). Farm-scale N balances can take the form of farm-gate balances, which account for the N that is imported onto, and exported off, farms via the farm-gate, such as synthetic fertilizers, concentrates, milk and livestock exported from the farm, or can take the form of whole-farm balances that also include other sources of N such as atmospheric deposition of N, biological N fixation in association with white clover (white clover-BFN) and net mineralization of N in the soil (Schröder *et al.*, 2003). The fate of N surpluses is highly variable and difficult to predict. It is affected by on-farm factors such as soil type and hydrology, intensity of land use, farm structure and management practices, and by off-farm factors such as weather conditions (Ledgard, Crush and Penno, 1998; Aarts, 2003). However, substantial proportions are lost to the environment through processes such as denitrification, ammonia volatilization, surface run-off and nitrate leaching (Jarvis, 1999). Surplus N also accumulates in grass roots and stubble, or is immobilized in soil organic matter. The quantity of surplus N generated by a production system is a useful indicator of the environmental sustainability of that system: the lower the surplus the lower the risks of damaging losses to the wider environment (Aarts *et al.*, 1999).

There have been a number of studies describing N balances on dairy farms in different parts of the world (Ledgard, Penno and Sprosen, 1999; Oenema, Koskamp and Galama, 2001; Swensson, 2003; Nevens *et al.*, 2006; Roberts, Leach and Goldie, 2007). Many of these studies involved dairy production based on arable-grassland rotations where concentrates and maize silage comprised a large proportion of the diet. There is limited knowledge of N balances on intensive dairy farms in Ireland, which tend to be based on permanent grassland and where grazed grass is the major dietary component. The aim of the present study was to examine N use and farm-gate N balances on 21 intensive dairy farms located in the south west of Ireland for the years 2003 to 2006 inclusive.

Materials and Methods

Farm selection and on-farm recording

All farms in this study were involved in the Dairy Management Information System (DAIRYMIS) programme run by Teagasc, Moorepark Dairy Production Research Centre (Crosse, 1991). This is a computerised recorder-based system designed to capture detailed information on farm inputs, livestock production and reproduction. The selected farmers had a history of accurate record keeping. During the study, all nutrient applications on each paddock were recorded by the farmer on purpose-built recording boards. These data along with follow-up interviews were used to double-check the DAIRYMIS data and eliminate errors. Data on the recording boards were also used to establish differences in management practices between farms such as the mean quantity of fertilizer applied in the first application in spring, fertilizer N for first- and second-cut silage and use of organic manures generated on the farm or imported from pig farms.

Twenty-four farms located in counties Cork, Kilkenny, Limerick, Tipperary and Waterford were initially selected. Two farmers did not provide satisfactory records and one farmer left the study due to ill health. Data from these farms were not used, so the data included in this paper relate to the remaining 21 farms. Permanent grassland-based milk production from spring calving cows was the main enterprise on all the selected farms.

Stocking density was expressed as the quantity of N excreted by resident livestock relative to the area of the farm used for agricultural production (utilised agricultural area). This was calculated using the standard values for annual N excretion for the different categories of livestock in S.I. No. 378 of 2006 (e.g. one dairy cow excretes 85 kg N per year, one bovine less than one year old excretes 24 kg N per year). The same criteria were used to define a livestock unit (LU), with one dairy cow equivalent to one LU and one bovine less than one year old equivalent to 0.28 LU. As the emphasis in the study was on intensive dairy farms, the majority of farms selected had stocking densities of between 2 and 3 LU per hectare. Milk output from the area used for milk production was estimated to facilitate comparison with specialised dairy farms in other countries. This area was the proportion of the utilised agricultural area that was equivalent to the proportion of the total LU on the farm represented by dairy cows.

Weather and grass growth

Weekly grass growth was measured at Solohead Research Farm (latitude 52°51' N; 08°21' W; altitude 97 m above mean sea level) using the methodology described by Corral and Fenlon (1978). Precipitation and soil temperature at 100 mm soil depth were recorded at the climatological station located at Solohead Research Farm as described by Fitzgerald and Fitzgerald (2004).

Farm-gate N balance

Farm-gate N balance was calculated for each calendar year taking account of N imported onto and exported from a farm. All imports and exports of N were expressed relative to the utilised agricultural area. Imports did not take account of atmospheric deposition, biological N fixation in grassland in association with white clover or net mineralization of N in the soil as these sources of N did not pass through the farm gate (Aarts, 2003). Biological N fixation is difficult to determine accurately on farms. Annual atmospheric deposition is also difficult to measure and is generally low (<10 kg/ha) in Ireland (Jordan, 1997). The use of clover on each farm was recorded as the proportion of agricultural area that contained white clover and was being managed to promote the white clover in swards. Net mineralization of N was not included in the balance because it was assumed that this source of N would remain fairly constant from year to year on these predominantly permanent grassland farms (O'Connell and Watson, 2004). The farm-gate balance was the difference between imports of N onto the farm and recovery of N in agricultural products (mostly milk and live weight), while N use efficiency was calculated as the proportion of imported N recovered in agricultural products.

Nitrogen imported in concentrate feed was calculated by multiplying the total quantity of concentrate fed by its protein concentration divided by 6.25 (McDonald *et al*., 1995). The N concentration of pig slurry imported onto the farms was assumed to be 4.2 kg/m^3 as in S.I. 378 of 2006. Nitrogen in milk exported from farms was calculated assuming that milk protein concentration divided by 6.39 equals N concentration. Nitrogen exported in livestock leaving the farm was calculated by estimating the total live weight of the livestock sold (or died) from the farm and multiplying by 0.029 for calves and 0.024 for older animals (ARC, 1994).

Statistical analysis

Data were subjected to analyses of variance to compare differences between years in production factors. Farms were considered as replicates in the model. The relationships between stocking density and (i) fertilizer N use, (ii) N imports, (iii) surplus N, and (iv) N use efficiency were examined using linear regression. Likewise, the relationships between milk output (milk sold) per hectare of the farm area used for milk production and (i) fertilizer N use, (ii) N imports, (iii) surplus N, and (iv) N use efficiency were also examined using linear regression.

Results

Weather and grass growth

Mean monthly soil temperature at Solohead Research Farm for years 2003 to 2006 was 10.8, 10.9, 11.5 and 11.2 °C, respectively (Figure 1a). Corresponding annual precipitation was 882, 1032, 1029 and 1094 mm (Figure 1b). The summer of 2006 was particularly dry. Grass growth during that summer and early autumn was lower than in the preceding years (Figure 1c).

Utilised agricultural area, stocking density, concentrate use and milk production

Mean farm production data for the 4 years are shown in Table 1. The utilised agricultural area per farm ranged from 25 to 130 ha. The utilised agricultural area remained unchanged on twelve farms, decreased on three farms and increased on six farms during the study. There was no change ($P > 0.05$) in the mean utilised agricultural area between years. The mean stocking density (N excreted by livestock) was 202 kg/ha and did not change during the study. Stocking density on individual farms ranged from 162 to 246 kg/ha. The mean number of cows per farm increased ($P < 0.001$) from 85 (range 45 to 183) in 2003 to 93 (range 44 to 190) in 2006. Increases in the number of dairy cows were offset by decreases in other livestock (mainly beef cattle), which decreased ($P < 0.05$) from 53 LU in 2003 to 48 LU in 2006. Mean concentrate feed input per LU ranged from 529 kg in 2004 to 808 kg in 2006, and was higher ($P < 0.001$) in 2006 than in other years because of below average grass growth caused by a prolonged period of exceptionally dry weather. The mean volume of milk supplied per hectare used for milk production ranged from 11,667 L in 2005 to 13,087 L in 2003. Mean protein concentration in milk was 34.1 g/kg and did not differ between years. In contrast, there was a difference ($P < 0.001$) between years in milk fat concentration, which ranged from 38.0 g/kg in 2003 to 39.1 g/kg in 2005.

Fertilizer N use and farm-gate N balance

Mean annual fertilizer N use declined ($P < 0.001$) from 266 kg/ha in 2003 to 223 kg/ha in 2006 (Table 2). The mean

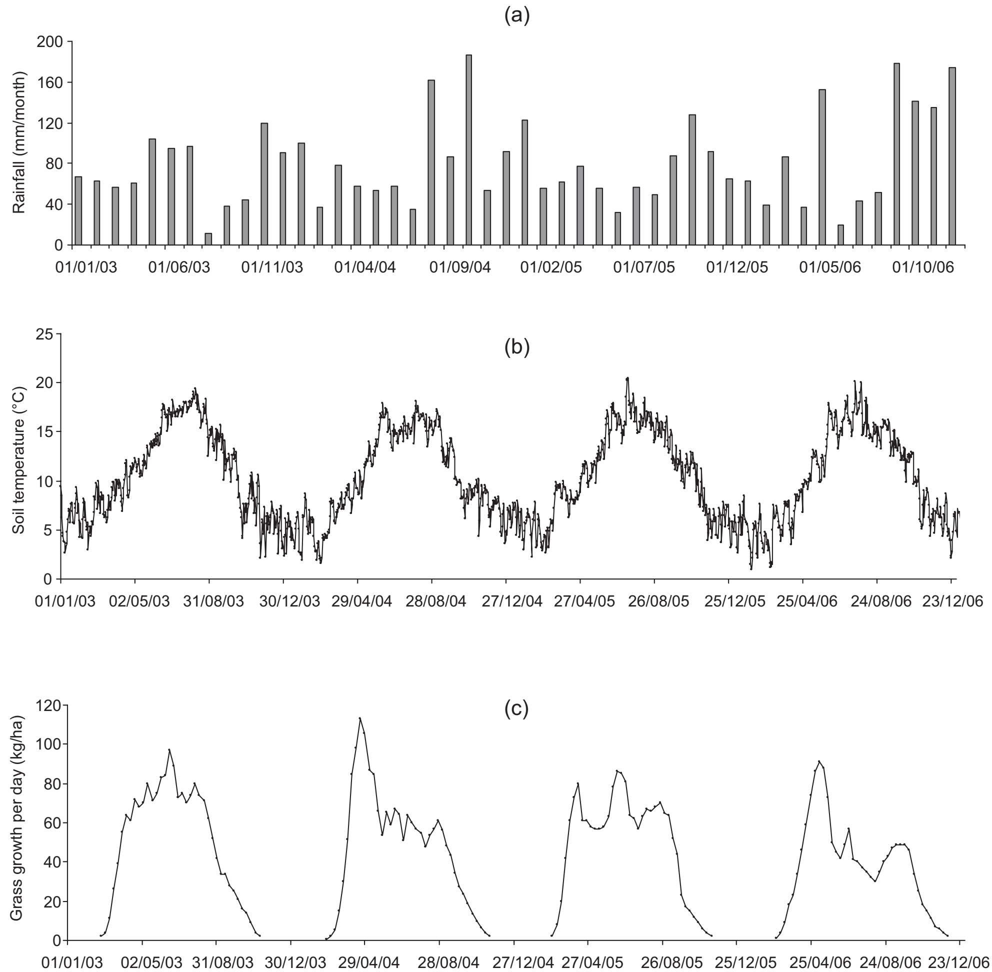

Figure 1. (a) Monthly rainfall, (b) daily soil temperature at 100 mm depth and (c) mean weekly grass growth rate (dry matter) measured using the methodology of Corral and Fenlon (1978) at Solohead Research Farm between 1 January 2003 and 31 December 2006.

quantity of fertilizer N used in the first application in spring declined ($P < 0.001$) from 48.9 to 33.3 kg/ha (s.e. 2.67), and the quantity of fertilizer N applied for first-cut silage declined ($P < 0.05$) from 106 to 96 kg/ha (s.e. 2.9). The proportion of total slurry that was applied during the spring (before mid-April) increased ($P < 0.05$) from 0.50 in 2004 to 0.65 in 2006 (s.e. 0.036). White clover was introduced on four farms during the study and the proportion of swards containing clover on these four farms in 2006 ranged from 0.15 to 0.85.

Fertilizer N was the main source of N imported onto farms, accounting for nearly 0.80 of the total N imports. Nitrogen contained in imported concentrate feed was the second largest source of N (0.15 of total N imports), while N imported in manure was an important source of N on six farms

Table 1. Mean values for utilised agricultural area, stocking density (excreted N per ha), mean number of dairy cows, mean number of other livestock per farm, annual concentrate feed use, annual fertilizer N use, annual milk sales from the area used for milk production, annual mean milk protein and fat concentrations

	Year				s.e.	F-test
	2003	2004	2005	2006		
Utilised agricultural area (ha)	59.3	60.2	58.8	59.0	0.98	
Stocking density (excreted N, kg/ha)	206	195	203	205	3.9	
Number of dairy cows per farm	85	86	90	93	1.4	***
Other livestock (LU/farm)	53	46	46	48	2.3	*
Concentrate feed (kg/LU)	675	529	544	808	31.2	***
Volume of milk sold (L/ha)	13,087	11,859	11,667	12,657	264.0	***
Milk protein (g/kg)	34.0	34.3	34.1	34.1	0.07	
Milk fat (g/kg)	38.0	38.6	39.1	38.7	0.12	***

Table 2. Mean values for imports of N in fertilizer, concentrates and organic manures, exports of N in milk and livestock and farm-gate N balances for 21 dairy farms over 4 years

	Year				s.e.	F-test
	2003	2004	2005	2006		
Farm-gate N imports (kg/ha)						
Fertilizer	266	234	232	223	6.5	***
Concentrate	48	36	37	54		
Organic manures	22	20	18	12		
Total	335	290	287	288	6.9	***
Farm-gate N exports (kg/ha)						
Milk	44	43	42	45		
Livestock	15	12	12	11		
Total	58	55	54	57	1.2	
Farm-gate N surplus (kg/ha)	277	235	233	232	6.8	***
N-use efficiency	0.18	0.20	0.20	0.20	0.007	

(ranging from 130 to 462 kg/ha per year). The mean imported N declined ($P < 0.001$) from 335 kg/ha in 2003 to 288 kg/ha in 2006. In 2006, the quantity of N imported had fallen to less than 0.90 of that imported in 2003 on 14 farms, and had increased to more than 1.10 of that imported in 2003 on one farm. On the six remaining farms imported N remained within 0.10 of that recorded in 2003.

Annual N exports from farms ranged from 41 to 85 kg/ha, with no change in mean N exports during the study. Nitrogen contained in milk sold accounted for 0.78 of N exports. The remaining N exports were from sales of livestock and the disposal of dead animals.

Nitrogen surplus ranged from 87 to 389 kg/ha across farms and years. There was a decrease ($P < 0.001$) in the mean N surplus from 277 kg/ha in 2003 to 232 kg/ha in 2006. Nitrogen surplus declined on 17 farms during the study. Mean efficiency of N use did not change during the study and ranged from 0.10 to 0.34 across farms and years.

Annual fertilizer N input was higher on farms with a higher stocking density ($R^2 = 0.37$, $P < 0.001$, Figure 2a) using data combined over four years. There was

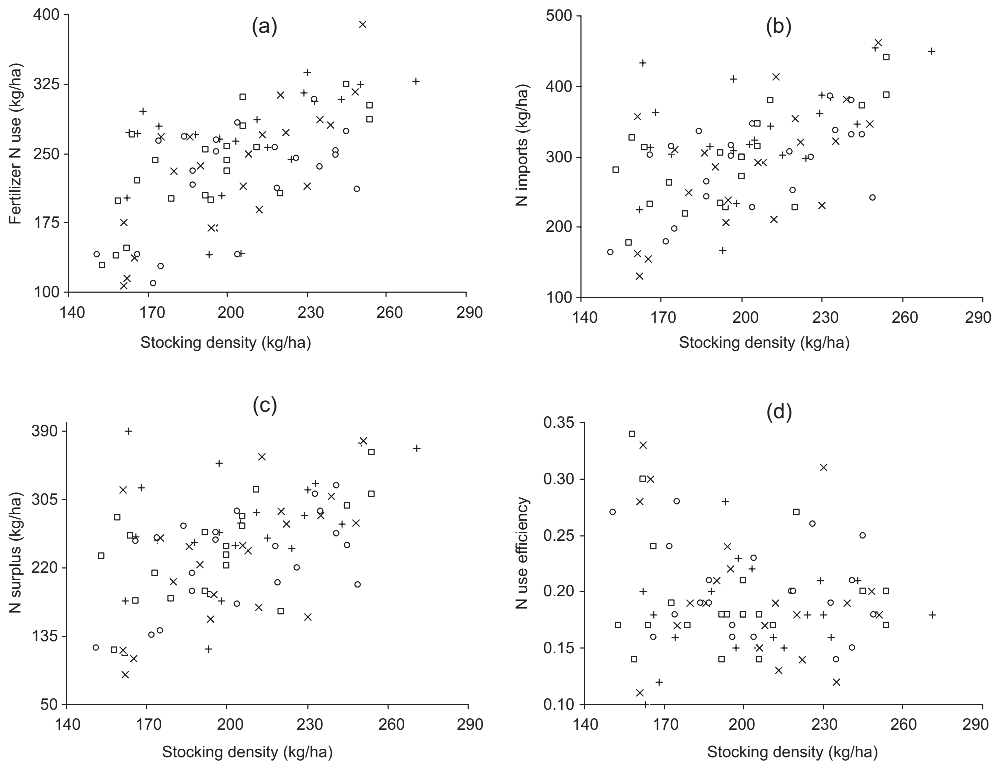

Figure 2. Stocking density (excreted N per ha) and (a) fertilizer N use, (b) N imports, (c) N surplus and (d) N use efficiency on 21 intensive spring calving dairy farms in the south west of Ireland for 2003 (+), 2004 (□), 2005 (×) and 2006 (○).

substantial variation in the quantity of fertilizer N applied on farms with similar stocking densities. Likewise, imported N was also higher on farms with a higher stocking density (R^2 = 0.32, P < 0.001, Figure 2b) and surplus N increased as stocking density increased (R^2 = 0.26, P < 0.001, Figure 2c). There was no relationship between stocking density and N use efficiency (Figure 2d).

The annual milk output per hectare of agricultural area ranged from 5,000 to 12,700 L across years and farms. Milk output per hectare used for milk production ranged from 8,500 to 17,500 L across farms and years. Fertilizer N input (R^2 = 0.37, P < 0.001, Figure 3a), total imports of N (R^2 = 0.33, P < 0.001, Figure 3b) and surplus N (R^2 = 0.24, P < 0.001, Figure 3c) increased with increasing milk output per hectare (data combined over four years). There was no relationship between milk output per hectare used for milk production and N use efficiency.

Discussion

Stocking density and milk production

Relatively low milk output per hectare of utilised agricultural area on some farms was partly due to a high proportion of other livestock on the farm (mostly beef

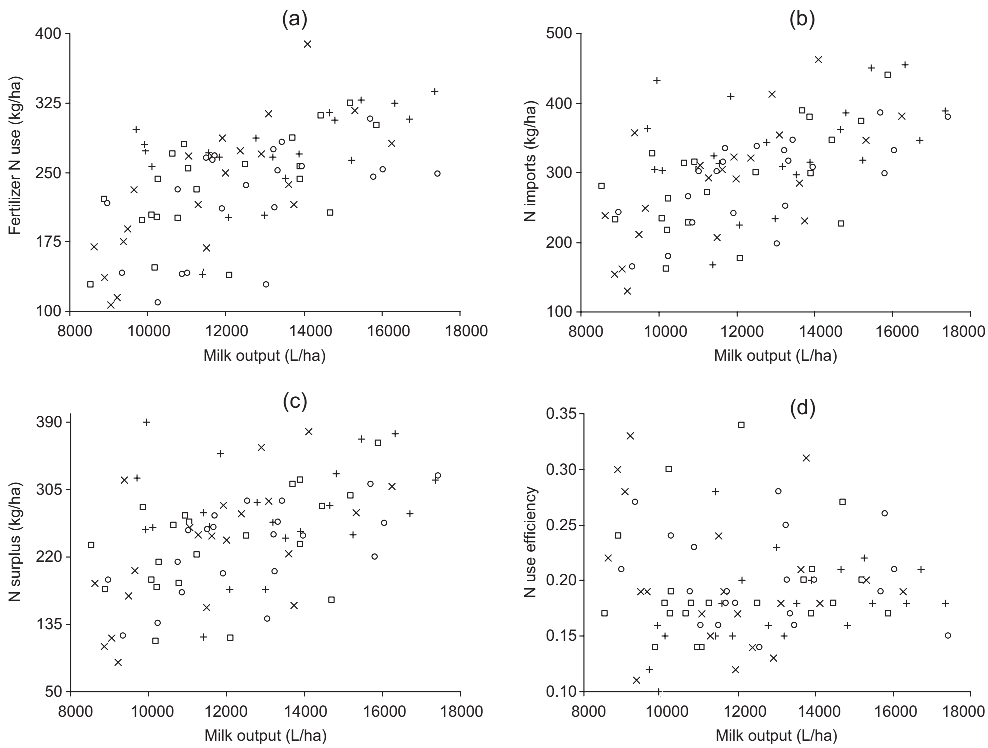

Figure 3. Milk output per hectare used for milk production and (a) fertilizer N use, (b) N imports, (c) N surplus and (d) N use efficiency on 21 intensive spring calving dairy farms in the south west of Ireland during 2003 (+), 2004 (□), 2005 (×) and 2006 (○).

cattle or replacement heifers for sale) and a relatively low concentrate input compared with studies in other countries. Dairy farms in Ireland tend to be less specialised in milk production than dairy farms in other regions of intensive dairy production in northwest Europe (Raison, Pflimlin and Le Gall, 2006). In the present study, dairy cows accounted for 0.65 of the LU on farms, which is close to the value of 0.61 reported by Humphreys, Casey and Carton (2004).

Fertilizer N use

In general, the quantity of fertilizer N applied increased with stocking density. However, there was large variation in the quantity of fertilizer N applied on farms with a similar stocking density, with the greatest variation on the lower stocked farms. While part of this variation could be attributed to soil type (O'Connell *et al.*, 2004) and the use of white clover, the results suggest that there is considerable potential to reduce fertilizer N input on many of these farms.

The reduction in fertilizer N use between 2003 and 2006 can be attributed largely to decreases in the quantities of fertilizer N applied in the first application in spring and for the production of first-cut silage. This reduction was made possible, in part, by increasing the proportion of slurry applied during the spring, and by the introduction of white clover on four farms. It appears that the quantity of fertilizer N applied in the first application has been declining on Irish dairy farms over the past decade in line with recommendations (Humphreys, O'Connell and Watson, 2003; Humphreys, 2007). The mean quantity applied in 2006 (33.3 kg/ha) was substantially less than that applied in 2003 (48.9 kg/ha), and considerably lower than the 60.1 kg/ha reported by Mounsey *et al.* (1998) in a study of nutrient management on 12 intensive dairy farms. The mean quantity of fertilizer N applied for the production of first-cut silage decreased from 106 to 96 kg/ha reflecting the substitution of some fertilizer N with N contained in slurry. This is in line with current recommendations that where 33 m^3/ha of slurry is applied for first-cut silage the quantity of fertilizer N should be reduced from 115 to 90 kg/ha (Humphreys, 2007).

Since 1 August 2006, farmers are legally required to comply with maximum application limits for fertilizer N as specified in S.I. No. 378 of 2006. In 2006, these limits were exceeded on two farms both stocked at >210 kg/ha of excreted N and permitted to apply 256 kg/ha of fertilizer N per year. While farms stocked at >210 kg/ha had the greatest difficulty in complying with the limits on fertilizer N use in the S.I. No. 378 of 2006, seven of the nine farms stocked at >210 kg/ha were compliant with the N fertilization limits in the final year of the study.

Farm-gate N balance

Surpluses of N were clearly linked to N imports as reported elsewhere (Oenema *et al.*, 1998; Jarvis, 1999). Humphreys *et al.* (2004) found that the mean use of fertilizer N on 32 intensive Irish dairy farms was 307 kg/ha for the years 1993 to 2001. Farms involved in that study were stocked at a mean of 229 kg/ha of excreted N (range 172 to 304 kg/ha) and had a mean milk output in 2001 of 8,700 L (range 4,400 to 20,200 L) per hectare of utilised agricultural area. Total annual N imports averaged 327 kg/ha and annual N surplus averaged 262 kg/ha. Nitrogen use efficiency (0.20) did not change during the study. These results are similar to the present findings. In a study of 12 intensive Irish dairy farms, Mounsey *et al.* (1998) found a mean N surplus of 304 kg/ha (range 198 to 408 kg/ha). In the present study, both the N surplus and the stocking density were lower than reported by Mounsey *et al.* (1998) and the mean efficiency of N use tended to be higher.

Comparison with N surplus and N use efficiency in other countries

Farm-gate N balances were first calculated in the 1980s for farms in regions with intensive dairy production, particularly in the Netherlands. These studies reported low N use efficiency. On farms with a mean annual N import of 533 kg/ha, Van der Meer and van Uum-van Lohuyzen (1986) reported a mean N use efficiency of 0.16. Similarly, in a study of farms with an annual N import of 568 kg/ha, Aarts *et al.* (1988) reported that N use efficiency was 0.14. These efficiency values are in general agreement with findings from later studies on Dutch farms (Ledgard *et al.*, 1997; Aarts, 2003). The latter author showed, under experimental conditions in the Netherlands, that an N use efficiency of approximately 0.36 is technically attainable on intensive dairy farms producing around 12,000 L milk per hectare.

In Flanders, Nevens *et al.* (2006) found that the mean annual N imports decreased from 446 kg/ha in 1989 to 305 kg/ha in 2001 while N surpluses correspondingly decreased from 378 kg/ha to 238 kg/ha. This decrease was attributed to lower mineral fertilizer use and a reduction in concentrate use. Corresponding N use efficiencies increased from 0.15 to 0.22. In the latter study account was taken of the contribution of white clover and of atmospheric N deposition, which was 48 kg/ha for the relevant period. In contrast, Ireland experiences a low annual deposition of atmospheric N (approximately 10 kg/ha; Jordan, 1997) and therefore this source of N has much less influence on N balances under Irish conditions.

Surplus N values similar to those measured in Ireland have also been reported for the UK. In a study of dairy farms in the south west of England in the 1990s, Ledgard *et al*. (1997) found that annual N imports averaged 337 kg/ha, including 10 kg/ha due to biological N fixation and 25 kg/ha from deposition of atmospheric N. Mean N use efficiency was 0.20. In a study of dairy farms in Scotland in the late 1990s Roberts *et al.* (2007) reported N surpluses ranging from 259 to 785 kg/ha and N use efficiencies from 0.10 to 0.23. Under experimental conditions in Scotland, Leach and Bax (1999) calculated N use efficiency for intensive and extensive grass-based dairy production systems, taking into account biological N fixation and atmospheric deposition (12 kg/ha per year). On the intensive systems, annual milk output ranged from 13,600 to 16,300 kg/ha, imports of N ranged from 307 to 404 kg/ha, surplus N ranged from 242 to 304 kg/ha, and N use efficiency ranged from 0.14 to 0.22. On the extensive systems, the corresponding values were milk output 10,600 to 11,500 kg/ha, N imports 183 to 189 kg/ha, N surplus 131 to 140 kg/ha, and N use efficiency 0.22 to 0.26. In a study of grassland-based dairy farms in New Zealand, Ledgard *et al.* (1997) calculated a mean surplus (including biologically fixed N) of 131 kg/ha, and an mean N use efficiency of 0.30. Likewise, taking into account biologically fixed N, on relatively low stocked mixed dairy farms in Sweden with fertilizer N inputs of 88 to 101 kg/ha, Swensson (2003) found N use efficiencies of between 0.24 and 0.29. The systems of production involved were quite different from those in Ireland because of a high proportion of arable crops. Mean annual milk production on the Swedish farms was 6,800 kg/ha compared with 10,000 kg/ha on the farms in Flanders mentioned earlier (Nevens *et al*., 2006) and over 12,000 kg/ha on the Dutch farms studied by Aarts (2003). In contrast to the present findings, the results from the UK, Swedish, Flanders and Dutch studies suggested that lower intensity of production, lower N imports and lower surpluses were generally associated with higher N use efficiency.

Environmental implications

Higher N surpluses result in higher losses of N from grassland-based systems (Jarvis, 1993; Scholefield *et al*., 1993; Tyson *et al*., 1997; Ledgard *et al*., 1999; Watson *et al*., 2000). It is generally accepted that there is a need to increase the recovery of imported N in products exported off farms. Within the European Union there are a number of directives with the objective of lowering N emissions to groundwater, surface water and the atmosphere. These include the Nitrates Directive (European Council, 1991), the Water Framework Directive (European Parliament and Council, 2000) and the Directive on National Emissions Ceilings (European Parliament and Council, 2001).

In the current study, N use efficiency ranged from 0.10 to 0.34. Highest and lowest efficiencies were recorded at relatively low stocking densities (160 kg/ha; Figure 2). This can be partly explained by the use of white clover on four of the lower stocked farms. Nitrogen fixation, in association with white clover, was not included in the N balances, making these farms appear more efficient. Losses of N are generally closely related with the amount of N cycling within the system. In a review of the topic, Andrews *et al.* (2007) concluded that where N fixed in association with white clover replaces an equivalent quantity of fertilizer N there was no difference in N surplus generated or in N use efficiency. However, white clover can be used to lower fertilizer N costs on farms stocked at around 170 kg/ha of excreted N resulting in profitability similar to higher stocked farms (Humphreys and Lawless, 2008). This provides an environmental benefit: lower stocked clover-based farms generate lower N surpluses (and consequently lower N losses) compared with higher stocked farms. The economic benefit associated with white clover is increasingly evident taking into account the escalating cost of fertilizer N in recent years.

In the present study, very low N use efficiencies were associated with high imports of N in manures and synthetic fertilizers. The availability of N in organic manures is low compared with that in synthetic fertilizers (Pain, 2000). Hence, where manure was imported it resulted in relatively high N imports compared to farms where no manure was imported, particularly in the early years, when little or no account was taken of the N in the imported manure; it was used primarily to replace P and K fertilizers. Towards the end of the study, the import of organic manure was curtailed by limits imposed by S.I. No. 378 of 2006. Import of manure was not the only reason for low N use efficiency. On some farms there was considerable scope to make more efficient use of farm-produced manures as well as imported fertilizer N or, alternatively, to increase N output in products relative to the quantities of N being imported.

Conclusions

The N surpluses and N use efficiencies recorded in the present study were generally within the ranges found in other studies in Ireland and elsewhere. There were large variations in the quantity of N imported onto farms and in the surplus of N generated at similar stocking density and milk output per hectare, particularly on the lower stocked farms. Fertilizer N accounted for 0.80 of N imported onto farms and there is considerable potential to lower the quantity of N, particularly fertilizer N, imported onto some farms. This should be the focus of future research. Compliance with the fertilization limits in S.I. No. 378 of 2006 was readily achievable on the majority of the farms.

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References

Aarts, H.F.M. 2003. Strategies to meet requirements of the EU-nitrates directive on intensive dairy farms. *Proceedings No. 518. The International Fertilizer Society, York, United Kingdom,* 27 pages.

Aarts, H.F.M., Biewinga, E.D., Bruin, G., Edel, B. and Korevaar, H. 1988. Melkveehouderij en millieu. Rapport 111, Proefstation voor de Rundveehouderij, Schapenhouderij and Paardenhouderij, Lelystad, The Netherlands, 136 pages.

Aarts, H.F.M., Habekotté, B. and Van Keulen, H. 1999. Limits to intensity of milk production in sandy areas in The Netherlands. *Netherlands Journal of Agricultural Science* **47:** 263–277.

Andrews, M., Scholefield, D., Abberton, M.T., McKensie, B.A., Hodge, S. and Raven, J.A. 2007. Use of white clover as an alternative to nitrogen fertiliser for dairy pastures in nitrate vulnerable zones in the UK: productivity, environmental impact and economic considerations. *Annals of Applied Biology* **151:** 11–23.

ARC (Agricultural Research Council). 1994. The nutrient requirements of ruminant livestock. Technical review by an Agricultural Research Council Working Party. CAB International, Oxon, UK, 351 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* **91:** 61–67.

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 (Central Statistics Office). 2007. Principal Statistics in Relation to Agriculture. CSO, Cork, Ireland.

DAF (Department of Agriculture and Food) 2007. Annual Review and Outlook for Agriculture and Food 2006/2007. DAF, Economics and Planning Division, Dublin 2, Ireland. 87 pages.

DEHLG (Department of Environment, Heritage and Local Government) 2007. Ireland: National Climate Change Strategy 2007–2012. Dublin: DEHLG, 59 pages.

European Council. 1991. Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. *Official Journal of the European Union* **L 375:** 1–8.

European Parliament and Council. 2000. Directive 2000/60/EC establishing a framework for Community action in the field of water policy. *Official Journal of the European Union* **L 327:** 1–73.

European Parliament and Council. 2001. Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants. *Official Journal of the European Union* **L 309:** 22–30.

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

Humphreys, J. 2007. Cutting back on fertilizer for grassland in 2007. *Proceedings of the Fertilizer Association of Ireland* **43:** 2–35.

Humphreys, J. and Lawless, A. 2008. A guide to the management of white clover in grassland. Moorepark Dairy Research Update No. 3. Teagasc, Oak Park, Co. Carlow, Ireland.

Humphreys, J., Casey, I.A. and Carton, O.T. 2004. Meeting environmental objectives and potential constraint on dairy production in Ireland. *In:* "Nutrient Management at Farm Scale: How to Attain Policy Objectives in Regions with Intensive Dairy Farming?", (eds. J. Bos, F. Aarts, F. Vertes, and A. Pflimlin) Wageningen, The Netherlands, pages 145–164.

Humphreys, J., O'Connell, K. and Watson, C.J. 2003. Effect of Nitrate Legislation on Fertiliser Nitrogen Management for Grassland. Proceedings No. 517. The International Fertilizer Society, York, 35 pages.

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

Jarvis, S.C. 1999. Accounting for nutrients in grassland: Challenges and needs. In: "Accounting for Nutrients – A Challenge for Grassland Farmers in the 21st Century (ed. A. Corrall), *British Grassland Society Occasional Symposium, Great Malvern, UK,* **33:** 3–12.

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

Leach, K.A. and Bax, J.A. 1999. Efficiency of nitrogen use in dairy systems. In: "Accounting for Nutrients– A Challenge for Grassland Farmers in the 21st Century", (ed. A. Corrall), *British Grassland Society Occasional Symposium, Great Malvern, UK,* **33:** 69–74.

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

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* **59:** 49–53.

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 fertiliser application. *Journal of Agricultural Science, Cambridge* **132:** 215–225.

McDonald, P., Edwards, R.A., Greenhalgh, J.F.D. and Morgan, C.A. 1995. Animal Nutrition (5th edition). Prentice Hall, UK, 607 pages.

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, ISBN 1 901138 87 9.

Nevens, F., Verbruggen, I., Reheul, D. and Hofman, G. 2006. Farm gate nitrogen surpluses and nitrogen use efficiency of specialized dairy farms in Flanders: Evolution and future goals. *Agricultural Systems* **88:** 142–155.

O'Connell, K., Humphreys, J. and Watson, C.J. 2004. Quantification of nitrogen sources for grassland. *Proceedings of the Fertilizer Association of Ireland*, *Abbeyleix, Ireland*, **40:** 15–29.

Oenema, J., Koskamp, G.J. and Galama, P.J. 2001. Guiding commercial pilot farms to bridge the gap between experimental and commercial dairy farms; the project 'Cows & Opportunities'. *Netherlands Journal of Agricultural Science* **49:** 277–296.

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.

Pain, B.F. 2000. Control and utilization of livestock manures. In: "Grass: Its Production and Utilization", 3rd edition, (ed. A. Hopkins). Blackwell Science Ltd., Oxford, UK, pages 343–364.

Raison, C., Pflimlin, A. and Le Gall, A. 2006. Optimisation of environmental practices in a network of dairy farms in the Atlantic area. Green Dairy Project Interreg Atlantic Area IIIB N°100: *Proceedings of the Final Seminar, Rennes (France), 13–14 December 2006*, pages 43–65. Institut de l'Élevage; IBSN 2-84148-255-3.

Roberts, D.J., Leach, K.A. and Goldie, J. (2007) Assessment and improvement of the efficiency of nitrogen use on commercial dairy farms. *International Journal of Agricultural Sustainability* **5:** 295–304.

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 fertiliser input, field drainage, age of sward and pattern of weather. *Journal of Soil Science* **44:** 601–613.

Schröder, 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.

S.I. (Statutory Instrument) No. 378 of 2006. European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2006, The Stationary Office, Dublin, 49 pages.

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.

Toner, P., Bowman, J., Clabby, K., Lucet, 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. Wexford, Ireland: Environmental Protection Agency (EPA). www.epa.ie. EPA Publications Office, Dublin.

Tyson, K.C., Scholefield, D., Jarvis, S.C. and Stone, A.C. 1997. A comparison of animal output and nitrogen leaching losses recorded from drained fertilised grass and grass/clover swards. *Journal of Agricultural Science, United Kingdom* **129:** 315–323.

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:* "Nitrogen Fluxes in Intensive Grassland Systems", (eds. H.G. Van der Meer, J.C. Ryden and G.C. Ennik). Martinus Nijhoff Publishers, Dordrecht, The Netherlands, pages 1–18.

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.

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