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Farm-gate N and P balances and use efficiencies across specialist dairy farms in the Republic Ireland.

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Abstract

This study establishes farm gate N and P balances and use efficiencies based on the average of 2 years of Teagasc National Farm Survey data in 2009 and 2010. The weighted average farm gate N surplus for this nationally representative sample of specialist dairy farms was 143.4 kg N ha^{-1}. Average farm gate nitrogen use efficiency was 23.2%. For dairy farms operating under an EU Nitrates Derogation, the average N surplus was higher at 181.8 kg N ha^{-1} and average N use efficiency was slightly lower at 22.2%. The total average farm gate P balance was 4.1 kg ha^{-1} in surplus, and P use efficiency averaged 83.9%. P balance ranged from -7.3 to 23.0 kg ha^{-1}. A total of 27% had a negative P balance. The average P surplus for farms with a Nitrates Derogation was below the average of all farms at 3.5 kg P ha^{-1} and average P use efficiency for these Derogation farms was above the average of all farms at 90%.

1.0 Introduction

Chemical nitrogen (N) and phosphorus (P) fertilizer use is one of the main factors underpinning the increased agricultural production and food security in Europe and many other regions achieved in the twentieth and early twenty first centuries. However, intensification in the use of these fertilizers in agricultural production over that time has sometimes lead to excessive losses of these nutrients to groundwaters and surface water bodies, having a detrimental effect on water quality (Oenema et al., 1998; Aarts et al., 2000; Kersebaum et al., 2003; Sutton et al., 2011). In addition, associated gaseous losses of N can contribute to problems of air quality and anthropogenic acidification and greenhouse gas emissions. According to the European Environment Agency (2012), despite some progress, diffuse pollution from agriculture is still significant in more than 40% of Europe's water bodies in rivers and coastal waters, and in one third of the water bodies in lakes and transitional waters. The issue of eutrophication in Irish watercourses has been highlighted as a problem since the 1970s (Flanagan and Toner, 1972, 1975; Inland Fisheries Trust, 1973, 1974). Recently, it was estimated that approximately 29% of monitored river channel length is polluted to some degree across the Republic of Ireland. Agricultural sources were suspected as the cause of 47 per cent of these suboptimal water quality results (EPA, 2012).

Increasing public concern about these issues has lead to policy, legislation and international, agreements such as the EU Nitrates Directive (1991) (ND) and Water Framework Directive (WFD) and the Kyoto Protocol agreement and EU 2020 targets on the reduction of green house gas (GHG) emissions. The ND, now under the umbrella of the WFD, was enacted to minimise surplus N (and P in some member states, including Ireland) from being applied on farms to reduce the associated N (and P) losses from agriculture to water bodies. The Republic of Ireland implemented the EU Nitrates Directive on a whole territory basis (the regulations apply across the whole territory) in 2005-06 and the first National Action Programme (NAP) covered the period from 2006 to 2010. This legislation (SI 610 of 2010) is intended to constrain the use of N and P on farms to agronomic optima and land application to locations, application rates and time periods where nutrient loss to water will be minimised (e.g. closed periods for application of slurry (liquid manure) from mid October to mid to late January). While a stocking rate limit of 170 kg organic N ha^{-1} (2 livestock units per ha) has been set as standard, grassland farmers in Ireland may apply for a derogation from this limit to allow them to stock at levels up to 250 kg organic N ha^{-1} (2.9 livestock units per ha), but this obliges them to meet more stringent recording and reporting requirements. This derogation has principally been used by dairy farmers.

At the same time, increasing livestock feed and fertiliser prices, and increased volatility in these prices, have combined with these public concerns and policy initiatives to elevate efficient nutrient management as a key objective of sustainable agricultural production. Inefficient use of nutrients on farms has significant economic implications for farmers as well as for the wider environment (Oenema and Pietrzak, 2002; Buckley and Carney, 2013). Stakeholders (farmers, policy makers, consumers, NGOs) are increasingly interested in the environmental performance and efficiency of different farming systems and seek reliable indicators of improvements in sustainability (Brouwer, 1998; Halberg et al., 2005). Farm-gate nutrient balances and nutrient use efficiencies can act as such indicators (Oborn et al. 2003). Such nutrient accounting systems have been proposed as a means of assessing nutrient management efficiency at farm level while providing an indicator of environmental pressure. These accounting systems measure nutrient (Nitrogen and Phosphorus, most commonly) inputs onto a farm, mainly through imported feedstuffs and fertilisers, and subtracts quantities exported from the farm through outputs such as milk, meat, cereals, wool and organic manures (Breembroek, et al., 1996; Ondersteijn et al., 2002; 2003; Nevens et al., 2006; Bassanino et al., 2007; Treacy et al., 2008; Ghebremichael and Watzin, 2011; Huhtanen et al., 2011).

Farm scale (farm inputs and outputs) or soil surface (at the scale of the growing crop) are the most commonly used accounting systems (Oenema et al. 2003; Bassanino, 2007). Farm scale balances can take the form of farm-gate or whole farm balances. The farm gate approach restricts analysis to imports and exports of nutrients over which the farmer has direct control (through the farm gate), whereas whole farm balances also account for nutrient inputs and exports that are less directly controllable by the farmer, such as atmospheric deposition, biological fixation and mineralisation of nutrients in soils and losses to air and water (Schröder et al., 2003). The link between nutrient surplus at farm, field and soil surface level and loss to the aquatic environment and atmosphere is a complex process and can be difficult to predict, depending on factors such as soils, hydrology, weather, farm structures and management practices (Jordan et al., 2011). However, all things being equal, farm gate balances can be considered a useful indicator in assessing agronomic efficiency and environmental pressure (Aarts et al., 1999; Schroder et al., 2003) and, critically, farm gate balances highlight the nutrient imports, exports and management practices most directly under the farmers control.

Exports of Irish dairy products and ingredients are an important part of the national economy, valued at some €2.74 billion in 2011 (Bord Bia, 2013). Total milk production was 5.37 billion litres in 2011 and production is set to expand with the end of EU milk quotas in 2015 (CSO, 2013). A national target of a 50% increase in dairy production by 2020 has been set (Department of Agriculture, Fisheries and Food 2010). Irish milk production is based on a low-cost, low-input, seasonal (compact spring calving) grazed grass model that seeks to maximise the utilization of grass grown on-farm and minimise the proportion of imported feed in the cow's diet (Dillon and Delaby, 2009). Dairy farms also tend to have the highest stocking densities and fertilizer inputs of grassland systems in Ireland (Teagasc National Farm Survey, 2010), and are therefore perceived as being of some concern in terms of pressures on the environment. However, dairy systems also tend to have higher nutrient off-takes from fields and farm-gate exports than other grassland systems. For these reasons, it is important to assess the environmental and economic sustainability of dairy production systems in Ireland. This paper aims to do this using the farm-gate nutrient balance and nutrient use efficiency indicators for 195 specialist dairy farms taking part in the Teagasc National Farm Survey (NFS).

2.0 Data

The main data source employed in this analysis is from the NFS conducted by Teagasc (the Irish Agriculture and Food Development Authority) in 2009 and 2010. The Teagasc NFS is collected annually as part of the Farm Accountancy Data Network requirements of the European Union (FADN, 2005). Detailed farm accounts and enterprise level transactions are recorded on a random representative sample of farms throughout the Republic of Ireland by a team of trained recorders. The data used in this paper is for 195 specialist dairy farms which were included in the NFS for both 2009 and 2010. The farm profile of the 195 farms is summarised in Table 1. Results are population weighted to represent 12,798 dairy farms nationally. Population weights are available through the NFS based on data provided by the Central Statistics office of Ireland (see Teagasc National Farm Survey 2010 for a full description of data collection and weights derivation). All statistics presented in this analysis are population weighted unless otherwise stated. Dairy farms that reported importing or exporting organic manures were excluded from the analysis as no data were available on quantities of organic fertiliser imported or exported[1].

A specialist dairying farm is defined as a system where at least two-thirds of farm standard output is from grazing livestock and dairy cows are responsible for at least

[1] A total of 8 farms were importing and 15 farms were exporting organic manures.

three-quarters of the grazing livestock output. Dairy farms in the Republic of Ireland tend to have other farm enterprises also. This is clearly illustrated in Table 1, where 34% of total livestock were non-dairy cows, although some of this number are replacement heifers being reared for the dairy herd. It should be noted that the farm gate balances presented here, while being for specialist dairy farms, are for the whole-farm and are not broken down to the dairy enterprise only. An analysis of the dairy enterprise alone would be unrealistic, in the sense that most Irish dairy farms operate with at least some element of another enterprise. Therefore, some of the nutrient imports and exports included in the balances will be associated with other on-farm enterprises and their management such as livestock reared or crops grown for sale off-farm. Some of the dairy farms grew arable crops for the market, but the area devoted to this was small (1 hectare, on average) with the maximum area devoted to tillage for sale across the sample totalling only 10 hectares. This would be typical for Irish dairy farms as milk production in Ireland is predominantly grass-based. Average farm stocking rate was 1.8 LU ha^{-1}, milk production on the portion of the farm devoted to dairying was 8,499 litres ha^{-1} and production per cow averaged 4,636 litres.

Table 1: Farm profile of specialist dairy farms in sample

Production Profile	Mean (standard deviation)	Range
Farm size (ha)	46.0 (25.6)	8 – 157.6
Grassland (ha)	45.0 (24.3)	8 – 147.0
Cereals or root crops (ha)	1 (1.9)	0 – 10.6
Total livestock units	82.4 (47.9)	13.8 – 265.2
Dairy livestock units	54.2 (30.3)	7.5 – 176
Other livestock units	28.2 (20.7)	1 – 127.2
Stocking rate (LU ha^{-1})	1.8 (0.5)	0.5 – 3.3
Milk (l ha^{-1})(land in milk production)	8,499 (3,064)	1,580 – 24,017
Milk (l cow^{-1})	4,636 (1,016)	1,950 – 8,621

3.0 Methodology

This study establishes farm gate N and P balances and use efficiencies based on the average of 2 years of Teagasc NFS FADN data in 2009 and 2010. Average farm gate nutrient balances were calculated by subtracting the total quantities of N and P exported from total quantities imported over the two-year period, dividing by two, and applying population weights to establish the weighted average. Farm gate nutrient use efficiencies were similarly calculated by dividing N and P exports by imports and expressing as a percentage.

3.1 Imports

The main imports that crossed the farm gate in this analysis were chemical fertilisers, concentrate feeds, forage feeds, milk replacer (for feeding calves) and purchased livestock. Chemical fertiliser composition and quantities purchased are recorded as part of the Teagasc NFS. It was assumed that purchased fertiliser was used on the farm during the year of purchase. Nitrogen and P imported in concentrate feeds were established from quantities of each feed type purchased and average N and P composition using standard values (Ewing, 2002). This approach was also adopted for other imported forage crops. A micro-level analysis of the NFS data indicates that a wide range of forage crops were imported onto these specialist dairy farms, such as silage, straw, cereals and root crops. These were converted to kg of N and P based on quantities imported and standard N and P contents (Ewing, 2002). Milk replacer is a calf nutrition product sometimes fed to calves on dairy farms as a substitute for raw milk. Milk replacer imported was converted to kg of N and P using standard N and P contents (Tikofsky et al., 2001). The majority of the dairy farmers in the survey didn't purchase livestock. Hence, the net effect (imports – exports) was presented under exports, as outlined below. It should be noted that imports did not account for atmospheric deposition, biological fixation or net soil mineralisation of N or P released from soil as these fluxes of N and P do not pass through the farm gate and are not as directly controlled by the farmer (Aarts, 2003).

3.2 Exports

Exports of N and P included milk, livestock, cereal crops, forage crops and wool as many farms had a smaller farming enterprise (beef, sheep, tillage) in conjunction with the dominant dairy enterprise. Nitrogen and P in milk based farm gate exports were calculated by applying standard co-efficients (Lenstrup, 1925; DePeters &. Ferguson. 1992) to quantities of milk solids sold. Net exports (imports - exports) of N and P through livestock (cattle and sheep) exiting the farm were established by estimating live-weights at sale (or death) and applying standard co-efficients by age and category of animals (ARC, 1994). Live weight at sale was established from the recorded sale price of the animal dividing by the prevailing prices (cent per kg) for the type and age of animal (Bord Bia, CSO, Eurostat). A minority of farms in the sample had a cereal crop or root crop enterprise where crop outputs were exported post harvest. The N and P content exported in the crop products were established by multiplying the quantities of each crop type sold by their respective standard co-efficient (Ewing, 2002). Finally, some farms had a sheep enterprise where wool was sold post shearing. The N and P export in wool was estimated from quantities sold and a co-efficient as estimated by Burns et al (Jarvis et al. 2002).

4.0 Results

4.1 Nitrogen balance and use efficiency

Chemical fertiliser was the dominant N import, accounting for 85% of total N imports (154.9 kg N ha^{-1}, on average), as outlined in Table 2. However, this ranged from 10.2 to 436.7 kg N ha^{-1}. Concentrate feedstuff accounted for the majority of the remaining N imports at 13% (23.1 kg N ha^{-1}, on average), with forage crops accounting for the remaining 2% of total N farm-gate imports. Total N imports averaged 181.8 kg N ha^{-1}. However, the range was substantial at 13.7 to 473.7 kg N ha^{-1}.

Milk was the primary N export through the farm gate from these specialist dairying systems, accounting for 74% (29.2 kg N ha^{-1}) of total N exports. The range was substantial at 4.2 to 62.7 kg N ha^{-1}. Net livestock exports (calculated from exports less imports) accounted for a further 24% of total farm N exports at 9.5 kg N ha^{-1}. Crops and wool exports accounted for less than 2% of total N exported through the farm gate.

When N exports were subtracted from N imports on these farms there was a positive N balance (i.e. N surplus) in all cases. The weighted average farm gate N surplus for this nationally representative sample of specialist dairy farms was 143.4 kg N ha^{-1}. Sixty one per cent of farms had a farm-gate N balance below 150 kg N ha^{-1}. Average farm gate nitrogen use efficiency was 23.2%. For those dairy farms operating under a Nitrates Derogation, the average N surplus was higher at 181.8 kg N ha^{-1} and average N use efficiency was slightly lower at 22.2%.

Table 2: Nitrogen imports, exports, balance and use efficiency on specialist dairy farms.

Nitrogen imports (kg ha^{-1})	**Mean**	**Standard Deviation**	**Range**	**% of total imports**
Chemical fertiliser	**154.9**	60.7	10.2 - 436.7	85
Concentrate feedstuffs	**23.1**	12.9	2.6- 98.82	13
Forage feeds	**4.8**	8.6	0 - 52.5	2
Milk replacer	**0.003**	0.01	0 - 0.2	0
Total imports	**182.8**	68.1	13.7 - 473.7	100
Nitrogen exports (kg ha^{-1})	**Mean**	**Standard Deviation**	**Range**	**% of total outputs**
Milk	**29.2**	11.1	4.0 - 62.7	74
Livestock	**9.5**	4.8	-3.6 - 26.1	24
Crop	**0.7**	3.7	0 – 32.0	2
Wool	**0.01**	0.06	0 – 0.7	0

Total N exports	**39.4**	13.1	8.1 – 75.52	100
N Surplus (kg ha^{-1})	**143.4**	60.0	5.6 - 419.3	
N use efficiency (%)	**23.2**	8.2	5.3 – 59.3	

(N=195, populated weighted to 12,798)

Key relationships between variables are presented in the figures that follow. Figure 1 shows the strong positive relationship between N surplus and chemical N fertiliser imports (R^2=0.94). This shows that N surplus at farm-gate level tends to closely track chemical N import. A positive relationship was also found between importation of concentrate N and N balance, as outlined in Figure 2, but this relationship was not as strong (R^2=22) as for chemical fertiliser N.

Figure 1: The relationship between N balance (surplus) and imports of chemical N (kg ha^{-1}) for 195 dairy farms (averaged over two years)

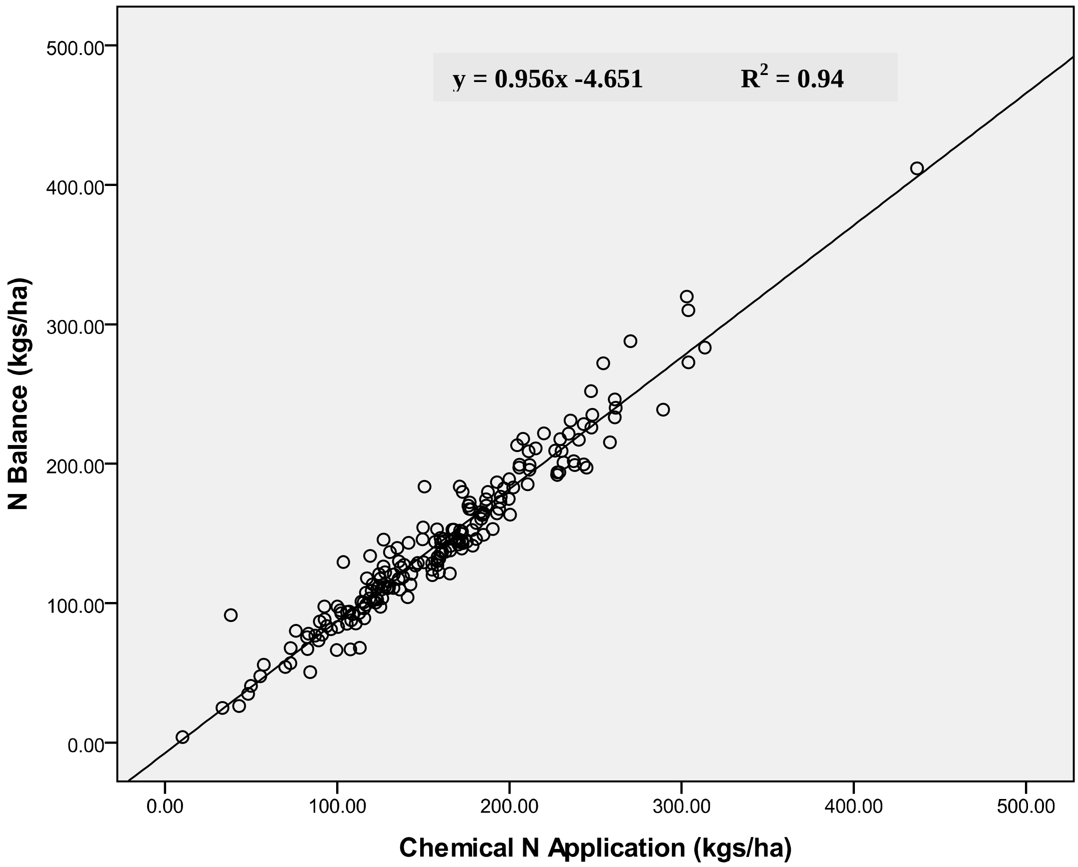
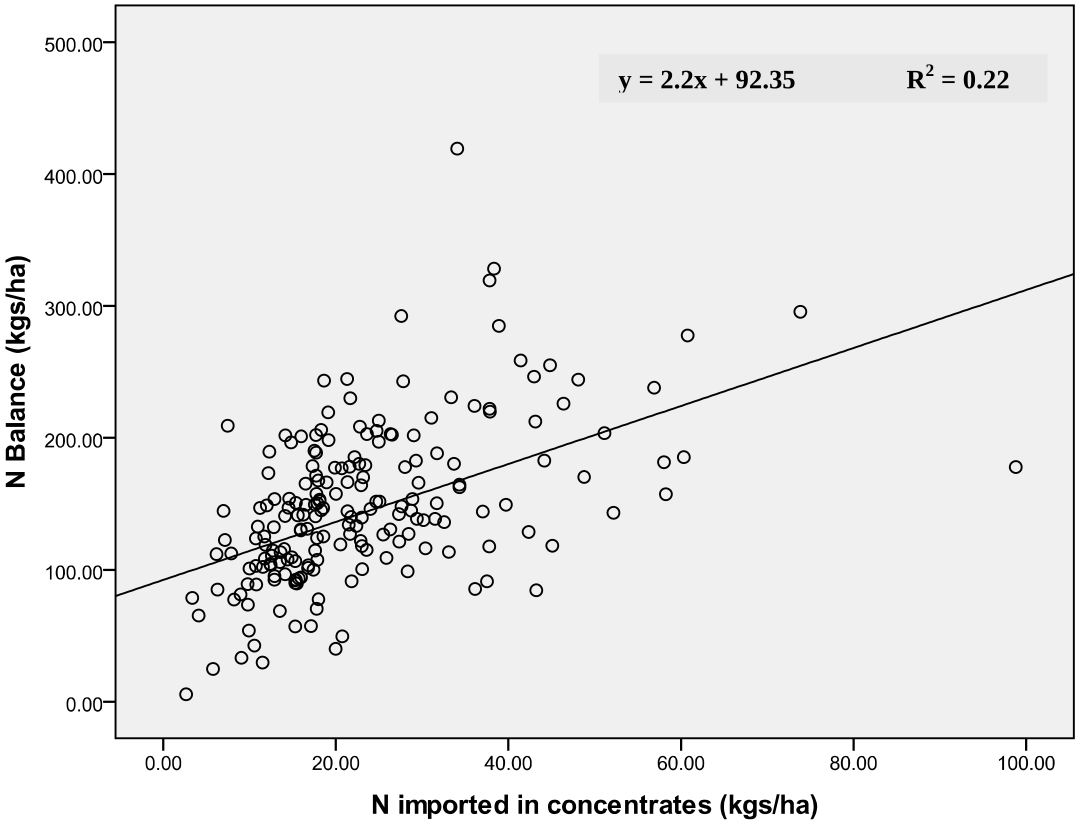


Figure 2: The relationship between N balance (surplus) and imports of N in concentrates (kg ha^{-1}) for 195 dairy farms (averaged over two years).



A positive relationship (R^2 =0.45) was found between N surplus (kg ha^{-1}) and total milk production (l ha^{-1}) as illustrated by Figures 3. A positive relationship was also found between N surplus and stocking rate (R^2=0.37) as shown in Figure 4.

Figure 3: The relationship between N balance (surplus) (kg ha^{-1}) and total milk production (l ha^{-1}) for 195 dairy farms (averaged over two years)

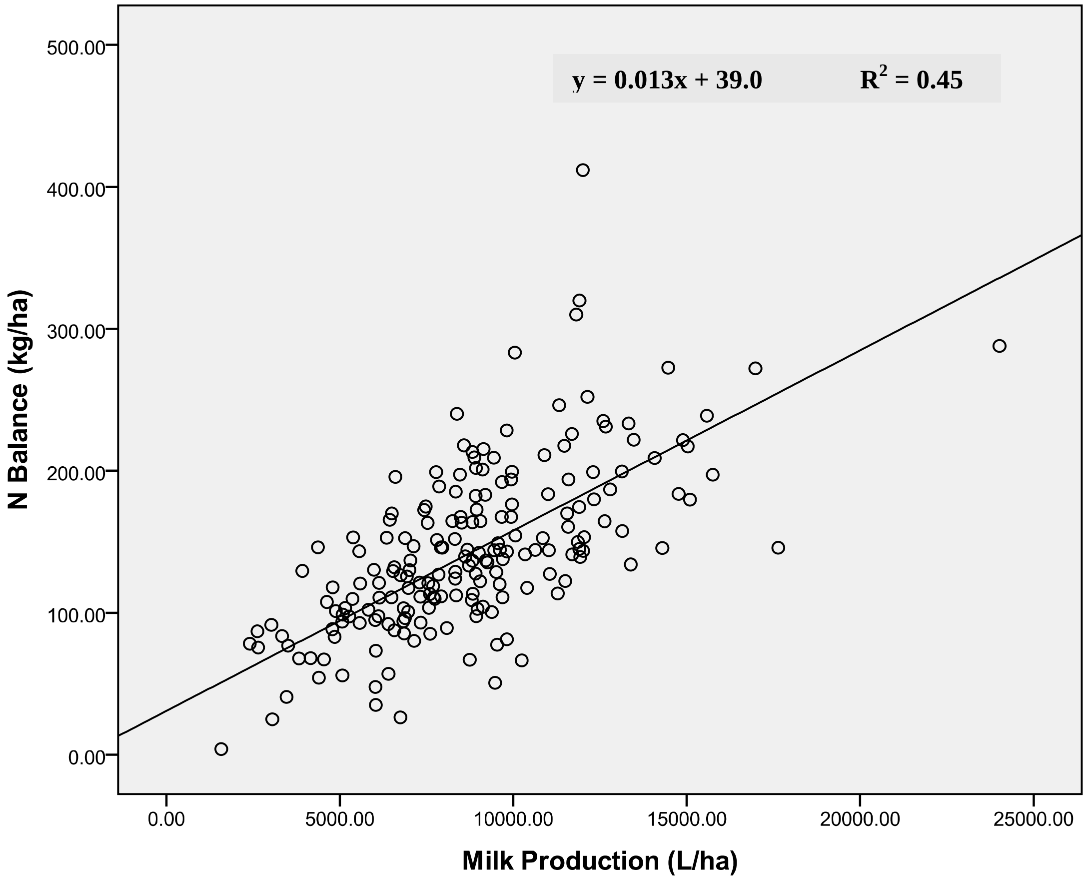


Figure 4: The relationship between N balance (surplus) and farm stocking rate (LU's ha^{-1}) for 195 dairy farms (averaged over two years).

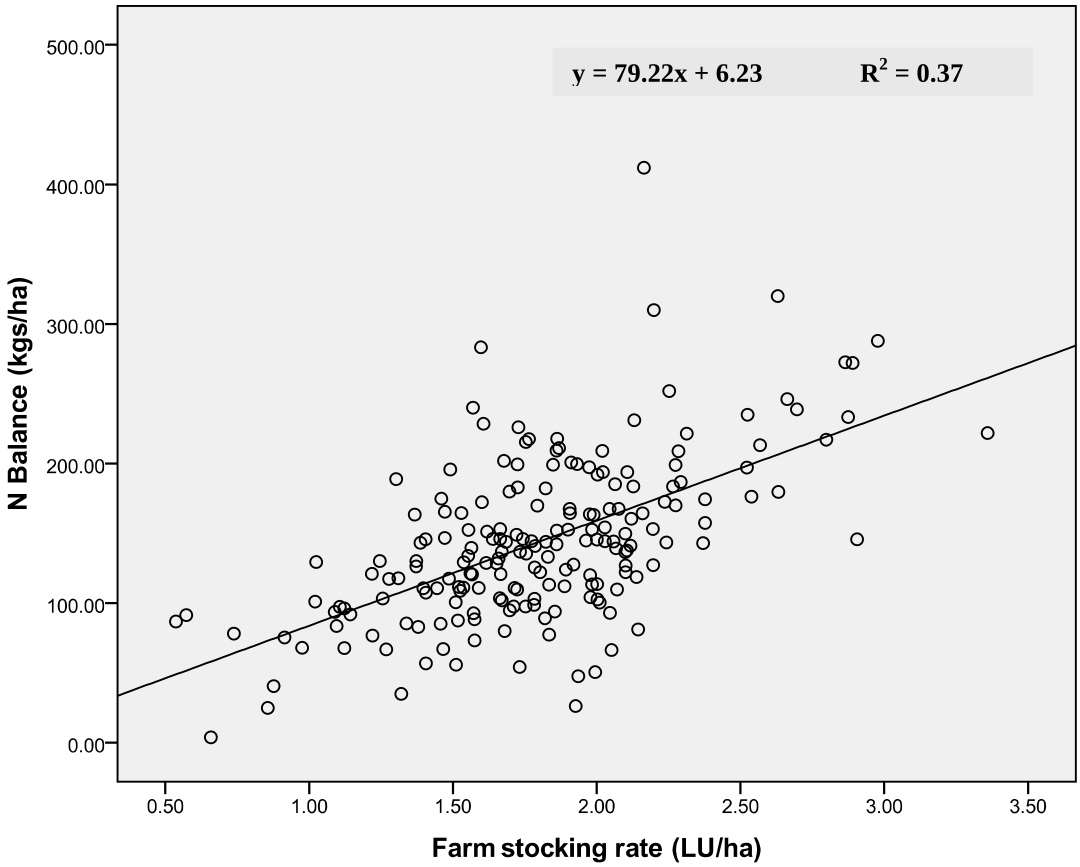
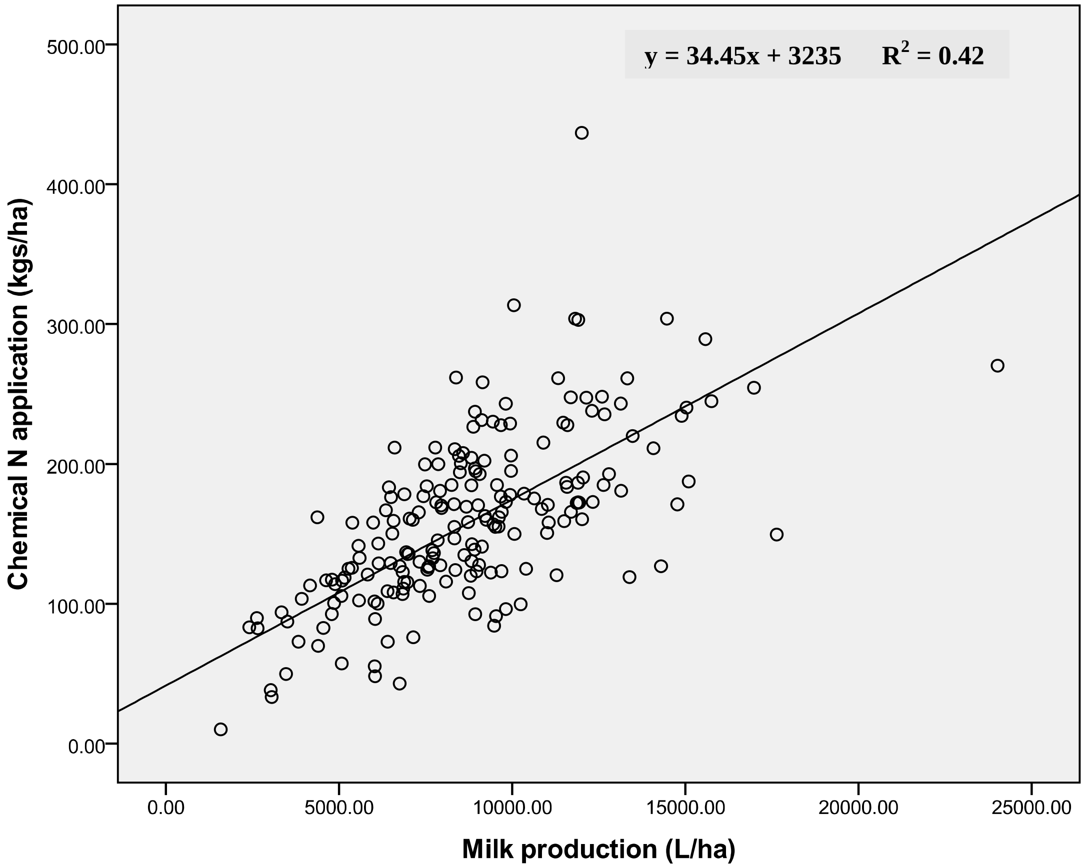


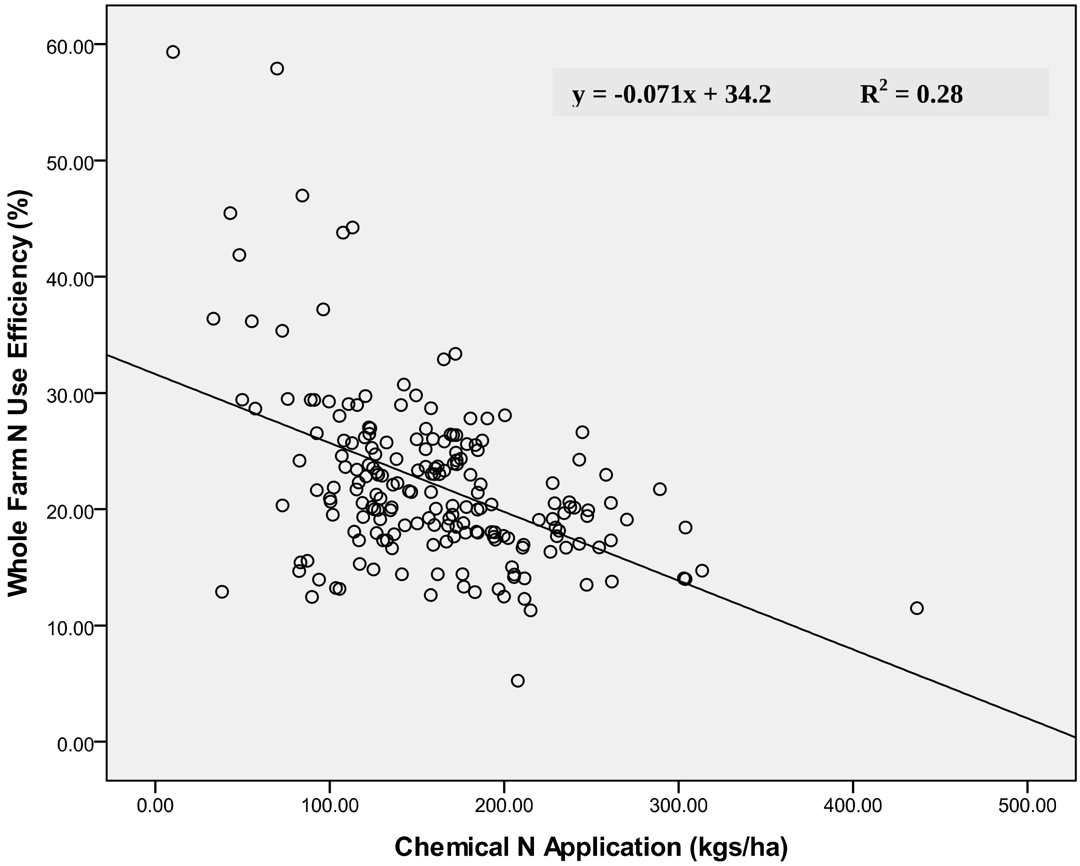
Figure 5 illustrates the relationship between milk production and chemical fertilizer N import. The result closely mirrors that of Figure 1, suggesting that chemical fertiliser application rates to milk output is a key relationship in determining N balances across specialist dairy systems in the Republic of Ireland.

Figure 5: Relationship between chemical N fertiliser imports (kgs ha^{-1}) and total milk production (L ha^{-1}) for 195 dairy farms (averaged over two years)



Nitrogen use efficiency was negatively related to chemical N fertiliser application (kgs ha^{-1}) as illustrated in Figure 6 below (R^2=0.24). A negative but non-statistically significant relationship was found between N use efficiency and imported feeds, milk production and stocking rate.

Figure 6: Relationship between N use efficiency (%) and imports of chemical N fertiliser (kg ha^{-1}) for 195 dairy farms (averaged over two years).



4.2 Phosphorus balance and use efficiency

Total farm gate P imports averaged 13 kg ha^{-1}, ranging from 2.0 – 33.1 kg ha^{-1}. In total, 52% of farm gate P imports were derived from chemical fertiliser (6.7 kg ha^{-1}) and 42% from concentrate feeds (5.5 kg ha^{-1}). A further 6% was accounted for by imported forage crops (0.8 kg ha^{-1}).

Milk was the main source of P export from farms, averaging 63% of total P exports (5.6 kg ha^{-1}). Livestock was the other main output, accounting for 35% of total P exports (13 kg ha^{-1}). Cereal and forage crops were responsible for the remaining 2% of P output, at 0.2 kg ha^{-1}. The total average farm gate P balance was 4.1 kg ha^{-1} in surplus, and P use efficiency averaged 83.9%. P balance ranged from -7.3 to 23.0 kg ha^{-1}. A total of 27% had a negative P balance. Ten per cent of farms didn't purchase chemical P fertilisers in the years studied. The average P surplus for farms with a

Nitrates Derogation was below the average of all farms at 3.5 kg P ha^{-1} and average P use efficiency for these Derogation farms was above the average of all farms at 90%.

Table 3: Phosphorus imports, exports, balance and use efficiency for 195 specialist dairy farms.

Phosphorus imports (kg ha^{-1})	Mean	Standard Deviation	Range	% of total inputs
Chemical fertiliser	**6.7**	5.5	0 - 25.5	52
Concentrate feedstuffs	**5.5**	3.1	0.3 – 19.2	42
Forage feeds	**0.8**	1.6	0 – 9.3	6
Milk replacer	**0.0**	0.0	0.0	0
Total imports	**13.0**	6.5	2.0 – 33.1	100
Phosphorus exports (kg ha^{-1})	**Mean**	**Standard Deviation**	**Range**	**% of total outputs**
Milk	**5.6**	2.2	0.8 – 14.7	63
Livestock	**3.1**	1.6	-1.2 – 9	35
Cereal & forage crops	**0.2**	0.8	0 – 6.6	2
Wool	**0.0**	0.0	0.0	0
Total exports	**8.9**	2.9	2.2 – 19.7	100
P Balance (kg ha^{-1})	**4.1**	6.2	-7.3 – 23.0	
P use efficiency (%)	**83.9**	47.2	16.5 – 247.8	

(N=195, populated weighted to 12,798)

Results indicated a strong linear relationship between P balance and inputs of chemical P fertiliser as illustrated by Figure 7 (R^2=0.72). There was a positive relationship between P balance and P imported in concentrates but the strength of the relationship was not statistically strong (R^2=0.05). However, there was no statistical relationship found between P balance (kg ha^{-1}) and stocking density or milk production (litres ha^{-1}) across the sample.

Figure 7: Relationship between P balance and imports of chemical P fertiliser (kg ha^{-1}) for 195 dairy farms (averaged over two years).

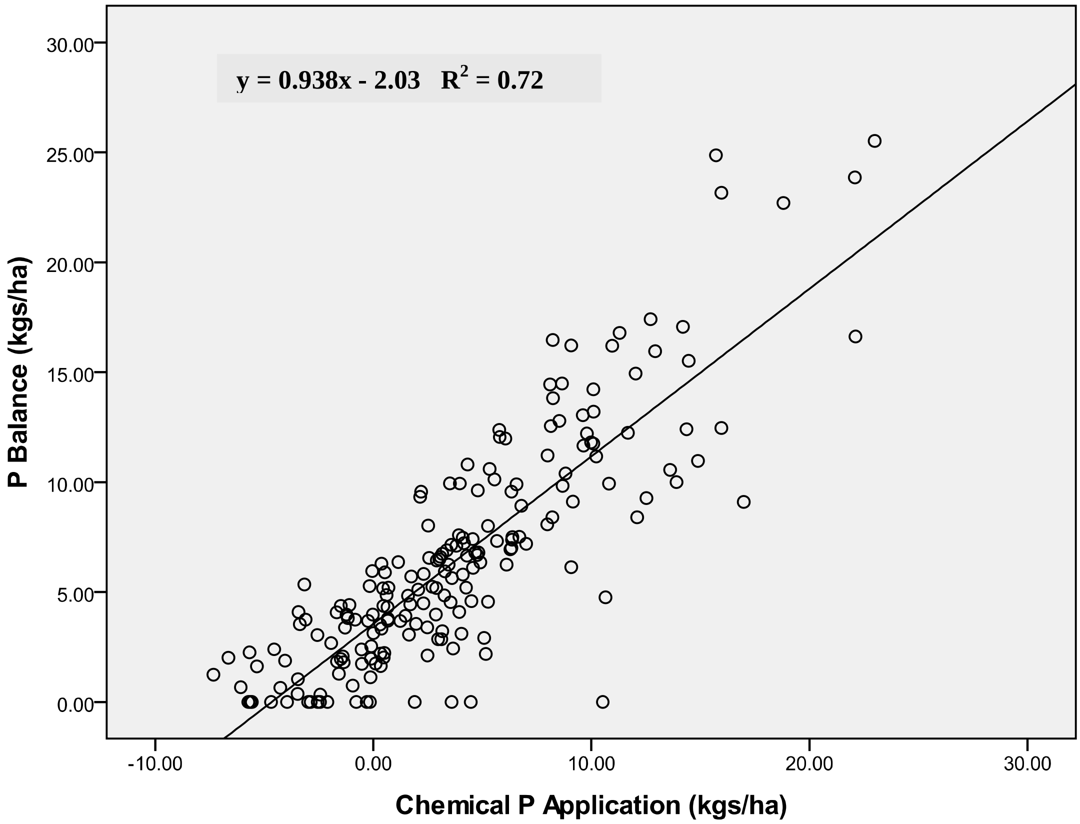
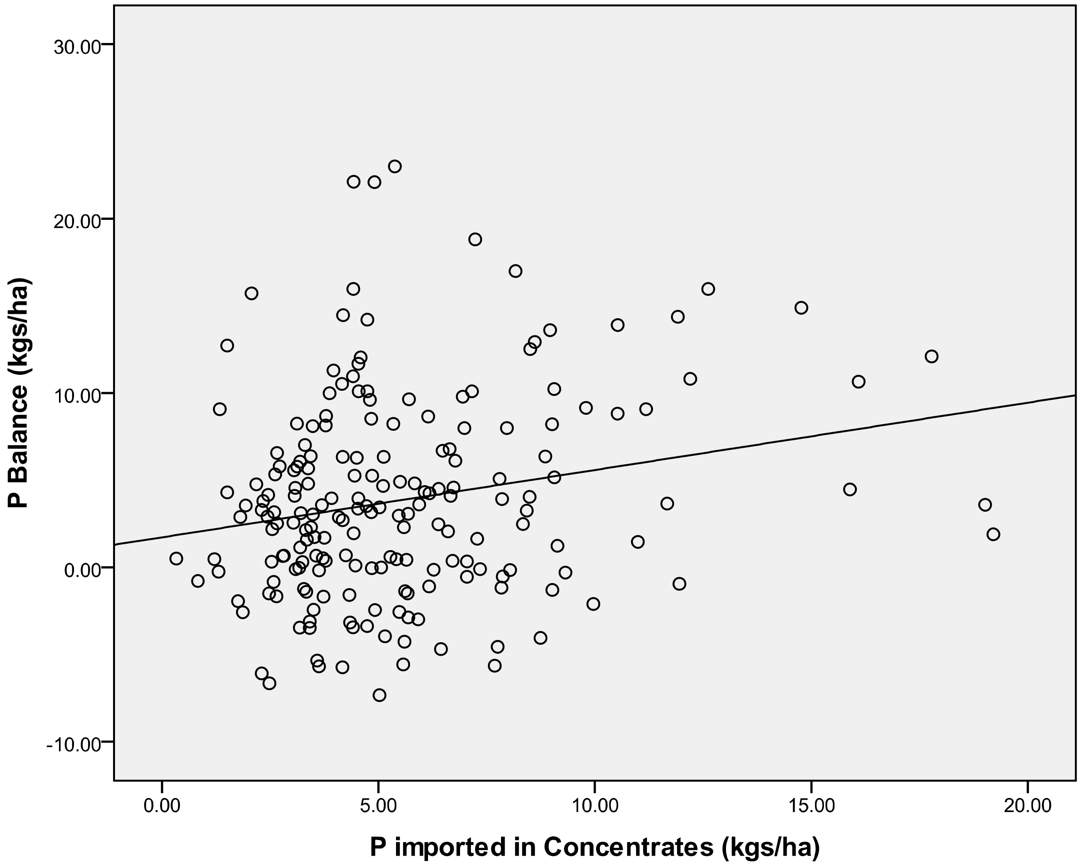
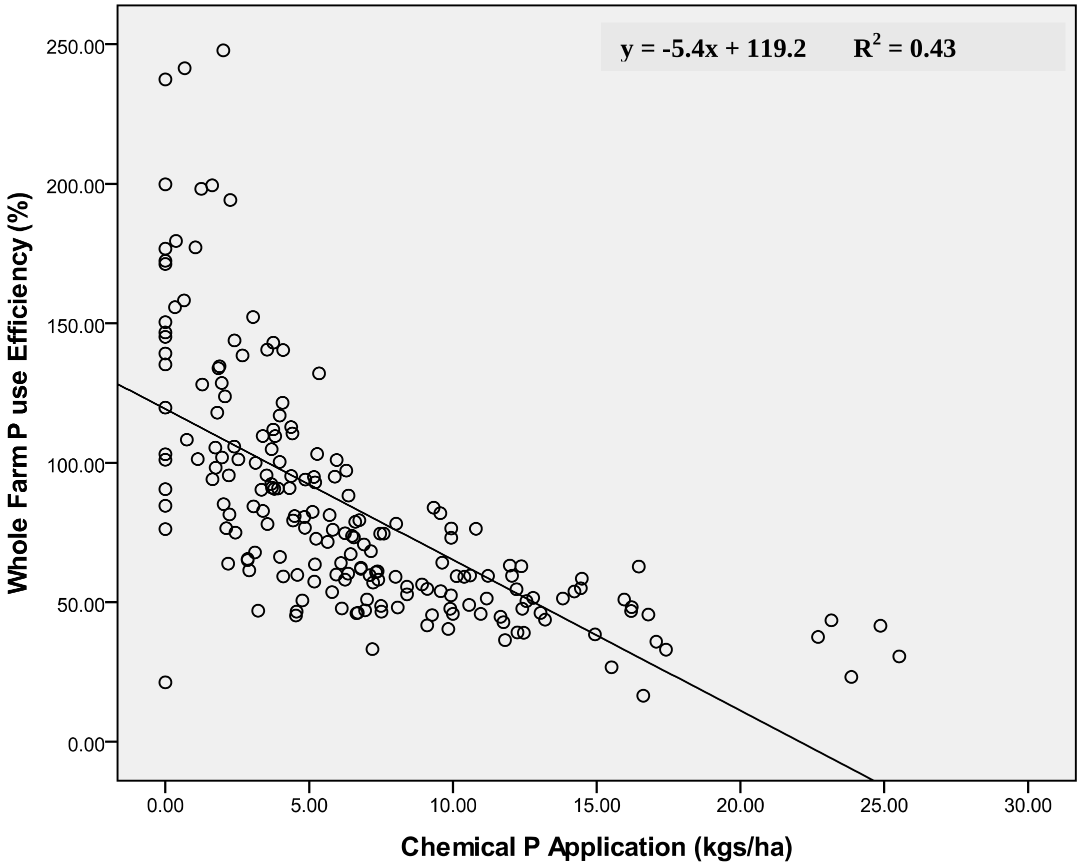


Figure 7: Relationship between P balance and imports of P in concentrates (kg ha^{-1}) for 195 dairy farms (averaged over two years).



Phosphorus use efficiency was negatively related with imports of chemical P as outlined in figure 8 (R^2=0.43). Phosphorus use efficiency was also positively related to imported concentrate feedstuffs, imported forage crops, stocking rate and milk production (L ha^{-1}) but the strength of the relationship was low (R^2>0.05).

Figure 6: Relationship between P use efficiency (%) and imports of chemical P (kg ha^{-1}) for 195 dairy farms (averaged over two years)



5.0 Conclusions and Discussion

5.1 Nitrogen Balance and Use Efficiency

The average farm-gate N surplus from this study (143 kg N ha^{-1}) was relatively low and the average NUE (23.2%) was within the lower range in comparison to internationally reported values for dairy farms. Additionally, farm-gate N surpluses for farmers operating under a Nitrates Derogation (181.8 kg N ha^{-1}) were also generally below international averages. For example, Nevens et al. (2006), also using data from the FADN network, found an average farm-gate N surplus (excluding biological N fixation and deposition) on Flemish specialized dairy farms of 184 kg N ha^{-1} in 2001 and a N use efficiency of 26.7%. Oenema et al. (2012), also using FADN data, estimated a national average N surplus for specialist dairy farms in the Netherlands of 210 kg N ha^{-1} in 2009. Nielsen and Kristensen (2005) reported an average surplus (excluding biological N fixation and deposition) of 134 kg N ha^{-1} for 25 conventional dairy farms in Denmark that were progressive and cooperating with advisors. Raison et al. (2006), in a study across 9 EU Atlantic regions and 139 pilot farms, found regional average N surpluses of between 79 and 502 kg N ha^{-1} (excluding N attributed to biological fixation), with only 3 regions (Scotland, Brittany & Pays de la Loire) having an average N surplus lower than that found in this study. Notably, these three regions also operate dairy systems with an important component of grazed grass in the diet. Nitrogen use efficiencies from that study ranged between 19 and 44%. Roberts et al. (2007) reported N surpluses of 259 to 785 kg N ha^{-1} on nine British dairy farms, with NUEs of 10-23%, while Cherry et al. (2012) reported average surpluses of 208 to 222 kg N ha^{-1} for five British commercial dairy farms.

On grassland-based commercial dairy farms in the Netherlands, Groot et al. (2006) found average initial N surpluses of 219 to 366 kg N ha^{-1}, for different farm groups, but that these were reduced to 148 to 182 kg N ha^{-1}over six years of participation in a nutrient management project. Oenema et al. (2012), reported an average surplus of 191 kg N ha^{-1} and a NUE of 24% for 16 grassland-based Dutch dairy farms participating in a project to improve management. Beukes et al. (2012) reported an average farm-gate N surplus (including estimates of biological fixation and atmospheric deposition) of around 150 kg N ha^{-1} for 247 commercial dairy farms with grazed grass-based production systems in New Zealand, with a range of 70 to 400 kg N ha^{-1}. Gourley et al. (2012) reported N balances (including estimates of biological fixation and atmospheric deposition) ranging from 47 to 601 kg N ha^{-1}, with a median value of 193 kg N ha^{-1}, across 41 commercial dairy farms in Australia with a year-round grass grazing production system. Nitrogen use efficiency in that study ranged from 14 to 50%, with a median value of 25%.

In contrast, high input/high output production systems with none or a lower component of grazed grass in the diet tend to have much higher N surpluses. The large proportion of total N inputs accounted for by N fertiliser (85%) in this study reflects the grass based system of dairy production which pre-dominates in the Republic of Ireland. These milk production systems require large quantities of N fertiliser to produce grass for the cow and, in contrast to the systems in many other developed countries, where large proportions of the feed for the cows is imported onto the farm (maize and grass silage, alfalfa, and concentrates) reducing quantities of N fertiliser imported to the farm and increasing quantities imported in feed. The higher surplus European regions in Raison et al. (2006) were those with minimal or no grazing and a greater component of maize and imported feeds in the diet. Ledgard et al. (1997) compared "average" surpluses (including N fixation) of 131 kg N ha^{-1} for New Zealand grazed-grass-based dairy farms to 270 kg N ha^{-1} for dairy farms in southwest England and 487 kg N ha^{-1} in the Netherlands, the difference being mostly due to higher rates of fertiliser and feed input in the English and Dutch systems, despite having similar stocking rates. Fangueiro (2008) reported average N surpluses (excluding atmospheric deposition) of 393-493, 528-566 and 572-728 kg N ha^{-1} for medium, intense and very intense case study dairy farms, respectively, across north-west Portugal for 2003-2005, and NUEs of 22-34, 28-33 and 28-42%, respectively. These farms operated a zero-grazing production system with a large component of maize and concentrates in the diet.

It is notable that the average N surplus of the Irish dairy farms is much lower than values reported internationally for commercial dairy farms operating higher input/higher output systems which are less grass-based, but is also low in the range of values reported for grass-based production systems. For example, the average of 139 kg N ha^{-1} was lower than the 148 to 182 kg N ha^{-1} reported by Groot et al. (2006) for Dutch grassland-based farms participating in a nutrient management project, despite the fact that the farms included in the Irish survey were nationally representative and were not selected on the basis of participation in any projects. This is likely due to the emphasis placed on optimising grazed grass in the diet and fertiliser N use and minimising feed imports in Ireland and the climatic and soil characteristics (long grass growth and grazing season) which make Ireland well suited to such a management system.

In addition to the grazed-grass low-input system of production, the relatively low N surpluses may also due to the introduction of the Good Agricultural Practice (GAP) Regulations in 2006, advisory efforts focusing on nutrient management, and increased fertilizer N prices. These can all have been expected to lead to more prudent use of N fertilisers. Indeed, national N fertiliser use on grassland between 2003 and 2008 decreased by 24% (Wall *et al.* 2012). The farm-gate N surplus found in this study of 139 kg N ha^{-1} is considerably lower, and the N use efficiency of 24% is considerable higher, than those found in earlier, and smaller scale, studies of intensive Irish dairy farms. Treacy et al. (2008) reported average N surpluses of 232 to 277 kg N ha^{-1} and N use efficiencies of 18 to 20 % from 2003 to 2006 on 21 commercial dairy farms. Mounsey et al. (1998) reported a mean N surplus of 304 kg N ha^{-1} on 12 intensive commercial dairy farms. Dillon and Delaby (2009), citing McCarthy *et al.* (2007), reported a N surplus of 226 kg N ha^{-1} and a N use efficiency of 29% from a Teagasc research farm over the period 2001-2005.

These other studies were carried out prior to the introduction of the EU Nitrates Regulations (SI 610 of 2010) in 2006 and, while these studies were not directly comparable and nationally representative, this result would suggest that N surplus on Irish dairy farms has decreased. Results presented by Mihailescu *et al.* (In prep) for 21 intensive commercial Irish dairy farms in 2009-2011, some of which were also involved in the pre-Regulations study of Treacy *et al*. (2006), would be consistent with this in that Mihailescu *et al.* (In prep) found a mean surplus of 160 kg N ha^{-1}, compared to 232 to 277 kg N ha^{-1} in Treacy *et al*. (2006). The Nitrate Regulations introduced a maximum allowable available N fertilisation rate for grassland, as well as other measures to improve N use efficiency, and this result would suggest that they have been effective in decreasing N surpluses on dairy farms.

The considerable range in N surplus (S.D. 59; range 6 - 419 kg N ha^{-1}) and NUE (S.D. 8, range 5 – 59 %) implies considerable potential for further improvements in NUE and N balances on Irish dairy farms. The relative importance of fertiliser N as a component of N imports (85%) and the close relationship between fertiliser N use and N surplus (Figure 1) indicate that efforts to improve the efficiency of use of available N resources within the farm system and minimise fertiliser N imports will be critical to improving N balances and NUE on Irish dairy farms. At the same time, the large range in chemical fertilizer N use for a given milk production per hectare (Figure 5), indicates their maybe significant potential to decrease fertiliser N use while maintaining or increasing milk production per hectare as found by Buckley and Carney (2013). Due to the very close relationship between fertiliser N use and N surplus (Figure 1), we might expect this to improve N balances. However, this will be dependent on prevailing environmental conditions.

At present, Ireland is subject to the EU milk quota regime where production is constrained. With milk quota abolition due in 2015, the expectation is that there will be an intensification of milk production. Indeed, the national strategy for Ireland is to increase milk production by 50% by 2020 (Department of Agriculture, Fisheries and Food 2010). Achieving this intensification in an environmentally sustainable fashion presents a significant policy challenge. It is expected that some of this increase in production will be achieved by intensification of existing dairy farms, while some will be achieved by conversion of new dairy farms. Farm profile data from this research indicates that specialist dairy farms have significant non-dairy livestock units. Some of the intensification (increased milk output per ha) on existing dairy farms is likely to be through substitution of more profitable dairy cows for less profitable livestock units. Some is also likely to be through increased stocking rates and increased milk production per cow.

Results from this study and elsewhere (Nevens 2006; Gourley, 2012) suggest that higher stocking rates and milk production per ha are associated with higher N surpluses at the farm scale (Figure 3 and 4) with consequential risk of adverse impacts to the wider aquatic environment and for gaseous N losses. However, it is important to note that milk production per ha and stocking rate only explained 45% and 37%, respectively, of the variability in N surplus in this survey (Figure 3), indicating that N balance (environmental pressure) need not necessarily increase with stocking rate and milk production per ha. There would appear to be significant potential for improving N balance while maintaining or increasing stocking rates and/or milk production per ha on Irish dairy farms. Much of the remaining variability may be explained by differing management practices, farm facilities, structures and environmental factors such as soils and weather. Some of the potential strategies to improve N use efficiency on Irish dairy farms would include optimisation of application of available nitrogen (timing, rate, form, method of application), enhanced use of clover, improved grazing management and grass utilization and better slurry and soiled water management.

Nitrogen use efficiency was not as closely associated with fertiliser N input as was N surplus (Figures 1 and 6). Gourley et al. (2012) also found that high N surpluses were generally associated with high milk production per ha and high imports of fertilizer and feed but that NUE was variable, irrespective of milk production per ha. The weak nature of this relationship suggests that many Irish dairy farms would have significant potential to improve NUE at the same level of N fertiliser input. The negative relationship suggests that NUE does tend to decrease on dairy farms as fertiliser N use increases but this relationship is weak ($r^2 = 0.28$). Therefore, many farms may have potential to increase stocking rate, fertiliser N input and milk output per ha without decreasing NUE, or even while increasing NUE. The reason the relationship is so weak, and that no significant relationship was found with imported feeds, milk production or stocking rate, is probably because most of NUE is being determined by farmer practice, farm facilities and structure and environmental factors. These results highlight the importance of good nutrient management practices and the potential for improvements on Irish dairy farms.

Hristov et al. (2006) also found high N surpluses but also high NUE for zero-grazing, predominantly maize forage production system in Idaho, USA. Raison et al. (2006) also showed that low grazing, high feed systems can have quite high NUEs but also very high N surpluses. NUE in these high input/high output dairy production systems are probably high because they are less susceptible to losses associated with the grazed-grass production model, such as those associated with fertilizer application, grass uptake of N, utilization by grazing cows etc. However, N surplus in these systems is often much higher, placing much higher pressure on the environment, in terms of water quality, ammonia emissions and GHG emissions. In addition, the environmental impact of the feed grown off-farm but imported into these systems and the manures exported from these systems should also be accounted for, if a complete life cycle analysis approach is taken.

5.2 Phosphorus Balance and Use Efficiency

Average farm-gate P surplus in this study (4.1 kg P ha^{-1}) are also considerably lower than results from other international studies.. Raison et al (2006) reported average P surpluses of between 18 to 163 kg P ha^{-1} across 9 regions of Europe. Gourley et al (2012) reported a median value of 25.8 kg P ha^{-1} (a value of 0.1 kg P ha^{-1} was included for atmospheric deposition) in Australia with a range of a range from -7 to 133 kg ha^{-1}. Other Australian based research recorded broadly similar outcomes of 1 to 127 kg P ha^{-1} (Lawrie et al. 2004) and 3 to 200 kg P ha^{-1} (Ovens et al. 2008). Average values of 30.8 to 43.6 kg P ha^{-1} were reported by Fangueiro et al. (2008) for a sample of dairy farms in Portugal.

This trend was repeated in P use efficiency. Average farm-gate P use efficiency in this study was found to be nearly 84%, with a range of 16.5 to 247.8%. This was again significantly higher than results from Raison et al. (2006) who reported an average P use efficiency of 24 to 62%. The highest P use efficiency value is that study (62%) was reported for farms in southern Ireland. Gourley et al (2012) reported a median P use efficiency of 26% with a range of 6-158%. Results from Fangueiro et al. (2008) suggest average P use efficiency of between 53-68%.

Although the majority of the studies reported above were not based on a nationally representative sample, the findings in this study suggest that specialist dairy production system across the Republic of Ireland have one of the lowest P surplus and highest P use efficiencies reported internationally. Strict limits apply to overall quantities of P that can be imported onto farms across the Republic of Ireland under the Nitrate Regulations (SI 610 of 2010), implementing the EU Nitrates Directive. Under these regulations, soil P status is determined and allowable limits of P import are established based on P requirement to achieve and maintain soil fertility and supply the crop. This allowable limit of P import can be filled either through imported feeds or chemical fertilisers. There is evidence to suggest that farmers have responded to these regulations, since their introduction in 2006, and to rising and increasingly unstable chemical fertiliser prices (CSO, 2012) by reducing P fertilizer use. National P fertilizer use decreased from 62,410 tonnes in 1995 to 26,350 in 2008 (Lalor et al., 2010). The average price of P in synthetic fertilizer doubled between 2005 and 2008 (CSO, 2009). Between the price of chemical fertilisers and regulatory restriction there were strong incentives for farmers to optimize P application rates.

Results here indicate a cohort of dairy farmers are mining soil stores of P as 27% of the sample (population weighted) had a negative P balance. No data was available on the soil P status of these farms. However, excessive historical P applications could have resulted in soil P increasing beyond agronomic requirements (Mekken et al. 2006; Gourley et al. 2007; Wall 2012). Phosphorus, unlike N, can be strongly stored and immobilised by soils and can remain stored in the soil over long periods of time, being variously available to plants. Periodic soil testing can inform P management and it was interesting to note that farmer dairy farmers who farm at a stocking rate of between 170 and 250 kg (20% of this sample) organic N ha^{-1} are subject to a derogation under Ireland's EU Nitrates regulations and are required to submit an annual nutrient management plan underpinned by a soil test to secure this derogation. Interestingly, the average P surplus for farms with a Nitrates Derogation was below the average of all farms at 3.5 kg P ha^{-}1**,** suggesting these farms are more tightly managing P resources.

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