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Developing the EU Farm Accountancy Data Network to derive indicators around the sustainable use of nitrogen and phosphorus at farm level.

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Abstract

This study uses a national farm survey which is part of the European Union (EU) Farm Accountancy Data Network (FADN) to develop environmental sustainability indicators in the use of nitrogen (N) and phosphorus (P) across a range of farm systems in the Republic of Ireland. Farm level micro data were used to calculate all inputs and outputs of N and P that cross the farm gate and to derive balances (kg ha^{-1}) and overall use efficiencies across 827 farms in 2012. The sample is populated weighted to represents 71,480 farms nationally. Results indicated an average N balance of 71.0 kg ha^{-1} and use efficiency of 36.7% across the nationally representative sample. Nitrogen balances were between two and four times higher across specialist dairy farms compared to livestock rearing and specialist tillage systems. Nitrogen use efficiency was generally lowest across milk producing systems compared to livestock rearing and tillage systems. Phosphorus balance and use efficiency averaged 4.7 kg ha^{-1} and 79.6% respectively across the sample. Specialist tillage and dairying farms had higher average P balances compared to other livestock based systems. The approach developed in this analysis will form the benchmark for temporal analysis across these indicators for future nutrient balance and efficiency trends and could assist other members of the EU FADN to develop similar nationally representative indicators.

Keywords: Farm gate balance, Nitrogen, Phosphorus, use efficiency, sustainability indicators, water quality.

1.0 Introduction

Producing sufficient food to feed a growing global population while complying with environmental legislation is a significant policy challenge for the agricultural industry and policymakers in general (Sutton et al. 2011). The agricultural sector has come under pressure to improve environmental performance while maintaining economic efficiency and competitiveness in a global marketplace (Jay 2007). This is especially true where member states are bound by the European Union (EU) Water Framework Directive (WFD) which sets a target for all surface water to achieve good status by 2015 or subsequent cycles. Historic over-application of chemical nitrogen (N) and phosphorus (P) fertilisers in agricultural production has in some instances lead to losses of these nutrients to groundwaters and surface water bodies, with a detrimental effect on water quality (Oenema et al. 1998; Aarts et al. 2000; Kersebaum et al. 2003; Sutton et al. 2011). According to the European Environment Agency (2012), despite some progress, diffuse pollution from agriculture is still significant in over 40% of Europe's rivers and coastal waters, and in over 30% of lakes and transitional waters.

The EU Nitrates Directive (ND), now under the umbrella of the WFD, was introduced to minimise surplus N (and P in some member states) from being applied on farms in order to reduce the associated N (and P) losses from agriculture to water bodies (Wall et al. 2011). At the same time, rising and volatile livestock feed and fertiliser prices have combined with 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, policymakers, consumers, Non-Governmental Organisations) 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 also providing an indicator of environmental pressure on water quality, all other things being equal. These accounting systems measure nutrient inputs onto a farm, mainly through imported feedstuffs and fertilisers, and subtract 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). The underlying assumption is that lower balances and increasing efficiencies will result in a lower burden of environmental risk (Ghebremichael and Watzin 2011; Huhtanen et al. 2011). 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 (Schroder et al. 2003). The links between nutrient surplus at farm, field and soil surface level and loss to the aquatic environment and atmosphere are complex and can be difficult to predict, depending on factors such as soils, hydrology, weather, farm structures and management practices (Jordan et al. 2012). However, farm gate balances can be considered a useful indicator in assessing agronomic efficiency and environmental pressure (Aarts et al. 1999; Schroder et al. 2004) and, critically, farm gate balances highlight the nutrient imports, exports and management practices most directly under the farmers control. This study uses the Teagasc National Farm Survey (NFS) in the Republic of Ireland, which is part of the EU Farm Accountancy Data Network (FADN) to derived N and P balances and use efficiencies across a range of farm systems. The EU FADN aims to gather accountancy data from farms across the EU for the determination of incomes and business analysis of agricultural holdings. The annual sample covers approximately 80,000 farm holdings, representing a population of about 5 million farms across the EU.

This sample is representative of approximately 90% of the total utilised agricultural area of the EU and accounts for about 90% of the total agricultural production. The information collected generally includes physical and structural data, such as location, crop areas, livestock numbers, labour force as well as economic and financial data. This includes value of production of the different crops, stocks, sales and purchases, production costs, assets, liabilities, production quotas and subsidies, including those connected with the application of Common Agricultural Policy (CAP) measures (EU Commission 2013a). Increasingly, the EU FADN is being analysed to generate sustainability indicators (Hennessy et al. 2013a). Nevens et al. (2006), for example, previously used the FADN network in Belgium to examine N balances across specialist dairy farms in Flanders. Dalgaard et al. (2006) modelled a range of area-based environmental indicators including N and P farm gate balances across a range of farm systems using data from the FADN for Denmark. The OECD and the EU Commission (EU Commission 2012a, b; OECD 2014) have previously generated N and P balance and use indicators on a whole country basis. In the past it has been highlighted that within the FADN some important content data necessary for balance calculation is not available. For example, fertiliser purchases tended to be recorded in monetary terms and not disaggregated into different units such as N, P and K (Poppe and Meeusen 2000; European Environmental Agency 2005; Dalgaard et al. 2006). Hence, approaches using the FADN to-date tended to rely on modelling or imputing some elements of the inputs or outputs data necessary (Dalgaard et al. 2006; Nevens et al. 2006). This current study develops both N and P based environmental sustainability indicators at a sectorial level using observed volume based data from the NFS in the Republic of Ireland. Expansion of the FADN to include the collection of all necessary volume based data to estimate N and P balances would allow cross country EU comparisons as well as an analysis of temporal trends in these indicators. In this context, the objectives of this paper is to firstly outline the micro level methodological approach to developing N and P based environmental sustainability indicators and secondly to examine results of the derived N and P based indicators across a range of farm systems in the context of benchmarking and potential environmental risk.

2.0 Methodology

2.1 Data

The Teagasc (the Irish Agriculture and Food Development Authority) NFS is collected annually as part of the EU FADN requirements in the Republic of Ireland; the data employed in this analysis is for 2012. A random, nationally representative sample is selected in conjunction with the Central Statistics Office (CSO) to fulfil Ireland's statutory obligation to provide data on farm output, costs and income to the European Commission. Each farm is assigned a weighting factor so that the results of the survey are representative of the national population of farms (Hennessy et al. 2013b). Detailed farm accounts and enterprise level transactions are recorded on a random representative sample of farms throughout Ireland by professional recorders. Farmers who indicated importing or exporting organic manures were excluded from the analysis as no data were available on the quantities of manures imported or exported[1]. The final data set included for this analysis consisted of 827 farms weighted to be representative of 71,480 farms nationally. Results are reported by farm systems. Farms are assigned to six farm systems on the basis of farm gross output, as calculated on a standard output basis. Standard output measures are applied to each animal and crop output on the farm and only farms with a standard output of €8,000 or more (the equivalent of six dairy cows, six hectares of wheat or 14 suckler cows, are included in the sample). Farms are then classified as one of the six farm systems on the basis of the main outputs of the farm. Farms falling into the pigs and poultry system are not included in the survey, due to the inability to obtain a representative sample of these systems (Hennessy et al. 2013b). Farm systems adopted in this analysis can be categorised as Specialist Dairying (dominant enterprise is specialist milk production), Cattle Rearing (specialist cattle rearing and fattening where greater than or equal to 50% of the standard output is from suckler cows), Cattle Other (specialist cattle rearing and fattening where less than 50% of the standard output is from suckler cows), Sheep (dominant enterprise is sheep; either specialist sheep or sheep and cattle combined), Tillage (dominant enterprise is cereals or root crops), Mixed Livestock (some combination of grazing livestock (dairy, cattle, sheep) or a grazing livestock combined with a crop enterprise; dairying tends to be the main livestock enterprise). System titles refer to the dominant, but not exclusive, enterprise in each group. In this context it should be noted that the farm gate balances presented here are for the whole-farm and not just for the dominant enterprise. A lot of Irish farms tend to operate with at least one other enterprise in addition to the main enterprise, hence balances in this analysis take account of all inputs and outputs related to milk, livestock and cereal production on a farm level basis. The profile of the sample is outlined in Table 1.

[1] In line with results from Hennessy et al. (2011) a total of 5% of total sample were importing or exporting organic manures. Hence, no determination can be made on the nutrient use efficiency of these farms

Table 1: Profile of farms contained in the analysis

	Specialist Dairying	Cattle Rearing	Cattle Other	Specialist Sheep	Specialist Tillage	Mixed Livestock	Total
Farm Size (ha^{-1})	54.5	35.7	43.5	48.4	58.0	62.8	46.3
Grassland pasture area (ha^{-1})	50.8	32.7	39.8	45.0	22.9	57.4	40.8
Tillage area (ha^{-1})	2.2	0.1	1.3	0.7	32.1	2.7	3.0
Livestock units ha^{-1}	1.9	1.1	1.3	1.4	0.6	1.7	1.4
Sample size	242	139	202	109	57	78	827
Weighted to population	14,771	16,776	21,284	11,864	4,385	2,399	71,480

2.2 Indicator development

Two indicators are derived in this study. Farm gate balances are an indicator of pressure on environmental quality and are calculated by subtracting the total quantities of N or P (kg ha^{-1}) exported from the total quantities imported. The second indicator, nutrient use efficiency is calculated by dividing total N or P exported (kg) by total imported (kg), expressed as a percentage. Both indicators require a full audit of imported and exported nutrients across the farm gate to be established. The methodological approach to calculation of N and P imported and exported is outlined below.

2.2.1 Imports

The imports that crossed the farm gate in this analysis were chemical fertilisers, concentrate feeds, forage feeds, milk replacer (for feeding calves) and purchased livestock. Each import is converted to N and P mass (kg) as outlined below:

Chemical fertilisers - Data on the composition (N, P,K) and quantities of chemical fertiliser purchased (as well as opening and closing stocks) are collected by the Teagasc NFS. This allows kg of N and P chemical fertiliser applied to land to be calculated directly.

Concentrate feedstuffs - Data on the quantity of concentrates purchased across the sample is collected. This is converted to kg of N and P by using standard values for concentrates (Ewing 2002). It was assumed that purchased feedstuffs were used during the year of purchase as would tend to be the case.

Forage feeds - A micro-level analysis of the NFS data indicates that a wide range of forage based crops were purchased onto farms in the sample including silage, straw, cereals and root crops. Data is collected on the quantity (tonnes) of each forage crop imported and these were converted to kg of N and P based on standard values for each crop (Ewing 2002). Only purchased quantities of forage feeds actually fed to livestock in 2012 were included in the analysis, this was established from quantity purchased less closing inventory of the relevant crop. Additionally, crops grown on farm in 2011 but fed to livestock in 2012 were treated as imported forage feeds and kg of N and P were derived based on standard values and quantities fed (Ewing 2002). This analysis was possible as the Teagasc NFS tracks whether opening and closing inventories are sold or fed to livestock.

Livestock - Where possible the NFS collects data on the liveweight of animals purchased onto the farm. This liveweight was used to calculate N and P imported by applying standard coefficients to kg of liveweight purchased (ARC 1994; McDonald et al. 1995). Where actual liveweight at purchase was not available this was then estimated based on the purchase price of the animal dividing by the prevailing prices (cent per kg) for the type and age of animal (Bia 2012; CSO 2012). Relevant N and P coefficients where then applied (ARC 1994; McDonald et al. 1995).

Other imports - This comprises milk replacer which is a calf nutrition product sometimes fed to calves as a substitute for raw milk. The Teagasc NFS collects data on quantities of milk replacer purchased which was converted to kg of N and P using standard values (Tikofsky et al. 2001). It was not possible to track imports of N and P contained in veterinary products, seeds and crop sprays but this is not expected to have a major effect on the overall outcome of the analysis.

2.2.2 Exports

The principle exports of N and P across the farm-gate were through milk, livestock, cereal crops, forage crops and wool. Each export is converted to kg of N and P and the methodological approach is outlined below:

Milk - The Teagasc NFS collects data on both litres of milk sold as well as kg of milk solids (protein and butterfat). Kilogrammes of nitrogen exported through milk was calculated by applying standard coefficients (ARC 1994) to kg of milk protein sold. Kilogrammes of P exported in milk was estimated from litres of milk sold and application of a standard value for P content (McDonald et al. 1995).

Livestock - Where possible, the NFS collects data on live or carcass weight of animals at point of sale. Where carcass weight is returned this was converted back to liveweight using standard coefficients (Teagasc 2014). This liveweight was used to calculate N and P exported through livestock sold by applying standard coefficients (ARC 1994; McDonald et al. 1995). Where neither liveweight nor carcass weight at sale were available liveweight was estimated based on the sale price of the animal dividing by the prevailing prices (cent per kg) for the type of animal sold based on age category (Bia 2012; CSO 2012). Relevant N and P coefficients were then applied (ARC 1994; McDonald et al. 1995).

Crops - The Teagasc NFS collects data on yields from cereals or root crops grown. These crops were sold, fed to livestock or remained as closing inventory at the end of the year. If crops were not fed or sold then they appeared as closing inventory and this was treated as an export as these crops are either sold or fed to livestock in the following year (and, therefore, do not contribute to the farm balance for the year in question). Kilogrammes of N and P in crops exported were estimated from quantities of each crop exported (sold + closing inventory) and their respective standard coefficients for N and P (Ewing 2002).

Wool - The Teagasc NFS collects data on kilogrammes of wool sold for farms with a sheep enterprise. The N and P exported in wool were estimated from quantities sold in kg and a coefficient (Jarvis et al. 2002).

3.0 Results

Mean N and P balances kg ha^{-1} is reported in this section. However, for nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) the mean and median values are reported. This approach was adopted as very extensive farmers (mainly livestock) with minimal inputs and relatively low outputs can skew mean nutrient use efficiency results.

3.1 Nitrogen balance and use efficiencies

Due to the mainly grass based system of production, chemical N fertiliser was the principle N import across all livestock systems as well as the specialist tillage system, accounting for, on average 82% of all N imports across all farm systems (Table 2). This highlights the importance of adhering to best management practices when applying chemical N fertiliser in terms of improving overall farm-level N balances and NUE. Concentrates were the next largest import accounting for nearly 13% of total N imports across all systems. This ranged from only 3% for specialist tillage to 8–17% for livestock systems, indicating that improved feed management will also play a role in improving N balances in such systems. It is also worth noting that a high proportion of imported feed N [approximately 80% for beef cattle (Yan et al. 2007)] will be excreted by the animals, and where animals are housed a proportion of this will be captured as manure and managed as organic N fertilizer. The dominant export varied by farm system depending on the dominant enterprise. For specialist dairying and mixed livestock systems, milk accounted for 78 and 56% of total N exports respectively. Livestock were the primary N based exports for cattle rearing (99%), cattle other (90%) and specialist sheep (79%) systems, while crops accounted for 88%of total N exports from specialist tillage systems.

The highest N exports were indicated by specialist tillage systems (64.4 kg ha^{-1}), largely due to high crop N exports, followed by specialist dairying (42.3 kg ha^{-1}), largely due to milk N exports. These were also two of the systems with the highest N imports and this highlights the need to improve efficiency of converting N imports to N outputs in crops and milk to improve N balances and NUE in these intensive production systems. The average N balance across all farm systems was 71.0 kg ha^{-1} and the mean and median NUE was 36.7 and 23.3% respectively. However, there was a considerable range across the farming systems. As might be expected due to their higher N inputs, N balance was highest and NUE was generally lowest for milk producing systems. Specialist dairying systems had an average N balance of 145.5 kg ha^{-1} and a NUE of 24.6%, followed by 105.9 kg ha^{-1} and 25.1% for mixed livestock systems (which tend to have a significant dairy enterprise). Due to nutrient loading these dairying systems might be expected to exert a greater source pressure for N loss to water and the atmosphere and associated environmental impacts, further highlighting the importance of improving the efficiency of conversion of imported N to exported N in milk in these systems.

The cattle rearing system (48.3 kg ha^{-1}) and cattle other system (55.9 kg ha^{-1}) had much lower N balances than the dairying based systems. Similarly, Bassanino et al. (2007) found that suckler cow systems had lower surpluses than dairy systems in Italy (even accounting for atmospheric disposition and biological fixation). Despite the additional N export in milk from milk-producing systems, the greater import of fertiliser and feed N to support the higher stocking rates associated with these systems leads to greater N surpluses. This highlights the close link between stocking rate and nutrient source pressure on environmental quality in livestock-based production systems (Gourley et al. 2012). However, it should be noted that nutrient source pressure does not necessarily equate directly to nutrient losses to water or air, however, as this will be dependent on a range of management and biophysical factors (Jordan et al. 2012). Specialist sheep systems had the lowest balance of 38.2 kg ha^{-1} and highest mean NUE of the livestock based systems at 67.1%. However, the median value was significantly lower at 28.5%. Some specialist sheep farmers are utilizing mountainous pastures where fertilizer is generally not applied and this may help explain the higher NUE and lower balance results. That said the mean and median values were higher than cattle rearing and cattle other systems. (Table 2). This indicates that specialist sheep production systems operate relatively efficiently with regard to N use and recovery and with a relatively low pressure on environmental quality, as expressed in N surplus. This is due to lower levels of fertilizer N input and relatively high livestock and wool exports and is likely also related to higher grass utilisation and greater feed conversion efficiencies (Lapierre and Lobley 2001) in sheep systems. Notably, cattle other systems had a higher NUE (34.3%) than the cattle rearing production system (26.5%), mostly due to relatively low fertilizer N imports and greater exports of N in livestock from these non suckler cow orientated systems. Median NUE of the cattle rearing system at 15.6% is significantly lower than all other systems indicating much lower N recovery from the pre-dominantly suckler cow based system. Suckler cow based cattle rearing systems tend to be more resource intensive as energy needs of a cow have to be met for calf rearing and this may explain difference between cattle systems. While much of this difference is doubtless due to inherent differences in the systems, finding management practices that could move N balances and NUE of this and the cattle other systems at least some of the way towards the sheep systems should be a research priority.

Specialist tillage systems also had a relatively low N balance of 52.5 kg ha^{-1} and a high NUE of 52.5%. This is despite their high inputs (116.9 kg ha^{-1}) and due to their high offtakes (64.4 kg ha-1), indicating a better matching of N supply to crop N requirement and more effective capture and export of N off-farm in crops. Schroder et al. (2003) also found similar differences between arable and livestock based systems using the Dutch MINAS model, with N surplus increasing from <100 kg ha^{-1} for fully arable systems to >200 kg ha^{-1} for fully livestock systems. This difference highlights the limitations for NUE in livestock production systems based on grazed grass where losses of N are inherent in the production processes in the conversion of grass and other feeds into animal product (Steinfeld et al. 2006).

Table 2: Mean N imports, exports, balance (kg N ha^{-1}) and use efficiency (%) by farm system

Farm system	Specialist Dairying	Mixed Livestock	Cattle Other	Cattle Rearing	Specialist Tillage	Specialist Sheep	All Systems
Imports (mean)							
N Fertiliser	155.8	111.6	54.7	47.5	107.5	38.6	76.8
N Concentrates	26.4	20.7	9.9	4.7	4.0	9.0	11.8
N Livestock Imports	0.5	1.3	5.4	1.0	3.3	2.8	2.7
N Forage Feeds	5.1	2.9	2.1	2.4	2.1	2.7	2.9
N Other Imports	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total N Imports	187.8	136.5	72.1	55.6	116.9	53.1	94.2
Exports (mean)							
N Milk Exports	32.9	17.0	0.0	0.0	0.0	0.0	7.3
N Livestock Exports	7.8	11.2	14.6	7.2	7.3	11.7	10.4
N Crops Exports	1.6	2.1	1.4	0.1	56.9	1.1	5.1
N Wool Exports	0.0	0.2	0.2	0.0	0.2	2.1	0.4
Total N Exports	42.3	30.6	16.2	7.3	64.4	14.9	23.2
N Balance (mean)	***145.5***	***105.9***	***55.9***	***48.3***	***52.5***	***38.2***	***71.0***
NUE (mean)	***24.6***	***25.1***	***34.3***	***26.5***	***51.9***	***67.1***	***36.7***
NUE (median)	***23.3***	***23.3***	***23.4***	***15.6***	***52.1***	***28.5***	***23.3***

While Table 2 presents averages, Figure 1 reports the distribution of N balances by farm system, illustrating the range of N balances across Irish production systems. The box range in the diagram represent the 25 and 75th percentile range and the black line in the boxplot represent the median. While some of the factors controlling N balance are beyond the control of the farmer, many are not, and this range illustrates the considerable potential to improve N balances across all production systems. In particular, N balances for dairying orientated systems (specialist dairying and mixed livestock) showed the largest range of N balances. This is important as these are the most intensive users of N inputs and are the highest stocked systems. Mean N balance results by system could not be analysed with standard ANOVA procedures as the normal distribution condition was not satisfied as indicated by a Kolmogorov–Smirnov test. The rank based nonparametric Kruskal–Wallis test was hence used to determine if there are differences in N balances across the different systems. Results indicate that the distributions of balances were statistically significantly different between groups (significant at the 1% level). Pairwise comparisons between the different systems was performed using Dunn’s (1964) procedure with a Bonferroni correction for multiple comparisons. Results indicate statistically significant difference across all groups except between the cattle rearing, cattle other and specialist tillage systems. Additionally, no statistically significant difference was indicated between the cattle other and the specialist sheep system.

Figure 1: N balance kg ha^{-1} by farm system

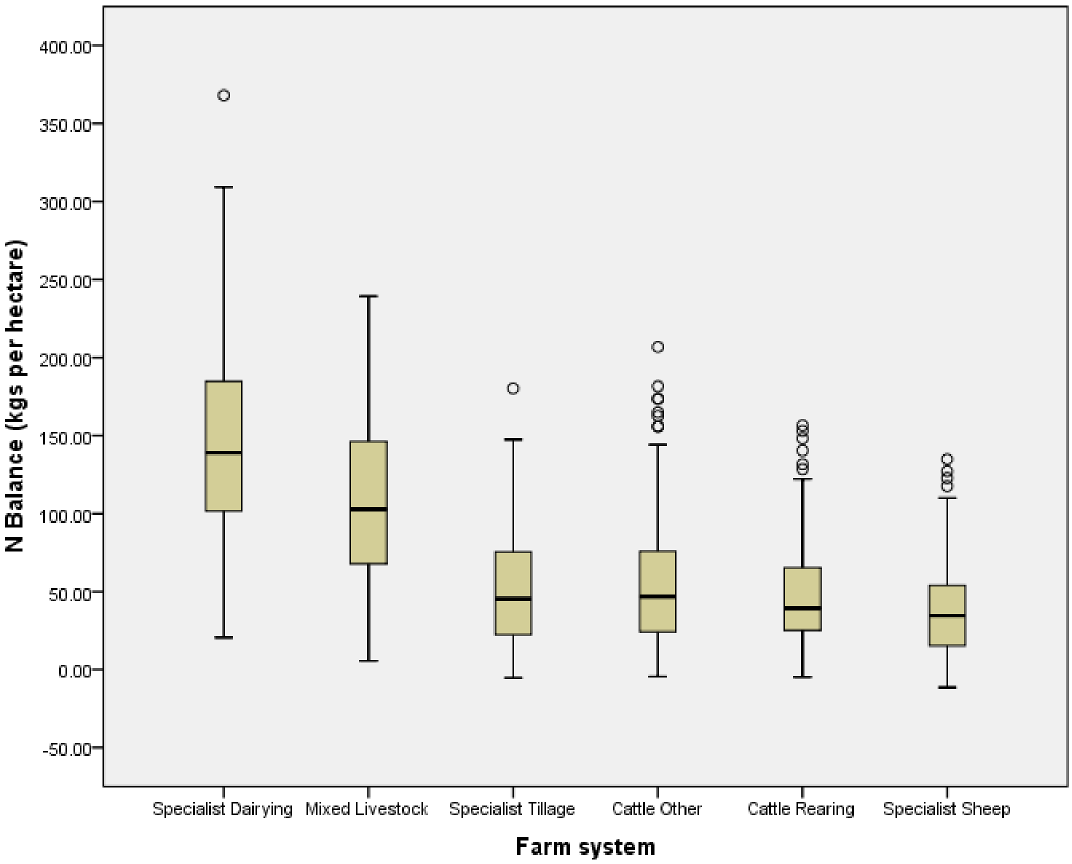
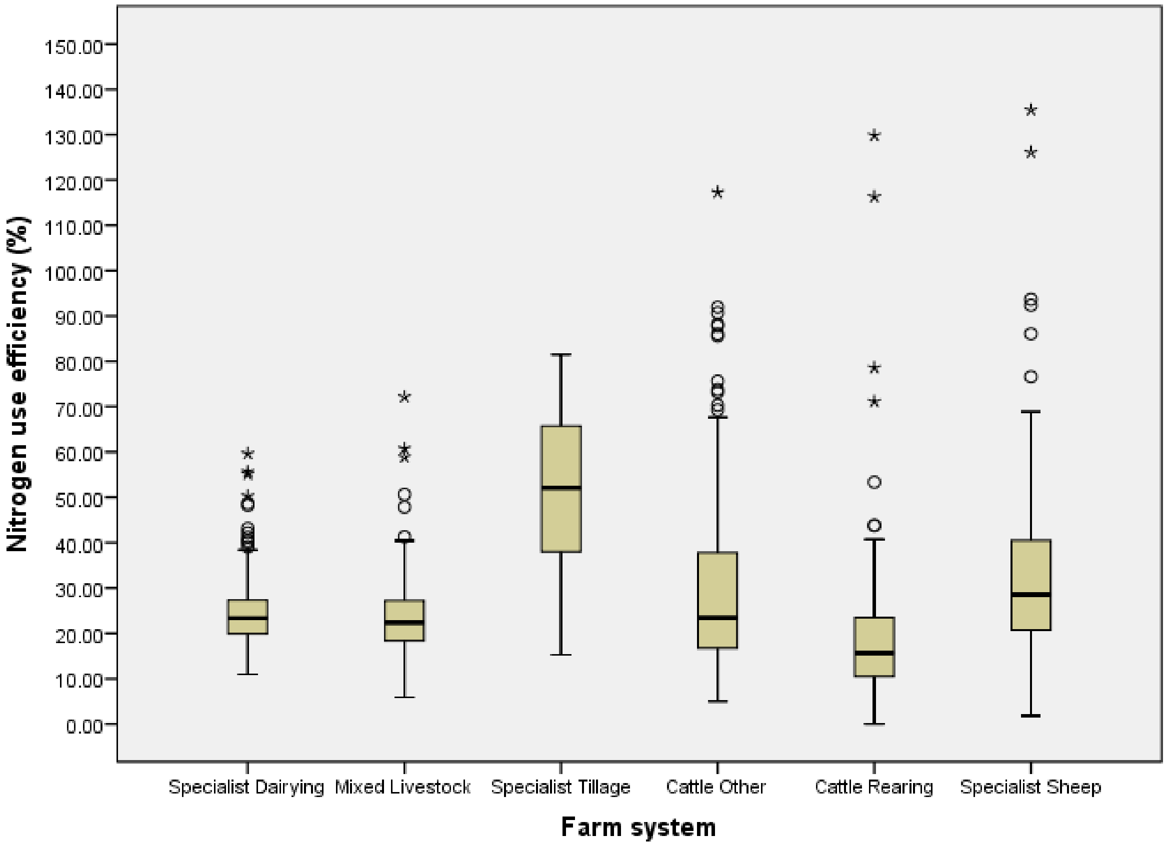


Figure 2 shows the distribution of nitrogen use efficiency by farm system. The dairying orientated systems (specialist dairying and mixed livestock) and cattle rearing suckler based system have a similar distribution around NUE. The cattle other and specialist sheep also tend to be similarly distributed while the largest distribution was recorded for specialist tillage systems. A Kruskal–Wallis test was used to determine if there are differences in nitrogen use efficiency across the different systems. Results again indicate that the distributions of NUE were statistically significantly different between systems (1% significance level). Pairwise comparisons between the different systems indicated that cattle rearing and specialist tillage systems was statistically significantly different from each other and to all other systems. Comparing Figs. 1 and 2, the systems can be generally grouped into three categories: (1) Low NUE but also low N imports and N balance (cattle rearing, cattle other and specialist sheep), (2) Low NUE and high N imports and balance (specialist dairying and mixed livestock), (3) High NUE and high N imports but low N balances (specialist tillage). Again, this categorisation reveals the importance of improving NUE and N balances in dairy production systems (category 2), in particular.

Figure 2: Nitrogen use efficiency by farm system.



3.2 Phosphorus

Chemical fertiliser was the largest category of P imports, accounting for 56% on average across all farm systems. However, this ranged from 86% for specialist tillage systems to 45% for specialist dairying. Indeed, specialist dairying was the only system where fertiliser was not the major P import as 48% of P imports were derived from concentrate feeds. Under the

EU ND as implemented in the Republic of Ireland, P imports are limited according to certain criteria[2]. Hence, limitations on fertiliser P import, after feed P import has been accounted for, may explain this, as specialist dairying had the highest concentrate and forage feed imports. Fertiliser P application, under the ND, is also limited by soil test P status, with a prohibition on P application to high P soils. This may also limit fertiliser P use on these farms due to historically high stocking rates, fertiliser P use and soil P status. The importance of feed P implies that, in dairying systems in particular, efforts to improve P balances and PUE should be focused on feed P management as well as fertilizer P management, and organic fertiliser P management, in particular. As with N, but to a greater degree, a proportion of the P fed to livestock will be captured in manures and slurries when animals are housed and will be managed as organic fertilisers. In specialist tillage systems, crops accounted for 80% of exports. In cattle based systems livestock accounted for 95–100% of exports, while, in specialist dairy systems, milk accounted for 62% of total exports. The farm gate P balance across all farm systems averaged 4.7 kg P ha^{-1} (Table 3). This is relatively low by international standards (Haygarth et al. 1998; Raison et al. 2006; Gourley et al. 2012). In contrast to N, P management accounts for soil pools of plant-available P and these soil pools can be used to supply the P required for crop growth. As a result, P deficits can be maintained, for a period of time at least, as can be seen in the negative P balance values in Figure 3. Fertiliser P use in Ireland has decreased in recent years, particularly on grazed grassland; by 63% between 2003 and 2008 (Wall et al. 2012). This is likely due to increased fertiliser P prices and restrictions under the ND. It may also be the case that P is given a lower priority than N in farm nutrient management. All these factors may help explain the fact that the P balances observed in this study were relatively low.

[2] A restriction on chemical P imports is primarily related to a soil P index system which is based on the measured concentration of available P in soil as determined by the Morgan's P test (Morgan 1941). Total allowable chemical P fertiliser application limits is hence based on soil P status and crop demand with reductions for any organic manure or concentrate feedstuff imported.

In contrast to N balances, specialist tillage systems had the highest average P balance at 6.3 kg P ha^{-1}, followed by specialist dairy and mixed livestock systems at 6.2 and 5.2 kg P ha^{-1} respectively. As with N, the lowest P balances were associated with cattle rearing and specialist sheep systems at 3.5 and 3.9 kg P ha^{-1} respectively. Again, this indicates the link between stocking rate and nutrient source pressure in livestock based systems.

Phosphorus use efficiency (PUE) averaged 79.6% across all farm systems. This is more than twice the efficiency of N use observed. Phosphorus use efficiency can be considerably higher than that of N (e.g. Gourley et al. 2012), in part, at least, due to the greater potential for loss of N to air and water at all stages of the production system. Specialist sheep had the highest mean PUE at 97.7%, however the median value for specialist sheep was the second lowest at 57.9%. A cohort of specialist sheep farmers are utilizing mountainous pastures where fertilizer is generally not applied and this may help explain this contrasting result.

Cattle other had the second highest PUE at 79.2%. Specialist dairying, mixed livestock, cattle rearing and specialist tillage systems averaged PUE's between circa 70–74%. Cattle rearing had the lowest median PUE at 46.1%, this was over 10 percentage points lower the next closest system. It is notable (in contrast to the situation with N) that while the dairying systems have the highest feed P imports, they do not have the highest fertiliser P imports, as they are considerably lower than the specialist tillage system. The relatively high PUE of dairying systems was associated with this relatively low fertiliser P import and relatively high P export due to milk and livestock exports.

Table 3: Mean P imports, exports, balance (kg ha^{-1}) and use efficiency (%) by farm system.

Farm system	Specialist Dairying	Mixed Livestock	Cattle Other	Cattle Rearing	Specialist Tillage	Specialist Sheep	Total
P Fertiliser	6.9	6.5	5.7	4.4	18.2	4.5	6.3
P Concentrates	7.3	5.7	2.7	1.3	1.1	2.5	3.3
P Forage Feeds	0.9	0.5	0.4	0.4	0.4	0.5	0.5
P Livestock Imports	0.2	0.5	2.2	0.4	1.4	1.1	1.1
P Other Imports	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total P Imports	15.3	13.2	11.0	6.5	21.1	8.6	11.2
P Milk Exports	5.6	2.9	0.0	0.0	0.0	0.0	1.2
P Livestock Exports	3.2	4.6	6.0	3.0	3.0	4.5	4.2
P Crops Exports	0.3	0.5	0.3	0.0	11.8	0.1	1.1
P Wool Exports	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Total P Exports	9.1	8.0	6.3	3.0	14.8	4.7	6.5
P Balance (mean)	***6.2***	***5.2***	***4.7***	***3.5***	***6.3***	***3.9***	***4.7***
PUE (mean)	***71.4***	***71.4***	***79.2***	***73.6***	***70.3***	***97.7***	***79.6***
PUE (median)	***66.8***	***58.3***	***56.8***	***46.1***	***62.1***	***57.1***	***57.4***

Figure 3 illustrates the distribution of P balances by farm system. Specialist dairying and tillage systems have the largest distribution. These are the systems with the highest P inputs and these results indicate the potential for improvement in P balances within these systems. Conversely cattle rearing and specialist sheep systems have the narrowest distribution. A Kruskal–Wallis test indicated a statistically significant difference in the distribution of P balances across the different systems (1% significance level). Pairwise comparisons between the different systems indicated a statistically significantly difference between the specialist tillage system and the three livestock based systems (cattle rearing, cattle other and specialist sheep). A statistically significant difference was also indicated between the specialist dairying and cattle rearing system.

Figure 3 indicates that there are a proportion of farms across all systems in negative P balance. Such scenarios indicate reliance on soil P reserves and are not sustainable indefinitely on a macro scale if productivity levels are to be maintained (EU Commission

2013b). That said, this situation maybe appropriate in critical source areas where the risk of P transfers from agricultural production to the aquatic environment is greatest are identified and adaptive management strategies are necessary to protect water quality (Heathwaite et al. 2005).

Figure 3: Distribution of P balance (kg ha^{-1}) by farm system.

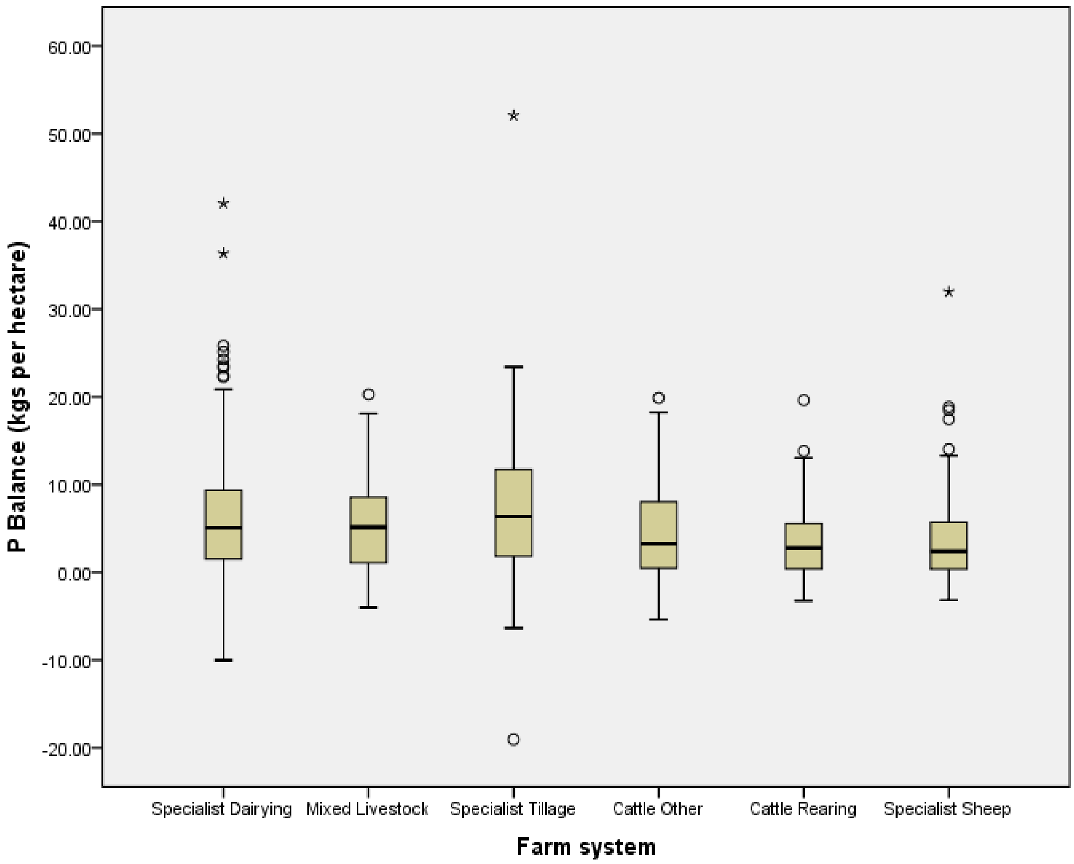
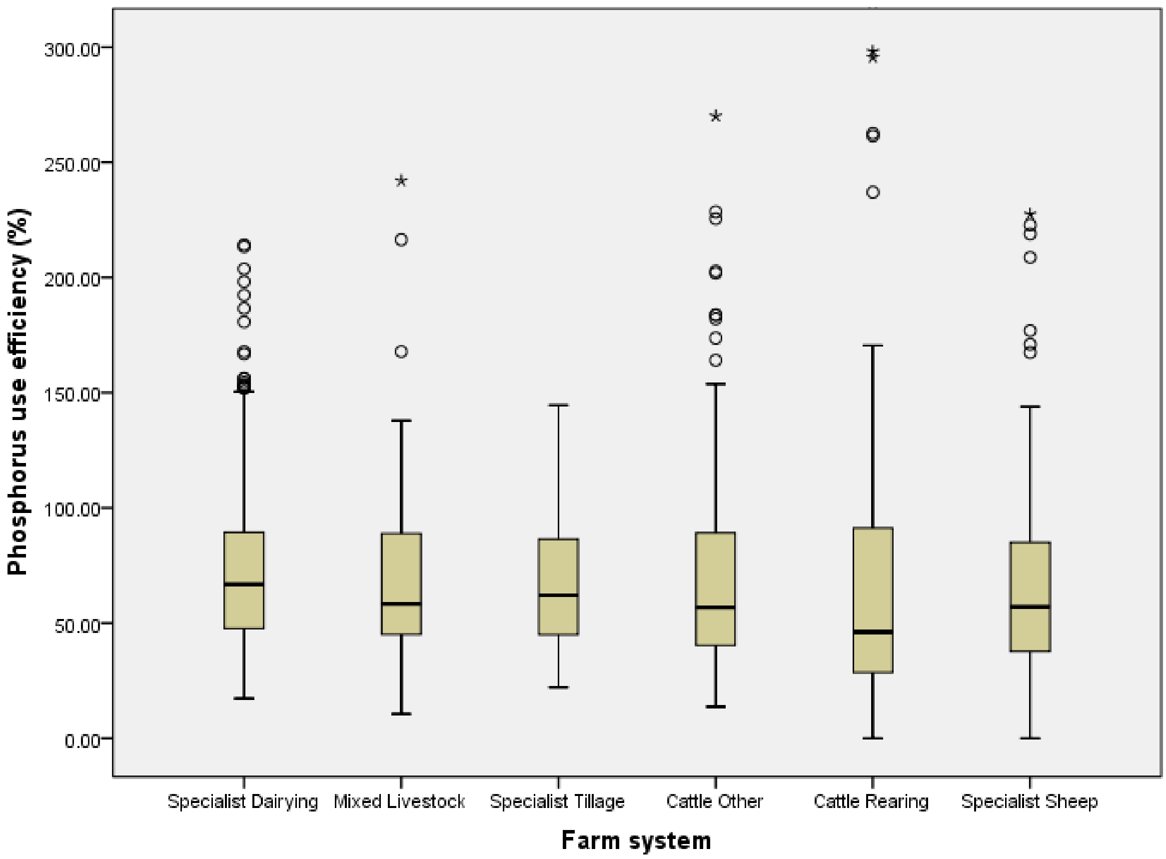


Figure 4 illustrates the distribution of PUE by farm system. In general, the distributions are broadly similar with cattle and sheep based systems showing somewhat of a wider distribution and the specialist tillage systems indicate a slightly tighter distribution. That said, a Kruskal–Wallis test indicated a statistically significant difference in the distribution of PUE across the different farm systems (1% significance level). However, pairwise comparisons between the different systems indicated statistically significantly differences only between the specialist dairying and the two cattle based systems (cattle rearing and cattle other).

Figure 4: Distribution of phosphorus use efficiency by farm system.



4.0 Discussion

It was possible to derive N and P balances and use efficiencies across a range of farm systems for the Republic of Ireland as the Teagasc NFS has been extended beyond normal EU FADN requirements to collect relevant data across the sample to allow for these indicators to be developed. The approach outlined here could assist other members of the EU FADN to develop similar nationally representative indicators. However, the regular schedule of data collection under the FADN would have to be extended to collect variables such as fertiliser and feed volumes, live weight sales and volume of milk solids sold. This issue has previously been highlighted as a constraint to using the FADN for nutrient balance and use efficiency calculation (Poppe and Meeusen 2000; European Environmental Agency 2005). Observed volume based data was used to derive indicators. There is however some limitations and areas for future development in the approach adopted.

It was not possible to establish imports of N and P contained in veterinary products, seeds and crop sprays as no volume based data was collected in this area. While not expected to have a major influence on the final outcome it will underestimate N and P inputs, more so for arable orientated farmers. Collection of volume based data in this area would improve the accuracy of results. Additionally, standard coefficients were applied to volume based data to estimate nutrient inputs/outputs. Future research could validate the accuracy of this approach and perhaps develop more country or region specific coefficient applicable to FADN based data. Farms importing or exporting organic manure were excluded from this analysis, collection of volume based data on organic manure imports and exports on these farms would enhance the sample and results from this analysis. These indicators are developed at the farm gate level. This doesn’t take account of symbiotic N fixation, atmospheric N deposition or changes in soil organic matter stocks and hence does not consider all inputs and outputs (Godinot et al. 2014). Gourley et al. (2012) argue that while farm-level N balance and NUE can greatly assist management decision, P balance and use efficiency is less useful unless combined with soil fertility levels to account for accumulation or depletion trends. Hence, the approach could be developed further if soil test results for sample farms could be incorporated into the analysis. In addition, the environmental impact of the feed grown off-farm but imported into these systems and the output value of manures exported from systems could be explored further in the context of developing the approach towards a full life cycle analysis (Gerber et al. 2014; Godinot et al. 2014).

There is no published work at a national scale to validate the results of this analysis across the six different farms systems. Most published work (nationally and internationally) tends to focus on dairying systems. In this context, although more intensive and for a different time period (2009–2011) recent Republic of Ireland based studies by Mihailescu et al. (2014, 2015) for 21 Irish dairy farms indicate N and P balances and use efficiencies broadly in line with results found in this study. Mihailescu et al. (2014) reported N balances of 175 kg N ha^{-1} and NUE of 23% compared to 145.5 kg N ha^{-1} and NUE of 24.6% for specialist dairying systems in this study. The P balances and use efficiencies in Mihailescu et al. (2015) were 5.09 kg P ha^{-1} and 70% respectively compared to 6.2 kg P ha^{-1} and 71.7% for specialist dairying systems here. Due to the lack of published results at a nationally representative level direct international comparisons are difficult. Comparison with smaller scale international studies suggest N and P balances in this study are relatively low, NUEs are quite typical and PUE are relatively high for the dairying systems in this study[3] (Aarts 2003; Groot et al. 2006;

[3] This holds when results from these studies are adjusted for N inputs through atmospheric deposition and nitrogen fixation.

Nevens et al. 2006; Raison et al. 2006; Bassanino et al. 2007; Cherry et al. 2012; Gourley et al. 2012).

Results indicate N balances are lower and N use efficiencies are generally higher for livestock rearing and tillage systems compared to milk producing systems. This is consistent with findings internationally (Dalgaard et al. 2006; Bassanino et al. 2007). Although a different methodological approach[4] was used the OECD (2014) reported national N balance for Ireland of 51 kg N ha^{-1} and a P balance of 3 kg P ha^{-1} for 2008–2009. This compares with results for all systems in this study of 71 kg N ha^{-1} and a P balance of 4.7 kg P ha^{-1}. Further research should be undertaken to identify the key structural, environmental and management factors that determine nutrient balance on farms and identify best management practices that could be implemented to improve balances and use efficiencies. Nutrient balances and use efficiencies could be used as key agronomic efficiency and environmental performance benchmarks to rate the performance of a farm and used as targets to encourage improvement in nutrient management (Goodlass et al. 2003).

5.0 Conclusions

Policymakers are increasingly exercised about the environmental performance and efficiency of different farming systems and seek reliable indicators of improvements in sustainability. The Teagasc NFS in the Republic of Ireland has in recent times been extended beyond normal EU FADN requirements to collect relevant data across the sample to allow N and P balances and use efficiencies to be developed across a range of farm systems. Results

[4] Results not directly comparable as the OECD approach estimates on a national basis and includes should elements are N fixation and atmospheric disposition. Additionally, the Teagasc NFS in 2012 excludes farms below €8000 of standard output, smaller farms representing represent 18% of the total farm population are hence excluded in the sample (Hennessy et al. 2013b).

indicated an average N balance of 71.0 kg ha^{-1} across the nationally representative sample. Nitrogen balances were between two to four times higher across specialist dairy farms (145.5 kg ha^{-1}) compared to livestock rearing (38.2–55.9 kg ha^{-1}) and specialist tillage systems (52.5 kg ha^{-1}). Nitrogen use efficiency was generally lowest across milk producing systems compared to livestock rearing and tillage systems. Phosphorus balance averaged 4.7 kg ha^{-1} across the sample. Specialist tillage farms had higher average P balances (6.3 kg ha^{-1}) compared to dairying (6.2–5.2 kg ha^{-1}) and livestock based systems (3.5–4.7 kg ha^{-1}). Phosphorus use efficiency across all systems averaged 79.6%.

Nutrient balances and use efficiencies have the potential to be used as key agronomic and environmental performance indicators and benchmarks to rate the performance of a farm and encourage improvement in nutrient management. Results from this study provide a template and benchmark for temporal analysis across these indicators going forward for the Republic of Ireland. Additionally, the template developed in this study could assist other members of the EU FADN to develop similar nationally representative indicators and allow overall EU assessments to be made for global comparisons.

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7.0 References

Aarts HFM, Habekotté B, Van Keulen, H, (1999) Limits to intensity of milk production in sandy areas in The Netherlands. Netherlands Journal of Agricultural Science 47:263-277.

Aarts HFM, Habekotte B, van Keulen H, (2000) Nitrogen (N) management in the ‘De Marke’ dairy farming system. Nutrient Cycling in Agroecosystems 56: 231-240.

Aarts HFM, (2003) Strategies to Meet Requirements of the EU-nitrate Directive on Intensive Dairy Farms. Proceedings 518 of the International Fertilizer Society. London, UK: International Fertilizer Society.

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.

Bassanino M, Grignani C, Sacco D, Allisiardi E, (2007) Nitrogen balances at the crop and farm-gate scale in livestock farms in Italy. Agriculture, Ecosystems and Environment 122:282-294.

Bord Bia, (2012) Cattle prices. Available at: http://www.bordbia.ie/industryservices/ information/cattle/pages/prices.aspx. Accessed 02 February 2012.

Breembroek JA, Koole B, Poppe K J, Wossink GAA, (1996) Environmental Farm Accounting: The Case of the Dutch Nutrients Accounting System. Agricultural Systems 51:29-40.

Brouwer F, (1998) Nitrogen balances at farm level as a tool to monitor effects of agri-environmental policy. Nutrient Cycling in Agroecosystems 52:303-308.

Buckley C, Carney P, (2013) The potential to reduce the risk of diffuse pollution from agriculture while improving economic performance at farm level. Environmental Science and Policy 25:118-126.

Central Statistics Office, (2012) Cattle and Sheep Price by Type of Cattle, Month and Statistic. Available: http://www.cso.ie/px/pxeirestat/Statire/SelectVarVal /Define.asp? maintable=AJM01&PLanguage=0. Accessed 02 February 2012.

Cherry K, Mooney SJ, Ramsden S, Shepherd MA, (2012) Using field and farm nitrogen budgets to assess the effectiveness of actions mitigating N loss to water. Agriculture, Ecosystems and Environment 147:82-88.

Dalgaard R, Halberg N, Kristensen, IS, Larsen I, (2006) Modelling representative and coherent Danish farm types based on farm accountancy data for use in environmental assessments. Agriculture, Ecosystems and Environment 117:223–237.

Dunn, O. J. (1964). Multiple comparisons using rank sums. *Technometrics, 6,* 241-252.

EEA, 2005. Agriculture and environment in EU-15. An indicator report. European Environmental Agency, Copenhagen. Available: http://webpubs.eea.eu. int/content/irena/Latestproducts.htm. Accessed 10 April 2014.

European Environment Agency, (2012) European waters — assessment of status and pressures.

European Union Commission, (2012a) Agri-environmental indicator - gross nitrogen balance. Available: http://epp.eurostat.ec.europa.eu/statistics_ explained/index.php /Agri-environmental_indicator_-_gross_nitrogen_balance. Accessed 02 February 2012.

European Union Commission, (2012b) Agri-environmental indicator - gross phosphorus balance. Available: http://epp.eurostat.ec.europa.eu/statistics _explained/ index.php/Phosphorus_balance_in_agriculture. Accessed 02 February 2012.

European Union Commission, (2013a) Concnept of FADN. Available: http://ec.europa.eu/agriculture/rica/concept_en.cfm. Accessed 02 February 2012.

European Union Commission, (2013b) Nutrient Budgets - EU-27, Norway, Switzerland. Available: http://epp.eurostat.ec.europa.eu/portal/page/portal/ agri_environmental _indicators/documents/Nutrient_Budgets_Handbook_ (CPSA_AE_109)_corrected3.pdf. Accessed 02 February 2012.

Ewing W N, (2002) The Feeds Directory: Commodity Products Guide, Context Publications.

Gerber PJ, Uwizeye A, Schulte RPO, Opio CI, and de Boer IJM, (2014) Nutrient use efficiency: a valuable approach to benchmark the sustainability of nutrient use in global livestock production? Current Opinion in Environmental Sustainability 9–10:122–130.

Ghebremichael LT, Watzin MC, (2011) Identifying and controlling critical sources of farm phosphorus imbalances for Vermont dairy farms. Agricultural Systems 104:551-561.

Godinot O, Carof M, Vertes F, Leterme P, (2014) SyNE: an improved indicator to assess nitrogen efficiency of farming systems. Agricultural Systems 127:41-52.

Goodlass, G., Halberg, N., and Verschuur, G., (2003) Input output accounting systems in the European community—an appraisal of their usefulness in raising awareness of environmental problems. European Journal of Agronomy, 20: 17-24.

Gourley CJP, Dougherty WJ, Weaver DM, Aarons SR, Awty IM, Gibson DM, Hannah MC, Smith AP, Peverill KI, (2012) Farm-scale nitrogen, phosphorus, potassium and sulphur balances and use efficiencies on Australian dairy farms. Animal Production Science 52:929-944.

Groot JCJ, Rossing WAH, Lantinga, EA, (2006) Evolution of farm management, nitrogen efficiency and economic performance on Dutch dairy farms reducing external in-puts. Livestock Science 100:99-110.

Halberg N, Verschuur G, Goodlass G, (2005) Farm level environmental indicators; are they useful? An overview of green accounting systems for European farms. Agriculture, Ecosystems and Environment 105:195-212.

Haygarth PM, Chapman PJ, Jarvis SC, Smith, RV, (1998) Phosphorus budgets for two contrasting grassland farming systems in the UK. Soil use and Management 14:160-167.

Heathwaite, A.L., Quinn,P.F. and Hewett, C.J.M. 2005. Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. Journal of Hydrology 304: 446-461.

Hennessy T., Buckley C, Cushion M, Kinsella A, Moran B, (2011) National Farm Survey of Manure Application and Storage Practices on Irish Farms. Teagasc, Athenry, County Galway. Available: http://www.teagasc.ie/publications /2011/1001 /TeagascNationalFarmSurveyOfManureApplication.pdf. Accessed 01 February 2014.

Hennessy T, Buckley C, Dillon E, Donnellan T, Hanrahan K, Moran B, and Ryan M, (2013a) Measuring Farm Level Sustainability with the Teagasc National Farm Survey. Available at: http://www.teagasc.ie/publications/2013 /3042 /SustainabilityReport.pdf. Accessed 01 February 2014.

Hennessy T, Moran B, Kinsella A, and Quinlan G, (2013b) Teagasc National Farm Survey Results 2012. Dairy Enterprise. Available: http://www.teagasc.ie /publications/2013/2862 /NFS_Dairy2012.pdf. Access 10 October 2014.

Huhtanen P, Nousiainen J, Turtolad E, (201) Dairy farm nutrient management model: 2. Evaluation of different strategies to mitigate phosphorus surplus. Agricultural Systems 104:383-391.

Jarvis PJ, Boswell CC, Metherell AK, Davison RM, Murphy JA, (2002) A nutrient budget for the Meat and Wool Economic Service of a New Zealand Class 1 high-country farm model. New Zealand Journal of Agricultural Research 45:1-15.

Jay M, (2007) The political economy of a productivist agriculture: New Zealand dairy discourses. Food Policy 32:266–279.

Jordan P, Melland AR, Mellander PE, Shortle G, Wall D, (2012) The seasonality of phosphorus transfers from land to water: implications for trophic impacts and policy evaluation. Science of the Total Environment 434:101-109.

Kersebaum KC, Steidl J, Bauer O, Piorr HP, (2003) Modelling scenarios to assess the effects of different agricultural management and land use options to reduce diffuse nitrogen pollution into the river Elbe. . Physics and Chemistry of the Earth 28:537-545.

Lapierre H, Lobley GE, (2001) Nitrogen recycling in the ruminant: A review. Journal of Dairy Science 84:223-236.

McDonald P, Edwards RA, Greenhalgh JFD, Morgan CA, (1995) Animal Nutrition, 5th edition. Harlow, UK: Longman Scientific and Technical.

Mihailescu E, Murphy P, Ryan W, Casey I, Humphreys J, (2014) Nitrogen balance and use efficiency on twenty-one intensive grass-based dairy farms in the South of Ireland. The Journal of Agricultural Science 152: 843-859. doi:10.1017/S0021859614000045

Mihailescu E, Murphy P, Ryan W, Casey I, Humphreys J, (2015) Phosphorus balance and use efficiency on twenty-one intensive grass-based dairy farms in the South of Ireland. The Journal of Agricultural Science 153: 520-537. doi:10.1017/S0021859614000641

Morgan MF, (1941) Chemical Soil Diagnosis by the Universal Soil Testing System. Connecticut Agricultural Experimental Station Bulletin 450.

Nevens F, Verbruggen I, Reheul D, 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.

Öborn I, Edwards AC, Witter E, Oenema O, Ivarsson K, Withers PJA, Nilsson SI, Richert-Stinzing A, (2003) Element balances as a tool for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context. European Journal of Agronomy 20:211-225.

Oenema O, Boers PCM, van Eerdt MM, Fraters B, van der Meer HG, Roest CWJ, Schroder JJ, Willems WJ, (1998) Leaching of nitrate from agriculture to groundwater: the effect of policies and measures in The Netherlands. Environmental Pollution 102:471-478.

Oenema O, Pietrzak S, (2002) Nutrient management in food production: achieving agronomic and environmental targets. Ambio 31:159-168.

Ondersteijn CJM, Beldman ACG, Daatselaar CHG, Geisen GWJ, Huirne, RBM, (2002) The Dutch Mineral Accounting System and the European Nitrate Directive: implications for N and P management and farm performance. Agriculture, Ecosystems and Environment 92:283-296.

Ondersteijn CJM, Beldman ACG, Daatselaar CHG, Giesen GWJ, Huirne RBM, (2003) Farm structure or farm management: effective ways to reduce nutrient surpluses on dairy farms and their financial impacts. Livestock Production Science 84:171-181.

Organisation for Economic Cooperation and Development (OECD), (2014) Green Growth Indicators for Agriculture: A Preliminary Assessment, OECD Green Growth Studies, OECD Publishing. Available: http://dx.doi.org/10.1787/9789264223202-en. Accessed 14 October 2014.

Poppe KJ, Meeusen MJG, (2000) Using a Farm Accountancy Data Network in data management for LCA. In: Weidema, B., Meeusen, M.J.G. (Eds.), Agricultural Data for Life Cycle Assessments, vol. 1. LEI, The Hague, pp. 115–127.

Raison C, Pflimlin A, Le Gall A, (2006) Optimisation of environmental practices in a network of dairy farms in the Atlantic area. In Green Dairy Project Interreg Atlantic Area IIIB N°100: Proceedings of the Final Seminar, pp. 43-65. Rennes, France.

Schröder JJ, Aarts HFM, Ten Berge HFM, Van Keulen H, Neeteson JJ, (2003) An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. European Journal of Agronomy 20:33-44.

Schröder JJ, Scholefield D, Cabral F, Hofman G, (2004) The effects of nutrient losses from agriculture on ground and surface water quality: the position of science in developing indicators for regulation. European Journal of Agronomy 7:15-23.

Sutton M, Oenema O, Erisman JW, Leip A, Grinsven H, Winiwarter W, (2011) Too much of a good thing. Nature 472:159.161.

Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, De Haan C, (2006) Livestock's long shadow (p. 2006). Rome: FAO.

Teagasc (2014) Management Data for Farm Planning 2013/2014. Teagasc, Rural Economy and Development Programme.

Tikofsky JN, Van Amburgh ME, Ross DA, (2001) Effect of varying carbohydrate and fat content of milk replacer on body composition of Holstein bull calves. Journal of Animal Science 79:2260-2267.

Treacy M, Humphreys J, Mc Namara K, Browne R, Watson CJ, (2008) Farm-gate nitrogen balances on intensive dairy farms in the south west of Ireland. Irish Journal of Agricultural and Food Research 47:105-117.

Wall DP, Jordan P, Melland AR, Mellander P-E, Buckley C, Reaney SM, Shortle G, (2011) Using the nutrient transfer conctinuum concept to evaluate the European Union Nitrates Directive National Action Programme. Environmental Science and Policy, 14: 664-674.

Wall DP, Murphy PNC, Melland AR, Mechan S, Shine O, Buckley C, Jordan P, (2012) Evaluating nutrient source regulations at different scales in five agricultural catchments. Environmental Science and Policy 24:34-43.

Yan T, Frost JP, Keady TWJ, Agnew RE, Mayne CS, (2007) Prediction of nitrogen excretion in faeces and urine of beef cattle offered diets containing grass silage. Journal of Animal Science 85:1982-1989.