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AgriBenchmark: Benchmarking Sustainable Nutrient Management on Irish Farms

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AgriBenchmark

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Government of Ireland

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EPA RESEARCH PROGRAMME 2014–2020

AgriBenchmark: Benchmarking Sustainable Nutrient Management on Irish Farms

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EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Dublin

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Executive Summary

AgriBenchmark explored the possibilities for benchmarking of nutrient management performance on Irish farms. Teagasc National Farm Survey (NFS) data (2008–2015; 1446 farms) were used to characterise and explore the potential for improvement of farm nutrient management performance and resultant aspects of environmental and economic sustainability through the derivation of three key performance indicators (KPIs) at the farm-gate level: farm nutrient balance (kg ha^{-1}), nutrient use efficiency (NUE; %) and profitability (gross margin; € ha^{-1}). In this report, the farm nutrient balance is defined as the farm-gate nutrient imports (fertiliser, feed, animals, etc.) minus the exports (animals, crops, wool and milk). A positive balance (surplus) is considered to represent a nutrient source pressure in terms of the risk of nutrient losses to the wider environment. The data and analyses in this report cover the main, more intensive agricultural systems in Ireland (excluding pig and poultry farms) and are representative of, on average, 61% of farms nationally and 76% of the total utilised agriculture area (UAA; excluding commonage).

Large ranges in these KPIs between farms of the same type show that there is scope to reduce nutrient source pressure (nutrient balance) and increase efficiency (NUE). Although some of this variability in performance will be related to factors beyond the immediate control of the farmer, some of this variability relates to farm and nutrient management practices that are under the control of the farmer. Therefore, using these KPIs as benchmarks to measure and motivate improved management practices would appear to have considerable scope to reduce nutrient source pressures and increase NUEs.

Dairy and tillage systems are the most intensive in terms of nutrient imports but this study shows that dairy farms perform relatively well in terms of NUE compared with other livestock types, and tillage farms are the best performers for both balances and use efficiencies. This has important implications if a balance is sought between agricultural production and environmental source pressure at the farm scale, but also at the landscape, regional and national scales.

Dairy farms exert the greatest nutrient source pressure in terms of both surplus per ha (mean 156 kg N ha^{-1} yr^{-1} and 7.0 kg P ha^{-1} yr^{-1}) and estimated national aggregate agricultural surplus (111,210 t N yr^{-1} and 4994 t P yr^{-1}), equivalent to 43% of the total agricultural N surplus and 31% of the total agricultural P surplus from only 21% of the total UAA, based on the representative sample. As the European Union milk quota system ended in 2015, and with the planned expansion (and likely intensification) in milk production under the Food Harvest 2020 and Food Wise 2025 programmes, the need to encourage improved nutrient management on dairy farms, in particular, should be emphasised.

General trends of reduced N and P surpluses and increased efficiencies across farm types (except for sheep farms) in the last 2 or 3 years of this study indicate improved sustainability and reduced nutrient source pressures. However, increases in P balances and decreases in P use efficiencies for all livestock sectors over the whole period from 2008 to 2015 indicate that P farm gate-level source pressures have increased over this time, largely because of increased fertiliser P imports.

Benchmarking analysis based on nutrient balance per ha (nutrient source pressure), nutrient export per ha (output intensity) and gross margin per ha (profitability) revealed that benchmark farms minimise surpluses to relatively low levels for a given level of production intensity, with lower fertiliser and feed imports per ha, greater exports of agricultural products per ha, relatively high stocking rates (except for tillage, mixed livestock and non-suckler cattle farms) and higher gross margins (€ ha^{-1}). For example, the optimal benchmark zone for dairy farms is characterised by farms with relatively high stocking rates [2.2 livestock units (LU) ha^{-1}] but relatively low N and P surpluses (122 kg N ha^{-1} and 4.5 kg P ha^{-1}, compared with 271 kg N ha^{-1} and 26.6 kg P ha^{-1} for the poorest performing farms), relatively high N- and P-NUE (31% N-NUE and 72% P-NUE, compared with 14% N-NUE and 26% P-NUE for the poorest performing farms) and high gross margin returns (€2734 ha^{-1}, compared with €1909 ha^{-1} for the poorest performing farms). To

achieve these improvements in both nutrient source pressure *and* profitability and resource use efficiency, it is necessary to focus both on optimisation of nutrient imports and their management *and* on optimisation of nutrient exports, which, in the case of dairy farms, is milk.

For the ambitious scenario of all non-benchmark farms reaching the optimal benchmark zone, moderate reductions in nutrient surpluses were found with great improvements in profitability and resource use efficiency. For dairy, farm gross margins improved by €919 ha^{-1}, associated with a decrease in N surplus of –35 kg N ha^{-1} and an increase in NUE of 11.2 percentage points, principally because of a combination of reduced fertiliser and concentrate N imports (–22 and –29 kg N ha^{-1}, respectively) and increased N exports in milk (+13 kg N ha^{-1}). This scenario led to a 31% decrease in aggregate surplus N, from 258,893 t to 179,108 t, with the largest proportions of this decrease coming from dairy (30%) and non-suckler cattle (29%) farms, reflecting the large contribution of these two farm types to the aggregate N surplus but also indicating significant potential to reduce that surplus.

Effective knowledge transfer to farmers would be central to achieving the potential improvements in nutrient management and associated improvements in economic and environmental sustainability highlighted in this study. Central to this knowledge transfer strategy would be a web-based management decision support benchmarking tool, highlighting the KPIs for individual farms, ranking farms against the benchmark, summarising the potential gains that could be made by improving management and suggesting some management practices that could help to move farms in the right direction.

1 Introduction

Agriculture faces the challenge of achieving sustainable, profitable production while maintaining environmental quality (Tilman *et al*., 2002; EC, 2007; Sutton *et al*., 2011). In Ireland, for example, ambitious national growth targets for agricultural output have been set in the Food Harvest 2020 (DAFF, 2010) and Food Wise 2025 (DAFM, 2015) reports. At the same time, Ireland, like other countries, must meet international environmental obligations in terms of water quality [e.g. European Union (EU) Nitrates Directive (91/676/EEC) and Water Framework Directive (2000/60/EC)] and greenhouse gas (GHG) emissions (e.g. EU 2020 targets), for example. Furthermore, the ecosystem services demanded by society place sometimes competing demands on agriculture, e.g. food production versus clean water provisioning. Conventional agricultural production is highly dependent on nutrient inputs of N and P in fertiliser and feed, both of which are costly non-renewable resources and form one of the main variable input costs on any farm. Price increases, and also increased price volatility, have made efficient management of these resource a greater priority. In addition, all fertiliser N and P in Ireland is imported and P is a finite mineral resource with some estimates of peak global production in as little as 30 years (Cordell and White, 2011). Furthermore, poor use efficiency of these resources is associated with losses to the environment and impacts on water quality, GHG emissions (N_2O), air quality (ammonia), acidification and biodiversity. Stakeholders 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*., 2005a,b).

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. 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, 2003a; Nevens *et al*., 2006; Bassanino *et al*., 2007; Treacy *et al*., 2008). Farm-level balances are calculated by subtracting the exports from the imports and are an indication of pressure on environmental quality as the balance (surplus) nutrient remaining in the farm system will be vulnerable to loss to the environment as gaseous or aqueous emissions. Nutrient use efficiency (NUE) is calculated by dividing the exports by the imports, expressed as a percentage, and is a measure of agronomic efficiency of recovery of nutrients in the exported farm produce.

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 (Öborn *et al*., 2003; Jordan *et al*., 2012). However, nutrient accounting approaches can be considered a useful indicator in assessing agronomic efficiency (Mihailescu *et al*., 2015a) and environmental pressure (Aarts *et al*., 2000a,b; Schröder *et al*., 2003, 2004; Murphy *et al*., 2015). 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). Recently, Murphy *et al*. (2015) demonstrated improvements in P balances and management on farms in a dairy-dominated Irish catchment and related these to early indications of reductions in environmental pressures and P delivery to streams. Farm nutrient balance indicators have been used as a policy tool to drive improvements in the Netherlands using the MINAS (Mineral Accounting System) tool and in Sweden using the STANK tool, for example Öborn *et al*. (2003). A similar benchmarking tools approach has been successful in Ireland in improving farm management in the areas of genetic merit (Herd Economic Breeding Index; Berry *et al*., 2005) and grazing management (Pasture Base Ireland; Hanrahan *et al*., 2017), for example. The experience with these tools, and in particular with the Teagasc Carbon Navigator that estimates GHG emissions (Murphy *et al*., 2013), has shown that benchmarks that can relate environmental improvements to profit gains are more likely to motivate farmer behaviour as farmers are more likely to respond to financial incentives.

AgriBenchmark will apply a similar approach to the field of nutrient management with the ultimate intention that nutrient management be considered in the same way as one of the key farm management objectives, with target benchmark indicators to rank performance and use of profit gains to motivate improvements.

There is little published work at a national scale that looks at nutrient balances and use efficiencies across different farm systems. Most published work (nationally and internationally) tends to focus on dairy systems (e.g. Mihailescu *et al*., 2014, 2015a,b). However, a recent study by Buckley *et al*. (2015) used the Teagasc National Farm Survey (NFS), which is part of the EU Farm Accountancy Data Network (FADN), to develop environmental sustainability indicators in the use of N and P across a range of farm sectors in 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 farm gate-level balances (kg ha^{-1}) and overall use efficiencies across 827 farms in 2012. The sample was population weighted to represent 71,480 farms nationally. The results indicated an average N balance of 71.0 kg ha^{-1} and use efficiency of 36.7% across the nationally representative sample. The results indicated that N balances were between two and four times higher across specialist dairy farms than for livestock rearing and specialist tillage systems. N-NUE was generally lowest across milk-producing systems compared with livestock rearing and tillage systems. P balance and use efficiency averaged 4.7 kg ha^{-1} and 79.6%, respectively, across the sample. Specialist tillage and dairy farms had higher average P balances than other livestock-based systems. Whereas N will largely be either exported in farm products or lost to the environment within a short period of time, P accumulates in soil and P management aims to build up and maintain optimal soil P concentrations. Therefore, Murphy *et al*. (2015) recently pioneered an “optimal P balance”, accounting for this soil P requirement. The approaches developed by Buckley *et al*. (2015) and Murphy *et al*. (2015) formed the basis for developing nutrient balance and use efficiency indicators in this study. There are numerous potential approaches to the benchmarking process, ranging from simple comparative ranking schemes to more complex approaches such as efficient-frontier techniques (Malano *et al*., 2004). In this AgriBenchmark study these approaches were reviewed and the most suitable for application to this aspect of farm management were selected.

1.1 Objectives

The overarching aim of the AgriBenchmark study was to produce national sectoral benchmarks for the agricultural sector in the area of farm nutrient management and explore ways to put such benchmarks into operation at the farm level. This was achieved through four work packages:

1. a literature review and synthesis;
2. deriving farm nutrient balance and use efficiency indicators for N and P across different Irish farm sectors;
3. a benchmark analysis;
4. exploring strategies to put a benchmarking tool into operation at the farm level.

2 Literature Review and Synthesis

2.1 Farm Nutrient Budgeting Models

Environmental accounting of farm nutrients and the externalities associated with agricultural production, such as climate change impacts and water quality, is largely concerned with measuring nutrient inputs and outputs associated with agricultural production. The greater the nutrient surplus, the greater the risk of nutrient loss to the wider environment and resultant detrimental impacts, all other things being equal. The nutrient management environmental pressure indicator has three broad purposes: (1) to increase understanding of nutrient cycling, (2) to act as a performance indicator and (3) to act as a regulatory instrument (Oenema *et al.*, 2003).

Defining the boundaries of the system is the first step in selecting a model for measuring farm performance in nutrient management. Six models of nutrient budgeting were identified from the literature: farm-gate balance, gross farm balance, chain-gate farm balance, soil surface balance, soil system balance and full life cycle analysis (LCA). These models differ in both the system boundaries imposed and the complexity of system components/processes that are measured, estimated or modelled (Figure 2.1). As a result, the different models are suited a priori to both asking and answering different questions about the sustainability of agricultural production systems. It would be an important first step, therefore, in any benchmarking approach to sustainability in agricultural systems to select the model most suited to answering the particular questions of interest for that benchmarking system.

2.1.1 Farm-gate nutrient balance models

Conceptually, the farm-gate nutrient balance model is relatively simple: a nutrient balance consists of farm nutrient inputs minus outputs. The remaining balance (nutrient surplus or deficit) represents an indicator of the environmental pressure generated by the system and can also be adapted to measure NUE by dividing outputs by inputs. The actual nutrient losses to the wider environment from the system, and the forms of and pathways for those losses, will depend on a range of factors such as weather, soils, hydrology and management practices. For example, surplus N for a given year on a given farm may accumulate in farm biomass or soils, may be lost as environmentally benign N_2 gas or as environmentally

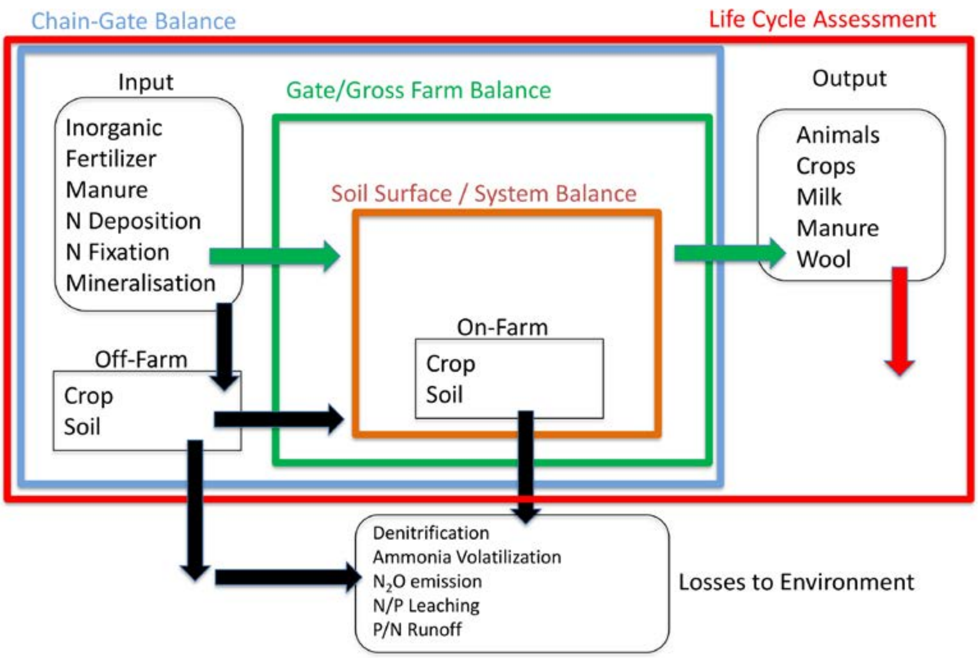

Figure 2.1. Nutrient budgeting models identified in the literature and their system boundaries and flows.

problematic ammonia or N_2O gas or may be leached to groundwater as nitrate or nitrite. Accurate estimation of these loss pathways and impacts would require data that are difficult to acquire and which are subject to large uncertainties and also more complex process-based modelling approaches that are likewise subject to high degrees of uncertainty. The farm-gate nutrient balance approach operates on the principle that changing management to reduce the overall environmental pressure associated with the system, as indicated by the farm nutrient balance, will generally act to reduce the overall environmental impact of the system. This approach does not attempt to estimate specific environmental impacts of such changes.

In addition, the farm-gate NUE metric serves as an indicator of resource use efficiency that is related to both the economic (profitability) and the environmental sustainability of the farm system. The farm-gate nutrient balance approach, therefore, can generate indicators of both economic and environmental performance, which can help to benchmark the performance of a farm (against some target level of performance) and measure changes in performance over time linked to management changes.

Nutrient balances can be evaluated at a wide range of scales: field scale (soil surface), farm scale and regional, national and global scales (Bouwman *et al*., 2005; McDonald *et al*., 2011; Smit *et al*., 2015). However, the farm and field scales are those over which the farmer has most direct control in terms of nutrient management decisions. The farm balance provides farmers, policymakers and other stakeholders with an assessment of the environmental performance of individual farms with regard to their nutrient balance on a per-ha basis and their efficiency in terms of nutrient recovery in farm products.

Broadly, three types of nutrient balance are prevalent in the literature: farm gate, soil surface and soil system (Oenema and Heinen, 1999). The farm-gate budget is more precise, owing to less uncertainty in its calculation (Oenema *et al*., 2003). The uncertainties in soil surface budgets relate to biases and errors, notably in the partitioning of nutrient losses. Soil surface budgets focus on the soil nutrient gains and losses and the surplus or deficit is a measure of net depletion or enrichment of the soil system and an indicator of the fate of nutrient surpluses (forms and pathways of nutrient loss).

The majority of studies in agriculture have focused on the arable or dairy sector. This project intends to broaden the scope to other farming systems, aiming to also incorporate accounting metrics for beef and sheep systems. The calculation of nutrient balances requires multiple data sources on a multi-annual basis. This is particularly important in the assessment of trends. The selection of a baseline year, which is generally used to assess change over time, can introduce a degree of subjectivity in assessing nutrient balance trends, because of, for example, inter-annual variability in weather and other factors (e.g. fertiliser or feed costs, product prices), which can have significant impacts. The year-on-year trends must be interpreted in the context of prevailing weather conditions. Alternatives to this include the use of a rolling trend over a number of years, which may yield more meaningful interpretations of nutrient surpluses at farm level than a time-averaged baseline approach.

In the calculation of a metric for nutrient balances at the boundary of the farm there are two quite similar approaches: a farm-gate balance and a gross or extended farm balance. More recently, a chain-gate balance, which examines nutrient balances from the cradle to the gate, has been proposed (Mu *et al*., 2016). At the farm-gate level, nutrient inputs and outputs over which the farmer has direct control are included. For example, animal imports and exports, fertiliser and feed imports and crop exports are considered. The balance per ha indicates the total quantitates of N or P ($kg\,ha^{-1}$) imported minus the quantities exported ($kg\,ha^{-1}$). This provides an indicator of the environmental pressure. The NUE indicator, derived using the same data, provides an indicator of agronomic efficiency on the farm, calculated by dividing the total number of kg of N or P exported by the total number of kg imported.

There are additional biophysical factors and processes that will influence the cycling and losses of nutrients on a farm, and hence the calculated farm-gate balance, but these are not so directly controlled by the farmer. These include N and P mineralisation from soils, biological N fixation, atmospheric N deposition and nutrient accumulation in soils and biomass and nutrient losses to the atmosphere and water. It should be noted, however, that farm management practices can affect these factors in a less direct way, particularly over the longer term. For example, sowing and maintenance of clover in a grass sward can greatly increase biological N fixation and, if inorganic fertiliser N use is reduced accordingly, could reduce farm-gate N surplus. Similarly, in a situation where soil P concentrations are in excess of the agronomic optimum because of historical over-application of fertiliser P, a farm-gate P deficit may be maintained for a number of years, relying on the release of P from soil reserves until the soil P concentration has decreased to the agronomic optimum.

In experimental scenarios, N losses to water and the atmosphere and accumulation within the farm system in soils and biomass can be monitored to some degree (e.g. Burchill *et al*., 2016). They can also be modelled (e.g. de Vries *et al*., 2015). However, monitoring of these aspects of the farm N cycle is not very feasible on a widespread basis on commercial farms and modelling is subject to significant uncertainty. The farm-gate nutrient balance model is considered a useful approach because it provides a more directly measurable indicator of system performance with metrics that are easily understood by farmers.

Nutrient outputs are calculated on the basis of farm exports of, for example, milk, animals and crops but also exports of organic fertilisers such as manures and slurries. The balance is calculated on a per-ha basis but also as a NUE indicator. To take this further, an eco-efficiency indicator can be calculated on a per-kg product basis, e.g. kg of milk/meat produced per kg of N/P surplus (Hennessy *et al*., 2013; Ryan *et al*., 2015). This provides an indicator of environmental pressure per unit output, allowing comparisons of systems in terms of their potential environmental impact per unit product produced. However, this approach does not indicate the local environmental pressure associated with a production system. For example, a farm may have a relatively low N surplus per unit product (i.e. high eco-efficiency) because of a relatively high product output per ha, but it may also have a high surplus per ha because of high N inputs and inefficient conversion of those inputs to N outputs. The N balance per ha is a more direct indicator of the environmental pressure associated with the farm and the losses of N from that farm to the environment and the associated environmental impacts. This is particularly relevant to nutrient losses at the farm scale, which have impacts at local, regional and national scales with regard to water quality, air quality and GHG emissions for national-level inventories. If these are the primary environmental impacts of concern, therefore, the farm gate-level balance is a better indicator than the farm gate-level eco-efficiency indicator.

The method used for indicator calculation must meet several criteria including accuracy, solid scientific basis, usability, reliability (to facilitate comparative studies and replication over time), understandability and feasibility. Data must be available on an annual basis to assess trends. Assessments of nutrient balance results based on one-off data collection need to be approached with caution because of the inter-annual variability in conditions affecting nutrient management and nutrient budgets. It is therefore preferable to use multi-annual data. Mu *et al*. (2016) highlighted a potential bias when comparing findings based on 1 year of results because of weather effects in particular.

2.1.2 Gross farm nutrient balance models

More detailed farm-level nutrient balance models, termed here “extended” or “gross farm” system models, may incorporate additional nutrient inputs, most typically net soil N mineralisation, biological N fixation and atmospheric N deposition. Such models have greater data requirements and are subject to greater uncertainty in that data. Such processes are also not directly controlled by the farmer.

2.1.3 Chain-gate nutrient balance models

Chain-gate balances move the boundaries of the system outside the farm to include nutrient balances associated with upstream production of farm inputs such as imported feeds. Mu *et al*. (2016) compared farm-level and chain-gate balances for N and P based on 1 year of data for Dutch and Irish dairy farms and found significant differences in the N balances of farms but no significant differences in the P balances. They concluded that farm-level balances are an appropriate measure when differences in on-farm losses between systems are large and pre-farm losses are unimportant, that is, when most nutrient surpluses and losses are at the farm level rather than being associated with pre-farm processes.

2.1.4 Soil nutrient balance models

Soil surface and soil system nutrient balance models have a narrower system boundary, being focused on nutrient inputs and outputs at the soil surface, and typically include system-specific processes and nutrient fluxes that may not be directly under the control of the farmer. Soil surface balance models are used by the Organisation for Economic Co-operation and Development (OECD) and EU countries to meet the needs of Eurostat. They facilitate the calculation of national N balances and can be used across all farm systems. Soil surface balances can be calculated and analysed across a range of scales, up to the global scale (e.g. Bouwman *et al*., 2005). However, the soil surface balance is not a gross calculation of all losses from agriculture. For example, the volatilisation of ammonia from stored manure and livestock housing is excluded. It is focused on soil and water, with all nutrients that enter the soil via the surface and that leave via crop uptake (harvested crops and forage crops produced and grass consumption are calculated as outputs) being recorded, and includes estimates of biological N fixation and atmospheric deposition.

In an extension of the soil surface balance approach, the soil system balance includes the same inputs and outputs as the soil surface balance, but also adjusts outputs for ammonia volatilisation, denitrification, leaching and run-off losses and net immobilisation in soil. This essentially accounts for nutrients recycled internally within the farm gate and re-deposited as manure. Both of these soil balance models, then, attempt to capture the internal cycling of nutrients within the farm and the specific losses to the environment, in a way that the farm-gate balance model does not. The internal cycling and losses of nutrients, however, are not as amenable to accurate measurement as farm-gate nutrient fluxes and also vary to a much greater degree based on changing environmental conditions. They are also difficult to model and the modelled estimates are subject to high degrees of uncertainty.

2.1.5 Life cycle assessment nutrient balance models

Life cycle analyses, or footprint analyses, that attempt to account for nutrient inputs and outputs along the entire chain of production to a product (e.g. per kg of milk solids for a dairy farm), its consumption and waste management have also been used to assess and benchmark farm performance using the product nutrient footprint as an indicator (e.g. de Vries *et al*., 2015; Grönman *et al*., 2016). Some studies have sought to assess performance in terms of total resource use (nutrients, water, energy, etc.) (e.g. Huysveld *et al*., 2015) and multiple environmental outcomes (water quality, GHG emissions, acidification, etc.) (e.g. de Vries *et al*., 2015). The distinction between farm gate, chain gate and full LCA is determined by the system boundaries chosen to define the system.

To a large degree, the appropriateness (or inappropriateness) of the chosen system boundaries and indicators depends on what aspect of performance is to be assessed. For example, if the principal aspect of environmental performance is the potential impact on water quality, then surplus nutrients per ha (e.g. $kg\,N\,ha^{-1}$) at the farm-gate level may be an appropriate indicator. However, if there is a significant export of nutrients from the farm, e.g. in manure, that is then land applied locally, the farm-gate balance may not fully capture the pressure on local to regional water quality resulting from this individual farm. This appears to be the case in a recent study comparing a small number of Irish and Dutch commercial dairy farms (Mu *et al*., 2016), in which the Dutch dairy farms had significant manure exports ($78\,kg\,N\,ha^{-1}$ net). This manure N was counted as an output from the farm system, leading, in part, to lower farm-gate N surpluses for the Dutch dairy farms. However, the manure would presumably not be transported very far and would probably be land applied in the locality, thereby adding to the local nutrient source pressure, particularly with regard to water quality. Although this additional nutrient source pressure would be accounted for in the nutrient balance of the receiving farms, and would, therefore, be accounted for in a regional assessment of nutrient source pressure, it is not accounted for by the dairy farms producing it and is therefore not accounted for in a systems-based comparative study such as that of Mu *et al*. (2016). Therefore, in regions of concentrated intensive dairy production, e.g. the Netherlands, the farm-gate balance may not fully capture the nutrient source pressure on water quality associated with that dairy production and, as a result, may not be an effective indicator of environmental performance. In such circumstances, the system boundary for the chain-level analysis should continue beyond the farm, to capture the environmental pressure generated by that manure and its management within the locality and the pressure that this may put on local to regional water quality. Huysveld *et al*. (2015) argued for the importance of an LCA total resource use assessment approach, because many of our agricultural systems, particularly in some regions such as the Netherlands, are high input/high output systems, in order to achieve higher productivity from the same land base. In the study by de Vries *et al*. (2015) the authors have gone some way towards addressing this regional/landscape issue through use of the INITIATOR model to model impacts at the landscape level.

As another example, if the principal interest is in reducing GHG emissions associated with the production of an agri-food product at a global level or in informing consumer choice about particular products, then the full LCA footprinting approach using net GHG emissions per unit product (e.g. $kg\,CO_2\,eq.\,kg^{-1}$ milk solids) may be appropriate. Alternatively, if the principal interest is in reducing total national GHG emissions under EU and United Nations Framework Convention on Climate Change (UNFCCC) commitments, and meeting the subsidiary sectoral requirements for reduced emissions (e.g. from agriculture or the dairy sector), then the farm-gate emissions (e.g. $kg\,CO_2\,eq.\,ha^{-1}$) and nutrient balance (e.g. $kg\,N\,ha^{-1}$) approach may be more appropriate, as these indicators more accurately reflect emissions produced by farm systems that cumulatively determine total sectoral and national-level emissions. Too much focus on LCA footprinting may lead to improved resource use efficiencies and reduced emissions per unit product (the high input/high output systems mentioned above), but higher absolute emissions, both per ha and at sectoral and national levels.

2.2 Evaluating Nutrient Budgeting Models for Benchmarking Suitability

Nutrient accounting methods vary based on the approach used, with varying levels of detail required for each. The complexity associated with calculating balances, as identified by Oenema *et al*. (2003), is associated with measurements that are dependent on dynamic natural processes and system-specific processes. For example, leaching of N to groundwater may be a function of weather events (rainfall), N cycling processes and system specifics such as soil type or slope.

Each model was evaluated in terms of the capture of nutrient sources, flows and losses, data requirements based on availability and certainty, usability in farm decision making and relevance to policy goals on a scale of 1–5. The data availability and certainty criteria reflect the strategy of Oenema *et al*. (2003) in selecting nutrient budget models, as data type, source and frequency, and the overarching selection criteria identified as fitting the purpose of the study, reflected here as usability in farm and policy decision-making processes.

The indicator evaluation of these models was as follows:

- data availability: 1 = all variables required are currently available (low data requirement); 5 = no available existing data set;
- data certainty: 1 = most data certainty; 5 = least data certainty;
- usability for policymaker and farmer: 1 = very usable; 5 = not very usable.

The nutrient budgeting model with the lowest score, therefore, would be the model evaluated as being most suitable for the purposes outlined above.

In relation to data certainty, the use of standard (non-dynamic) coefficients for variables that are affected by dynamic conditions will give uncertain results in the absence of additional data capturing those dynamic conditions. For example, N losses to the atmosphere would require dynamic weather data to reduce uncertainty as the rate of loss varies significantly with changing weather and soil conditions. In contrast, parameters using coefficients that are stable or verifiable will have less associated uncertainty. For example, the associated coefficient for N input or output based on quantity of concentrates imported onto the farm or litres of milk exported off the farm will be reasonably constant and is more verifiable.

The farm-gate balance was identified as the most appropriate nutrient budgeting model for the purposes of this project (Table 2.1). It scored well on data availability (fertiliser, feed, animal, milk, crop records × standard coefficients of N or P content), data certainty (based, mostly, on recorded weights and not including highly variable processes of soil N/P cycling and losses), usability for the farmer (based on nutrient fluxes directly under the control of farmers) and usability for monitoring/policy (repeatable,

Table 2.1. A ranking analysis of the identified nutrient budgeting models based on indicator criteria

Indicator criteria	LCA	Chain-gate balance	Gross farm balance	Farm-gate balance	Soil surface balance	Soil system balance
Data availability	5	4	3	1	1	3
Data certainty	5	4	3	1	1	3
Usability: farmer	3	3	3	2	4	4
Usability: monitoring/policy	3	3	2	2	2	2
Total score	16	14	11	6	8	12

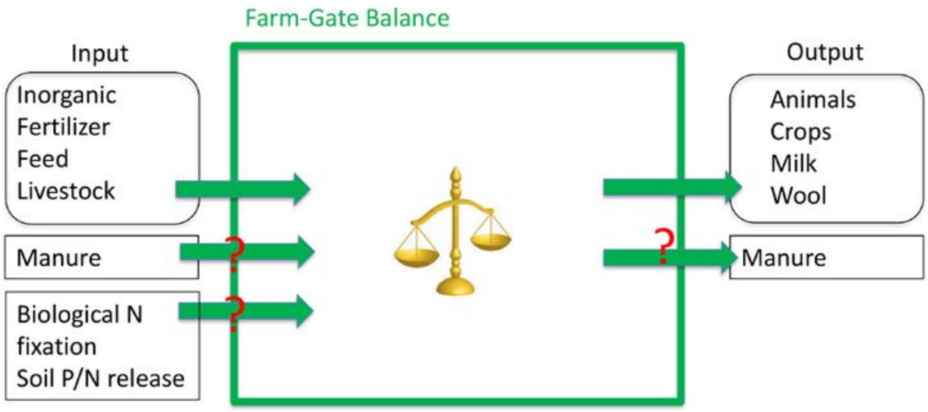

Figure 2.2. The AgriBenchmark nutrient budgeting model. Question marks indicate that nutrient fluxes are highly uncertain and/or data are not available and these fluxes were not included in the model used in this study.

standardised, annual data for yearly benchmarking and national monitoring of progress). It also has the added advantage that it is a well-established model both internationally and in Ireland, using Teagasc NFS data (Buckley *et al.*, 2015, 2016a,b).

In defining the system boundaries of the nutrient budgeting model to the farm-gate level (Figure 2.2), the identification of nutrient inputs and outputs over which the farmer has direct control is possible. The overall environmental pressure (nutrient source pressure) of the farm resulting from nutrient management is more directly characterised, and the contributions of different nutrient inputs and outputs to that pressure are quantified, thereby aiding in identifying changes in management practice that may reduce these nutrient source pressures.

2.3 Application of Farm Nutrient Indicators As Benchmarks

Key performance indicators (KPIs) are a widely used and well-established concept in management in a range of sectors, including supply chains (e.g. Bai and Sarkis, 2014), construction (e.g. Chan and Chan, 2004) and farm systems (e.g. Hansen *et al.*, 2005). KPIs allow assessment of performance on key aspects of a system that are considered critical to the overall success of that system and are therefore indicative of the system's success. KPIs are also central to benchmarking approaches in the management of systems. Benchmarking is the process whereby the performance of a system is compared, on the basis of KPIs, with the performance of other systems in order to rate the performance of that system, set targets for improvement and measure and monitor such improvements. Benchmarking has similarly been applied to a wide range of systems and activities.

Farm KPI and benchmarking approaches were first applied to farm economic performance using indicators such as net farm income and net profit per ha. In more recent times these approaches have been extended to other aspects of the farm system, e.g. livestock genetic merit through use of the Herd Economic Breeding Index (Berry *et al.*, 2007) (facilitated by the development and widespread application of genomic techniques and artificial insemination) and managing

GHG emissions through use of the Teagasc Carbon Navigator (Murphy *et al*., 2013).

During the 1990s several European countries (Denmark, UK, France, Germany, the Netherlands, Luxembourg, Belgium, Sweden) developed input–output accounting systems for farms, covering the areas of nutrient, pesticide and energy use, which were taken up by farmers to varying degrees (Goodlass *et al*., 2003; Halberg *et al*., 2005a,b). By far the most common indicator used for nutrient management in these systems was the farm-gate N balance, with some additionally using farm-gate N-NUE, emission risk (pointed scale, accounting for mitigation efforts, crop type and soil type) and eco-rating (indicator scale, accounting for fertiliser rates, timing, rainfall, soil type and crop N requirement). Obviously, these additional, more complicated indicators have larger data requirements and involve more implicit assumptions to calculate them.

As early as the early 1990s, the nutrient budgeting tool MINAS was developed in the Netherlands to rate and compare farm performance in nutrient management through benchmarking and to motivate practice change for both agronomic and environmental reasons (Breembroek *et al*., 1996). This tool was incorporated into Dutch law in 1998, with taxes imposed based on nutrient surpluses on individual farms (Ondersteijn *et al*., 2002). However, in 1993, the EU Court of Justice (NL vs Eur. Commission) ruled that the MINAS tool was incompatible with the EU Nitrates Directive and it was abandoned as a legislative instrument (ECJ, 2003).

In Sweden, the STANK farm-level nutrient balance tool was also developed in the 1990s and has continued to be used on a reasonably widespread basis (2274 farms in 2011) by advisors and farmers as part of the Greppa Näringen (Focus on Nutrients) voluntary programme (Greppa Näringen, 2011).

In New Zealand, the OVERSEER nutrient budgeting model was developed in the early 2000s as a farm decision support model, including fertiliser recommendations (Wheeler *et al*., 2003; Monaghan *et al*., 2007). The OVERSEER model has been extended to a relatively comprehensive farm nutrient model and management tool, designed to estimate nutrient emissions to water and GHG emissions, and it has been incorporated into New Zealand law as a tool to estimate emissions in cap-and-trade schemes, e.g. in the Lake Taupo watershed (Greenhalgh and Selman, 2012).

Halberg *et al*. (2005a) summarised that farmer response to farm-gate balance indicator systems across a range of European countries was generally positive, as long as the systems were not compulsory, and that such systems should be linked with production planning tools as used by the advisory service. Critically, they advised that "farmers and advisors need better reference values to evaluate the indicator levels on the individual farm possibly based on analysis of a larger number of farms". This essentially means a benchmarking system. The authors concluded that these systems "could become effective tools for agri-environmental improvement of European farms given further development and standardisation". The availability of farm-gate nutrient data from the Teagasc NFS (the Irish component of the EU-wide FADN) as a nationally representative data set covering the major farm sectors (Buckley *et al*., 2015) now offers the possibility of developing and standardising such a benchmarking system for Irish farms, and this is the main aim of the AgriBenchmark project.

In the Netherlands, Oenema *et al*. (2012) used the Dutch FADN data to benchmark the performance of commercial dairy farms in a small-scale study, benchmarking them against the national average, using farm-gate and grassland N balances as indicators. Dolman *et al*. (2014) and de Vries *et al*. (2015) also used FADN data to benchmark the performance of a small number of dairy farms against a number of economic, societal and environmental performance indicators, using statistical matching techniques to select a benchmarking group, or individual farm, from the FADN data (with comparable size, intensity and site-specific conditions) for each commercial farm.

In Australia, the Australian Dairy Industry Survey (part of the annual farm survey programme of the Australian Bureau of Agricultural and Resource Economics; similar to the EU FADN survey) has been used to track changes in the KPIs of whole farm N surplus (kg N ha^{-1}), N-NUE (%) and milk production surplus (g N l^{-1}) across the Australian dairy industry (Stott and Gourley, 2016). However, these data do not appear to have been applied yet in a farm benchmarking process.

The EU FADN has been used to collect KPI data on a nationally representative sample of farms that has been used to assess farm efficiency in Poland (Wrzaszcz and Prandecki, 2015; Wrzaszcz and Zegar, 2016), Hungary (Pesti and Keszthelyi, 2009) and the Netherlands (Dolman *et al*., 2014). De Koeijer *et al*. (2003) applied data envelopment analysis (DEA) to compute resource use efficiency scores for fertiliser N use on Dutch arable farms within the Dutch N fertiliser accounting scheme (MINAS; Hanegraaf and den Boer, 2003). An improvement in financial performance has been found to be significantly related to an improvement in environmental performance (Ondersteijn *et al*., 2003a). Barnes *et al*. (2009) applied DEA to English cereal and dairy farms to assess resource inefficiency in terms of N and P balance surpluses (over-application) in order to form the basis for a least-cost abatement approach or a pollution charge.

3 Nutrient Balance and Use Efficiency on Irish Farms

3.1 Objectives

The objectives of this work package were to (1) generate farm gate-level N and P balances and use efficiencies using Teagasc NFS data across a range of farm sectors, soil types and stocking rates to investigate differences and (2) generate these performance indicators over a multi-year period to investigate temporal trends in nutrient management performance and source pressures.

3.2 Materials and Methods

3.2.1 Data

The study used an unbalanced panel of 1446 NFS farms in Ireland from 2008 to 2015, representing a total of 7326 farm-year data points. Farms were randomly selected by the Central Statistics Office of Ireland and population weighted according to size and farm system (Buckley *et al*., 2015, 2016a,b; Teagasc, 2016), representing between 71,135 and 99,045 farms nationally depending on the year (mean 85,415 farms). The census of agriculture in 2010 (CSO, 2012a) showed that there were 139,860 farms in total in Ireland. However, the pig and poultry sectors were not considered in this study because of the small number of farms included in the NFS. The NFS excluded farms with a standard output below €8000 post 2012 (Hennessy *et al*., 2013; Buckley *et al*., 2015), but for this study farms below that criterion pre 2012 were included (representing on average 21% of the total farm population represented by the NFS over those years). The NFS collects data beyond normal FADN requirements, e.g. volume-based, enterprise- and crop-specific data (Buckley *et al*., 2015) and additional farm characteristics (Diazabakana *et al*., 2014). Farms that reported importing manure/slurry were excluded from the analysis as data on the quantities imported/exported were unavailable. NFS data prior to 2008 were not used as reporting on whether farms imported or exported manure/slurry began only in 2008. Therefore, the data and analyses detailed in this report cover the main production systems in Ireland and are representative of *c.* 51–71% of farms nationally depending on the year (mean 61%), and *c.* 72–83% of the total 4.568 million ha of utilised agriculture area (UAA; excluding commonage) used for agriculture in Ireland in 2010 (CSO, 2013) (mean 76% or 3.478 million ha).

3.2.2 Farm-gate nutrient balance and use efficiency

Annual import (fertiliser, forage, concentrates, livestock) and export (milk, wool, crops and livestock) data for each NFS farm were converted into imports and exports of N and P using standard coefficients (Kjeldahl, 1883; ARC, 1994; McDonald *et al*., 1995; Ewing, 2002; Jarvis *et al*., 2002; van Dijk, 2003; Centraal Veevoederbureau, 2012; Netherlands Enterprise Agency, 2016). If animal live weights were unavailable, they were estimated based on the purchase price divided by the prevailing price (€ kg^{-1}) for type and age of animal (Bord Bia, 2012; CSO, 2012b). Carcass weights were converted to live weights. Inventories were closed at the end of each year and purchases not used within the year of purchase were classed as imports in the following year. Annual farm-gate N and P balances and use efficiencies were then calculated for each NFS farm from 2008 to 2015. All results are means and national population weighted according to size and farm system, with the exception of NUEs, which are median unweighted values because of skew from extreme values.

3.2.3 Farm categories

Farms were categorised according to system type and subcategorised according to soil group (SG) and organic nitrogen (ON) stocking rate (based on S.I. No. 31 of 2014; Government of Ireland, 2014). Farm system type was based on the dominant, but not exclusive, enterprise on the farm (based on standard economic output) and included dairy, mixed livestock (mixed livestock with/without crops), suckler cattle, non-suckler cattle, sheep and tillage. SG classifications were from the National Soil Survey of Ireland (Gardiner and Radford, 1980), based on soil quality, texture, altitude, climate, topography and drainage, and were used as a proxy of land use potential (Table 3.1).

3.2.4 Estimating national agricultural nutrient source pressures

To estimate national agricultural nutrient source pressures arising from each farm type over the period 2008–2015, the mean of the annual mean values over that period was used. For each year and farm type, the number of farms represented nationally was multiplied by the mean farm size (UAA; ha) to estimate the total UAA for that farm type. The total UAA was then multiplied by the mean nutrient surplus ($t\,ha^{-1}$) to estimate the total national agricultural nutrient source pressures arising from that farm type for that year. The estimated nutrient surplus from each farm type was then summed to estimate the total aggregate agricultural nutrient source pressure for the farms represented for that year. The mean of these annual mean values (2008–2015) was then taken.

3.3 Results and Discussion

3.3.1 Performance of different farm types

Large ranges in the KPIs of farm nutrient balances and use efficiencies for farms of the same type show that there is considerable scope for nutrient management improvements (Tables 3.2 and 3.3 and Figure 3.1). Although some of this variability in performance will be related to factors beyond a farmer's control (e.g. soil type, climate and farm fragmentation), it is likely that much of this variability relates to farm and nutrient management practices that are under the control of the farmer, such as fertiliser and feed management, grazing management and all aspects of plant and animal husbandry. Therefore, using these KPIs as benchmarks to measure and motivate improved management practices would appear to have considerable scope to reduce nutrient source pressures and increase nutrient use efficiencies (at least within the observed range of performance for each farm type).

Table 3.1. Soil group classifications for NFS farms, from the National Soil Survey of Ireland

SG	Soil class	Soil class description
1	Class 1 – wide use range	Soils of wide use range have no limitations that cannot be overcome by normal management practices
1	Class 2 – moderately wide use range	Moderately wide use range refers to soils with minor limitations such as coarse texture, moderately high altitude, less favourable climatic conditions, somewhat shallow depth, hummocky topography and somewhat weak structure
2	Class 3 – somewhat limited use range	The somewhat limited use range category is used for soils with similar limitations to those of class 2 but these are present to a greater degree. For example, soils with altitude limitations in this category usually occur between 150 and 365 m, whereas those of the moderately wide use range with altitude limitations are at elevations mostly between 90 and 150 m
2	Class 4 – limited use range	Soils in this category are generally unsuited to tillage but are suited to a permanent grassland system. The predominant limitation is poor drainage
3	Class 5 – very limited use range	This class contains those soils whose agricultural potential is greatly restricted. They are widespread in the western and north-western regions, particularly in the mountain zones where high altitude and steep slopes are major limitations
3	Class 6 – extremely limited use range	This class contains soils in which agricultural potential is virtually non-existent. These are mostly mountain-top areas where steep slopes have contributed to the existence of very shallow soils with many boulders and rock outcrops. Because of these factors, the Burren, Co. Clare, has been included in this category although some extensive summer grazing is possible in the area

Source: Gardiner and Radford (1980).

Table 3.2. Mean weighted N imports, exports and balances (kg ha^{-1}) and median NUEs (%) for each SG and stocking rate (kg ON ha^{-1}) category within each system type (2008–2015)

	N imports			N exports				N KPIs	
	N fertiliser	N concentrates	Total N imports	N milk	N cash crops	N livestock exports	Total N exports	N balance	NUE
Dairy	**156**	**36**	**198**	**32**	**2**	**8**	**42**	**156**	**21.3**
SG									
1	168	37	211	35	3	9	46	165	21.8
2	142	37	186	30	1	7	38	148	21.1
3	119	30	153	23	0	7	30	123	19.2
Stocking rate									
< 85 kg ON ha^{-1}	73	13	90	12	8	4	25	65	21.9
86–130 kg ON ha^{-1}	113	24	140	22	3	6	31	109	21.9
131–170 kg ON ha^{-1}	153	35	193	31	1	8	40	153	21.2
171–210 kg ON ha^{-1}	189	46	243	41	0	9	51	193	21.2
> 210 kg ON ha^{-1}	218	57	292	49	0	12	61	230	21.0
Mixed livestock	**87**	**21**	**113**	**11**	**4**	**11**	**26**	**88**	**20.7**
SG									
1	98	24	130	12	7	12	32	98	21.5
2	83	21	108	11	1	10	22	86	19.5
3	38	7	47	3	0	5	9	38	19.1
Stocking rate									
< 85 kg ON ha^{-1}	43	9	56	3	4	9	16	40	23.8
86–130 kg ON ha^{-1}	94	19	118	12	6	10	28	90	22.9
131–170 kg ON ha^{-1}	131	28	164	17	2	12	32	132	18.8
171–210 kg ON ha^{-1}	169	47	221	24	0	16	40	181	18.0
> 210 kg ON ha^{-1}	137	79	232	29	0	17	47	185	17.9
Suckler cattle	**50**	**7**	**60**	**0**	**0**	**9**	**9**	**51**	**16.7**
SG									
1	64	7	76	0	0	12	12	64	17.6
2	44	7	53	0	0	8	8	45	16.2
3	30	4	38	0	0	6	6	32	16.1
Stocking rate									
< 85 kg ON ha^{-1}	36	4	42	0	0	7	7	35	17.4
86–130 kg ON ha^{-1}	61	9	75	0	0	12	12	63	16.3
131–170 kg ON ha^{-1}	108	14	130	0	0	18	18	112	13.8
171–210 kg ON ha^{-1}	119	15	143	0	0	20	20	123	13.7
> 210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP
Non-suckler cattle	**55**	**11**	**77**	**0**	**1**	**16**	**18**	**59**	**22.0**
SG									
1	62	13	87	0	2	18	21	66	23.4
2	49	10	68	0	0	14	15	53	21.1
3	42	8	57	0	0	10	10	47	16.9
Stocking rate									
< 85 kg ON ha^{-1}	33	6	45	0	1	11	12	33	24.6
86–130 kg ON ha^{-1}	66	14	91	0	1	18	20	71	20.2
131–170 kg ON ha^{-1}	88	20	128	0	2	25	27	100	21.6
171–210 kg ON ha^{-1}	116	24	158	0	2	27	30	128	23.4
> 210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP

Table 3.2. Continued

	N imports			N exports				N KPIs	
	N fertiliser	N concentrates	Total N imports	N milk	N cash crops	N livestock exports	Total N exports	N balance	NUE
Sheep	**38**	**12**	**56**	**0**	**1**	**12**	**15**	**41**	**26.7**
SG									
1	52	15	74	0	2	15	19	55	26.7
2	39	12	57	0	0	13	15	42	26.4
3	20	7	30	0	0	8	9	21	28.4
Stocking rate									
< 85 kg ON ha^{-1}	32	10	47	0	1	10	13	34	28.7
86–130 kg ON ha^{-1}	54	16	78	0	0	16	19	59	22.8
131–170 kg ON ha^{-1}	41	11	58	0	0	15	18	40	24.7
171–210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP
> 210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP
Tillage	**108**	**4**	**117**	**0**	**77**	**7**	**83**	**34**	**68.5**
SG									
1	109	4	118	0	78	7	85	33	70.1
2	104	4	114	0	67	5	73	41	55.7
3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Stocking rate									
< 85 kg ON ha^{-1}	108	3	116	0	81	5	87	29	70.0
86–130 kg ON ha^{-1}	104	10	132	0	22	23	45	87	37.4
131–170 kg ON ha^{-1}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
171–210 kg ON ha^{-1}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
> 210 kg ON ha^{-1}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
All	**72**	**15**	**94**	**6**	**6**	**12**	**24**	**70**	**22.2**

N/A, data not available; NP, data not presented for categories with fewer than 10 unique farms.

Table 3.3. Mean weighted P imports, exports and balances (kg ha^{-1}) and median NUEs (%) for each SG and stocking rate (kg ON ha^{-1}) category within each system type (2008–2015)

	P imports					P exports				P KPIs	
	P fertiliser	P concentrates	P forage crops	P livestock	Total P imports	P milk	P cash crops	P livestock exports	Total P exports	P balance	NUE
Dairy	**8.0**	**7.0**	**1.0**	**0.3**	**16.3**	**5.5**	**0.3**	**3.4**	**9.3**	**7.0**	**60.1**
SG											
1	8.3	7.0	1.0	0.3	16.6	6.0	0.5	3.7	10.2	6.4	64.7
2	7.8	7.1	1.0	0.4	16.3	5.2	0.1	3.1	8.3	8.0	55.0
3	7.0	5.7	0.6	0.2	13.5	3.9	0.0	2.7	6.6	6.9	54.2
Stocking rate											
< 85 kg ON ha^{-1}	6.6	2.5	0.5	0.3	9.9	2.1	1.8	1.6	5.5	4.4	53.0
86–130 kg ON ha^{-1}	7.4	4.5	0.6	0.3	12.7	3.7	0.7	2.7	7.1	5.7	58.4
131–170 kg ON ha^{-1}	8.3	6.8	0.6	0.3	16.0	5.4	0.2	3.4	9.0	7.0	59.1
171–210 kg ON ha^{-1}	8.2	8.8	1.4	0.3	18.7	6.9	0.1	3.9	10.9	7.8	63.8
> 210 kg ON ha^{-1}	8.6	10.9	2.7	0.4	22.6	8.3	0.1	4.9	13.3	9.3	63.5

Table 3.3. Continued

	P imports					P exports				P KPIs	
	P fertiliser	P concentrates	P forage crops	P livestock	Total P imports	P milk	P cash crops	P livestock exports	Total P exports	P balance	NUE
Mixed livestock	**6.5**	**4.2**	**0.6**	**0.6**	**11.9**	**1.9**	**0.8**	**4.4**	**7.1**	**4.8**	**62.3**
SG											
1	6.5	4.8	0.9	0.7	12.9	2.1	1.5	5.2	8.7	4.2	68.1
2	7.0	4.0	0.5	0.6	12.1	1.9	0.2	4.0	6.0	6.1	55.8
3	3.7	1.3	0.2	0.2	5.5	0.5	0.0	1.9	2.7	2.8	49.1
Stocking rate											
< 85 kg ON ha^{-1}	4.9	1.7	0.4	0.7	7.6	0.5	0.9	3.5	4.9	2.7	62.2
86–130 kg ON ha^{-1}	8.1	3.7	0.6	0.6	13.0	2.0	1.2	4.1	7.4	5.7	61.2
131–170 kg ON ha^{-1}	6.8	5.6	0.6	0.6	13.6	3.1	0.5	5.2	8.8	4.8	63.4
171–210 kg ON ha^{-1}	9.3	9.2	0.6	0.7	19.7	4.1	0.0	6.7	10.9	8.8	69.1
> 210 kg ON ha^{-1}	4.8	15.4	2.8	0.5	23.4	5.0	0.0	7.2	12.2	11.2	53.8
Suckler cattle	**5.0**	**1.4**	**0.4**	**0.4**	**7.2**	**0.0**	**0.0**	**3.6**	**3.6**	**3.7**	**56.2**
SG											
1	5.6	1.6	0.6	0.6	8.4	0.0	0.1	4.5	4.6	3.8	63.0
2	4.8	1.4	0.3	0.3	6.8	0.0	0.0	3.1	3.1	3.6	52.5
3	3.8	0.9	0.5	0.2	5.4	0.0	0.0	2.2	2.2	3.2	49.0
Stocking rate											
< 85 kg ON ha^{-1}	4.3	0.9	0.3	0.3	5.7	0.0	0.0	2.5	2.6	3.2	52.7
86–130 kg ON ha^{-1}	6.0	1.9	0.5	0.6	9.0	0.0	0.0	4.6	4.6	4.4	59.0
131–170 kg ON ha^{-1}	7.6	2.9	0.9	1.0	12.4	0.0	0.0	7.3	7.3	5.1	77.1
171–210 kg ON ha^{-1}	3.8	3.2	1.2	0.7	8.9	0.0	0.0	7.9	7.9	1.0	107.9
> 210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Non-suckler cattle	**5.8**	**2.4**	**0.5**	**2.8**	**11.5**	**0.0**	**0.3**	**6.8**	**7.1**	**4.4**	**64.7**
SG											
1	6.2	2.7	0.7	3.3	12.8	0.0	0.4	7.9	8.3	4.5	70.1
2	5.2	2.1	0.3	2.5	10.1	0.0	0.1	6.0	6.1	4.0	60.2
3	6.4	1.7	0.5	1.3	9.9	0.0	0.0	4.2	4.2	5.7	52.3
Stocking rate											
< 85 kg ON ha^{-1}	4.1	1.3	0.2	2.2	7.7	0.0	0.2	4.7	4.9	2.8	65.4
86–130 kg ON ha^{-1}	6.7	2.9	0.5	3.0	13.1	0.0	0.3	7.7	8.0	5.1	63.3
131–170 kg ON ha^{-1}	8.5	4.2	1.4	4.2	18.3	0.0	0.4	10.8	11.1	7.2	67.9
171–210 kg ON ha^{-1}	10.2	5.0	1.4	3.8	20.4	0.0	0.5	11.7	12.2	8.2	62.8
> 210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Sheep	**4.5**	**2.2**	**0.5**	**1.0**	**8.2**	**0.0**	**0.2**	**4.6**	**4.8**	**3.4**	**62.3**
SG											
1	5.3	2.7	0.6	1.3	10.1	0.0	0.5	5.7	6.1	3.9	70.3
2	4.6	2.3	0.4	1.2	8.6	0.0	0.0	4.9	5.0	3.6	59.5
3	3.3	1.3	0.4	0.3	5.3	0.0	0.0	2.8	2.8	2.5	58.6
Stocking rate											
< 85 kg ON ha^{-1}	3.6	1.9	0.4	0.9	6.8	0.0	0.2	3.8	4.0	2.7	62.3
86–130 kg ON ha^{-1}	6.8	3.1	0.7	1.4	12.0	0.0	0.1	6.3	6.4	5.7	57.6
131–170 kg ON ha^{-1}	5.1	2.2	0.6	0.8	8.6	0.0	0.0	5.7	5.8	2.9	68.4
171–210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
> 210 kg ON ha^{-1}	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP

Table 3.3. Continued

	P imports					P exports				P KPIs	
	P fertiliser	P concentrates	P forage crops	P livestock	Total P imports	P milk	P cash crops	P livestock exports	Total P exports	P balance	NUE
Tillage	**18.7**	**0.8**	**0.4**	**1.4**	**21.3**	**0.0**	**15.3**	**2.8**	**18.1**	**3.2**	**89.4**
SG											
1	19.2	0.8	0.4	1.4	21.8	0.0	15.5	2.9	18.4	3.4	90.3
2	15.5	0.8	0.8	0.7	17.8	0.0	13.5	2.3	15.8	2.0	83.0
3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Stocking rate											
< 85 kg ON ha^{-1}	18.8	0.6	0.4	1.0	20.9	0.0	16.2	2.2	18.4	2.5	90.5
86–130 kg ON ha^{-1}	17.2	2.1	0.7	5.6	25.8	0.0	4.2	9.9	14.1	11.7	64.7
131–170 kg ON ha^{-1}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
171–210 kg ON ha^{-1}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
> 210 kg ON ha^{-1}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
All	**6.6**	**2.9**	**0.6**	**1.4**	**11.4**	**1.0**	**1.1**	**4.8**	**7.0**	**4.5**	**63.5**

N/A, data not available; NP, data not presented for categories with fewer than 10 unique farms.

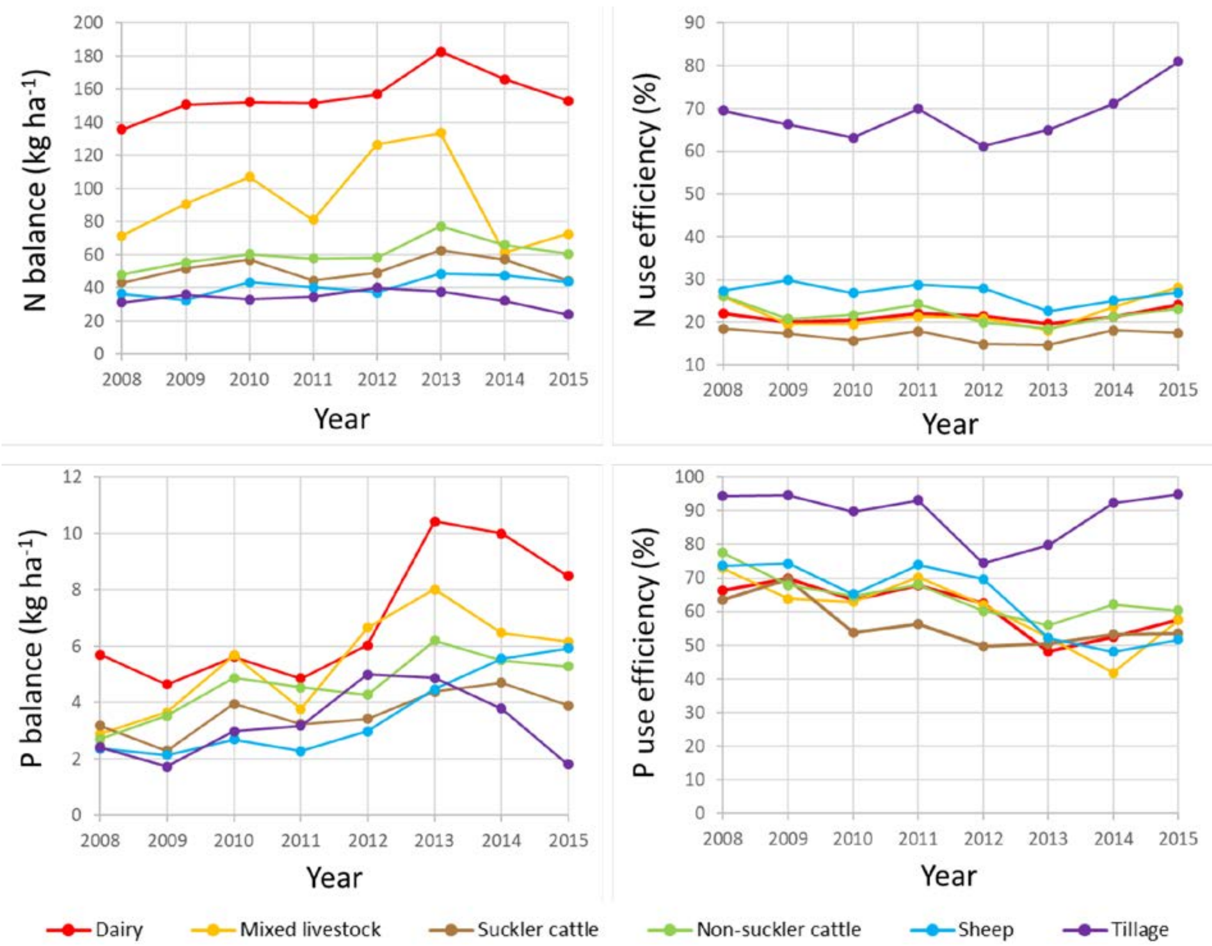

Figure 3.1. Annual mean N and P balances and use efficiencies from 2008 to 2015 for each farm type.

For both N and P, total imports are driven principally by fertiliser for all farm types (Tables 3.2 and 3.3 and Figures 3.2 and 3.3). However, concentrates make up a significant proportion of N and P imports and are roughly as important as fertiliser in terms of P imports for dairy and mixed livestock. Livestock and forage crops make up the remaining, and significantly smaller portion of, imports. Total exports of N and P are driven principally by livestock (for suckler/non-suckler cattle, mixed livestock and sheep farms), milk (for dairy farms) or crops (for tillage farms). These factors are therefore primary drivers of inter-annual differences in the KPIs of nutrient balance and NUE (see section 3.3.2).

Dairy and tillage systems are the most intensive with the highest nutrient inputs, principally in the form of fertiliser (dairy and tillage) and concentrate feeds (dairy) and therefore might be thought to pose the greatest risk of environmental losses (Buckley and Carney, 2013; FAO, 2015; Murphy *et al.*, 2015; Kelly *et al.*, 2016). However, this study shows that dairy systems are not the worst performers in terms of NUE and that tillage systems are actually the best performers for both balances and use efficiencies.

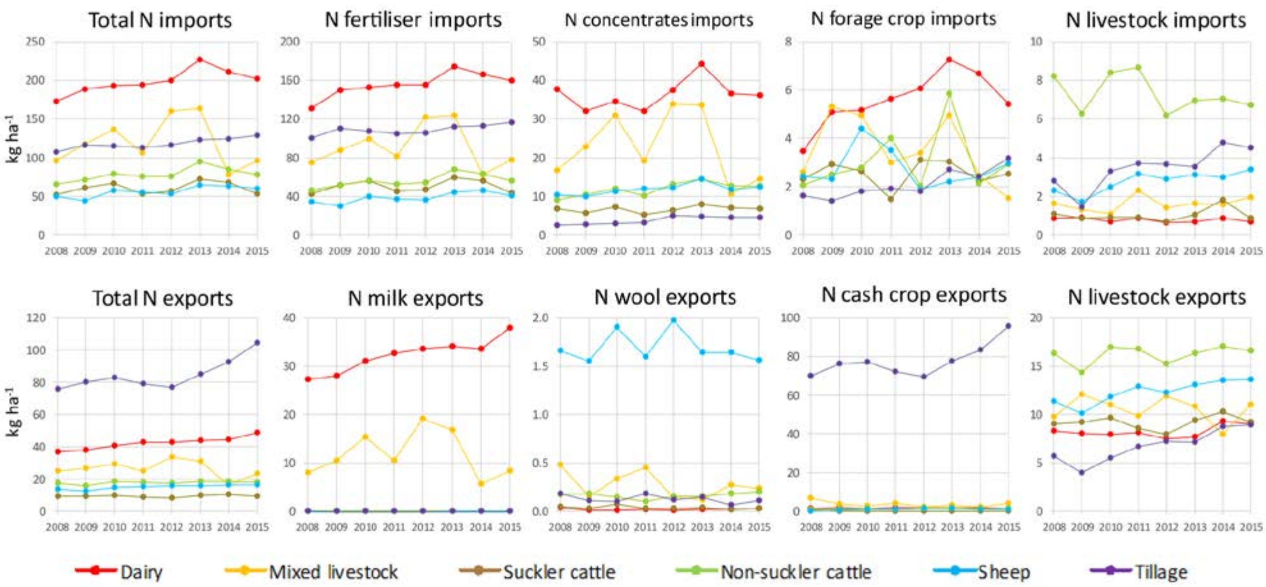

Figure 3.2. Annual mean N imports (top) and exports (bottom) from 2008 to 2015 for each farm type.

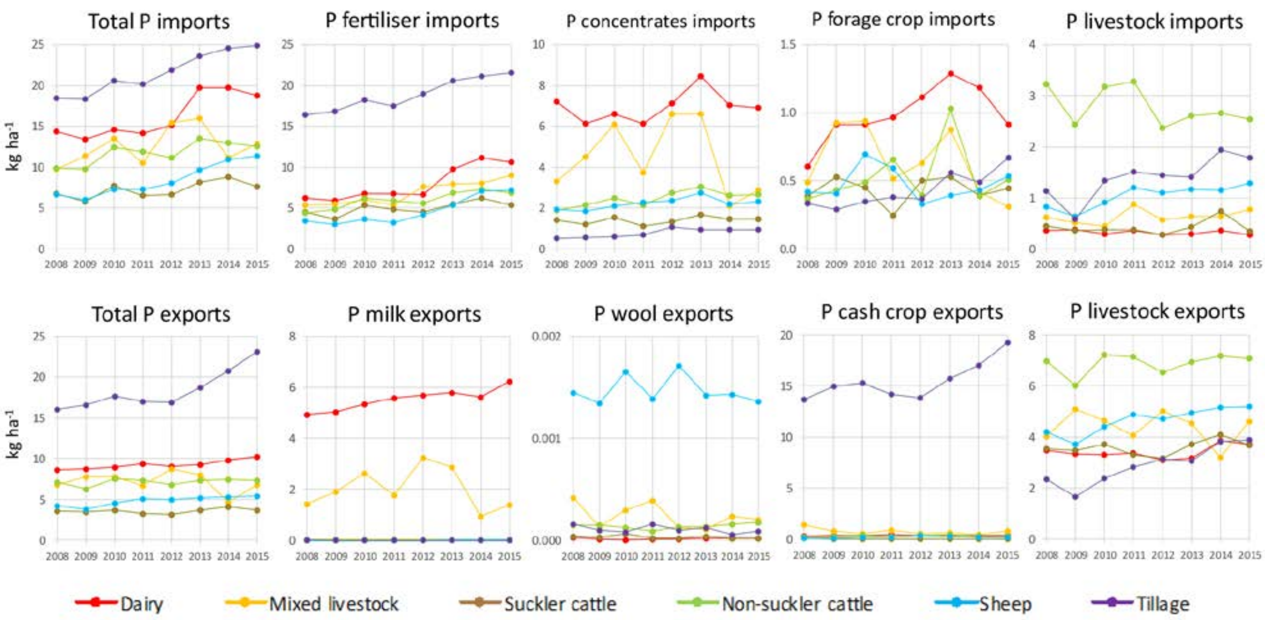

Figure 3.3. Annual mean P imports (top) and exports (bottom) from 2008 to 2015 for each farm type.

Although tillage is often thought of as being relatively intensive because of fertiliser import requirements, tillage N and P surpluses were the equivalent of only 22% and 46% of the dairy N and P surpluses, respectively, and N- and P-NUEs were 2.6 and 1.4 times higher, respectively, for tillage than for the next most efficient sector (sheep and non-suckler cattle systems). This reflects the greater opportunities for nutrient loss and greater challenges to efficient recovery of nutrients in farm products, particularly for N, in livestock systems than in tillage systems.

Although the dairy sector had the largest N and P surpluses out of the six sectors (related to its intensiveness in terms of stocking rates and nutrient imports), N- and P- NUEs were third and second lowest, respectively. Mihailescu *et al*. (2014, 2015a,b) also calculated N and P balances and use efficiencies for 21 Irish dairy farms and the results were broadly in line with those found in the study by Buckley *et al*. (2015) for NFS specialist dairy farms, although for a different time period (2009–2011 compared with 2012). Mihailescu *et al*. (2014) reported mean N balances of 175 kg N ha^{-1} and NUE of 23% whereas Buckley *et al*. (2015) reported mean values of 145 kg N ha^{-1} and 25%, respectively, for specialist dairy systems. The mean P balances and use efficiencies in the study by Mihailescu *et al*. (2015b) were 5.1 kg P ha^{-1} and 70%, respectively, whereas those in the study by Buckley *et al*. (2015) were 6.2 kg P ha^{-1} and 72%, respectively.

Although the suckler-based cattle system had the third lowest N and P surpluses, it had the worst (lowest) N and P use efficiencies. The non-suckler cattle and sheep sectors both performed relatively well for nutrient balance and NUEs.

When comparing SGs (Tables 3.2 and 3.3), all sectors showed trends of lower fertiliser and concentrate use and lower total imports and exports, with decreasing land use potential, from SG1 to SG3, for both N and P. N balances and N- and P-NUEs also showed a downward trend with decreasing land use potential (except for the tillage sector for N balance and the sheep sector for N-NUE). Although P balances showed a downward trend for the suckler cattle, sheep and tillage sectors, the other three sectors showed no trend because for SG2 or SG3 the incremental reductions in total imports compared with SG1 or SG2 were smaller than the incremental reductions in exports.

As stocking rates increase, the results show that all livestock sectors import more N and P fertiliser and feed and export more N and P through more agricultural produce and balance surpluses tend to increase (albeit with a couple of incremental exceptions). However, NUE trends vary by system and nutrient: N-NUE decreases with increasing stocking rate for the mixed livestock and suckler cattle sectors and slightly decreases for the dairy sector, whereas P-NUE increases with stocking rate for these sectors. Both non-suckler cattle and sheep sector N- and P-NUEs show no consistent trends. The downward trend in N-NUE for the first three sectors is predominantly due to incremental increases in fertiliser use, which are not converted efficiently into additional agricultural produce.

3.3.2 Temporal trends

Numerous factors contribute to inter-annual variations in nutrient balances and NUEs. With regard to management decisions, fertiliser imports were found to be the most significant (Figures 3.2 and 3.3). In addition, as a result of a combination of government initiatives for sustainable intensification (Food Harvest 2020 and Food Wise 2025) and the abolishment of milk quotas in 2015, dairy herds expanded and milk N and P exports increased sharply that year. Interannual variations can also be caused by factors outside a farmer's control, such as weather, pasture growth, housing periods, fertiliser/feed costs and market prices (Mihailescu *et al*., 2014, 2015a,b; Norton *et al*., 2015; Mu *et al*., 2016;). For example, a national fodder shortage in Ireland in 2013 following unusually cold and wet weather caused increases in imports of forage, concentrates and fertiliser and hence nutrient balances increased and NUEs decreased in that year for all livestock sectors (except suckler cattle NUEs).

Temporal analysis shows that mean N balances across all sectors from 2008 to 2015 tended to increase up to 2013 and decrease after this. Correspondingly, mean N-NUE tended to decrease up to 2013 and increase after this. P surpluses have tended to increase (by 23–151%) and use efficiencies have decreased (by 13–30%) across the period from 2008 to 2015 for all livestock sectors (Table 3.4). In contrast, tillage P surpluses increased from 2008 to 2013 and then sharply decreased in 2014–2015 (–25% change compared with 2008) and use efficiencies remained

Table 3.4. Percentage change in mean N and P nutrient balances and NUEs in 2015 relative to 2008

Sector	% change			
	N balance	N-NUE	P balance	P-NUE
Dairy	+12.8	+9.8	+48.9	–13.2
Mixed livestock	+1.7	+8.2	+112.5	–21.0
Suckler cattle	+2.9	–5.0	+22.8	–15.5
Non-suckler cattle	+25.9	–11.4	+94.6	–22.1
Sheep	+20.1	–1.4	+150.5	–29.8
Tillage	–23.5	+16.6	–25.0	+0.5

relatively constant with the exception of a sharp spike and dip in 2012–2013.

Buckley *et al*. (2016a,b) also used the NFS data to look at trends in N and P balances and use efficiencies of 150 nationally representative dairy farms between 2006 and 2012, which coincided with the introduction of the EU Nitrates Directive regulations in 2006. They found reductions in N and P surpluses because of reduced chemical fertiliser inputs and increased use efficiencies, with increasing milk solid outputs per ha and per cow, suggesting that regulations had had positive impacts on environmental/source pressures. The results from this study (see Table 3.4 and Chapter 4) indicate that higher N balances associated with intensification (at least for the dairy sector) can be associated with increased N-NUE.

Total N imports showed similar trends for all livestock farms, tending to increase moderately from 2008 to 2012, before peaking in 2013 and then decreasing to pre-2013 levels. Tillage N imports remained relatively constant at around 116 kg ha^{-1} pre 2013 before increasing gradually to 128 kg ha^{-1}. For most livestock farms, exports remained relatively constant and lower than 19 kg ha^{-1}. For the dairy sector, total N exports increased steadily from 37 kg ha^{-1} to 49 kg ha^{-1}, driven largely by increased milk exports (from 27 to 38 kg ha^{-1}), and this trend appeared to accelerate after 2013–2014 because of increased livestock exports [associated with higher stocking rates of 2.0 livestock units (LU) ha^{-1} compared with 1.8 LU ha^{-1} pre 2013]. This dairy intensification resulted in many mixed livestock farms becoming reclassified as dairy farms in 2014–2015 as more dairy cows entered the herd. This was likely, at least partly, because of farms increasing their dairy herd numbers in advance of the end of the milk quota system in 2015. For mixed livestock farms, total N exports decreased after 2013, because of a large decrease in milk N exports associated with the reclassification of many of these farms as dairy farms. For tillage, total N exports showed a large increase post 2012 to a maximum of 105 kg ha^{-1}, driven mostly by increased crop N exports.

For all sectors, the fodder crisis in 2012/2013 increased imports of forage crops, concentrates and fertilisers relative to pre 2012; post 2013 these imports tended to decrease for most sectors. Notably, this was generally not the case for P fertiliser imports. The fodder crisis therefore increased N/P surpluses and decreased N/P use efficiencies in all livestock sectors in 2013 (except for suckler farm P-NUE).

Total P imports tended to increase for all sectors over the period from 2008 to 2015, particularly for the sheep, tillage and dairy sectors (showing a shift change from 2013 onwards). These trends largely followed the trend in fertiliser P imports. The effects of a peak in fertiliser P prices in 2008–2009 (€555 t^{-1} of granular superphosphate in 2009), followed by a sharp decline in 2010 (€417 t^{-1} in 2014; CSO, 2018), may help explain the lower, and then higher, fertiliser P imports over those years, respectively. In addition, changes to the National Action Programme under the EU Nitrates Directive that came into force in 2014 (Government of Ireland, 2014) provided for greater farm P import allowances, particularly on dairy farms, because of changes in the system for accounting for P imports in concentrate feeds. As with N, the mixed livestock sector showed a large drop in total P imports in 2013–2014, again associated with a shift of farms from mixed livestock to dairy.

Total P exports from livestock farms remained relatively constant over 2008–2015, except for increases from dairy and sheep farms, largely driven by increases in milk and livestock exports, respectively. For tillage, total P exports increased steadily from 16 to 23 kg ha^{-1}, largely because of increased crop and, to a lesser extent, livestock exports.

For the dairy sector, increased P exports in 2014 and 2015 were maintained, despite slightly lower total P imports (compared with the peak of 2013) from concentrates and forage crops, and also reductions in fertiliser P imports in 2015, causing overall P surpluses and use efficiencies to sharply decrease and increase, respectively (although they remained worse than levels in 2011–2012). This trend was also found in the other sectors, but for sheep and tillage farms it was caused by exports increasing proportionally more than import increases. For all sectors except for non-suckler cattle farms, livestock exports generally increased from 2008 to 2015, particularly for tillage farms (by 65%).

Over the study period, sheep farms showed a particularly large percentage increase in P balance, of 151% (see Table 3.4 and Figure 3.1). This was largely because of a combination of the relatively small initial P balance in 2008 and an increase in fertiliser P imports and proportionally lower increases in P exports (see Figure 3.2). As a result, sheep farms went from having the lowest P balance (2.4 kg P ha^{-1}) to having a P balance that was higher than that for suckler/non-suckler cattle and tillage farms, at 5.9 kg P ha^{-1}. As sheep farms are often located within the catchments of vulnerable (e.g. karst groundwater) and high status (e.g. western lakes) aquatic systems, this trend may be worth monitoring and investigating further.

For tillage farms, there was a sharp spike and dip in P balance and use efficiency, respectively, in 2012–2013. This may have been caused by an excessively wet summer in 2012, which reduced crop growth and exports, as well as a large increase in fertiliser P imports. In fact, larger increases in fertiliser P imports from 2012 to 2015 relative to 2008–2011, and comparatively negligible increases in other import types, were associated with a consistent sharp increase in crop and livestock exports, which offset the increased imports and led to decreasing P balances and increasing P-NUE.

3.3.3 National agricultural nutrient source pressures

General trends of improved N and P management performance (reduced surpluses and increased efficiencies) across farm types (except for sheep farms) in the last 2 or 3 years of this study (see Figure 3.1) indicate improved sustainability and reduced nutrient source pressures. However, from 2008 to 2015, all livestock farms experienced significant increases in P surpluses, ranging from 23% to 150% (suckler cattle and sheep farms, respectively), and significant decreases in P-NUE, ranging from –13% to –30% (dairy and sheep farms, respectively) (see Table 3.4), indicating that P source pressures have increased overall over this time period. These increased P balances are largely the result of increased fertiliser P imports. N surpluses increased considerably only for dairy, non-suckler cattle and sheep farms, but for dairy farms this was associated with an increased NUE. Tillage P surpluses decreased by 25% at no expense to P-NUE and tillage N surpluses decreased by 24% with a 17% increase in N-NUE.

As soil P deficiency is found in over half of all soil samples nationally (Teagasc, 2018a), and many NFS farms have P balances below 0 kg ha^{-1} (see Figure 4.2), many farms may require P surpluses over a period of time to build soil P fertility in P-deficient soils to reach agronomically optimum levels. Furthermore, as discussed in Chapter 4, P surpluses lower than approximately 3 kg ha^{-1} could be considered unsustainable because of agronomic/livestock requirements, unaccounted environmental losses and P immobilisation pools. Thus, in 2008, only the dairy sector was well above this threshold. It is only from 2013 onwards that all livestock sectors were, on average, above this threshold. There is also a time lag between changes in P management at the farm gate and field level and changes in soil test P concentrations. Therefore, the resultant nutrient source pressure from increased farm-gate P balances will depend very much on where the additional P is applied: application following best management practices to P-deficient soils may improve soil fertility (and also improve N-NUE) without increasing environmental source pressure, but application to high P soils may be of no agronomic benefit, while increasing P source pressure. Application of P to high P soils is forbidden in most circumstances under the National Action Programme of the Nitrates Directive in Ireland (S.I. No. 605 of 2017; Government of Ireland, 2017) and good agricultural practice should involve regular soil testing to avoid such practices.

Dairy farms clearly exert the greatest nutrient source pressure in terms of both surplus per ha (mean

156 kg N ha^{-1} yr^{-1} and 7.0 kg P ha^{-1} yr^{-1}) and estimated national aggregate agricultural surplus (111,210 t N yr^{-1} and 4994 t P yr^{-1}) (Table 3.5), equivalent to 43% and 31% of the national agricultural N and P surpluses, respectively, from only 21% of the total UAA (Figure 3.4) (results representing, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally). Although non-suckler cattle farms have a relatively moderate nutrient surplus per ha (mean 59 kg N ha^{-1} yr^{-1} and 4.4 kg P ha^{-1} yr^{-1}), they account for the second highest contribution to the estimated agricultural surplus (60,269 t N yr^{-1} and 4498 t P yr^{-1}), equivalent to 23% of the agricultural N surplus and 28% of the agricultural P surplus. This is because this sector makes up the largest land area (1,014,043 ha; 29% of the total UAA). From a nutrient source pressure perspective, therefore, dairy farms in particular and, to a lesser degree, non-suckler cattle farms exert the greatest pressure and it could be argued that particular efforts should be made to reduce that source pressure and minimise risks to the environment on these farms. With the ending of the EU milk quota system in 2015, and the planned expansion in milk production under the Food Harvest 2020 and Food Wise 2025 programmes, the need to encourage improved nutrient management on dairy farms, in particular, is likely to increase.

Table 3.5. Estimates of the national aggregate agricultural N and P balances (nutrient source pressure) attributed to each of the main farm types, using 2008–2015 data

Farm sector	Mean number of farms represented nationally by annual NFS sample	Mean farm size (UAA, ha)	Total utilised agricultural area (ha)	Mean N balance (kg ha^{-1} yr^{-1})	Mean P balance (kg ha^{-1} yr^{-1})	Total N surplus (t yr^{-1})	Total P surplus (t yr^{-1})
Dairy	15,629	51.4	711,945	156.2	7.0	111,210	4994
Mixed livestock	5304	54.3	254,395	87.6	4.8	22,287	1233
Suckler cattle	19,236	33.2	608,586	50.6	3.7	30,816	2224
Non-suckler cattle	29,165	34.2	1,014,043	59.4	4.4	60,269	4498
Sheep	14,508	42.9	595,688	40.9	3.4	24,372	2033
Tillage	6797	58.1	293,392	33.9	3.2	9939	943
Total	90,638		3,478,049			258,893	15,925

Results representing, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally.

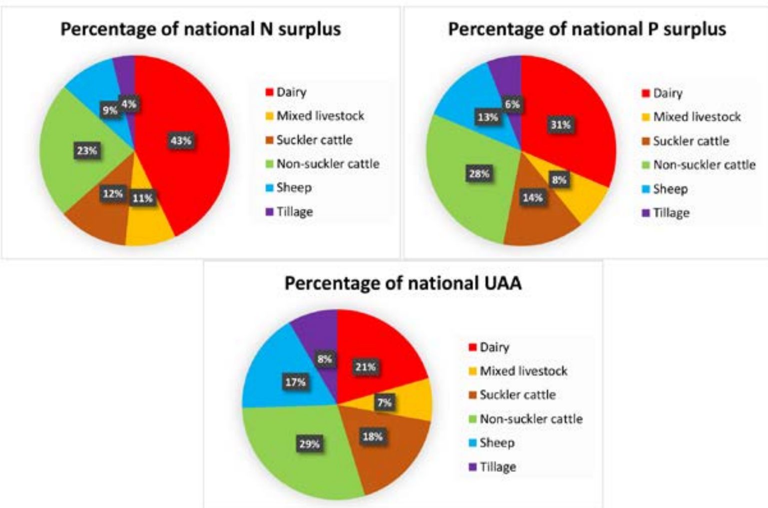

Figure 3.4. Share of the estimated total national aggregate agricultural N and P surplus and UAA attributed to each farm type for the period from 2008 to 2015 (results representing, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally).

4 Benchmarking Analysis

4.1 Objectives

This study aimed to establish nationally representative benchmarks of farm-gate N and P balances and use efficiencies in Ireland that could be used as targets by farmers and policymakers to motivate nutrient management improvements. The objectives were to (1) identify minimum sustainable balances, (2) benchmark NFS farms for each farm type, soil type and production intensity and (3) use scenario analysis to estimate potential economic gains and reductions in national surpluses (nutrient source pressures) that could be achieved through reaching benchmark targets.

4.2 Materials and Methods

Teagasc NFS data and farm nutrient balance analyses were carried out as detailed in section 3.2.

4.2.1 Identifying minimum sustainable nutrient balances

In this study, we took the approach that benchmarking should identify only long-term sustainable benchmark farms that (1) have nutrient balances that are sufficient to offset potential unaccounted and unavoidable environmental losses and maintain long-term soil fertility, (2) maintain agronomically optimum soil nutrient concentrations, (3) have a high NUE, (4) are economically profitable, (5) meet livestock nutritional requirements and (6) comply with agri-environmental regulations. A literature review was therefore undertaken to identify minimum sustainable farm-gate N and P balances that meet each of these criteria, in order to remove data points with unsustainably low balances prior to running benchmarking analysis.

4.2.2 Maintaining long-term soil fertility

Farm-gate nutrient balances do not consider environmental losses because of a lack of data and high spatiotemporal variability. Benchmark balances must therefore be set at a level that is sufficient to offset unavoidable environmental losses typically found in Irish agriculture in order to avoid loss of soil fertility in the medium to long term. Although it can be argued that farm-gate benchmarks should be set as close to balance (zero) as possible to reduce nutrient source pressure, at least some environmental losses are inevitable in any system, being controlled by soil and hydrological characteristics (Murphy *et al*., 2015; Thomas *et al*., 2016a,b, 2017) and climate (Mellander *et al*., 2018) among other factors. For P, catchment monitoring studies in Ireland show that in-stream total P losses are typically $< 1\,kg\,ha^{-1}\,yr^{-1}$ in the wettest years, even in catchments with predominantly poorly drained soils and associated high run-off potential (Kirk McClure Morton, 1999; McGuckin *et al*., 1999; McGuckin, 2000; Jordan *et al*., 2005, 2007, 2012; Smith *et al*., 2005; Ulén *et al*., 2007; Melland *et al*., 2012; Lewis *et al*., 2013; Mellander *et al*., 2013, 2015, 2016; Murphy *et al*., 2015; Shore *et al*., 2016, 2017; Mockler *et al*., 2017). For N, there is high spatiotemporal variability and uncertainty in rates of environmental losses and other unaccounted input/output factors (biological N fixation, atmospheric N deposition, immobilisation and mineralisation) (e.g. Oenema *et al*., 2003; McAleer *et al*., 2017) and a lack of farm-specific data. Furthermore, the relationship between N balances and nitrate leaching/groundwater concentrations has been found to be poor, unclear or non-existent both in Ireland (Humphreys *et al*., 2008; Burchill *et al*., 2016) and internationally (Lord *et al*., 2002; Schröder *et al*., 2004; de Ruijter *et al*., 2007). Therefore, this precludes identifying minimum farm-gate N balances that would offset unavoidable environmental losses.

4.2.3 Maintaining agronomically optimum soil nutrient concentrations

Benchmark farms must have nutrient balances that are sufficient to maintain agronomically optimum soil nutrient concentrations and prevent unsustainable mining of soil nutrient reserves (Aarts *et al*., 2000a,b; Schröder *et al*., 2003; Gourley *et al*., 2007; Kleinman *et al*., 2011; Gourley and Weaver, 2013; Godinot *et al*., 2014; Ruane *et al*., 2014; Davidson *et al*., 2015; Norton *et al*., 2015; Zhang *et al*., 2015). Recommended maintenance rates of P fertiliser application at the field scale are based on replacing offtakes in grass/crops, i.e. they aim to achieve a field-level balance, thus maintaining soil fertility (Government of Ireland, 2014; Teagasc, 2016, 2017).

A literature review and meta-analysis found that the agronomically optimum range of soil Morgan P concentrations related to a farm-gate P balance of 1.5–4.5 kg ha^{-1} for grassland livestock farms (Mounsey *et al*., 1998; Kirk McClure Morton, 1999; Humphreys *et al*., 2006; Ruane *et al*., 2014; Mihailescu *et al*., 2015b; Bailey, 2016; Roberts *et al*., 2017). Aiming for small surpluses could also offset potential issues with soil type-specific differences in P sorption, saturation and desorption rates, which are currently unaccounted for in fertiliser maintenance rates (Daly *et al*., 2015; Roberts *et al*., 2017). Because of the high spatiotemporal variability in soil N plant availability (there are no reliable soil tests for long-term N plant availability), relating farm-gate N balances to agronomically optimal soil N levels was not considered.

4.2.4 Maintaining livestock dietary requirements

Benchmark farm-gate P balances must also be high enough to maintain livestock dietary requirements to avoid nutrient deficiencies and associated impacts on livestock health and productivity. Numerous studies and life cycle experiments demonstrate that the minimum requirement of dietary P is between 3.0 and 4.2 g P kg^{-1} of dry matter for moderate- to high-yielding dairy cows (from 7500 to >11,000 l milk $lactation^{-1}$) (Brodison *et al*., 1989; Agriculture and Food Research Council, 1991; Morse *et al*., 1992; Metcalf *et al*., 1996; Peel *et al*., 1997; Valk and Šebek, 1999; Withers *et al*., 1999; Valk *et al*., 2000; Wu *et al*., 2000, 2001; Knowlton and Herbein, 2002; Knowlton *et al*., 2004; Lopez *et al*., 2004a,b; Satter *et al*., 2005; Odongo *et al*., 2007; Arriaga *et al*., 2009; Wang *et al*., 2014). Reducing dietary P levels to 3.6 g P kg^{-1} of dry matter intake for high-yielding dairy cows in Northern Ireland has been shown to have no detrimental impact on nutrition or milk yield (Ferris *et al*., 2010a,b; O'Rourke *et al*., 2010). Bailey (2016) related this dietary P level to dairy farm-gate P balances of 2.7 kg P ha^{-1}. No other studies relating farm-gate P balances to optimum livestock dietary requirements were found. In addition, there is a lack of studies relating optimum livestock dietary N requirements to farm-gate N balances.

4.2.5 Complying with agri-environmental regulations

Benchmark farms must also comply with EU Nitrates Directive statutory limits on stocking rates and associated chemical fertiliser application rates and timings, etc. (Council of the European Union, 1991; Government of Ireland, 2014; Teagasc, 2016). A minimal number of farms that did not comply with the Nitrates Directive stocking limit of 250 kg ON ha^{-1} were removed prior to analysis. Farm compliance with maximum chemical fertiliser applications could not be checked, as the NFS collects farm-gate rather than field-scale data and soil N and P indices were unknown.

4.2.6 Minimum sustainable farm-gate balances

On the basis of the factors outlined above, minimum sustainable farm-gate N and P balances of 0 kg ha^{-1} and 3 kg ha^{-1}, respectively, were selected. As outlined above, there was evidence from a number of perspectives for setting a minimum sustainable balance of 3 kg P ha^{-1}. However, because of a lack of evidence, and the greater complexity of N cycling, it was not possible to take the same approach for N. Operating a negative N balance was considered likely to be unsustainable over long time periods as it would likely result in degradation of soil N fertility. Therefore, 0 kg ha^{-1} was taken as the minimum sustainable N balance. Two copies of the NFS data set were then used to treat N and P benchmarking separately. The data points below the minimum sustainable N balance (for the N data set only) or P balance (for the P data set only) were removed prior to benchmarking analysis.

4.2.7 Establishing benchmarks and explaining performance

Benchmark farms need to be economically profitable (Ondersteijn *et al*., 2003a; Buckley and Carney, 2013; Mihailescu *et al*., 2015a; Ryan *et al*., 2015; Lynch, 2018). For both N and P data sets, farm economic performance was benchmarked using percentile rankings of farm gross margin (gross output minus direct costs; € ha^{-1}) per ha of UAA within its farm system category.

The relationship between production intensity (total N or P exports in kg ha^{-1}) and the N or P balance (kg ha^{-1}) was then investigated for each farm type using quantile regression analysis, which estimates the conditional mean or other quantiles of the response variable given certain values of the predictor variable. Percentile regression lines (10th, 25th, 50th, 75th and 90th percentiles) were fitted to the relationship [similar to the studies by Davidson *et al*. (2015) and Norton *et al*. (2015) and the isoquant approach used by Nevens *et al*. (2006) and Cela *et al*. (2014)] to identify farms with the lowest nutrient surpluses for each level of production intensity (data points located beneath the Q75 or Q90 lines). Data from all years were used to account for inter-annual variations controlled by factors such as farm management, weather, grass/crop growth, housing periods, fertiliser/feed costs and market prices (Mihailescu *et al*., 2014, 2015a,b; Norton *et al*., 2015; Mu *et al*., 2016). The resultant benchmarks are thus representative of time-integrated farm performance (integrated over 8 years). Excessive surpluses (varying according to production intensity) were then identified for each farm type using the Q10 regression line (i.e. points located above the Q10 line were judged to have excessively high surpluses, higher than those of 90% of the other farms of the same farm type at the same production intensity).

Data points in each scatter plot were then colour coded based on gross margin (€ ha^{-1}) percentile rankings for each farm system. Thus, for N and P, optimal benchmark zones were identified as farms with the lowest surpluses and highest gross margins (€ ha^{-1}) for a given level of production intensity (blue or dark-green points below the Q75 line; see Figures 4.3–4.5). The average farm characteristics and nutrient balance components of this optimal benchmark zone cohort were then compared with those from the poorer performing cohorts, to identify reasons for their benchmark nutrient management performance (Halberg *et al*., 2005b; Nevens *et al*., 2006).

4.2.8 Scenario analysis

To assess potential economic gains and reductions in surpluses and nutrient source pressure that could be achieved through moving towards benchmark targets four different benchmarking scenarios were explored:

1. all non-benchmark farms reach the optimal benchmark zone for their category;
2. all non-benchmark farms reach the next best performing zone (regression line) in their category;
3. all farms with excessive nutrient surpluses (highest 10%) reach the next best performing zone;
4. all farms, including those with a N surplus of < 0 kg ha^{-1} and those with a P surplus of < 3 kg ha^{-1} (i.e. the complete NFS data set), reach the optimal benchmark zone for their category.

The first three used only data points with minimum sustainable nutrient balances (i.e. N surplus ≥ 0 kg ha^{-1} or P surplus ≥ 3 kg ha^{-1}). For scenarios 1 and 4, the mean difference in nutrient balance, NUE and balance components between each non-benchmark farm and the mean values of optimal benchmark zone farms was calculated. For scenario 2, the mean of the difference in the nutrient balances, NUEs and balance components between a performance zone and the mean values of the next best performing zone was calculated. For scenario 3, the mean of the difference in values between Q1–10 and the mean of the Q11–25 zone calculated in scenario 2 was calculated. Results are provided for target farms only in each scenario (the analysis did not include farms in the optimal benchmark zone for scenarios 1 and 4 or farms located below the Q75 or Q10 percentile regression line in scenarios 2 and 3, respectively). The results were national farm population weighted and hence are representative at the national scale, as with all other results in this report (except for median NUEs).

Scenarios 1 and 4 represent extreme cases of all non-benchmark farms achieving benchmark performance. These scenarios were run to illustrate the maximum potential improvements within the currently (2008–2015) observed range of farm performance. This is not to suggest that these are realistically or easily achievable scenarios for all farms. Factors beyond the control of the farmer, such as soil and climatic limitations or farm fragmentation, may well prevent many farms from achieving the benchmarked level of performance.

Changes in fertiliser and feed costs, gross margins and other variables for each scenario were also calculated using the same approach. For gross margins, it is important to note that potential changes would reflect changes in all aspects of farm management, and not just nutrient management, such as herd health, grass and grazing management, technologies and energy use, soil management, herd genetic merit and fertility.

The potential impact of chemical fertiliser N use changes on direct GHG emissions was also estimated at the national level based on Ireland's provisionally revised 1.24% emission factor for N_2O from fertiliser N applied to soils (i.e. 1.24 kg N_2O-N is emitted for every 100 kg of fertiliser-N applied) (EPA, 2018).

4.3 Results and Discussion

4.3.1 Benchmarking

As production intensity increases (with higher total N or P exports), N and P balances tend to increase for livestock farms, but with much greater variability for P (Figures 4.1 and 4.2). For tillage farms, N and P balances tend to decrease with increasing production intensity. For all sectors, gross margins increase with production intensity. However, benchmark farms minimise surpluses to relatively low levels for a given level of production intensity (Figures 4.3 and 4.4). Within all farm types, large ranges in nutrient balances between benchmark farms (below the Q75 line) and poorer performers (e.g. above the Q10 line) show that there is considerable room for reducing surpluses on some farms. Although some of this variability in performance will be related to factors beyond a farmer's control (e.g. soil type, climate and farm fragmentation), it is likely that a significant proportion of this variability relates to farm and nutrient management practices that are under the control of the farmer, such as fertiliser and feed management, grazing management and all aspects of plant and animal husbandry (see section 4.3.2). Therefore, using these KPIs as benchmarks to measure and motivate improved management practices would appear to have considerable scope to reduce nutrient source pressures and increase nutrient use efficiencies (at least within the observed range of performance for each farm type).

Aiming for a minimum sustainable 3 kg P ha^{-1} balance would appear to be achievable for low- and high-intensity farms among all farm types and SGs. However, aiming for a 0 kg N ha^{-1} balance would

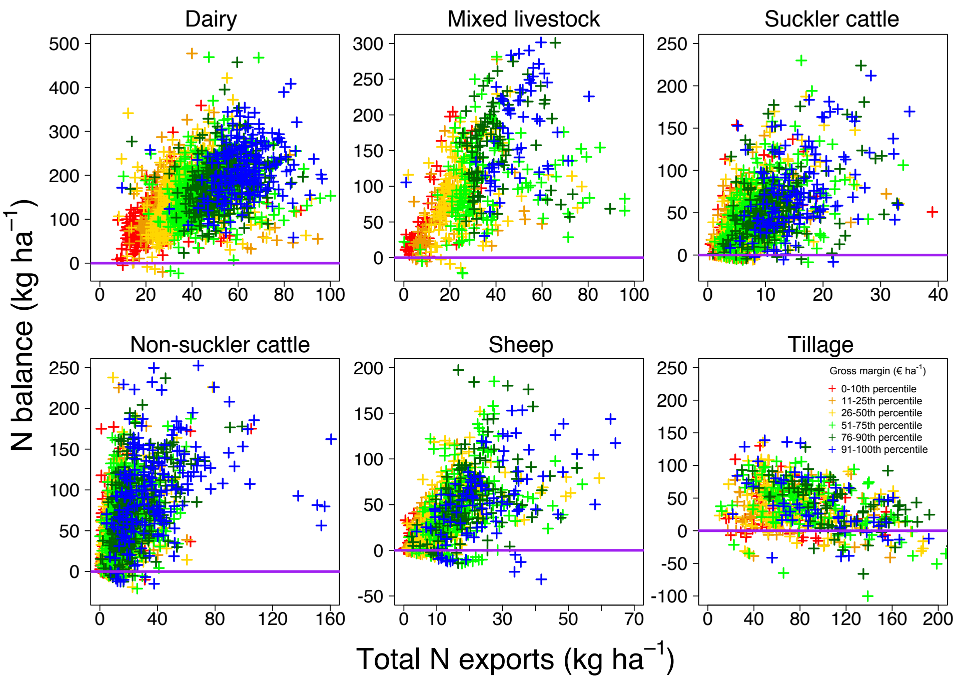

Figure 4.1. Relationship between total N exports (production intensity) and farm-gate N balance (N environmental pressure) for each farm type for all data points. The minimum sustainable zero farm-gate N balance (0 kg ha^{-1}) is indicated by a purple line. Data points are colour coded based on gross margin (€ ha^{-1}) percentile rankings.

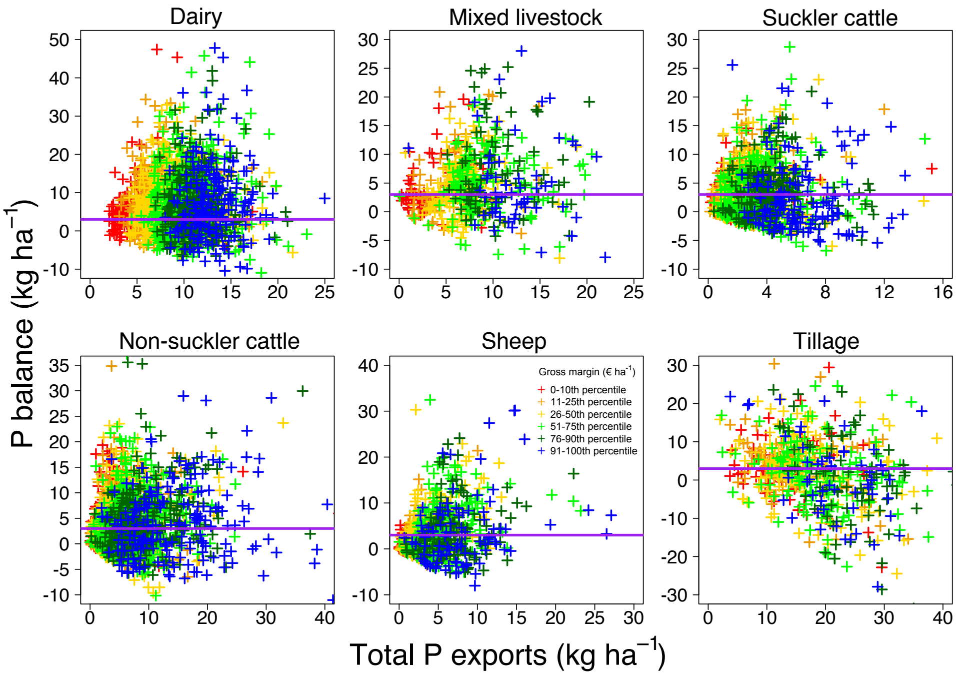

Figure 4.2. Relationship between total P exports (production intensity) and farm-gate P balance (P environmental pressure) for each farm type for all data points. The minimum sustainable farm-gate P balance (3 kg ha^{-1}) is indicated by a purple line. Data points are colour coded based on gross margin (€ ha^{-1}) percentile rankings.

appear to be much more challenging, as would be expected.

Mean N surpluses were higher than optimum benchmark zone N surpluses for all sectors (Figure 4.5). In contrast, the mean P surplus for suckler cattle, sheep and tillage farms was lower than the optimal benchmark zone (Figure 4.5). Taking the optimum benchmark zone surplus as being associated with optimum productivity, this indicates that current P balances are suboptimal on the majority of farms in these sectors and increased P inputs and surpluses may be required for a period of time to optimise production and soil P concentrations. These findings align with national Teagasc soil sample analyses showing large proportions of soils with suboptimal P fertility (Teagasc, 2018a).

4.3.2 *Characteristics of benchmark farms explaining good performance*

Compared with the other farm performance categories, benchmark farms have lower fertiliser and feed imports and greater exports of agricultural products, (Tables 4.1 and 4.2), as has been found by others (e.g. Aarts *et al*., 2000a,b; Öborn *et al*., 2003; Ondersteijn *et al*., 2003b; Nevens *et al*., 2006; Oenema *et al*., 2009; Buckley and Carney, 2013; Buckley *et al*., 2013, 2015, 2016a,b).

Interestingly, benchmarking based on N balance alone leads to relatively low benchmark stocking rates for dairy: 1.5 LU ha^{-1} (0–10th percentile) and 1.7 LU ha^{-1} (11th–25th percentile). However, when gross margin is considered, this changes dramatically: higher stocking rates are required to secure high gross margins per ha. The average stocking rate for the optimal N benchmark zone for dairy was 2.2 LU ha^{-1} (the same as for the optimal P benchmark zone). In Ireland, and many developed countries where the land resource is limited and land prices are high, this is extremely important. This result validates the approach taken in this study of including both environmental and economic KPIs to determine benchmarks of farm performance as the resultant benchmarks address both environmental and economic sustainability.

Benchmarking for dairy farms based on P balance alone showed little effect of stocking rate: 1.8 LU ha^{-1} for the 0–10th percentile, and 1.9 LU ha^{-1} for the 91st–100th percentile. Similar trends were seen for the other livestock farm types, with P balance benchmarks having only slightly lower stocking rates.

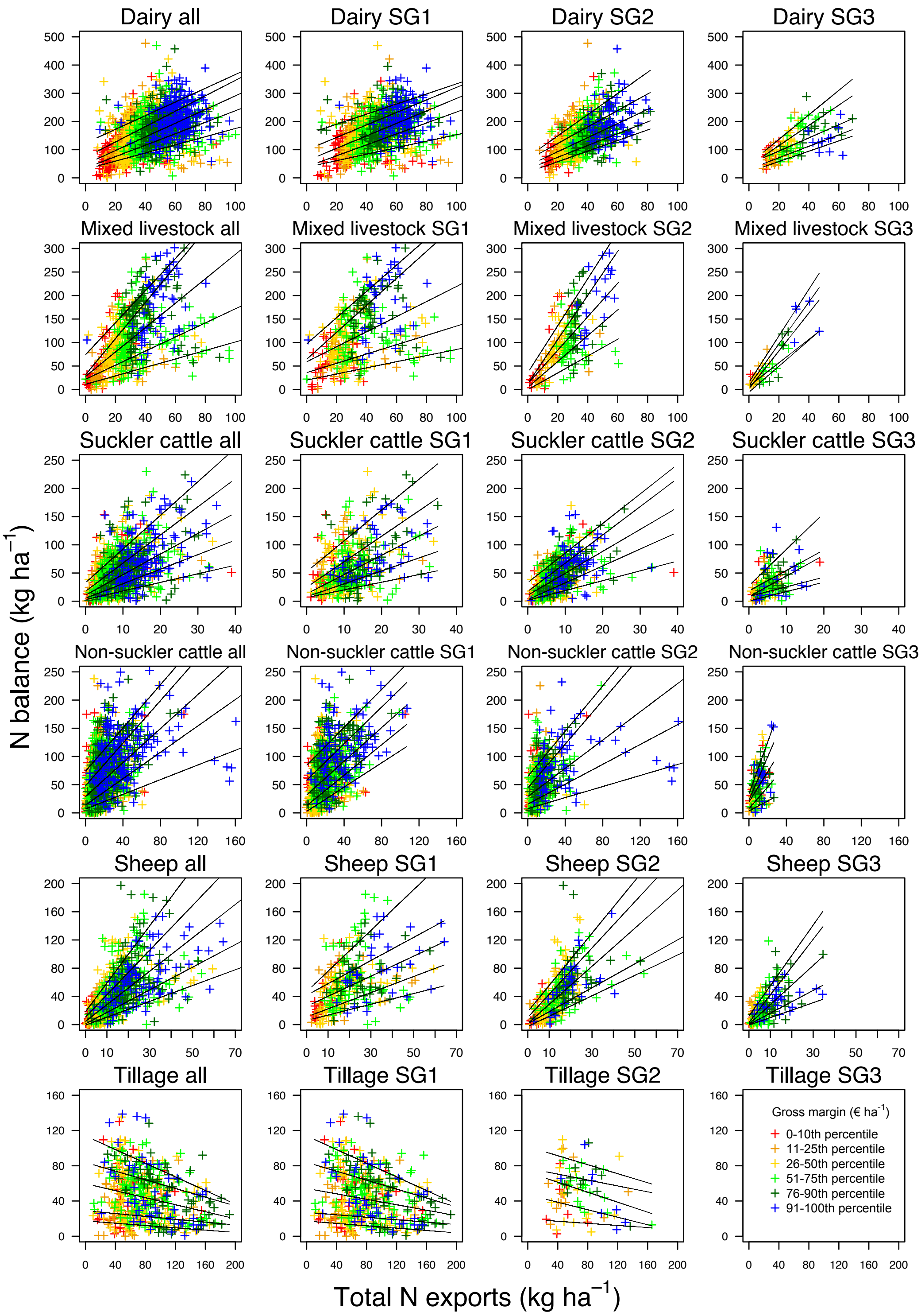

Figure 4.3. Relationship between total N exports (production intensity) and N balances (N environmental pressure) for each farm type and SG (1–3). Percentile regression lines of the relationship are plotted to indicate performance level and different benchmark zones. From top to bottom, these lines represent the 10th, 25th, 50th, 75th and 90th percentiles. Farms above the top line, Q10, are the bottom 10% of performers with the highest N surpluses, whereas farms below the bottom line, Q90, are the top 10% of performers with the lowest N surpluses. Data points representing unsustainable N balances (below 0 kg ha^{-1}) were removed prior to analysis and data points are colour coded according to gross margin (€ ha^{-1}) percentile rankings. Benchmark farms are identified as those with the lowest N balances for a given production intensity and highest gross margins (blue or dark-green points below the Q75 line, i.e. >75th percentile for each KPI). Tillage farms in SG3 did not have enough data points for benchmark analysis.

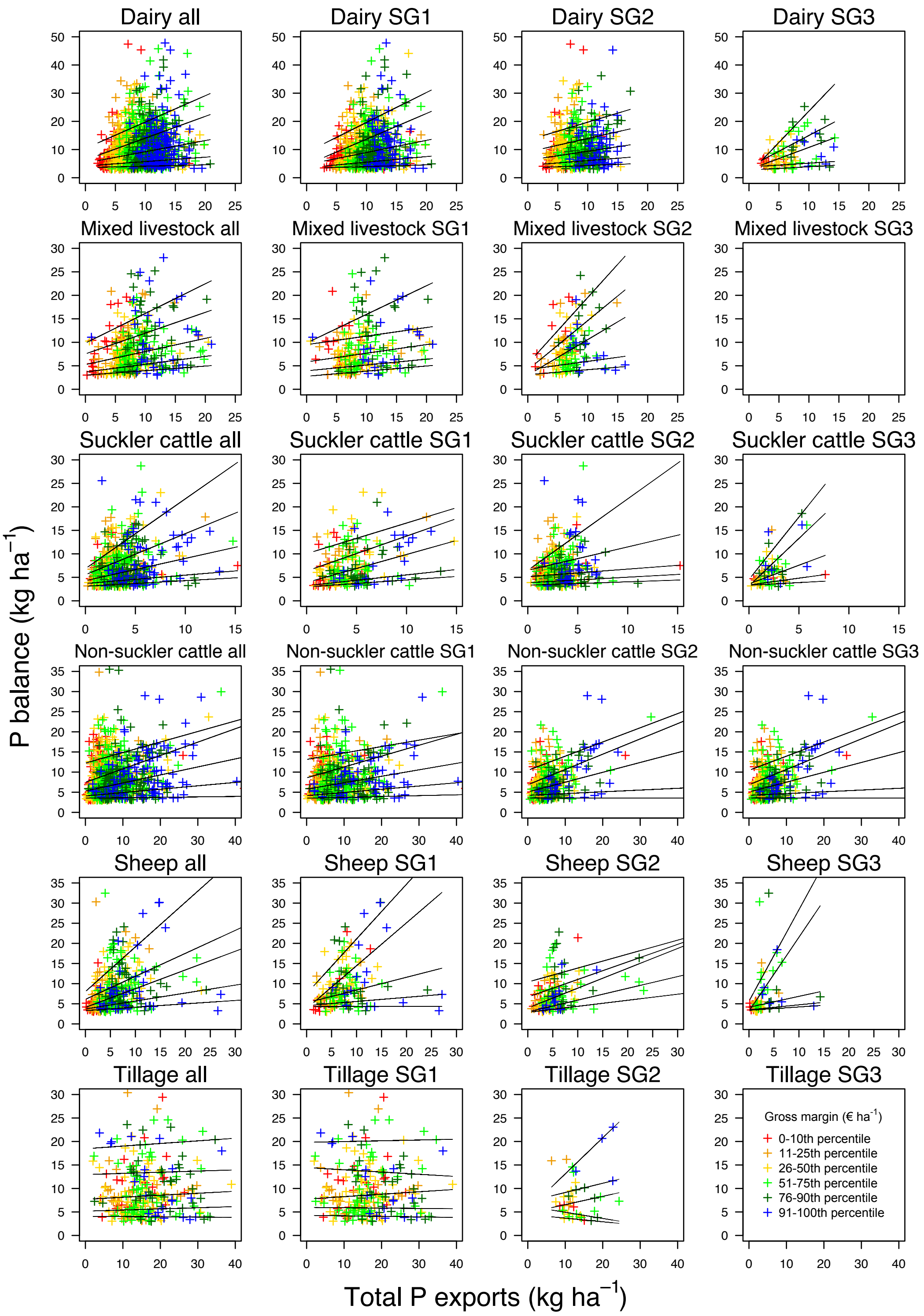

Figure 4.4. Relationship between total P exports (production intensity) and P balances (P environmental pressure) for each farm type and SG (1–3). Percentile regression lines of the relationship are plotted to indicate performance level and different benchmark zones. From top to bottom, these lines represent the 10th, 25th, 50th, 75th and 90th percentiles. Farms above the top line, Q10, are the bottom 10% of performers with the highest P surpluses, whereas farms below the bottom line, Q90, are the top 10% of performers with the lowest P surpluses. Data points with unsustainable P balances (< 3 kg ha^{-1}) were removed prior to analysis and data points are colour coded according to gross margin (€ ha^{-1}) percentile rankings. Benchmark farms are identified as those with the lowest P balances for a given production intensity and highest gross margins (blue or dark-green points below the Q75 line, i.e. > 75th percentile for each KPI). Mixed livestock and tillage farms in SG3 did not have enough data points for benchmark analysis.

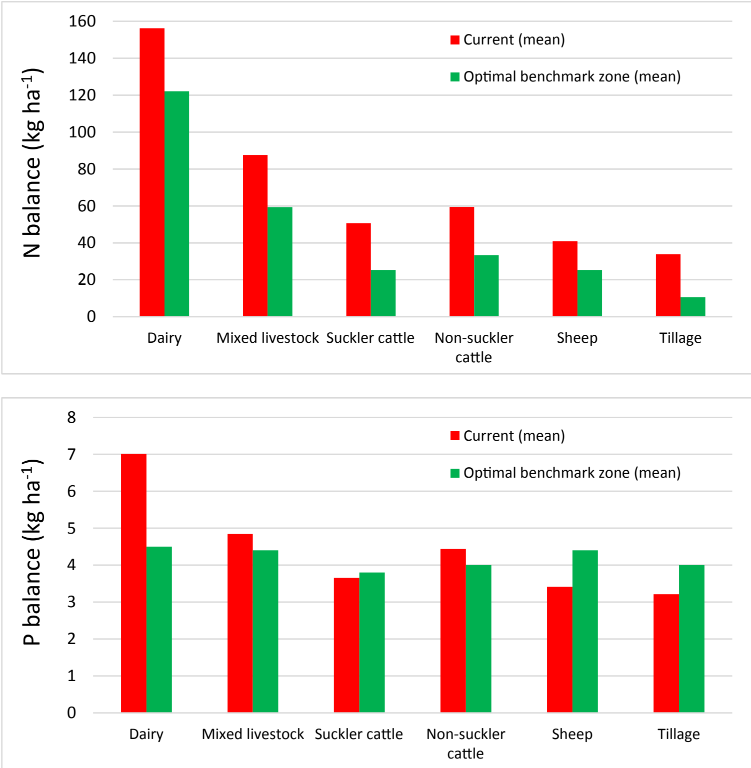

Figure 4.5. Current (2008–2015) and optimal benchmark zone mean farm-gate N balances (top) and P balances (bottom) for each farm type.

This is consistent with the far greater spread of data for the relationship between P exports (closely related to the stocking rate on livestock-dominated farms) and P balance compared with that for N (see Figures 4.1 and 4.2). P balance may be influenced more by factors such as soil P levels, which may require higher rates of fertiliser P application for a period of years to build soil fertility if soil P levels are low or, conversely, may require low rates of application if soil P levels are high. This may account for the apparent decoupling of P balance from the stocking rate. In the absence of soil-test P data for the farms, it is not possible to confirm this, but this result highlights the challenge for benchmarking farm P management in the absence of soil-test data. This apparent decoupling may also be the result of P in concentrate feeds on dairy farms, particularly if increased use of concentrate feeds is used to drive higher milk yields per cow.

The optimal benchmark zone for dairy farms is characterised by farms with relatively high stocking rates but relatively low N and P surpluses (122 kg N ha^{-1} and 4.5 kg P ha^{-1}, compared with 271 kg N ha^{-1} and 26.6 kg P ha^{-1} for the 90th percentile), relatively high N- and P-NUE (31% N-NUE and 72% P-NUE, compared with 14% N-NUE and 26% P-NUE for the 90th percentile) and high gross margin returns (€2734 ha^{-1} for the N benchmark and €2698 ha^{-1} for the P benchmark, compared with €1909 ha^{-1} and €1700 ha^{-1} for the N and P 90th percentiles, respectively). This pattern was similar for suckler cattle, non-suckler cattle and sheep farms, but with lower stocking rates (1.2–1.6 LU ha^{-1}), lower N and P surpluses (25–33 kg N ha^{-1} and 3.8–4.4 kg P ha^{-1}), higher N-NUE (31–47%), variable P-NUE (53–73%) and lower gross margin returns (€972–1351 ha^{-1}) relative to dairy farm benchmarks.

Interestingly, mixed livestock farms displayed the opposite trend in terms of stocking rates and N benchmarking, with those in the optimal N benchmark zone having relatively low (1.2 LU ha^{-1}) stocking rates compared with those in the worst-performing zone (1.8 LU ha^{-1}). This can be explained by the importance of tillage as a component of these systems. These benchmark farms were characterised by relatively high N exports in milk, crops and livestock, resulting in a low N balance, notably high NUE and high gross margins. As has been found by others (Oomen *et al*., 1998; Schröder *et al*., 2003; Wilkins, 2008; Godinot *et al*., 2014), there may be advantages in nutrient recycling and efficiencies for mixed crop–livestock

Table 4.1. Mean farm characteristics and N imports/exports/KPIs for benchmark farms and poorer performing percentiles for each farm type

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
N balance percentile				76–100	91–100	76–90	51–75	26–50	11–25	1–10
Gross margin percentile				76–100	1–100	1–100	1–100	1–100	1–100	1–100
Dairy	Farm characteristics	UAA	ha	47.2	48.1	48.2	53.3	53.3	53.8	50.4
		Stocking rate	LU ha^{-1}	2.2	1.5	1.7	1.8	1.9	2.0	2.1
		ON loading	kg ON ha^{-1}	180.5	120.6	145.3	151.9	157.8	164.9	173.8
		Milk production intensity	l cow^{-1}	5596.9	4700.8	5006.3	5093.4	5083.2	5117.8	5122.5
		Milk production intensity	l ha^{-1}	8440.2	4612.5	5858.0	6255.3	6410.8	6556.0	7104.9
		Soil class	1–6	2.1	2.1	2.6	2.4	2.2	2.2	2.4
	N imports	Fertiliser	kg N ha^{-1}	135.9	78.3	112.8	136.5	165.5	197.7	251.4
		Concentrates	kg N ha^{-1}	36.1	20.8	29.5	35.4	37.8	41.2	51.9
		Forage crops	kg N ha^{-1}	6.0	2.9	3.7	4.0	5.2	7.3	10.6
		Livestock	kg N ha^{-1}	0.9	0.5	0.9	0.9	0.7	0.8	0.8
		Total N imports	kg N ha^{-1}	178.9	102.4	146.9	176.8	209.3	247.0	314.7
	N exports	Milk	kg N ha^{-1}	45.1	24.0	30.8	32.7	33.1	33.8	34.8
		Cash crops	kg N ha^{-1}	2.6	9.2	2.2	1.0	0.6	0.1	0.1
		Livestock	kg N ha^{-1}	9.0	6.7	8.2	8.1	8.3	8.6	8.5
		Wool	kg N ha^{-1}	0.1	0.1	0.0	0.0	0.0	0.0	0.0
		Total N exports	kg N ha^{-1}	56.8	39.9	41.2	41.8	42.1	42.5	43.4
	KPIs	N balance	kg N ha^{-1}	122.1	62.5	105.7	135.0	167.2	204.5	271.3
		N-NUE	% (median)	30.7	36.5	27.6	23.4	20.0	17.2	13.8
		Gross margin	€ ha^{-1}	2733.8	1553.4	1815.3	1846.8	1841.9	1879.5	1909.0
	Finances	Fertiliser costs	€ ha^{-1}	110.0	54.7	91.2	115.3	137.6	171.3	220.6
		Concentrates costs	€ LU^{-1}	200.8	175.4	206.2	241.5	243.9	257.5	266.1
		Bulky feed costs	€ LU^{-1}	18.6	13.3	14.2	19.5	20.5	28.1	22.0
		Total direct costs	€ ha^{-1}	1241.2	766.0	974.0	1119.5	1200.9	1322.6	1424.1
		Total costs	€ ha^{-1}	2227.8	1397.7	1744.6	1909.2	2063.7	2186.8	2346.9
		Gross output	€ ha^{-1}	3976.4	2319.4	2789.7	2966.3	3042.8	3202.0	3333.1
	Number of data points	Number of data points	*n*	101	192	291	485	483	290	195
Mixed livestock	Farm characteristics	UAA	ha	83.1	42.2	55.7	53.5	56.9	58.3	59.9
		Stocking rate	LU ha^{-1}	1.2	1.1	1.2	1.4	1.5	1.8	1.8
		ON loading	kg ON ha^{-1}	94.7	63.1	75.9	107.9	117.4	140.5	133.3
		Milk production intensity	l cow^{-1}	5344.3	1619.3	2259.0	3552.8	4208.8	4574.1	3751.4
		Milk production intensity	l ha^{-1}	3240.6	783.4	1204.5	2286.9	2912.5	3189.8	3140.1
		Soil class	1–6	2.0	2.6	2.7	2.6	2.8	2.3	2.0
	N imports	Fertiliser	kg N ha^{-1}	87.7	30.4	54.1	75.5	107.4	143.9	166.0
		Concentrates	kg N ha^{-1}	15.1	7.8	10.8	22.4	27.7	31.5	35.7
		Forage crops	kg N ha^{-1}	3.2	2.3	3.4	3.6	2.8	2.8	6.3
		Livestock	kg N ha^{-1}	2.1	1.4	2.3	1.7	2.3	0.9	0.7
		Total N imports	kg N ha^{-1}	108.2	42.0	70.5	103.2	140.2	179.1	208.7

Table 4.1. Continued

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
Mixed livestock	N exports	Milk	kg N ha⁻¹	16.8	3.9	6.1	11.5	14.6	15.6	15.1
		Cash crops	kg N ha⁻¹	22.5	7.6	8.2	3.5	1.2	0.1	0.2
		Livestock	kg N ha⁻¹	9.4	8.7	9.7	10.8	10.4	11.4	9.3
		Wool	kg N ha⁻¹	0.1	0.6	0.7	0.2	0.1	0.1	0.0
		Total N exports	kg N ha⁻¹	48.8	20.8	24.7	26.1	26.5	27.2	24.7
	KPIs	N balance	kg N ha⁻¹	59.4	21.2	45.9	77.1	113.7	152.0	184.0
		N-NUE	% (median)	40.4	50.3	34.8	24.2	19.0	15.7	12.8
		Gross margin	€ ha⁻¹	1857.5	765.9	875.6	1098.0	1114.5	1238.5	1415.3
	Finances	Fertiliser costs	€ ha⁻¹	47.7	14.1	41.7	59.1	85.3	117.6	122.6
		Concentrates costs	€ LU⁻¹	170.4	95.1	154.2	200.5	200.5	202.6	210.8
		Bulky feed costs	€ LU⁻¹	7.5	16.0	9.3	14.5	11.4	13.8	20.4
		Total direct costs	€ ha⁻¹	615.7	346.0	496.5	711.6	818.3	893.5	1120.8
		Total costs	€ ha⁻¹	1367.1	837.3	962.2	1272.8	1419.0	1539.1	1853.8
		Gross output	€ ha⁻¹	2473.2	1111.9	1372.1	1809.6	1932.8	2132.0	2536.1
	Number of data points	Number of data points	*n*	15	55	85	143	142	86	57
Suckler cattle	Farm characteristics	UAA	ha	38.0	33.9	36.4	34.5	31.6	32.1	29.4
		Stocking rate	LU ha⁻¹	1.2	0.9	0.9	1.0	1.1	1.3	1.3
		ON loading	kg ON ha⁻¹	92.0	65.5	67.3	74.1	83.9	95.0	99.9
		Soil class	1–6	2.5	3.2	2.8	3.0	3.1	3.0	2.7
	N imports	Fertiliser	kg N ha⁻¹	29.4	12.5	25.1	38.2	53.7	72.6	105.3
		Concentrates	kg N ha⁻¹	6.7	4.5	4.6	5.5	7.4	9.2	9.0
		Forage crops	kg N ha⁻¹	1.0	2.1	1.3	1.8	2.1	2.6	6.6
		Livestock	kg N ha⁻¹	1.2	0.9	1.2	1.4	1.0	0.7	0.7
		Total N imports	kg N ha⁻¹	38.3	20.1	32.2	46.9	64.1	85.2	121.6
	N exports	Milk	kg N ha⁻¹	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Cash crops	kg N ha⁻¹	1.1	0.5	0.1	0.1	0.1	0.0	0.0
		Livestock	kg N ha⁻¹	11.9	8.8	8.8	9.4	9.4	9.5	8.9
		Wool	kg N ha⁻¹	0.1	0.1	0.1	0.0	0.0	0.0	0.0
		Total N exports	kg N ha⁻¹	13.0	9.4	9.0	9.6	9.5	9.5	8.9
	KPIs	N balance	kg N ha⁻¹	25.3	10.7	23.2	37.4	54.6	75.7	112.7
		N-NUE	% (median)	31.0	45.9	27.0	19.6	14.1	10.7	7.2
		Gross margin	€ ha⁻¹	1075.4	614.4	665.2	652.7	685.0	695.0	675.5
	Finances	Fertiliser costs	€ ha⁻¹	21.5	10.0	18.7	30.2	47.4	60.0	87.7
		Concentrates costs	€ LU⁻¹	71.0	72.9	68.9	73.7	85.2	95.8	89.2
		Bulky feed costs	€ LU⁻¹	5.7	18.5	12.3	14.4	14.5	15.1	19.5
		Total direct costs	€ ha⁻¹	332.2	235.0	269.4	311.5	381.7	434.9	516.7
		Total costs	€ ha⁻¹	819.7	560.2	606.5	683.6	789.6	857.9	1028.9
		Gross output	€ ha⁻¹	1407.4	849.3	934.6	964.3	1066.5	1129.8	1192.1
	Number of data points	Number of data points	*n*	76	127	190	318	318	191	128
Non-suckler cattle	Farm characteristics	UAA	ha	35.2	32.6	33.9	34.7	36.2	32.5	32.7
		Stocking rate	LU ha–¹	1.3	0.9	1.1	1.2	1.4	1.5	1.7
		ON loading	kg ON ha⁻¹	91.4	64.9	76.2	87.7	97.9	111.2	120.8
		Soil class	1–6	2.5	2.6	2.6	2.6	2.7	2.5	2.5

Table 4.1. Continued

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
Non-suckler cattle	N imports	Fertiliser	kg N ha^{-1}	33.5	11.6	27.9	44.3	62.9	82.7	124.2
		Concentrates	kg N ha^{-1}	12.0	5.2	7.9	9.8	13.2	16.2	18.7
		Forage crops	kg N ha^{-1}	3.6	1.8	1.6	1.7	2.9	4.4	7.8
		Livestock	kg N ha^{-1}	14.3	7.2	8.8	8.1	7.0	6.5	6.3
		Total N imports	kg N ha^{-1}	63.5	25.7	46.2	63.9	85.9	109.8	157.0
	N exports	Milk	kg N ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Cash crops	kg N ha^{-1}	3.7	1.7	1.6	1.6	1.5	0.7	0.7
		Livestock	kg N ha^{-1}	26.2	13.9	16.7	16.4	16.3	16.6	16.4
		Wool	kg N ha^{-1}	0.2	0.1	0.2	0.2	0.2	0.2	0.2
		Total N exports	kg N ha^{-1}	30.2	15.6	18.4	18.2	18.0	17.5	17.4
	KPIs	N balance	kg N ha^{-1}	33.3	10.1	27.8	45.7	67.9	92.4	139.7
		N-NUE	% (median)	44.7	58.0	36.5	24.9	18.4	14.6	11.1
		Gross margin	€ ha^{-1}	1239.2	625.5	692.0	765.1	801.4	798.9	847.8
	Finances	Fertiliser costs	€ ha^{-1}	18.6	10.3	19.5	35.4	51.7	71.6	103.5
		Concentrates costs	€ LU^{-1}	119.9	74.8	97.4	103.0	123.8	132.9	149.0
		Bulky feed costs	€ LU^{-1}	13.3	9.6	8.9	7.6	11.3	18.7	20.4
		Total direct costs	€ ha^{-1}	409.8	234.1	309.1	377.0	469.6	572.1	689.0
		Total costs	€ ha^{-1}	884.2	520.6	672.8	787.0	936.4	1077.0	1244.4
		Gross output	€ ha^{-1}	1649.2	859.7	1001.1	1142.2	1271.0	1371.0	1536.7
	Number of data points	Number of data points	*n*	84	182	281	466	464	279	187
Sheep	Farm characteristics	UAA	ha	33.2	42.5	61.1	51.9	40.0	35.7	32.0
		Stocking rate	LU ha^{-1}	1.6	1.1	1.2	1.2	1.5	1.5	1.6
		ON loading	kg ON ha^{-1}	84.9	58.3	61.8	65.9	79.9	80.1	79.1
		Soil class	1–6	3.2	3.3	3.4	3.4	3.2	3.2	2.4
	N imports	Fertiliser	kg N ha^{-1}	27.2	14.1	22.6	31.3	45.4	60.7	80.7
		Concentrates	kg N ha^{-1}	12.0	6.7	9.1	12.9	13.4	14.5	17.4
		Forage crops	kg N ha^{-1}	2.8	1.6	1.9	1.7	2.5	3.5	8.8
		Livestock	kg N ha^{-1}	6.5	3.1	3.8	3.6	2.8	2.1	2.2
		Total N imports	kg N ha^{-1}	48.6	25.6	37.4	49.4	64.1	80.8	109.1
	N exports	Milk	kg N ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.1	0.0
		Cash crops	kg N ha^{-1}	3.0	2.8	2.1	0.9	0.3	0.2	0.1
		Livestock	kg N ha^{-1}	18.5	10.7	12.1	13.2	12.9	12.8	12.8
		Wool	kg N ha^{-1}	1.9	1.4	1.4	1.5	1.8	1.8	1.8
		Total N exports	kg N ha^{-1}	23.3	15.0	15.6	15.6	15.0	14.8	14.7
	KPIs	N balance	kg N ha^{-1}	25.3	10.6	21.7	33.7	49.1	66.0	94.4
		N-NUE	% (median)	47.2	64.5	40.9	30.1	22.8	17.9	13.5
		Gross margin	€ ha^{-1}	1315.3	802.5	710.6	736.7	857.5	840.7	693.9
	Finances	Fertiliser costs	€ ha^{-1}	23.0	9.4	21.1	30.9	44.9	66.9	76.8
		Concentrates costs	€ LU^{-1}	85.7	74.1	92.1	123.9	112.9	126.0	136.7
		Bulky feed costs	€ LU^{-1}	9.6	14.0	13.0	10.4	12.4	18.0	21.6
		Total direct costs	€ ha^{-1}	350.5	215.3	282.0	354.2	418.6	475.8	546.8
		Total costs	€ ha^{-1}	868.7	578.7	607.6	709.7	852.3	991.8	1114.2
		Gross output	€ ha^{-1}	1665.8	1017.7	992.7	1090.9	1276.0	1316.5	1240.4
	Number of data points	Number of data points	*n*	43	84	130	214	214	129	86

Table 4.1. Continued

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
Tillage	Farm characteristics	UAA	ha	73.9	37.1	47.3	69.4	60.9	74.6	64.4
		Stocking rate	LU ha^{-1}	0.2	0.1	0.2	0.4	0.6	1.0	0.9
		ON loading	kg ON ha^{-1}	9.9	8.1	16.1	26.0	37.5	68.1	60.6
		Soil class	1–6	1.4	1.4	1.5	1.7	1.7	1.8	1.7
	N imports	Fertiliser	kg N ha^{-1}	121.6	80.7	90.8	105.6	121.2	123.0	149.7
		Concentrates	kg N ha^{-1}	1.9	0.5	1.6	3.0	4.3	7.8	12.3
		Forage crops	kg N ha^{-1}	0.8	0.7	1.0	2.0	2.7	3.8	5.1
		Livestock	kg N ha^{-1}	0.7	0.6	1.6	2.2	3.0	9.3	11.2
		Total N imports	kg N ha^{-1}	125.0	82.5	95.0	112.8	131.2	143.9	178.3
	N exports	Milk	kg N ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Cash crops	kg N ha^{-1}	110.8	74.1	73.6	76.3	68.8	52.5	62.7
		Livestock	kg N ha^{-1}	3.7	1.5	3.7	5.0	7.2	15.4	18.0
		Wool	kg N ha^{-1}	0.1	0.0	0.1	0.2	0.3	0.1	0.1
		Total N exports	kg N ha^{-1}	114.6	75.6	77.4	81.4	76.2	68.0	80.7
	KPIs	N balance	kg N ha^{-1}	10.5	6.9	17.6	31.4	54.9	75.9	97.7
		N-NUE	% (median)	92.1	91.9	79.9	69.9	57.1	49.4	43.9
		Gross margin	€ ha^{-1}	1572.8	897.5	880.0	977.3	894.9	1208.9	1142.1
	Finances	Fertiliser costs	€ ha^{-1}	3.6	3.7	7.1	14.8	30.6	56.9	57.0
		Concentrates costs	€ LU^{-1}	91.5	24.4	44.6	81.1	77.3	93.4	156.1
		Bulky feed costs	€ LU^{-1}	3.0	1.8	3.4	5.2	18.7	5.8	5.1
		Total direct costs	€ ha^{-1}	610.9	458.2	510.2	577.7	635.2	619.4	759.1
		Total costs	€ ha^{-1}	1296.7	816.2	917.3	1108.4	1222.2	1330.5	1375.5
		Gross output	€ ha^{-1}	2183.6	1355.6	1390.9	1555.0	1529.5	1827.8	1901.1
	Number of data points	Number of data points	*n*	29	50	72	122	124	72	50

systems and these results may reflect that. This result may be of particular importance as, of all of the livestock farm types included in this study, the mixed system was able to achieve high gross margin returns with low N balance and high NUE. Mixed crop–livestock systems may have the potential to deliver economic and environmental benefits in ways that more specialised systems cannot.

In contrast, tillage farms in the optimal N benchmark zone were more specialised, with a stocking rate of 0.2 LU ha^{-1} (almost no animals on the holding), compared with 0.9–1.0 LU ha^{-1} for the 76th–100th percentile zone. Stocking rate decreased steadily from the worst- to the best-performing benchmark zones and this was associated with a decrease in average N balance from 98 to 7 kg ha^{-1} and an increase in N-NUE from 44% to 92%. The same trends were found for P in tillage farms. This result would suggest that, despite the potential benefits of recycling nutrients between crops and livestock referred to above, the higher nutrient losses and inefficiencies associated with livestock production led to poorer overall nutrient balances and NUE on tillage farms as the livestock rate increases. The average gross margin for tillage farms in the optimal N benchmark zone was €1573 ha^{-1}, compared with €1142 ha^{-1} for the worst-performing zone.

Farm size (scale) and associated production intensity have been found to have a positive effect on efficiency (Latruffe *et al.*, 2008; Dolman *et al.*, 2014; de Vries *et al.*, 2015), although not in all studies (e.g. Buckley and Carney, 2013). Results from this study show a mixed picture. Larger farm size (UAA) tended to be associated with higher N balances and weaker nutrient management performance for the dairy, mixed livestock and tillage sectors (because of large increases in fertiliser use), whereas sheep farms showed the opposite trend and suckler/non-suckler

Table 4.2. Mean farm characteristics and P imports/exports/KPIs for benchmark farms and poorer performing percentiles for each farm type

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
P balance percentile				76–100	91–100	76–90	51–75	26–50	11–25	1–10
Gross margin percentile				76–100	1–100	1–100	1–100	1–100	1–100	1–100
Dairy	Farm characteristics	UAA	ha	53.9	47.8	52.8	51.5	53.0	53.0	50.5
		Stocking rate	LU ha^{-1}	2.2	1.8	1.8	1.8	1.9	1.9	1.9
		ON loading	kg ON ha^{-1}	183.9	146.2	150.9	151.4	156.3	158.0	158.2
		Milk production intensity	l cow^{-1}	5691.4	4943.2	4919.8	5063.5	5086.2	5111.8	5085.5
		Milk production intensity	l ha^{-1}	8269.8	5818.1	5726.8	6111.4	6360.4	6509.8	6644.7
		Soil class	1–6	1.8	2.3	2.5	2.4	2.4	2.6	2.5
	P imports	Fertiliser	kg P ha^{-1}	6.6	5.1	6.0	8.1	11.0	15.3	22.0
		Concentrates	kg P ha^{-1}	8.2	6.5	6.6	6.9	7.5	8.0	10.9
		Forage crops	kg P ha^{-1}	1.2	0.7	0.9	0.9	1.1	1.3	2.1
		Livestock	kg P ha^{-1}	0.3	0.3	0.3	0.4	0.4	0.4	0.6
		Total P imports	kg P ha^{-1}	16.3	12.6	13.8	16.3	19.9	25.0	35.6
	P exports	Milk	kg P ha^{-1}	7.4	5.2	5.0	5.4	5.6	5.8	5.9
		Livestock	kg P ha^{-1}	4.1	3.4	3.6	3.5	3.2	3.2	3.0
		Cash crops	kg P ha^{-1}	0.3	0.5	0.4	0.3	0.2	0.2	0.0
		Wool	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total P exports	kg P ha^{-1}	11.8	9.0	9.0	9.2	9.0	9.1	9.0
	KPIs	P balance	kg P ha^{-1}	4.5	3.5	4.8	7.1	10.9	15.9	26.6
		P-NUE	% (median)	71.9	70.3	63.5	55.0	44.6	35.7	26.0
		Gross margin	€ ha^{-1}	2698.3	1751.0	1772.7	1774.9	1784.5	1780.1	1699.7
	Finances	Fertiliser costs	€ ha^{-1}	159.8	106.5	114.4	128.4	147.4	176.3	181.9
		Concentrates costs	€ LU^{-1}	244.5	225.9	238.0	236.9	262.6	276.4	315.9
		Bulky feed costs	€ LU^{-1}	23.2	16.9	17.8	18.4	23.9	29.2	30.1
		Total direct costs	€ ha^{-1}	1586.0	999.2	1195.1	1162.2	1394.7	1457.1	1626.0
		Total costs	€ ha^{-1}	2807.9	1777.3	2127.6	2008.0	2345.6	2395.9	2643.0
		Gross output	€ ha^{-1}	4532.0	2709.5	3167.0	2998.1	3373.5	3402.5	3725.0
	Number of data points	Number of data points	*n*	89	129	198	323	327	195	131
Mixed livestock	Farm characteristics	UAA	ha	57.9	62.5	48.7	66.0	50.6	53.0	60.6
		Stocking rate	LU ha^{-1}	2.2	1.4	1.4	1.6	1.6	1.6	1.6
		ON loading	kg ON ha^{-1}	177.1	93.5	102.7	119.5	122.8	118.9	116.8
		Milk production intensity	l cow^{-1}	5226.7	2897.1	3322.7	4173.3	4174.3	3979.6	3601.0
		Milk production intensity	l ha^{-1}	5558.3	2043.0	2315.6	2612.8	2860.2	2626.1	3227.3
		Soil class	1–6	2.1	2.2	2.9	2.2	2.6	2.6	2.5
	P imports	Fertiliser	kg P ha^{-1}	4.6	4.6	5.6	7.5	9.0	12.5	17.5
		Concentrates	kg P ha^{-1}	9.5	3.8	4.0	5.1	6.2	5.5	7.0
		Forage crops	kg P ha^{-1}	1.7	0.6	0.7	0.9	0.8	0.8	0.6
		Livestock	kg P ha^{-1}	1.2	0.7	0.5	0.8	0.7	0.7	0.3
		Total P imports	kg P ha^{-1}	16.9	9.6	10.8	14.2	16.7	19.5	25.5

Table 4.2. Continued

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
Mixed livestock	P exports	Milk	kg P ha^{-1}	4.9	1.8	2.0	2.3	2.5	2.3	2.8
		Livestock	kg P ha^{-1}	7.0	3.6	4.0	4.7	4.7	4.2	3.5
		Cash crops	kg P ha^{-1}	0.7	0.9	0.8	1.1	0.5	0.7	0.2
		Wool	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total P exports	kg P ha^{-1}	12.6	6.3	6.7	8.2	7.6	7.1	6.8
	KPIs	P balance	kg P ha^{-1}	4.4	3.3	4.1	6.0	9.0	12.4	18.7
		P-NUE	% (median)	73.3	58.9	57.0	54.6	43.4	34.3	24.1
		Gross margin	€ ha^{-1}	2069.2	1035.2	1025.1	1149.4	1108.1	1008.0	1652.9
	Finances	Fertiliser costs	€ ha^{-1}	134.3	52.7	63.4	72.2	88.5	97.1	120.9
		Concentrates costs	€ LU^{-1}	266.6	148.9	158.7	180.0	237.6	193.9	316.9
		Bulky feed costs	€ LU^{-1}	36.9	15.1	23.2	12.3	16.9	12.5	11.8
		Total direct costs	€ ha^{-1}	2337.6	839.7	890.1	1184.6	874.2	983.8	1497.6
		Total costs	€ ha^{-1}	3887.5	1507.2	1656.1	2175.9	1550.6	1731.2	2437.3
		Gross output	€ ha^{-1}	6344.7	2248.3	2416.1	3123.3	2128.7	2287.1	3360.2
	Number of data points	Number of data points	*n*	22	32	52	84	87	50	33
Suckler cattle	Farm characteristics	UAA	ha	34.7	34.5	35.1	32.9	32.9	30.1	23.2
		Stocking rate	LU ha^{-1}	1.3	1.0	1.0	1.2	1.1	1.1	1.2
		ON loading	kg ON ha^{-1}	100.4	74.5	78.2	87.6	83.2	81.6	91.7
		Soil class	1–6	2.5	2.9	2.9	2.9	3.2	2.6	3.0
	P imports	Fertiliser	kg P ha^{-1}	6.0	4.7	5.2	6.2	8.6	11.0	16.6
		Concentrates	kg P ha^{-1}	1.7	1.3	1.4	1.6	1.5	1.6	1.8
		Forage crops	kg P ha^{-1}	0.4	0.3	0.4	0.8	0.4	0.6	1.0
		Livestock	kg P ha^{-1}	0.4	0.3	0.4	0.4	0.8	0.4	0.3
		Total P imports	kg P ha^{-1}	8.5	6.5	7.5	8.9	11.3	13.6	19.7
	P exports	Milk	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Livestock	kg P ha^{-1}	4.5	3.3	3.4	3.8	3.8	3.5	3.5
		Cash crops	kg P ha^{-1}	0.2	0.0	0.1	0.0	0.0	0.0	0.0
		Wool	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total P exports	kg P ha^{-1}	4.7	3.3	3.5	3.8	3.9	3.6	3.5
	KPIs	P balance	kg P ha^{-1}	3.8	3.3	3.9	5.1	7.4	10.0	16.1
		P-NUE	% (median)	53.3	46.8	43.8	39.7	31.1	24.8	17.8
		Gross margin	€ ha^{-1}	972.3	659.7	597.0	705.2	664.6	635.2	698.3
	Finances	Fertiliser costs	€ ha^{-1}	56.6	38.4	39.0	48.5	60.3	62.8	82.4
		Concentrates costs	€ LU^{-1}	81.7	81.3	86.8	88.3	83.9	87.4	76.2
		Bulky feed costs	€ LU^{-1}	9.4	7.2	18.1	24.4	14.7	18.0	19.0
		Total direct costs	€ ha^{-1}	187.4	132.9	142.0	133.0	136.3	111.6	92.6
		Total costs	€ ha^{-1}	380.7	290.3	293.7	278.7	272.7	226.7	174.2
		Gross output	€ ha^{-1}	574.4	386.8	387.0	373.6	364.2	278.8	212.9
	Number of data points	Number of data points	*n*	35	58	87	144	145	86	58
Non-suckler cattle	Farm characteristics	UAA	ha	46.1	39.0	38.1	35.8	33.4	29.9	24.6
		Stocking rate	LU ha^{-1}	1.6	1.2	1.3	1.3	1.4	1.5	1.6
		ON loading	kg ON ha^{-1}	111.4	84.2	95.1	95.2	100.2	103.9	116.6
		Soil class	1–6	2.1	2.7	2.6	2.5	2.7	2.6	2.8

Table 4.2. Continued

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
Non-suckler cattle	P imports	Fertiliser	kg P ha^{-1}	7.1	4.9	5.6	6.5	9.1	11.8	17.2
		Concentrates	kg P ha^{-1}	4.0	2.4	2.7	3.1	3.0	3.2	3.8
		Forage crops	kg P ha^{-1}	0.8	0.4	0.6	0.4	0.4	1.2	1.8
		Livestock	kg P ha^{-1}	5.2	2.8	2.8	3.6	3.3	3.1	3.1
		Total P imports	kg P ha^{-1}	17.2	10.5	11.8	13.6	15.8	19.4	26.0
	P exports	Milk	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Livestock	kg P ha^{-1}	12.2	6.5	7.3	7.6	7.2	7.2	7.2
		Cash crops	kg P ha^{-1}	1.0	0.6	0.3	0.3	0.3	0.4	0.3
		Wool	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total P exports	kg P ha^{-1}	13.1	7.2	7.6	8.0	7.6	7.5	7.5
	KPIs	P balance	kg P ha^{-1}	4.0	3.3	4.1	5.7	8.2	11.8	18.5
		P-NUE	% (median)	72.9	60.3	58.2	51.1	43.5	35.3	26.2
		Gross margin	€ ha^{-1}	1280.7	707.1	763.3	827.8	775.6	748.2	678.5
	Finances	Fertiliser costs	€ ha^{-1}	59.7	38.3	44.7	50.8	58.9	67.2	90.2
		Concentrates costs	€ LU^{-1}	162.1	121.2	130.9	134.3	128.0	141.1	141.1
		Bulky feed costs	€ LU^{-1}	18.9	6.6	19.2	8.8	11.0	17.6	32.4
		Total direct costs	€ ha^{-1}	457.7	253.6	223.4	214.2	216.9	196.3	161.2
		Total costs	€ ha^{-1}	784.0	467.1	421.6	397.4	389.0	353.0	270.7
		Gross output	€ ha^{-1}	1267.6	682.4	602.8	564.5	528.3	457.8	339.7
	Number of data points	Number of data points	*n*	57	95	145	240	240	145	96
Sheep	Farm characteristics	UAA	ha	31.8	44.5	35.6	35.6	35.1	35.2	29.3
		Stocking rate	LU ha^{-1}	1.8	1.5	1.4	1.6	1.5	1.5	1.6
		ON loading	kg ON ha^{-1}	105.6	79.3	78.7	81.8	79.0	82.5	90.1
		Soil class	1–6	2.7	3.0	2.9	2.8	2.8	3.0	3.1
	P imports	Fertiliser	kg P ha^{-1}	5.6	5.0	5.2	7.0	8.4	12.4	18.6
		Concentrates	kg P ha^{-1}	4.9	3.1	3.0	3.1	2.9	3.5	3.4
		Forage crops	kg P ha^{-1}	1.0	0.6	0.9	0.5	0.6	0.9	2.4
		Livestock	kg P ha^{-1}	3.3	1.2	2.1	1.8	1.6	1.3	1.2
		Total P imports	kg P ha^{-1}	14.9	10.0	11.2	12.4	13.5	18.1	25.5
	P exports	Milk	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Livestock	kg P ha^{-1}	9.8	6.0	6.3	6.1	5.5	5.4	5.7
		Cash crops	kg P ha^{-1}	0.6	0.5	0.5	0.2	0.2	0.5	0.1
		Wool	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total P exports	kg P ha^{-1}	10.5	6.5	6.8	6.4	5.7	6.0	5.8
	KPIs	P balance	kg P ha^{-1}	4.4	3.5	4.4	6.0	7.8	12.1	19.7
		P-NUE	% (median)	65.4	59.4	54.5	48.3	39.4	31.6	22.3
		Gross margin	€ ha^{-1}	1350.9	910.4	775.0	824.4	781.1	806.5	860.6
	Finances	Fertiliser costs	€ ha^{-1}	46.8	40.0	41.4	57.7	53.6	67.5	85.3
		Concentrates costs	€ LU^{-1}	177.9	131.4	135.1	126.5	130.0	160.0	144.6
		Bulky feed costs	€ LU^{-1}	17.7	14.8	22.0	12.1	15.2	18.9	38.5
		Total direct costs	€ ha^{-1}	154.6	181.8	155.3	160.2	185.4	222.7	196.7
		Total costs	€ ha^{-1}	327.9	388.3	310.0	306.7	349.1	420.8	350.6
		Gross output	€ ha^{-1}	550.9	570.4	438.8	445.8	494.1	556.9	457.8
	Number of data points	Number of data points	*n*	25	35	54	92	88	55	36

Table 4.2. Continued

Sector	Variable type	Variable	Unit	Overall performance						
				Optimal benchmark zone	Benchmark		Above average	Below average	Worst	
Tillage	Farm characteristics	UAA	ha	42.2	39.3	64.6	57.0	56.3	54.4	33.5
		Stocking rate	LU ha^{-1}	0.5	0.5	0.6	0.5	0.5	0.6	0.8
		ON loading	kg ON ha^{-1}	38.9	27.0	39.7	30.3	31.5	41.2	54.2
		Soil class	1–6	1.4	1.5	1.8	1.5	1.5	1.5	1.8
	P imports	Fertiliser	kg P ha^{-1}	23.2	17.7	16.7	20.9	24.0	27.2	37.8
		Concentrates	kg P ha^{-1}	0.7	0.8	1.3	0.7	0.8	1.1	1.0
		Forage crops	kg P ha^{-1}	0.4	0.4	0.6	0.6	0.6	0.8	0.2
		Livestock	kg P ha^{-1}	3.0	0.8	2.1	1.2	1.0	1.5	3.9
		Total P imports	kg P ha^{-1}	27.2	19.6	20.6	23.4	26.5	30.5	43.0
	P exports	Milk	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Livestock	kg P ha^{-1}	5.2	2.2	4.0	2.5	2.4	3.4	5.8
		Cash crops	kg P ha^{-1}	18.0	14.0	12.0	13.8	13.7	11.6	9.0
		Wool	kg P ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total P exports	kg P ha^{-1}	23.2	16.2	16.0	16.3	16.0	15.0	14.8
	KPIs	P balance	kg P ha^{-1}	4.0	3.5	4.7	7.1	10.4	15.5	28.2
		P-NUE	% (median)	84.5	80.0	74.8	66.7	58.1	45.4	35.0
		Gross margin	€ ha^{-1}	1719.9	982.6	958.1	883.1	854.7	907.7	1342.0
	Finances	Fertiliser costs	€ ha^{-1}	38.3	18.9	32.7	18.6	31.0	44.3	49.6
		Concentrates costs	€ LU^{-1}	128.2	104.4	143.2	64.0	65.5	86.6	50.6
		Bulky feed costs	€ LU^{-1}	1.8	21.4	5.3	8.7	12.1	13.9	2.6
		Total direct costs	€ ha^{-1}	491.0	394.2	675.0	560.6	645.4	621.1	437.5
		Total costs	€ ha^{-1}	1017.2	766.9	1323.3	1092.8	1177.3	1256.4	990.0
		Gross output	€ ha^{-1}	1627.4	1009.8	1833.7	1468.8	1488.0	1641.0	1069.0
	Number of data points	Number of data points	*n*	12	26	40	63	65	39	27

cattle farms showed no trend (see Tables 4.1 and 4.2). Farm size (UAA) was larger, on average, for the optimal N benchmark zones than for the poorest performers (76th–100th percentile zone) for suckler cattle, non-suckler cattle and mixed livestock farm types. For optimal sheep and tillage farms, the UAA was approximately the same as for the poor performers for N, whereas optimal dairy farms were smaller. This may suggest that a smaller farm size for dairy may encourage intensification in output per ha and more efficient management of N resources per ha, in order to maximise profit per ha, leading to improved performance in the KPIs of nutrient balance, NUE and gross margin per ha. It may also reflect an association between larger farm size and poorer soil land use potential (see Table 4.1).

For P, larger farm UAA size was associated with lower P balances for suckler/non-suckler cattle farms, whereas other farm types showed no consistent trend. With regard to P benchmarks, optimal suckler cattle and non-suckler cattle farms were larger than the worst P balance performers, whereas P benchmarks of the other farm types had similar UAA sizes as the worst performers. This indicates that economies of scale do not appear to be as important as other factors in determining benchmark performance on a per-ha basis on some farms.

For all sectors except for sheep farm N, optimal N and P benchmark zone cohorts consistently had higher land use potential soils than the poorer performing groups (i.e. a lower mean soil class, with 1 being wide use potential and 6 being extremely limited use potential),. This shows the importance of soil quality as a key driver of productivity. However, in terms of N or P balance percentile alone (which does not consider productivity or gross margins), no clear trend in soil class was found from the best-performing to the worst-performing cohorts, suggesting that individual farmer nutrient management decisions are more important than soil quality or land use potential in dictating nutrient management performance.

Fertiliser imports make up a much larger proportion of total N imports than feed imports (concentrates or forage crops) for all farm types and therefore have a much larger effect on N surpluses and use efficiencies. This agrees with Buckley *et al*. (2013) and indicates that most gains in N balances and use efficiencies are to be obtained through improved fertiliser management. Other studies also show that lowering fertiliser imports will reduce nutrient surpluses in dairy systems to a far greater extent than increasing the stocking rate and associated nutrient exports in milk (Peyraud and Delaby, 2007; Dillon and Delaby, 2009). Caution should be exercised here to avoid externalisation of nutrient losses through increased feed imports if on-farm forage production is not maintained. If feed imports are increased to offset lower on-farm forage production because of lower fertiliser use, this may simply lead to externalised nutrient surpluses and losses where the imported feed is produced.

Fertiliser P also dominated P imports for most farm types, but not for dairy and mixed livestock farms. Feed P imports were often higher than fertiliser P imports for these farm types. In both cases, farms in the optimal benchmark zone had higher average feed P imports (8.2 and 9.5 kg P ha^{-1}, respectively) than fertiliser P imports (6.6 and 4.6 kg P ha^{-1}, respectively). Interestingly, dairy and mixed livestock farms in the optimal benchmark zone do not have the lowest levels of fertiliser and feed imports. The relatively high stocking rates, low N and P surpluses, high N- and P-NUE and high gross margin returns of these farms are associated with total imports of fertiliser and feed that are more typical of the 51st–75th or 26th–50th percentile benchmark zones. What distinguishes these optimal benchmark farms is a moderate level of fertiliser and feed imports combined with a high level of exports in milk. The same is true for other livestock farm types, which have moderate levels of fertiliser/feed imports combined with high levels of livestock exports.

Consequently, efforts to improve management to improve the KPIs of nutrient balance, NUE and gross margin should focus not only on reducing fertiliser and feed imports, but also on maximising the principal farm exports in milk and livestock. This highlights the importance of the many other factors that would influence these exports such as herd genetics (Ryan *et al*., 2011; Beukes *et al*., 2012), herd health (FAO, 2012a,b) and fertility management (Huhtanen *et al*., 2011; Beukes *et al*., 2012; Kelly *et al*., 2012a,b, 2013) and grassland and grazing management (Murphy, 2005; MacDonald *et al*., 2008; Finneran *et al*., 2012; Kelly *et al*., 2012a,b, 2013; French *et al*., 2015). This would support the idea that efforts to improve nutrient management on farms for environmental and economic reasons should always be considered as an integral part of overall farm management.

4.3.3 Benchmarking scenario analysis

Table 4.3 shows the estimated mean changes in farm performance for the four different benchmarking scenarios, revealing the significant potential for improvements in KPIs that could be achieved. For scenario 4, in which all non-benchmark farms reach the optimal benchmark zone for their category, estimated mean dairy farm gross margins improved by €919 ha^{-1}, associated with a decrease in N surplus of 35 kg N ha^{-1} and an increase in NUE of 11%, principally because of a combination of reduced fertiliser N imports (–20 kg N ha^{-1}) and increased N exports in milk (+13 kg N ha^{-1}). Gross output increased by €1031 ha^{-1}, whereas total direct costs increased by only €110 ha^{-1}. It is important to note that changes in gross margins were calculated based on the mean difference between each non-benchmark farm and the mean value of optimal benchmark zone farms. Potential changes in gross margin would reflect changes in all aspects of farm management and not just nutrient management, such as herd health, grass and grazing management, technologies and energy use, soil management, herd genetic merit and fertility. Furthermore, scenarios 1 and 4 represent an extreme case of all non-benchmark farms achieving benchmark performance. These scenarios were run to illustrate the maximum potential improvements within the currently (2008–2015) observed range of farm performance. This is not to suggest that these

Table 4.3. Mean changes in N and P imports, exports and KPIs for each farm type if benchmark targets were met for each scenario

Sector	Variable type	Variable	Unit	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
				N	P	N	P	N	P	N	P
Dairy	Nutrient imports	Fertiliser	kg N ha^{-1} or kg P ha^{-1}	–19.3	–4.4	–30.3	–3.3	–53.9	–6.4	–20.3	–1.5
		Concentrates	kg N ha^{-1} or kg P ha^{-1}	+0.9	+0.8	–5.2	–0.8	–11.1	–2.9	+0.5	+1.4
		Forage crops	kg N ha^{-1} or kg P ha^{-1}	+0.8	+0.1	–1.4	–0.2	–4.0	–1.0	+0.5	+0.2
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+0.1	–0.1	–0.0	–0.1	–0.1	–0.2	+0.1	–0.1
		Total nutrient imports	kg N ha^{-1} or kg P ha^{-1}	–17.5	–3.5	–37.0	–4.4	–69.1	–10.5	–19.1	+0.1
	Nutrient exports	Milk	kg N ha^{-1} or kg P ha^{-1}	+13.8	+2.0	–1.3	–0.3	–1.5	–0.2	+13.4	+1.9
		Cash crops	kg N ha^{-1} or kg P ha^{-1}	+1.2	+0.1	+1.0	+0.2	+0.1	+0.2	+1.3	+0.0
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+1.0	+0.9	–0.0	+0.2	+0.1	+0.3	+0.9	+0.8
		Wool	kg N ha^{-1} or kg P ha^{-1}	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0
		Total nutrient exports	kg N ha^{-1} or kg P ha^{-1}	+16.0	+2.9	–0.3	+0.1	–1.3	+0.2	+15.6	+2.7
	KPIs	Nutrient balance	kg N ha^{-1} or kg P ha^{-1}	–33.5	–6.5	–36.7	–4.5	–67.8	–10.7	–34.7	–2.6
		NUE	% (median)	+11.2	+24.4	+3.3	+8.8	+2.9	+9.1	+11.2	+13.5
		Gross margin	€ ha^{-1}	+937.7	+991.6	–9.0	+20.9	–35.4	+79.0	+919.3	+895.2
	Finances	Fertiliser costs	€ ha^{-1}	–20.8	+17.9	–27.3	–17.8	–51.5	–6.7	–21.8	+28.4
		Concentrates costs	€ LU^{-1}	–30.1	–10.5	–16.4	–17.0	–11.1	–40.7	–29.4	+12.7
		Bulky feed costs	€ LU^{-1}	–0.9	+1.2	–3.1	–3.7	+4.0	–2.7	–1.6	+3.1
		Total direct costs	€ ha^{-1}	+123.9	+545.8	–116.8	+220.6	–124.4	+262.6	+110.1	+629.9
		Total costs	€ ha^{-1}	+309.5	+1093.8	–156.2	+460.9	–178.9	+506.1	+291.6	+1191.0
		Gross output	€ ha^{-1}	+1063.1	+2062.4	–125.7	+680.5	–159.9	+686.9	+1031.0	+2098.3
	Emissions	N_2O	kg N_2O ha^{-1}	–0.239	N/A	–0.376	N/A	–0.669	N/A	–0.252	N/A
Mixed livestock	Nutrient imports	Fertiliser	kg N ha^{-1} or kg P ha^{-1}	+6.7	–4.3	–15.1	–2.1	–13.9	–4.9	+9.1	–1.4
		Concentrates	kg N ha^{-1} or kg P ha^{-1}	–6.9	+3.7	–5.2	–0.2	+0.7	+0.0	–6.3	+4.8
		Forage crops	kg N ha^{-1} or kg P ha^{-1}	+0.9	+0.4	+0.1	+0.0	–3.1	+0.2	+0.7	+0.5
		Livestock	kg N ha^{-1} or kg P ha^{-1}	–0.1	+0.1	+0.3	+0.0	+0.3	+0.6	–0.1	+0.1
		Total nutrient imports	kg N ha^{-1} or kg P ha^{-1}	+0.5	–0.2	–19.9	–2.3	–15.9	–4.2	+3.4	+4.0
	Nutrient exports	Milk	kg N ha^{-1} or kg P ha^{-1}	+4.9	+2.3	–1.0	+0.2	+3.3	+0.2	+5.2	+2.7
		Cash crops	kg N ha^{-1} or kg P ha^{-1}	+21.3	+0.2	+5.1	+0.4	+0.1	+0.4	+21.0	+0.1
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+0.2	+2.1	+0.2	+0.2	+2.7	+1.2	–0.1	+1.9
		Wool	kg N ha^{-1} or kg P ha^{-1}	–0.2	+0.0	+0.1	+0.0	+0.1	+0.0	–0.2	+0.0
		Total nutrient exports	kg N ha^{-1} or kg P ha^{-1}	+26.2	+4.5	+4.4	+0.8	+6.0	+1.5	+25.8	+4.6

Table 4.3. Continued

Sector	Variable type	Variable	Unit	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
				N	P	N	P	N	P	N	P
Mixed livestock	KPIs	Nutrient balance	kg N ha^{-1} or kg P ha^{-1}	–25.7	–4.6	–24.3	–3.1	–21.8	–5.7	–22.4	–0.6
		NUE	% (median)	+23.0	+23.8	+4.9	+7.3	+2.7	+6.9	+22.9	+10.7
		Gross margin	€ ha^{-1}	+856.2	+961.7	+24.4	+51.8	+13.1	–399.0	+845.5	+1010.4
	Finances	Fertiliser costs	€ ha^{-1}	–14.7	+44.5	–15.1	–2.8	+0.7	–8.0	–12.7	+60.0
		Concentrates costs	€ LU^{-1}	–24.9	+59.5	–22.9	–17.5	+6.3	–77.6	–20.9	+90.2
		Bulky feed costs	€ LU^{-1}	–6.1	+11.6	–2.2	–0.4	–6.6	+0.4	–7.1	+12.0
		Total direct costs	€ ha^{-1}	–71.1	+2413.6	–112.6	+985.4	–148.2	+890.7	–63.0	+2545.3
		Total costs	€ ha^{-1}	+148.8	+3813.4	–127.9	+1827.0	–191.4	+1824.8	+154.0	+4002.0
		Gross output	€ ha^{-1}	+785.1	+6661.3	–88.2	+2691.6	–135.1	+2247.7	+782.5	+6839.2
	Emissions	N_2O	kg N_2O ha^{-1}	+0.083	N/A	–0.187	N/A	–0.172	N/A	+0.113	N/A
Suckler cattle	Nutrient imports	Fertiliser	kg N ha^{-1} or kg P ha^{-1}	–21.9	–2.8	–19.9	–2.7	–36.4	–5.9	–19.9	+1.0
		Concentrates	kg N ha^{-1} or kg P ha^{-1}	+0.2	+0.5	–1.2	–0.1	+0.2	–0.1	+0.4	+0.6
		Forage crops	kg N ha^{-1} or kg P ha^{-1}	–1.7	+0.0	–1.1	–0.2	–4.1	–0.4	–1.6	+0.2
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+0.4	+0.0	+0.0	–0.1	+0.0	+0.1	+0.5	+0.1
		Total nutrient imports	kg N ha^{-1} or kg P ha^{-1}	–22.9	–2.3	–22.2	–3.0	–40.3	–6.3	–20.6	+1.9
	Nutrient exports	Milk	kg N ha^{-1} or kg P ha^{-1}	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0
		Cash crops	kg N ha^{-1} or kg P ha^{-1}	+1.2	+0.3	+0.1	+0.0	+0.0	+0.0	+1.2	+0.3
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+3.2	+1.3	–0.5	–0.2	+0.0	–0.1	+3.3	+1.4
		Wool	kg N ha^{-1} or kg P ha^{-1}	+0.1	+0.0	+0.0	+0.0	+0.0	+0.0	+0.1	+0.0
		Total nutrient exports	kg N ha^{-1} or kg P ha^{-1}	+4.5	+1.7	–0.5	–0.2	+0.0	–0.1	+4.6	+1.7
	KPIs	Nutrient balance	kg N ha^{-1} or kg P ha^{-1}	–27.4	–4.0	–21.7	–2.8	–40.4	–6.3	–25.2	+0.2
		NUE	% (median)	+21.2	+24.4	+5.1	+5.9	+3.2	+6.5	+20.7	–0.6
		Gross margin	€ ha^{-1}	+424.2	+329.5	–17.0	–47.1	–13.2	–86.8	+428.0	+319.6
	Finances	Fertiliser costs	€ ha^{-1}	–23.9	–0.7	–18.7	–13.4	–32.6	–22.8	–22.3	+14.2
		Concentrates costs	€ LU^{-1}	–8.6	+6.0	–3.0	+7.3	+9.5	+16.7	–7.1	+10.9
		Bulky feed costs	€ LU^{-1}	–10.6	–5.4	–2.2	–0.6	–5.5	–2.7	–10.1	–2.1
		Total direct costs	€ ha^{-1}	–41.4	+182.3	–79.0	+80.7	–109.9	+64.6	–33.2	+188.4
		Total costs	€ ha^{-1}	+40.4	+356.1	–128.7	+169.2	–218.2	+145.9	+53.0	+353.0
		Gross output	€ ha^{-1}	+382.7	+584.6	–95.9	+231.6	–123.3	+172.1	+394.7	+545.9
	Emissions	N_2O	kg N_2O ha^{-1}	–0.271	N/A	–0.247	N/A	–0.452	N/A	–0.247	N/A
Non-suckler cattle	Nutrient imports	Fertiliser	kg N ha^{-1} or kg P ha^{-1}	–24.9	–2.4	–20.4	–2.4	–39.7	–5.1	–22.8	+1.1
		Concentrates	kg N ha^{-1} or kg P ha^{-1}	+3.8	+1.3	–2.8	–0.1	–1.5	–0.2	+4.1	+1.9
		Forage crops	kg N ha^{-1} or kg P ha^{-1}	+4.3	+0.5	–1.1	–0.2	–4.4	–0.9	+4.3	+0.7
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+11.1	+3.1	–0.0	–0.3	–0.5	–0.1	+11.2	+3.5
		Total nutrient imports	kg N ha^{-1} or kg P ha^{-1}	–5.8	+2.4	–24.4	–3.0	–46.1	–6.3	–3.2	+7.2

Table 4.3. Continued

Sector	Variable type	Variable	Unit	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
				N	P	N	P	N	P	N	P
Non-suckler cattle	Nutrient exports	Milk	kg N ha^{-1} or kg P ha^{-1}	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0
		Cash crops	kg N ha^{-1} or kg P ha^{-1}	+4.8	+1.0	+1.1	+0.2	+0.6	+0.4	+4.9	+1.1
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+15.5	+6.2	–0.8	–0.1	–0.2	+0.0	+15.5	+6.6
		Wool	kg N ha^{-1} or kg P ha^{-1}	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0
		Total nutrient exports	kg N ha^{-1} or kg P ha^{-1}	+20.3	+7.3	+0.2	+0.1	+0.5	+0.3	+20.4	+7.6
	KPIs	Nutrient balance	kg N ha^{-1} or kg P ha^{-1}	–26.1	–4.9	–24.6	–3.2	–46.6	–6.6	–23.7	–0.5
		NUE	% (median)	+28.7	+28.4	+6.2	+6.9	+3.5	+9.8	+28.0	+9.4
		Gross margin	€ ha^{-1}	+527.8	+547.4	–57.5	+13.1	–35.9	+77.8	+526.1	+534.2
	Finances	Fertiliser costs	€ ha^{-1}	–29.4	+2.4	–19.9	–9.2	–34.6	–21.6	–27.7	+16.2
		Concentrates costs	€ LU^{-1}	+22.3	+35.4	–13.1	+3.9	–7.4	+17.9	+24.7	+57.2
		Bulky feed costs	€ LU^{-1}	+16.5	+12.1	–1.7	–1.5	–4.4	–16.2	+16.7	+15.5
		Total direct costs	€ ha^{-1}	+45.8	+665.1	–101.4	+213.1	–124.0	+257.6	+55.9	+698.6
		Total costs	€ ha^{-1}	+96.5	+1050.3	–167.3	+383.9	–188.1	+475.7	+108.6	+1089.2
		Gross output	€ ha^{-1}	+573.6	+1793.6	–158.9	+557.7	–159.9	+640.5	+582.0	+1822.2
	Emissions	N_2O	kg N_2O ha^{-1}	–0.309	N/A	–0.253	N/A	–0.493	N/A	–0.283	N/A
Sheep	Nutrient imports	Fertiliser	kg N ha^{-1} or kg P ha^{-1}	–12.4	–3.3	–15.3	–2.6	–21.3	–5.4	–7.9	+1.6
		Concentrates	kg N ha^{-1} or kg P ha^{-1}	+0.3	+1.7	–2.9	–0.2	–3.1	–0.2	+1.3	+2.6
		Forage crops	kg N ha^{-1} or kg P ha^{-1}	+1.6	+0.2	–1.3	–0.2	–5.7	–1.5	+1.9	+0.6
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+5.0	+1.8	+0.1	+0.2	+0.1	+0.2	+5.2	+2.3
		Total nutrient imports	kg N ha^{-1} or kg P ha^{-1}	–5.5	+0.4	–19.5	–2.9	–30.0	–7.0	+0.5	+7.0
	Nutrient exports	Milk	kg N ha^{-1} or kg P ha^{-1}	–0.0	+0.0	+0.0	+0.0	+0.1	+0.0	–0.0	+0.0
		Cash crops	kg N ha^{-1} or kg P ha^{-1}	+4.1	+0.8	+1.0	+0.2	+0.2	+0.6	+4.1	+0.9
		Livestock	kg N ha^{-1} or kg P ha^{-1}	+7.6	+4.0	–1.5	+0.0	–0.6	–0.1	+7.9	+5.1
		Wool	kg N ha^{-1} or kg P ha^{-1}	+0.3	+0.0	–0.3	+0.0	–0.1	+0.0	+0.2	+0.0
		Total nutrient exports	kg N ha^{-1} or kg P ha^{-1}	+11.9	+4.8	–0.8	+0.2	–0.4	+0.5	+12.2	+6.0
	KPIs	Nutrient balance	kg N ha^{-1} or kg P ha^{-1}	–17.4	–4.4	–18.7	–3.1	–29.6	–7.5	–11.7	+1.0
		NUE	% (median)	+25.2	+25.7	+7.0	+5.7	+3.6	+9.7	+24.2	+4.2
		Gross margin	€ ha^{-1}	+544.9	+583.7	–97.5	–41.3	+61.1	–67.3	+515.8	+567.7
	Finances	Fertiliser costs	€ ha^{-1}	–20.3	–10.1	–17.5	–10.3	–16.4	–16.6	–15.8	+10.2
		Concentrates costs	€ LU^{-1}	–24.6	+38.8	–9.6	–3.0	–3.9	–1.3	–15.7	+68.2
		Bulky feed costs	€ LU^{-1}	+2.2	–1.7	–1.5	–3.2	–6.4	–22.8	+3.1	+3.8
		Total direct costs	€ ha^{-1}	–8.4	+30.4	–97.5	+102.1	–90.6	+175.1	+18.7	+70.9
		Total costs	€ ha^{-1}	+95.7	+121.1	–203.6	+201.1	–235.7	+336.5	+136.6	+176.9
		Gross output	€ ha^{-1}	+536.6	+319.8	–194.9	+295.9	–29.2	+465.6	+534.6	+356.8
	Emissions	N_2O	kg N_2O ha^{-1}	–0.154	N/A	–0.190	N/A	–0.264	N/A	–0.098	N/A

Table 4.3. Continued

Sector	Variable type	Variable	Unit	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
				N	P	N	P	N	P	N	P
Tillage	Nutrient imports	Fertiliser	kg N ha^{-1} or kg P ha^{-1}	+16.4	–1.2	–13.5	–5.2	–19.0	–10.4	+18.3	+4.6
		Concentrates	kg N ha^{-1} or kg P ha^{-1}	–2.3	+0.0	–1.5	+0.2	–3.6	+0.3	–1.8	+0.1
		Forage crops	kg N ha^{-1} or kg P ha^{-1}	–1.2	+0.0	–0.5	+0.2	–0.3	+0.9	–0.9	+0.1
		Livestock	kg N ha^{-1} or kg P ha^{-1}	–3.1	+0.9	–1.8	–0.2	–4.5	–2.4	–2.5	+1.2
		Total nutrient imports	kg N ha^{-1} or kg P ha^{-1}	+9.8	–0.3	–17.3	–5.0	–27.4	–11.6	+13.1	+6.1
	Nutrient exports	Milk	kg N ha^{-1} or kg P ha^{-1}	–0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0
		Cash crops	kg N ha^{-1} or kg P ha^{-1}	+47.7	+6.4	+5.5	+0.3	+2.7	+3.0	+39.4	+3.5
		Livestock	kg N ha^{-1} or kg P ha^{-1}	–3.2	+1.5	–2.5	+0.1	–4.9	–1.9	–2.2	+1.8
		Wool	kg N ha^{-1} or kg P ha^{-1}	–0.0	+0.0	+0.0	+0.0	+0.1	+0.0	–0.0	+0.0
		Total nutrient exports	kg N ha^{-1} or kg P ha^{-1}	+44.5	+7.9	+3.0	+0.4	–2.0	+1.1	+37.1	+5.3
	KPIs	Nutrient balance	kg N ha^{-1} or kg P ha^{-1}	–34.7	–8.2	–20.3	–5.3	–25.4	–12.7	–24.0	+0.8
		NUE	% (median)	+27.8	+21.4	+8.2	+7.3	+6.1	+11.0	+23.3	–5.5
		Gross margin	€ ha^{-1}	+620.4	+668.3	–30.3	–60.1	–4.4	–350.9	+601.9	+630.3
	Finances	Fertiliser costs	€ ha^{-1}	–21.9	–4.2	–13.7	–1.2	–11.5	+3.1	–18.3	+5.8
		Concentrates costs	€ LU^{-1}	+38.5	+123.7	–7.5	+35.0	–47.8	+53.2	+32.0	+116.7
		Bulky feed costs	€ LU^{-1}	–3.0	–8.8	–3.5	–1.8	+2.4	+6.5	–2.5	–5.0
		Total direct costs	€ ha^{-1}	+1.4	+218.8	–70.5	+284.4	–122.6	+533.1	–1.1	+128.1
		Total costs	€ ha^{-1}	+181.5	+507.3	–121.8	+538.7	–47.7	+978.4	+191.0	+341.9
		Gross output	€ ha^{-1}	+621.8	+1194.5	–100.6	+781.9	–127.2	+1506.2	+600.7	+858.4
	Emissions	N_2O	kg N_2O ha^{-1}	+0.204	N/A	–0.167	N/A	–0.236	N/A	+0.227	N/A

N/A, not applicable.

Note: potential changes in N_2O emissions are also indicated based on changes in N fertiliser use (using a 1.24% emissions factor). Results are for affected farms only in each scenario (farms in the optimal benchmark zone would not change in scenarios 1 and 4 and farms located below the Q75 or Q10 percentile regression lines would not change in scenarios 2 and 3, respectively).

are realistically or easily achievable scenarios. Factors beyond the control of the farmer, such as soil and climatic limitations or farm fragmentation, may well prevent many farms from achieving the benchmarked level of performance.

In contrast, for scenario 2, in which all non-benchmark farms reach the next best performing zone (regression line) in their category, there is a relatively small reduction in gross margin (–€9 ha^{-1}) for dairy farms, a more moderate improvement in NUE (3 percentage points) and a slightly greater reduction in N surplus (–37 kg N ha^{-1}). The reduction in nutrient balance was associated largely with reductions in fertiliser N use but, in contrast to scenario 4 or 1, there was little change in N exports in milk. The results for scenario 3, in which all farms with excessive nutrient surpluses (highest 10%) reach the next best performing zone, were similar to those for scenario 2, but with even greater reductions in fertiliser N use, N balance and gross margins. Scenarios 2 and 3, then, resulted in reductions in N source pressure (improved environmental sustainability), but with slightly negative impacts on profitability (economic sustainability). Results for P benchmarking were similar, except that gross margins increased in all scenarios (but much more in scenarios 1 and 4). These results illustrate the potential trade-offs between economic and environmental sustainability that may need to be made. Scenarios 2 and 3 (which principally involve reductions in fertiliser imports) may lead to greater reductions in farm N and P surpluses (nutrient source pressure) for dairy farms, but without much gain in profitability for N alone (unless combined with P reductions at the same time). This illustrates the importance of selecting appropriate benchmark farms and criteria.

To achieve the more moderate, incremental gains associated with scenarios 2 and 3, it may be adequate for poorer performing farms to focus only on reducing current wasteful levels of nutrient imports without much focus on improving the nutrient output (milk yield per ha for dairy farms). However, to achieve the more substantial changes in both nutrient source pressure *and* profitability and resource use efficiency associated with scenarios 1 and 4 it is necessary to focus both on optimisation of nutrient imports and their management *and* on optimisation of nutrient exports, principally in milk. This would require improvements in management of all aspects of the farm related to improving milk yield per ha (herd health, grass and grazing management, livestock nutrition, soil management, herd genetic merit and fertility, etc.) and, in many instances, may require an increase in intensity, in terms of stocking rate, for example.

The pattern for dairy farms was similar to that for all other farm types in terms of N (see Table 4.3). The scenario 4 results indicated an estimated potential mean increase in farm gross margin of between €428 ha^{-1} (suckler cattle) and €601 ha^{-1} (tillage), significantly lower than for dairy and mixed livestock farms (reflecting the fact that specialist dairy farms tend to have the highest gross margins per ha) but, nonetheless, indicating significant potential for improved gross margins across all of the major farm types if optimal benchmark performance were achieved. Potential mean reductions in N surplus ranged from 12 kg N ha^{-1} for sheep farms to 25 and 24 kg N ha^{-1} for suckler cattle and non-suckler cattle farms, 24 kg N ha^{-1} for tillage farms and 22 kg N ha^{-1} for mixed livestock farms, indicating that all sectors have good potential to reduce nutrient source pressure through benchmarking (Table 4.4). These reductions in surplus were associated with improvements in NUE of between 21 (suckler cattle farms) and 28 (non-suckler cattle farms) percentage points, again indicating significant potential for improvement in NUE.

For P, optimal benchmark balances were higher than mean farm values for suckler cattle, sheep and tillage (see Figure 4.5). This suggests that many dairy, mixed livestock and non-suckler farms are operating at a P balance that may be higher than is required for optimal performance, as represented by the benchmark farm cohort, whereas the opposite is the case for all other farm types. It would appear that the main factor in these higher than optimal P balances on dairy, mixed livestock and non-suckler farms is higher use of fertiliser P, as there is little change in concentrate P use per ha from the best-performing to the worst-performing cohort, whereas fertiliser P use per ha tends to increase from the best- to the worst-performing cohorts (see Table 4.2). Therefore, scenario 4 decreased P surpluses by a mean of 2.6, 0.6 and 0.5 kg P ha^{-1} for dairy, mixed livestock and non-suckler cattle farms, respectively, but increased P surpluses for other sectors (Table 4.5), ranging from +0.2 kg P ha^{-1} for suckler cattle to +1.0 kg P ha^{-1} for sheep.

This result may indicate a requirement to increase the P surplus for a period of time on some farms if optimal productivity and soil P concentrations for all soils is the desired outcome. To achieve this, scenario 4 identified the need to increase fertiliser and/or feed P inputs depending on the sector. It is important to note that optimum P management should be guided by frequent soil sampling to prevent farms from losing soil P fertility because of persistent farm P deficits or from developing excessive soil P concentrations because of persistent farm P surpluses. The current Good Agricultural Practice measures under the EU Nitrates Directive (Government of Ireland, 2014) allow for such temporary surpluses to build soil P fertility, subject to regular soil sampling. It should be noted that agronomic optimum soil P concentrations (soil P index 3; Wall and Plunkett, 2016) for all soils on a farm may not be a desirable, or even an optimal, outcome. Significant losses to water may well occur from soils at agronomic optimum soil P concentrations and adequate crop yield and quality may be achieved at lower soil P concentrations; much would depend on a farmer’s objectives (e.g. desired level of production) and the soil type and its physicochemical properties. It should also be noted that the sensitivity of receiving water bodies to P would also be critical in determining

Table 4.4. Estimated aggregate national agricultural N balances currently (2008–2015) and under benchmark scenario 4

Sector	Current (2008–2015)									Scenario 4							
	Mean number of farms that the annual NFS sample represents nationally	Mean farm size (UAA, ha)	Total UAA (ha)	%	Mean N balance (kg ha^{-1} yr^{-1})	Aggregate N balance (t yr^{-1})	% of total	Optimal benchmark zone mean N balance (kg ha^{-1} yr^{-1})	Optimal benchmark zone total UAA (ha)	Mean national N balance change (kg ha^{-1} yr^{-1})	Aggregate N balance change (t yr^{-1})	Aggregate N balance (t yr^{-1})	% of total	% change compared with current	Proportion (%) of total change to aggregate N balance	Mean aggregate N_2O emission change (kg N_2O-N ha^{-1} yr^{-1})	Aggregate change to N_2O emissions (t N_2O-N)
Dairy	15,629	51.4	711,945	20.5	156.2	111,210	43.0	122.1	32,459	–34.7	–23,578	87,632	48.9	–21.2	29.6	–0.252	–171.2
Mixed livestock	5304	54.3	254,395	7.3	87.6	22,287	8.6	59.4	6323	–22.4	–5557	16,730	9.3	–24.9	7.0	0.113	28.0
Suckler cattle	19,236	33.2	608,586	17.5	50.6	30,816	11.9	25.3	35,580	–25.2	–14,440	16,377	9.1	–46.9	18.1	–0.247	–141.5
Non-suckler cattle	29,165	34.2	1,014,043	29.1	59.4	60,269	23.3	33.3	45,440	–23.7	–22,956	37,313	20.8	–38.1	28.8	–0.283	–274.1
Sheep	14,508	42.9	595,688	17.2	40.9	24,372	9.4	25.3	25,164	–11.7	–6675	17,697	9.9	–27.4	8.4	–0.098	–55.9
Tillage	6797	58.1	293,392	8.4	33.9	9939	3.8	10.5	19,254	–24.0	–6579	3359	1.9	–66.2	8.2	0.227	62.2
Total	90,638		3,478,049	100.0		258,893	100.0		164,220	–23.6	–79,785	179,108	100.0	–30.8	100.0	–0.090	–552.5

Note: also estimated are changes in N_2O emissions following changes in N fertiliser use. Results represent, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally.

Table 4.5. Estimated aggregate national agricultural P balances currently (2008–2015) and under benchmark scenario 4

Sector	Current (2008–2015)									Scenario 4					
	Mean number of farms that the annual NFS sample represents nationally	Mean farm size (UAA, ha)	Total UAA (ha)	%	Mean P balance (kg ha^{-1} yr^{-1})	Aggregate P balance (t yr^{-1})	% of total	Optimal benchmark zone mean P balance (kg ha^{-1} yr^{-1})	Optimal benchmark zone total UAA (ha)	Mean aggregate P balance change (kg ha^{-1} yr^{-1})	Aggregate P balance change (t yr^{-1})	Aggregate P balance (t yr^{-1})	% of total	% change compared with current	Proportion (%) of total change to aggregate P balance
Dairy	15,629	51.4	711,945	20.5	7.0	4994	31.4	4.5	31,604	–2.6	–1769	3225	22.3	–35.4	119.8
Mixed livestock	5304	54.3	254,395	7.3	4.8	1233	7.7	4.4	5421	–0.6	–149	1083	7.5	–12.1	10.1
Suckler cattle	19,236	33.2	608,586	17.5	3.7	2224	14.0	3.8	16,803	0.2	118	2343	16.2	5.3	–8.0
Non-suckler cattle	29,165	34.2	1,014,043	29.1	4.4	4498	28.2	4.0	33,664	–0.5	–490	4007	27.7	–10.9	33.2
Sheep	14,508	42.9	595,688	17.2	3.4	2033	12.8	4.4	13,388	1.0	582	2615	18.1	28.6	–39.4
Tillage	6797	58.1	293,392	8.4	3.2	943	5.9	4.0	5001	0.8	231	1174	8.1	24.5	–15.6
Total	90,638		3,478,049	100.0		15,925	100.0		105,881	–0.3	–1477	14,447	100.0	–9.3	100.0

The results represent, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally.

the actual water quality impact of any P losses. In less intensively managed catchments, with high status and sensitive water bodies, any increase in soil P concentrations might be viewed as a potential risk to water quality. There may need to be some weighing of risks and priorities, environmental and economic, before deciding if a particular benchmark should be targeted in a particular catchment or farm. Gross margins increased in scenario 4 for P, ranging from +€320 ha^{-1} for suckler cattle farms to +€1010 ha^{-1} for mixed livestock farms.

For the estimated national aggregate agricultural N and P surplus (results representing, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally), benchmark scenario 4 led to a 31% decrease in surplus N, from 258,893 t to 179,108 t, indicating the significant potential for reducing nutrient source pressure through benchmarking. The largest proportions of this potential decrease in aggregate surplus N came from dairy (30%) and non-suckler cattle (29%) farms, reflecting the large contribution of these two farm types to the aggregate N surplus (Figures 3.4, 4.6 and 4.7) but also indicating significant potential to reduce that surplus. Despite the large reductions in total surplus N from dairy farms, benchmark scenario 4 would leave dairy farms

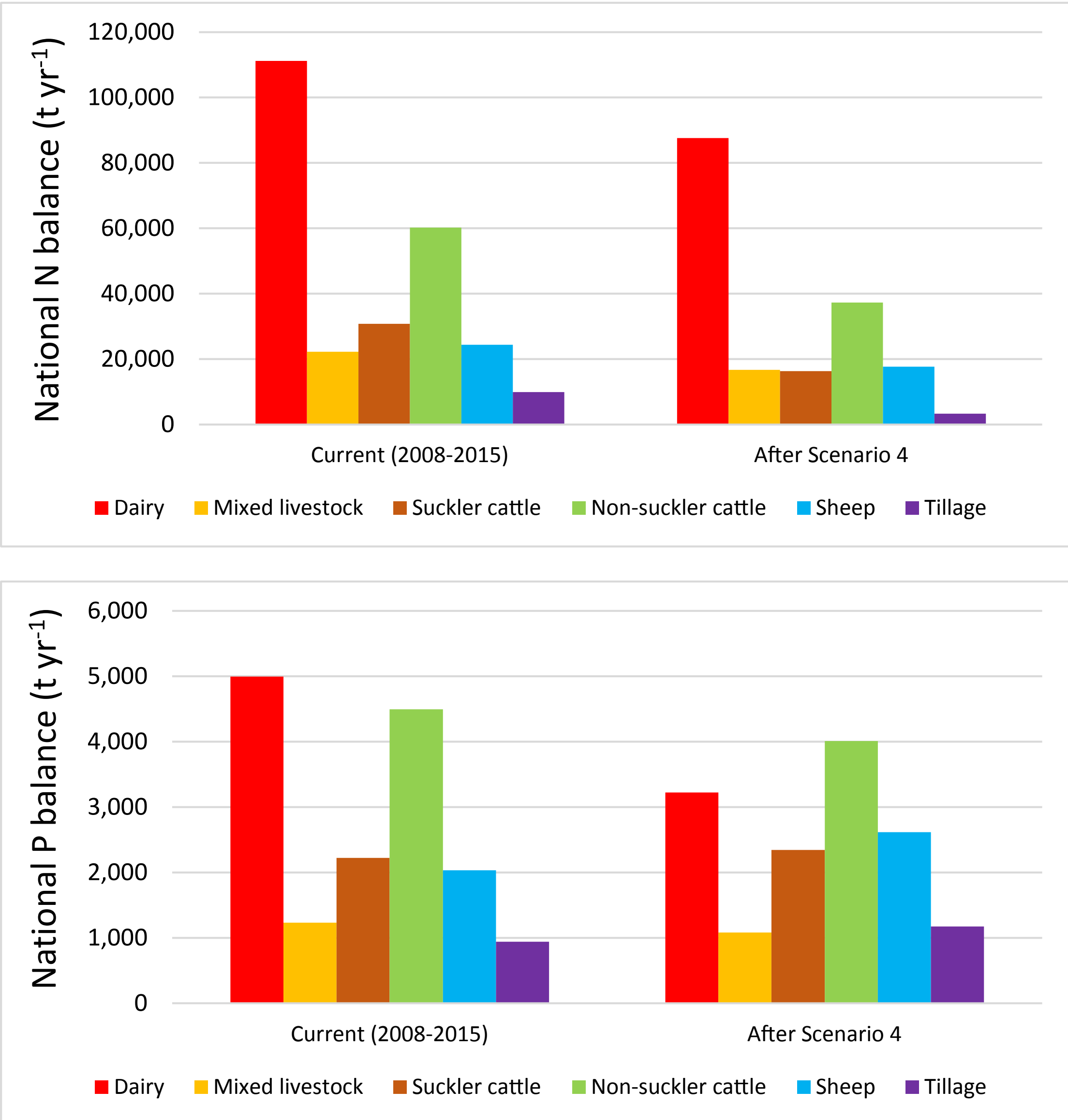

Figure 4.6. Estimated national aggregate agricultural N surplus (top) and P surplus (bottom) for each farm type currently and under benchmarking scenario 4. Results represent, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally.

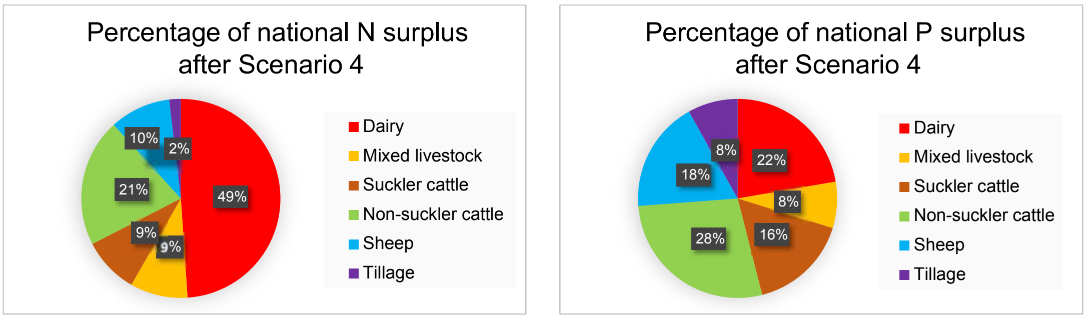

Figure 4.7. Percentage of the estimated national aggregate agricultural N surplus (left) and P surplus (right) attributed to each farm type under benchmarking scenario 4. Results represent, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally.

even more dominant as the major source of surplus N source pressure, at 49% (Figure 4.7), further highlighting the importance of addressing N surpluses in dairy farms. For P, scenario 4 led to a 9% reduction in the aggregate agricultural P surplus, from 15,925 to 14,447 t yr^{-1} (see Table 4.5), almost entirely as a result of dairy and non-suckler cattle farm reductions, which offset increases in P surpluses from sheep, tillage and, to a lesser extent, suckler cattle farms. As a result, scenario 4 would cause the source of the aggregate P surplus to be much more evenly distributed between sectors, with non-suckler cattle farms the greatest contributor at 28% (see Figure 4.7).

4.3.4 Benchmarking scenarios and N_2O emissions from fertiliser

Estimated changes in N_2O emissions following changes in N fertiliser use under scenario 4 were between +0.227 and –0.283 kg N_2O-N ha^{-1} yr^{-1} (for tillage and non-suckler cattle farms, respectively) (see Table 4.3). On a national scale, this would equate to a reduction of 553 t N_2O-N yr^{-1}, mostly from non-suckler/suckler cattle and dairy farms (Figure 4.8). This would equate to a reduction of 0.259 Mt CO_2-eq or a 4.2% reduction in N_2O emissions from the agricultural sector, based on 2016 emissions of 6.192 Mt CO_2-eq (EPA, 2018). In terms of overall GHG emissions from the agricultural sector, this would equate to a reduction of 1.3%. These relatively moderate reductions in sectoral emissions reflect the fact that overall GHG emissions from the agricultural sector are strongly linked to livestock numbers, in particular through CH_4 emissions from livestock and N_2O emissions from dung and urine deposited by grazing cattle. They also reflect the fact that many farms would increase N fertiliser use under the benchmark scenario. Again, this highlights the balance that may need to be struck between environmental and economic goals: greater reductions in N_2O emissions from N fertiliser use could potentially be achieved through nutrient management benchmarking if it was decided to weight GHG emissions more heavily in the benchmarking approach.

4.3.5 Policy implications

Benchmark farm KPI values can be used as quantitative targets by farmers and policymakers wanting to achieve high nutrient management performance to improve both economic and environmental sustainability. However, because of the many factors influencing nutrient balance, NUE and profitability that may be outside a farmer's control (e.g. biophysical/environmental factors, farm fragmentation or financial constraints), it may not be possible for a given farm to reach optimal benchmark zone targets. It may therefore be more reasonable, practical and achievable to set stepwise benchmark targets (such as in scenario 2) whereby a farm aims to reach below the next percentile regression line (next best quartile of performance). Figure 4.9 illustrates this for a dairy farm as well as the potential different paths that a farm could take towards achieving a benchmark target.

In the context of national policy under Food Harvest 2020 and Food Wise 2025, the results indicate that increased production per ha is likely to increase nutrient surpluses, use efficiencies and gross margins. This agrees with the findings of Dillon *et al*. (2016), Lynch *et al*. (2018), Ryan *et al*. (2016), Hennessy *et al*. (2013), Humphreys *et al*. (2008) and Beukes *et al*. (2012). However, this study shows that benchmark

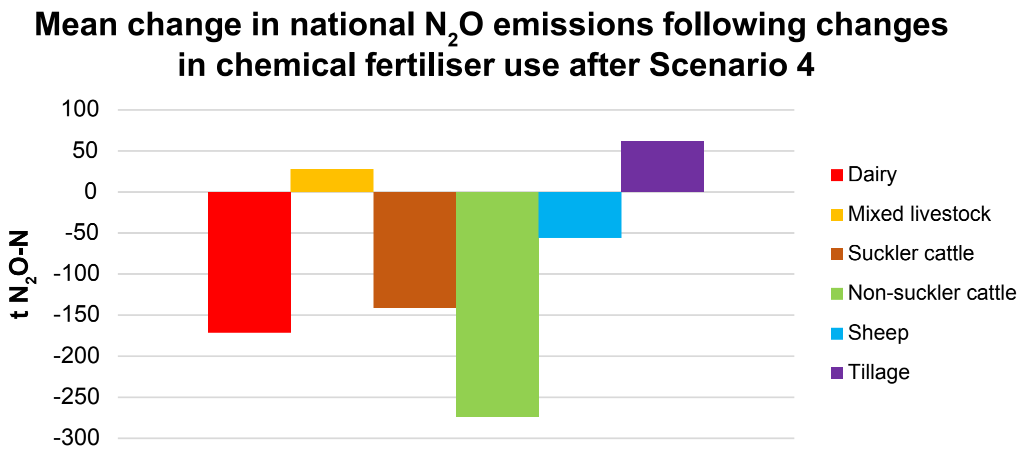

Figure 4.8. Estimated change in national aggregate agricultural N_2O emissions for each farm type from changes in fertiliser N use under benchmarking scenario 4. Results represent, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally.

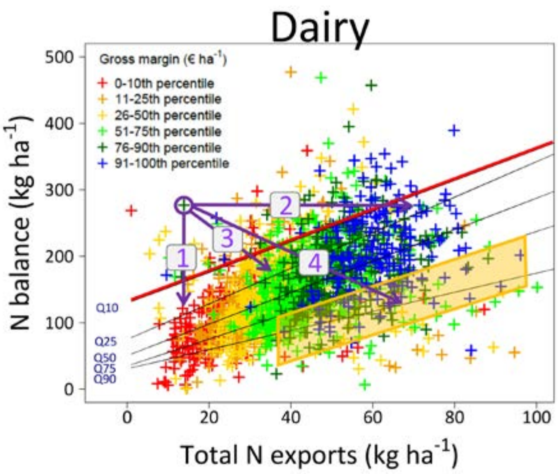

Figure 4.9. Illustration for dairy farms of how the benchmarking approach could be used by farmers and policymakers to improve nutrient management performance. Percentile regression lines act as zone-specific benchmark targets. For example, the circled farm located above the Q10 line should be aiming to (1) reduce surpluses, (2) increase production intensity or (3) do both, until it reaches below the Q10 line. The ultimate aim (4) is to reach the optimal benchmark zone (gold), where benchmark farms with the lowest surpluses and highest gross margins ha^{-1} are located (> 75th percentile for each KPI, i.e. blue and dark-green points below the Q75 line). Policymakers could use the Q10 regression line (highlighted in red) to set maximum permitted farm-gate surpluses for a given production intensity.

farms can buck that trend by achieving high output and gross margins per ha while minimising nutrient surpluses, challenging the assumption that more intensive farms, in terms of production per ha, will automatically have greater surpluses and exert larger source pressures on the environment than low-intensity enterprises. Certainly the performance of these benchmark farms should be of great interest in terms of identifying strategies to achieve the ambitious production targets for the agricultural sector in Ireland while also meeting environmental policy commitments such as those under the EU Water Framework Directive and UNFCCC.

Currently, the Good Agricultural Practice measures under the EU Nitrates Directive in Ireland (Government of Ireland, 2017) are based on the aim of achieving a zero farm-gate P balance, subject to soils being at the optimum P index of 3 (Teagasc, 2016, 2017). However, this fails to consider that farms in farm-gate balance may actually be in soil P deficit because of unavoidable environmental losses and soil P fixation and immobilisation, which are not accounted for. Policy may therefore need to change, aiming for benchmark targets of at least a minimum sustainable slight surplus (3 kg P ha^{-1} was used in this study) that are associated with agronomically optimum soil P concentrations. In Northern Ireland, for example, 5 kg P ha^{-1} is currently deemed sustainable (Bailey, 2016).

The quantile regression analysis used in this study could also be used to set upper limits on N and P balances (specific to each farm category and level of production intensity) in order to reduce excessive surpluses and nutrient source pressures from poorly performing farms as part of a benchmarking process. Some EU countries currently have "flat rate" maximum permitted balances based on relationships with the Nitrates Directive water quality targets (e.g. Del Hierro *et al*., 2005; Nevens *et al*., 2006; Schröder *et al*., 2007; van Grinsven *et al*., 2016) or political decisions weighing agro-economic and environmental consequences (Oenema *et al*., 2003). For example, permissible nutrient surpluses of 100 kg N ha^{-1} and 9 kg P ha^{-1} (20 kg of P_2O_5) were set by the Dutch government for 2003 (Wright and Mallia, 2008) and 10 kg P ha^{-1} cannot be exceeded by a derogated holding in Northern Ireland (Government of Northern Ireland, 2010). However, rather than a "flat rate" policy, upper limits of surplus could be set depending on production intensity, to provide a more appropriate upper limit for the given farm type and intensity of operation.

The approach outlined in this study and others (Buckley and Carney, 2013; Buckley *et al*., 2015) could assist EU FADN members and other countries in the development of their own nationally representative benchmarks (Diazabakana *et al*., 2014; Kelly *et al*., 2015, 2018). In some EU countries, additional FADN variables would be required to calculate nutrient balances, including fertiliser and feed volumes, live weight sales and volume of milk solids sold (Buckley *et al*., 2015).

The benchmarking approach explored here is based on current (2008–2015) levels of performance for these farm types. It is important to note that this does not define the absolute optimum level of performance that could potentially be achieved by these farm systems. It cannot be assumed, even for the benchmark farms, that all management is optimal. There may be management practices, strategies and technologies, either currently existing but not adopted or that may be developed in the future, that might shift the boundaries of performance for a particular farm type.

5 Knowledge Transfer Strategies

Effective knowledge transfer to farmers would be central to achieving the potential improvements in nutrient management, and associated improvements in economic and environmental sustainability, highlighted in this study. Central to this knowledge transfer strategy would be a web-based management decision support benchmarking tool, highlighting the KPIs for individual farms, ranking farms against the benchmark, summarising the potential gains that could be made by improving management and suggesting some management practices that could help to move farms in the right direction.

There are some core criteria to consider that make technology adoption more likely among users. These reflect user perceptions of its usefulness and ease of use. These beliefs are defined as "the extent to which using an IT will enhance job performance" and "the degree to which the use of the IT will be free from effort", respectively (Davis, 1989; Davis *et al*., 1989; Venkatesh and Bala, 2008). These criteria supported our design of a potential benchmarking tool. We considered these from the perspective of two "users": the advisor and the farmer.

In designing this tool we considered four criteria:

1. data availability;
2. data reliability and representativeness;
3. usefulness to farmers;
4. ease of use for farmers and advisors.

The potential web-based benchmark tool explored in this task assesses the nutrient management performance of Irish farms reflecting three indicators: nutrient balance, NUE and profitability (gross margin per ha) (Figure 5.1). A farm nutrient benchmarking tool would need to be able to derive these indicators automatically for a farm once the required farm-specific data are submitted online. The Teagasc NFS data could be used to derive the appropriate benchmark for the specific farm type and intensity level, as detailed in the previous two chapters of this report. The visual representation of the indicators as per the research outputs (e.g. Figure 4.5) might be accompanied with a qualitative explanation designed for use by both farmers and advisors.

The tool might have seven pages:

1. Home. Basic information on farm nutrient management benchmarking and disclaimer.
2. Farm characteristics. Farm type (for benchmarking purposes), UAA, livestock numbers, crops, etc.
3. Import data. Data entry (or autofill from other data sources) for all relevant farm import data (fertiliser type and volumes, livestock, feed, etc.).
4. Export data. Data entry (or autofill from other data sources) for all relevant farm export data (farm product type and volumes, organic fertiliser exports, etc.).
5. Benchmark results. Detailed benchmarking results with a breakdown of all KPIs and import and export categories and comparison with benchmarks for both P and N. Include options on pathways towards the benchmark and graphical representation of the farm's performance relative to its peers and the benchmark farms, e.g. maintain production (stocking rate) and focus on minimising imports or focus simultaneously on minimising imports and increasing production (potentially including stocking rate).
6. Best management practices. Recommendations for best management practices that could be adopted to move the farm's performance towards the benchmark. These would be selected from a database of best management practices and would be appropriate to the farm type and the farmer's intentions for the farm (chosen pathway). These could be automatically selected or could be chosen by the farmer/advisor from a list of potential options.
7. Summary page. Summary information with simple graphical representations of the KPIs for the farm, its performance relative to its peers and relative to the benchmark KPIs, the direction of movement of the farm in recent years and suggested best management practices that could help the farm progress along a pathway towards benchmark performance (see Figure 5.1).

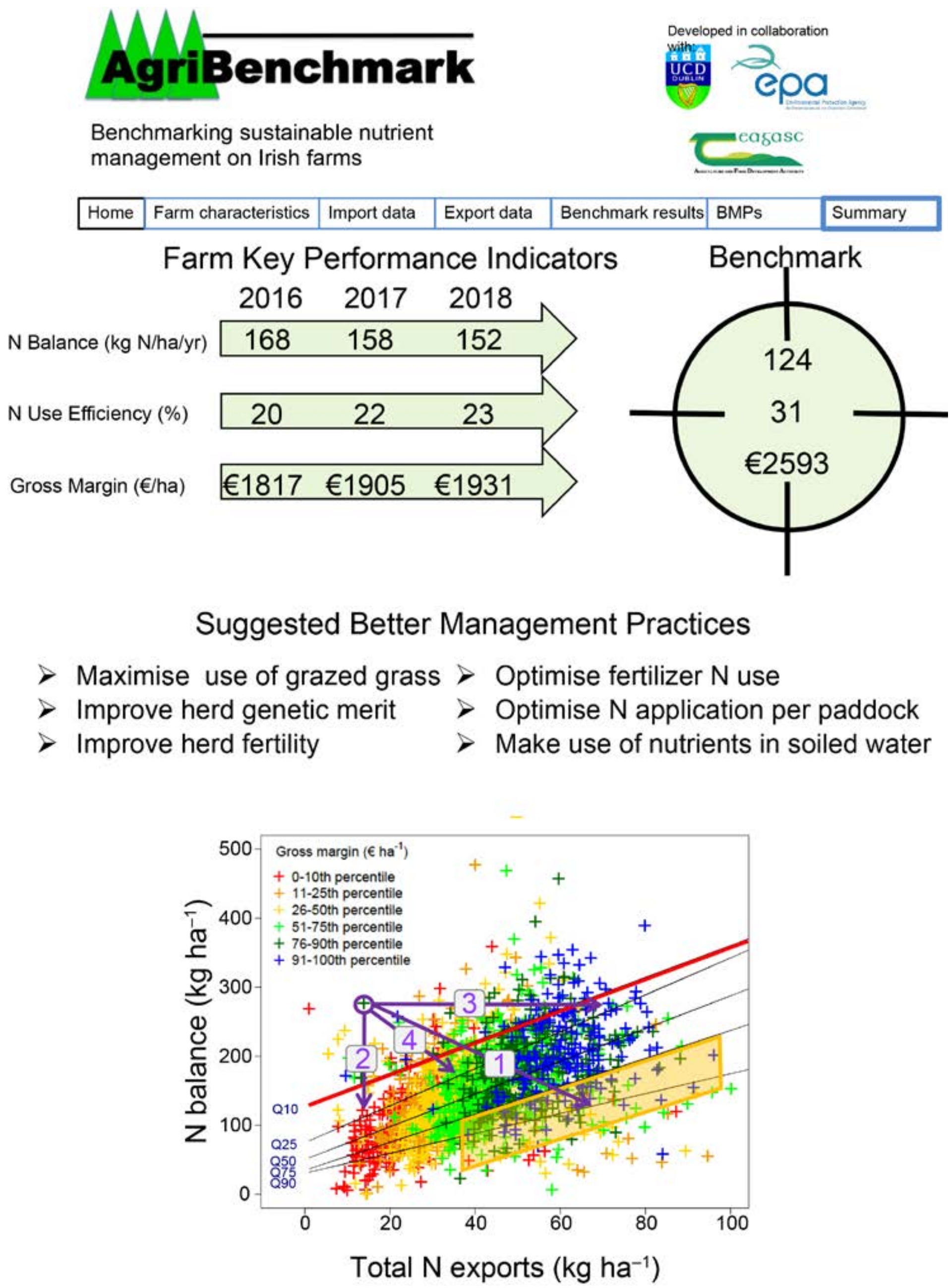

Figure 5.1. Wireframe for the summary page of an online nutrient management benchmarking tool.

For P, the tool would have to take account of the fact that a farm may need to operate at a significant P surplus for a number of years if soils on the farm are deficient in P and the farmer wants to raise the soil P status to the agronomic optimum (soil P index 3). It should be noted that index 3 for all agricultural soils may not be a desirable, or even an optimal, outcome. Significant losses to water may well occur from soils at agronomic optimum soil P concentrations and adequate crop yield and quality may be achieved at lower soil P concentrations; much would depend on a farmer's objectives (e.g. desired level of production) and the soil type and its physicochemical properties. It should also be noted that the sensitivity of receiving water bodies to P would also be critical in determining the actual water quality impact of any P losses. In less intensively managed catchments, with high status and sensitive water bodies, any increase in soil P concentrations might be viewed as a potential risk to water quality. There may need to be some weighing of risks and priorities, environmental and economic, before deciding if a particular benchmark should be targeted in a particular catchment or farm.

The tool could account for this by using soil test results for a farm, input by the farmer/advisor, to estimate the P build-up requirements, based on sample areas, using the "sustainable P balance" approach outlined by Murphy *et al*. (2015). If the target is to achieve an optimum index of 3 for all soils, the P build-up requirement (kg P ha^{-1}) should be subtracted from the farm-gate P balance (kg P ha^{-1}). Negative values of the sustainable P balance indicate that not enough P is being imported onto the farm to build up all soils to the optimum index of 3. This approach would avoid the appearance of large surplus P balances for farms that are in a phase of building soil P fertility. The sustainable P balance could be included as a standard KPI in the tool or could be included as an optional KPI if the farmer/advisor indicates that they are intending to build all soils to an optimum index of 3.

For the purpose of incorporating a dynamic user-led approach to extension, the visual benchmark would also highlight a range of applicable strategies designed to improve the nutrient management performance of individual farms (e.g. Figure 4.5), with each strategy aligning with different practices to suit farmers' resources, capabilities and motivations. Ideally, this tool might serve as a focal point for engagement between farmers and advisors, between farmers themselves and potentially between farmers and other stakeholders (policymakers, consumers, members of the public). Appropriate extension strategies would be necessary to introduce the concept of benchmarking of nutrient management performance at farm level across all farm types.

This web-based tool would be designed to be used as an add-on to existing web-based farm management tools such as the Teagasc Nutrient Management Planning Online (Teagasc, 2018b) or the Teagasc/Bord Bia Carbon Navigator (Murphy *et al*., 2013) tools, as these are tools with some traction among farmers already and they fit with the purpose of the proposed benchmarking tool, reflecting the approximate economic return for each strategy. We recommend that, in future, benchmarking approaches and other web-based farm management advisory tools such as the one outlined here, Nutrient Management Planning Online, the Carbon Navigator and the Herd Economic Breeding Index (Berry *et al*., 2007), be integrated to avoid the multiplication of such management tools and potential mixed messages around recommended management practices. A proliferation of such management tools may lead to confusion for many farmers. For environmental outcomes, in particular, multiple tools, each focused on different environmental risks (e.g. GHG emissions vs. nutrient emissions to water), increase the likelihood of mixed messages being communicated and the occurrence of "pollution swapping". Recommendations for improved management practice are more likely to be effective if they are consistent and focused on a number of key management practices that are easily understood by the farmer.

Although the role of extension services is important in advancing improvements in farm nutrient management, how services are delivered to farmers has begun to change. Existing extension strategies have displayed a movement away from one-to-one and prescriptive approaches to the dissemination of information to farmers and incorporation of more integrative approaches, such as farmer lead learning and group or shared learning between peers. This has resulted in a movement away from a singular way of doing, as per the "procedure"-like approach, to an approach that is much more dynamic and adaptive. This approach is often facilitated but is intended to be farmer led. This movement in Ireland can be seen by the national body of education and extension, Teagasc, actively changing its approach to extension. This is currently being achieved through programmes such as the Better Farms Programme and through discussion groups, now the main extension tool used by Teagasc to access farmers. However, it is evident that more work is needed to develop a broader range of tools to support farmers in their decision making. There has also been a movement towards more online platforms, increasing potential outreach opportunities. The benchmarking tool explored here would fit into this context.

The provision of information is vital for innovation at all stages in the adoption and post-adoption process (Läpple and Cullinan, 2012). There is evidence that the more simplistic Rogers framework of "transfer of technology" and "diffusion of innovations" has been partly replaced by an approach that seeks a wider understanding of the system and knowledge, information and advice and requirements of farmers as users (Kelly, 2014). This suggests that a change in approach is required if increased adoption and innovation in the agricultural sector is to be adequately achieved. This is particularly important for extension strategies targeted at environmental issues (Kelly *et al.*, 2016). One key area is the need for information on current and new technologies in real farm situations to appropriately understand economic performance, the impact on the environment and the role of sustainable food production systems.

A nutrient management benchmarking tool would need to be adaptable and would need to be constantly updated to reflect new information and technologies. For example, the benchmarking process would need to be updated on an annual basis, in terms of both the individual farm being benchmarked and the changing levels of performance of its peers, using the updated NFS data. This would allow farmers to establish the direction of change that might act to motivate incremental improvement in the KPIs and adoption of further improved management practices. Improvements in the KPIs among a farmer's peers might then also act, over time, to encourage further improvement. In particular, as "early adopter" farms improve their performance, this would have the effect of "moving the prize" of the benchmark performance level, encouraging further improvements among farmers who are slower to adopt new practices or technologies. Such an adaptive and dynamic benchmarking process would be very important to ensure that benchmarking is not based on a historical level of performance but, rather, reflects the best level of performance that can *currently* be achieved.

6 Conclusions

The AgriBenchmark study explored the possibilities for benchmarking of nutrient management performance on Irish farms. Of the various farm nutrient budgeting models available, it was decided that the farm-gate nutrient balance model was the most appropriate for a number of reasons: data availability, data certainty, usability for the farmer and usability for monitoring/policy. In defining the system boundaries of the nutrient budgeting model to the farm-gate level, the identification of nutrient inputs and outputs over which the farmer has direct control is possible. The overall environmental pressure (nutrient source pressure) of the farm resulting from nutrient management is more directly characterised and the contributions of different nutrient inputs and outputs to that pressure are quantified, thereby aiding in identifying changes in management practice that may reduce these nutrient source pressures.

Teagasc NFS data were used to characterise and explore the potential for improvement of farm nutrient management performance and resultant aspects of economic and environmental sustainability through the derivation of KPIs on farm nutrient balance, NUE and profitabilit y (gross margin). Temporal trends (2008–2015) were also explored.

Key findings were:

- Large ranges in the KPIs of farm nutrient balance and NUE between farms of the same type show that there is scope for nutrient management improvements. Within the observed range of performance for each farm type, there is considerable scope to reduce nutrient source pressure (nutrient balance) and increase efficiency (NUE). Although some of this variability in performance will be related to factors beyond the immediate control of the farmer, it is also likely that some of this variability relates to farm and nutrient management practices that are under the control of the farmer. Therefore, using these KPIs as benchmarks to measure and motivate improved management practices would appear to have considerable scope to reduce nutrient source pressures and increase NUE.
- For both N and P, the primary driver of inter-annual differences in the KPIs of nutrient balance and NUE was fertiliser import for most farm types. However, for dairy and mixed livestock farms, concentrates make up a significant proportion of N imports and are roughly as important as fertiliser in terms of P imports. Therefore, fertiliser management is a key area of focus for all farm types to improve nutrient KPIs, whereas feed management is also particularly important for dairy and mixed livestock farms.
- Nutrient exports in farm products are also important. Dairy and tillage systems are the most intensive in terms of nutrient imports, but this study shows that dairy farms perform relatively well in terms of NUE compared with other livestock types and tillage farms are the best performers for both balances and use efficiencies. This has important implications if a balance is sought between agricultural production and environmental source pressure at the farm scale, but also at the landscape, regional and national scales, in terms of the spatial distribution of agricultural production and nutrient source pressures.
- From a nutrient source pressure perspective, dairy farms exert the greatest pressure and it could be argued that particular efforts should be made to reduce that source pressure and minimise risks to the environment on these farms. Dairy farms clearly exert the greatest nutrient source pressure in terms of both surplus per ha (mean 156 kg N ha^{-1} yr^{-1} and 7.0 kg P ha^{-1} yr^{-1}) and estimated national aggregate agricultural surplus (111,210 t N yr^{-1} and 4994 t P yr^{-1}), equivalent to 43% of the total aggregate N surplus and 31% of the total aggregate P surplus, from only 21% of the total UAA (results represent, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally).
- As the EU milk quota system ended in 2015, and with the planned expansion (and likely intensification) in milk production under the Food Harvest 2020 and Food Wise 2025 programmes, the need to encourage improved nutrient

management on dairy farms, in particular, should be emphasised. Dairy herds have expanded and milk exports have increased post 2012. P imports for dairy farms showed a steady increase from 2009 onwards and stabilised at *c*. 18 kg P ha^{-1} after 2013.

- Although the tillage sector is conventionally thought of as being relatively intensive, its mean N and P surpluses were the lowest, representing only 22% and 46% of the mean dairy N and P balances, respectively. It also represented only 4% and 6% of the total aggregate N and P surpluses, respectively. Furthermore, its mean NUEs were the highest of all farm types, with N-NUE and P-NUE that were 2.6 and 1.4 times higher, respectively, than those of the most efficient livestock farms (sheep and non-suckler cattle). This reflects the greater opportunities for nutrient loss and greater challenges to efficient recovery of nutrients in farm products, particularly for N, in grass-based livestock systems than in tillage systems. It should be noted, however, that the frequent and intensive soil cultivation practices, periods of reduced vegetative cover, high yields and agrichemical use associated with tillage lead to other environmental pressures such as soil (and P) loss and soil organic matter (carbon) loss and CO_2 emissions.
- For all sectors, the national fodder shortage in 2013, as a result of unusually cold and wet weather, increased imports of forage crops, concentrates and fertilisers relative to 2012. This fodder shortage therefore increased N and P surpluses and decreased N and P use efficiencies in all livestock sectors in 2013, except for NUEs of suckler farms. Weather, pasture growth, housing periods, fertiliser/feed costs and market prices, among other factors, can all affect balances and use efficiencies year-to-year and it is therefore important to benchmark against a time-integrated metric, rather than a single year.
- General trends of improved N and P management performance (reduced surpluses and increased efficiencies) across farm types (except for sheep farms) in the last 2 or 3 years of this study indicate improved sustainability and reduced nutrient source pressures. However, increases in P balances and decreases in P use efficiencies for all livestock sectors over the whole period from 2008 to 2015 indicate that P source pressures have increased overall over this time. These increased P balances are largely the result of increased fertiliser P imports. N surpluses increased considerably only for dairy, non-suckler cattle and sheep farms, but for dairy farms this was associated with an increased NUE. Tillage P surpluses decreased by 25% at no expense to P-NUE, and N surpluses decreased by 24% with a 17% increase in N-NUE. As part of the wider context, it should be noted that the exit of the UK from the EU will likely have implications for Irish agriculture and some of the trends identified in this report, as the UK is a major market for Irish agri-food products.
- When comparing SGs, all sectors showed trends of lower fertiliser and concentrate use and lower total imports and export when going from SG1 to SG3 (from high to low land use potential) for both N and P. N balances and N- and P-NUEs also tended to decrease when going from soils with high land use potential to those with low land use potential (except for tillage farms for N balance and sheep farms for N-NUE). Although P balances showed a similar trend for suckler cattle, sheep and tillage farms, the other three sectors showed no trend.
- As stocking rates increase, all livestock sectors import more N and P fertiliser and feed and export more N and P through an increase in agricultural produce, and nutrient surpluses tend to increase. However, NUE trends vary by system and nutrient: N-NUE decreases for mixed livestock and suckler cattle farms and slightly for dairy farms, whereas P-NUE increases for these farm types. Both non-suckler cattle and sheep farm N-NUEs and P-NUEs show no trends.

A benchmarking analysis of the NFS data (using quantile regression analysis) based on nutrient balance per ha (nutrient source pressure), nutrient export per ha (output intensity) and gross margin per ha (profitability) produced benchmark KPIs for each farm type.

Key findings of this benchmarking analysis were:

- As production intensity increases (with higher total N or P exports), N balances increase and P balances remain the same for livestock farms, tillage N and P balances decrease and, for all sectors, gross margins increase. However, benchmark farms minimise surpluses to relatively low levels for a given level of production intensity. Within all farm types, large ranges in nutrient balances between benchmark farms and poorer performers show considerable room for reducing surpluses. Aiming for a minimum sustainable P balance of 3 kg P ha^{-1} (to maintain soil fertility and animal nutrition at adequate levels) would appear to be achievable for low- and high-intensity farms of all farm types. However, aiming for a 0 kg N ha^{-1} balance would appear to be much more challenging, as would be expected, and is likely not a realistic target.

- Compared with other farms, benchmark farms have lower fertiliser and feed imports per ha, greater exports of agricultural products per ha, relatively high stocking rates (except for tillage, mixed livestock and non-suckler cattle farms), higher land use potential (based on soil class) and higher gross margins (€ ha^{-1}).
- For dairy farms, higher stocking rates are required to secure high gross margins per ha; the average stocking rate for the optimal N benchmark zone for dairy farms was 2.2 LU ha^{-1} or 181 kg ON ha^{-1} (requiring a derogation from stocking rate limits under the EU Nitrates Directive). In Ireland, and many developed countries where the land resource is limited and land prices are high, this is extremely important. This result validates the approach taken in this study of including both environmental and economic KPIs to determine benchmarks of farm performance as the resultant benchmarks address both environmental and economic sustainability.
- The optimal benchmark zone for dairy farms is characterised by farms with high stocking rates but relatively low N and P surpluses (122 kg N ha^{-1} and 4.5 kg P ha^{-1}, compared with 271 kg N ha^{-1} and 26.6 kg P ha^{-1} for the 10 percentile), relatively high N- and P-NUE (31% N-NUE and 72% P-NUE, compared with 14% N-NUE and 26% P-NUE for the 10th percentile) and high gross margin returns (€2734 ha^{-1} for the N benchmark and €2698 ha^{-1} for the P benchmark, compared with €1909 ha^{-1} and €1700 ha^{-1} for the N and P 90th percentiles, respectively). This pattern was similar for suckler cattle, non-suckler cattle and sheep farms, where the benchmark zone is associated with lower stocking rates (1.2–1.6 LU ha^{-1}), lower N and P surpluses (25–33 kg N ha^{-1} and 3.8–4.4 kg P ha^{-1}), higher N-NUE (31–47%), variable P-NUE (53–73%) and lower gross margin returns (€972–1351 ha^{-1}) relative to dairy farm benchmarks.
- Fertiliser imports make up a much larger proportion of total N imports than feed imports for all farm types and, therefore, have a much larger effect on N surpluses and use efficiencies. Most gains in N balances and use efficiencies occur through improved fertiliser management. Lowering fertiliser imports will reduce nutrient surpluses on dairy farms to a far greater extent than increasing the stocking rate and associated nutrient exports in milk.
- Fertiliser P also dominated P imports for most farm types, but not for the dairy, mixed livestock and sheep sectors. For these farm types, farms in the optimal benchmark zone had higher average total feed P imports from concentrates plus forage crops (9.4, 11.2 and 5.9 kg P ha^{-1}, respectively) than from fertiliser (6.6, 4.6 and 5.6 kg P ha^{-1}, respectively). Dairy and mixed livestock benchmarks had high stocking rates, low N and P surpluses, high N- and P-NUE and high gross margin returns. What distinguishes these benchmark farms is a moderate level of fertiliser and feed imports combined with a high level of exports in milk. Consequently, efforts to improve management to improve performance in the KPIs of nutrient balance, NUE and gross margin should focus not only on reducing fertiliser and feed imports, but also on maximising the principal farm exports, in this case, milk. This highlights the importance of the many other factors that would influence these exports such as herd genetics, herd health and fertility management, and grassland and grazing management. This would support the idea that efforts to improve nutrient management on farms for environmental and economic reasons should always be considered as an integral part of overall farm management.

To assess the potential economic gains and reductions in surpluses and nutrient source pressure that could be achieved through moving towards benchmark targets, four different benchmarking scenarios were explored:

1. all non-benchmark farms reach the optimal benchmark zone for their category;
2. all non-benchmark farms reach the next best performing zone in their category;

3. all farms with excessive nutrient surpluses (highest 10%) reach the next best performing zone;
4. all non-benchmark farms, including those with a N surplus of $<0\,kg\,ha^{-1}$ and those with a P surplus of $<3\,kg\,ha^{-1}$ (i.e. the complete NFS data set), reach the optimal benchmark zone for their category.

The first three used only data points with minimum sustainable nutrient balances (i.e. farms with a N surplus of $\geq 0\,kg\,ha^{-1}$ or a P surplus of $\geq 3\,kg\,ha^{-1}$). Scenarios 2 and 3 reduced nutrient source pressures and increased NUEs (improving environmental sustainability) and also reduced fertiliser costs and concentrates in some farm types, but changes in gross margins were variable between sectors and nutrient type. Total costs, total direct costs and gross output increased for N but decreased for P. These results illustrate the potential trade-offs between economic and environmental sustainability that may need to be made. Scenarios 1 and 4 involve farms moving to higher production intensity and, as a result, more moderate reductions in nutrient surpluses were found than in scenario 3 for affected farms (and even small increases in P surplus for scenario 4 for suckler cattle, sheep and tillage farms), but with much greater improvements in profitability and resource use efficiency.

To achieve the more substantial improvements in both nutrient source pressure *and* profitability and resource use efficiency associated with scenarios 1 and 4, it is necessary to focus both on optimisation of nutrient imports and their management *and* on optimisation of nutrient exports, which, in the case of dairy farms, is milk. This would require improvements in management of all aspects of the dairy farm related to improving milk yield per ha (herd health, grass and grazing management, herd genetic merit and fertility, etc.) and, in many instances, may require increasing intensity in terms of the stocking rate, for example. For dairy farms in scenario 4, the estimated mean dairy farm gross margin improved by €919 ha^{-1}, associated with a decrease in N surplus of $-35\,kg\,N\,ha^{-1}$ and an increase in NUE of 11.2 percentage points, principally because of a combination of reduced fertiliser and concentrate N imports (–22 and -29 $kg\,N\,ha^{-1}$ respectively) and increased N exports in milk ($+13\,kg\,N\,ha^{-1}$).

For P, scenario 4 led to mean P balances that were higher than mean NFS farm values for the suckler cattle, sheep and tillage sectors, indicating that current P inputs are suboptimal for optimum productivity (as reflected by national Teagasc soil sample analysis; Teagasc, 2018a), and thus scenario 4 identified the need to increase fertiliser and/or feed P inputs. Optimum P management should be guided by frequent soil sampling and this should prevent farms from either losing soil P fertility because of persistent farm P deficits or developing excessive soil P concentrations because of persistent farm P surpluses.

On aggregate (results represent, on average, 61% of farms and 76% of the UAA, excluding commonage, nationally), benchmark scenario 4 led to a 31% decrease in surplus N, from 258,893 t to 179,108 t, indicating the significant potential for reducing nutrient source pressure through benchmarking. The largest proportions of this potential national decrease in surplus N came from dairy (30%) and non-suckler cattle (29%) farms, reflecting the large contribution of these two farm types to the national N surplus but also indicating the significant potential to reduce that surplus. Despite the large reductions in total surplus N from dairy farms, benchmark scenario 4 would leave dairy farms even more dominant as the major source of surplus N source pressure, at 49%, further highlighting the importance of addressing N surpluses in the dairy sector.

Estimated changes in mean N_2O emissions following changes in N fertiliser use under benchmark scenario 4 were between $+0.23\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ (tillage) and $-0.28\,kg\,N_2O\text{-}N\,ha^{-1}\,yr^{-1}$ (non-suckler cattle), with the largest potential reductions in emissions per ha coming from dairy and non-suckler cattle farms. On an aggregated basis, this would equate to a reduction of $553\,t\,N_2O\text{-}N\,yr^{-1}$, mostly coming from non-suckler cattle (274 t), dairy (171 t) and suckler cattle (141 t) farms. This would equate to a reduction of $0.259\,Mt\,CO_2$-eq or a 4.2% reduction in N_2O emissions and a 1.3% reduction in total GHG emissions from the agricultural sector nationally, based on 2016 emissions. These relatively moderate emissions reductions reflect the fact that overall GHG emissions from the agricultural sector are strongly linked to livestock numbers and the fact that many farms would have increased N fertiliser use under the benchmark scenario. This highlights the balance that may need to be struck between environmental and economic goals in any benchmarking approach.

In the context of national policy under Food Harvest 2020 and Food Wise 2025, the results indicate that increased production per ha is likely to increase nutrient surpluses, use efficiencies and gross margins. However, this study shows that benchmark farms can achieve high output and gross margins per ha while minimising nutrient surpluses, challenging the assumption that more intensive farms, in terms of production per ha, will automatically have greater surpluses and exert larger source pressures on the environment than low-intensity enterprises. Certainly, the performance of these benchmark farms should be of great interest in terms of identifying strategies to achieve the ambitious production targets for the agricultural sector in Ireland while also meeting environmental policy commitments such as those under the EU Water Framework Directive and UNFCCC.

The quantile regression analysis used in this study could also be used to guide targets for N and P balances (specific to each farm category and level of production intensity) in order to reduce excessive surpluses and nutrient source pressures from poorly performing farms, as part of a benchmarking process. The target surplus could be set depending on production intensity, to provide a more appropriate upper limit for the given farm type and intensity of operation.

The benchmarking approach explored here is based on current (2008–2015) levels of performance for these farm types. It is important to note that this does not define the absolute optimum level of performance that could potentially be achieved by these farm systems. It cannot be assumed, even for the benchmark farms, that all management is optimal. There may be management practices, strategies and technologies, either currently existing but not adopted or that may be developed in the future, that might shift the production frontier of performance for a particular farm type.

Effective knowledge transfer to farmers would be central to achieving the potential improvements in nutrient management, and associated improvements in economic and environmental sustainability, highlighted in this study. Central to this knowledge transfer strategy would be a web-based management decision support benchmarking tool, highlighting the KPIs for individual farms, ranking farms against the benchmark, summarising the potential gains that could be made by improving management and suggesting some management practices that could help to move farms in the right direction. We explored the possibility of developing such a tool and produced a wireframe of it. Some key conclusions from this exploratory work are as follows:

- For P, the tool would have to account for the fact that a farm may need to operate at a significant P surplus for a number of years if soils on the farm are deficient in P and the farmer wants to raise the soil P status to optimum (index 3). The tool could account for this using soil test results for the farm, input by the farmer/advisor, to estimate the P build-up requirements, based on sample areas, using the “sustainable P balance” approach. It should be noted that agronomic optimum soil P concentrations (soil P index 3) for all agricultural soils may not be a desirable, or even an optimal, outcome. Significant losses to water may well occur from soils at agronomic optimum soil P concentrations and adequate crop yield and quality may be achieved at lower soil P concentrations; much would depend on a farmer’s objectives (e.g. desired level of production) and the soil type and its physicochemical properties. It should also be noted that the sensitivity of receiving water bodies to P would also be critical in determining the actual water quality impact of any P losses. In less intensively managed catchments, with high status and sensitive water bodies, any increase in soil P concentrations might be viewed as a potential risk to water quality. There may need to be some weighing of risks and priorities, environmental and economic, before deciding if a particular benchmark should be targeted in a particular catchment or farm.
- The tool should be designed to be used as an add-on to existing web-based farm management tools such as the Teagasc Nutrient Management Planning Online or the Teagasc/Bord Bia Carbon Navigator tools. Such tools should be integrated to avoid their multiplication and potential mixed messages around recommended management practices and incidences of “pollution swapping”. Recommendations for improved management practice are more likely to be effective if they are consistent and focused on a number of key management practices that are easily understood by farmers.

- For the purpose of incorporating a dynamic user-led approach to extension, the visual benchmark tool would also highlight a range of strategies designed to improve nutrient management performance of individual farms, with each strategy aligning with different practices to suit farmers' resources, capabilities and motivations.
- The tool would need to be adaptable and dynamic. The benchmarking process would be updated on an annual basis, in terms of both the individual farm being benchmarked and the changing levels of performance of its peers, using the updated NFS data. This would allow farmers to establish the direction of change that might act to motivate incremental improvement in the KPIs and adoption of further improved management practices. Improvements in the KPIs among a farmer's peers might then also act, over time, to encourage further improvement. In particular, as "early adopter" farms improve their performance, this would have the effect of "moving the prize" of the benchmark performance level, encouraging further improvements among farmers who are slower to adopt new practices or technologies. Such an adaptive and dynamic benchmarking process would be very important to ensure that benchmarking is not based on a historical level of performance but, rather, reflects the best level of performance that can *currently* be achieved.

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Abbreviations

DEA	Data envelopment analysis
EU	European Union
FADN	Farm Accountancy Data Network
GHG	Greenhouse gas
KPI	Key performance indicator
LCA	Life cycle analysis
LU	Livestock unit
MINAS	Mineral Accounting System
NFS	National Farm Survey
NUE	Nutrient use efficiency
ON	Organic nitrogen
SG	Soil group
UAA	Utilised agricultural area
UNFCCC	United Nations Framework Convention on Climate Change

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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AgriBenchmark: Benchmarking Sustainable Nutrient Management on Irish Farms

Authors: Paul N.C. Murphy, Ian Thomas, Cathal Buckley, Edel Kelly, Emma Dillon and Thia Hennessy

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Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identifying Pressures

Large ranges in key performance indicators (KPIs) between farms show that there is significant scope to reduce nutrient source pressures and increase use efficiencies through benchmarking to measure and motivate improved management practices. Dairy farms exert the greatest nutrient source pressure (mean 156 kg N ha^{-1} and 7 kg P ha^{-1}), equivalent to 43% of the total agricultural N (nitrogen) surplus and 31% of the total agricultural P (phosphorus) surplus, from only 21% of the agricultural land. With the end of the milk quota system and the planned expansion in milk production under the Food Harvest and Food Wise programmes, the need to encourage improved nutrient management on dairy farms should be emphasised.

The AgriBenchmark study explored possibilities for benchmarking nutrient management on Irish farms, using National Farm Survey data (2008–2015) to derive three KPIs: nutrient balance (kg ha^{-1}), nutrient use efficiency (NUE; %) and profitability (gross margin; € ha^{-1}). A positive nutrient balance (surplus) represents a nutrient source pressure, in terms of risk of nutrient loss to the environment, with potential impacts on water quality, greenhouse gas (GHG) emissions, air quality and biodiversity. Trends of reduced N and P surpluses and increased efficiencies for most farm types in the last 3 years of this study indicate improved sustainability and reduced nutrient source pressures.

Informing Policy

Benchmark farms minimise surpluses to relatively low levels for a given level of production intensity, with lower fertiliser and feed imports per ha, greater exports of agricultural products per ha, relatively high stocking rates and higher gross margins. For example, the optimal benchmark for dairy farms is characterised by farms with relatively high stocking rates (2.2 livestock units ha^{-1}) but relatively low N and P surpluses (122 kg N ha^{-1} and 4.5 kg P ha^{-1}), relatively high NUEs (31% N-NUE and 72% P-NUE) and high gross margins (€2734 ha^{-1}).

To achieve these improvements, it is necessary to focus both on optimisation of nutrient imports and their management and on optimisation of nutrient exports, which, in the case of dairy farms, is milk.

For the ambitious scenario of all non-benchmark farms reaching the optimal benchmark, moderate reductions in nutrient surpluses were found with great improvements in profitability and resource use efficiency. The findings from this research may inform policy in areas such as programmes to achieve targets under the EU Nitrates and Water Framework Directives, the National Emissions Ceilings Directive (ammonia emissions), the EU 2020 and 2030 GHG commitments and the 2050 Low Carbon Economy Roadmap, as well as economic policies relevant to the agri-food sector and rural economies, such as the Food Harvest and Food Wise programmes.

Developing Solutions

The findings from this research illustrate that significant reductions in nutrient source pressure may be possible while also improving efficiency and profitability – a win-win scenario. For the most ambitious benchmarking scenario for dairy farms, the gross margin improved by €919 ha^{-1}, associated with a decrease in N surplus of –35 kg N ha^{-1} and an increase in NUE of 11.2 percentage points, as a result of reduced fertiliser and feed N imports (–22 and –29 kg N ha^{-1}, respectively) and increased milk N exports (+13 kg N ha^{-1}). Nationally, this scenario led to a 31% decrease in estimated agricultural surplus N, with the largest proportions of this decrease coming from dairy (30%) and non-suckler cattle (29%) farms.

Effective knowledge transfer to farmers would be critical to achieving the potential improvements highlighted in this study. Central to this would be a web-based management decision support benchmarking tool, highlighting the KPIs for individual farms, ranking farms against the benchmark, summarising the potential gains that could be made by improving management and suggesting management practices that could help to move farms in the right direction.

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