Post EU Nitrates Directive implementation: an examination of the sustainable use of phosphorus in milk production

Cathal Buckley

David P. Wall

Brian Moran

Stephen O'Neill

Paul N.C. Murphy

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Cathal Buckley*[1], David P. Wall[2] Brian Moran[3] Stephen O'Neill[4] Paul N.C. Murphy[5]

[1]Agricultural Catchments Programme, Teagasc, Athenry, Co. Galway.
[2]Teagasc, Environment Research Centre, Johnstown Castle, Wexford, Co. Wexford.
[3]Agricultural Economics and Farm Surveys Department, Teagasc, Athenry, Co. Galway.
[4]Department of Economics, J.E. Cairnes School of Business, National University of Ireland Galway.
[5]School of Agriculture and Food Science, University College Dublin, Belfield, Dublin 4.

*** Corresponding author: cathal.buckley@teagasc.ie**

Abstract

This research estimates farm gate phosphorus balances and use efficiencies across 147 specialist dairy farms over a seven year period (2006-2012) using nationally representative data and the Republic of Ireland as a case study. This period coincides with the introduction of phosphorus controls in agricultural production under EU Nitrates Directive based regulations. Results indicate that P balances declined by 50 per cent over the study period from 11.9 in 2006 to 6.0 Kgs Ha^{-1} in 2012. This decline was driven by a reduction in chemical fertiliser imports of 6.5 Kgs Ha^{-1} and is equivalent to a reduction of 281 kgs of P across the average farm and 2,392 tonnes of P across the weighted sample. This represents a cost saving of €812 per annum across the average farm and €6.89 million for the weighted sample over the study period. Phosphorus use efficiency also improved over the period from 60 per cent in 2006 to 78 per cent in 2012, peaking in 2011 at 88.3 per cent. Results of a random effects panel data model indicate that P balance and use efficiency are significantly influenced by factors such as fertiliser prices, stocking rates, land use potential, contact with extension services and rainfall patterns.

Keyword: Phosphorus, farm gate balance, phosphorus use efficiency, random effects panel data model.

1.0 Introduction

In Ireland phosphorus (P) is the major limiting element for eutrophication of surface freshwaters (McGarrigle, 2009) yet a vital element in agricultural production. Sustainable use of phosphorus has gained increased attention not only from an environment risk perspective but from a long term food security perspective due to finite reserves (Cordell et al. 2011; Huhtanen et al. 2011; Simpson et al. 2011; Amery and Schoumans, 2014). Phosphorus is an essential element for plant growth, however intensification of fertilizer use in agricultural production over time has sometimes lead to excessive losses of nutrients to the aquatic environment with a detrimental effect on water quality (Kronvang et al., 2005). Despite progress the European Environment Agency (2012) estimates that diffuse pollution from agriculture is still significant in more than 40% of Europe's water bodies in rivers and coastal waters, and in one third of the water bodies in lakes and transitional waters. Eutrophication in Irish watercourses emerged as an issue in the 1970s (Flanagan and Toner, 1972, 1975). Recently 29% of monitored river channel length is estimated to be polluted to some degree across the Republic of Ireland with agricultural sources suspected in 47 per cent of suboptimal outcomes (EPA, 2012). More recently due to the declining reserves of P it’s acknowledged that the sustainable use of P based fertilisers has repercussions for food security as well as economic returns to agricultural production (Science Communication Unit, 2013).

Phosphorus can be lost from the soil through a number of pathways namely; erosion, surface runoff, leaching and tile drainage (Amery and Schoumans, 2014). Farm and field level nutrient management is consistently found to be an optimal strategy (Schulte et al., 2009) and is predicated on matching fertiliser applications to crop demand. This can be achieved voluntarily where farmers follow fertilisation advice or through pricing or regulatory instruments (Scott, 2004). Amery and Schoumans (2014) notes that in contrast to nitrates, there is no overarching EU regulation directly governing P applications and losses from agricultural land. Some EU Member States address agricultural P loss through voluntary agri-environment schemes or through national or regional legislation under the auspices of the Nitrates Directive (91/676/EEC), Water Framework Directive (2000/60/IEC) or Industrial Emissions Directive (2010/75/EU). However, other member states (or regions therein) do not have direct P application restrictions outside of indirect controls applicable under the Nitrates Directive.

The Nitrates Directive (ND) is one of the earliest pieces of EU legislation aimed at controlling and improving water quality. The ND, now under the umbrella of the Water Framework Directive, was introduced in 1991 with the principal aim of minimizing surplus nitrogen from being applied on farms in order to reduce the associated nitrogen losses from agriculture to water bodies. The Republic of Ireland implemented the EU Nitrates Directive on a whole territory basis (the regulations apply across the whole territory) in 2005-06 and the first National Action Programme (NAP) covered the period from 2006 to 2010. The Republic of Ireland is in a minority of EU countries that included direct controls on chemical P fertilisers in its National Action Plans 2006-2010 and 2010-2014.

The ND as implemented in the Republic of Ireland aims to minimise surplus N and P losses from agriculture to the aquatic environment by constraining use to agronomic optima and limiting to periods where mobilisation during runoff events is minimised. Since 2006 the Directive has been implemented in the Republic of Ireland through Statutory Instrument (Government of Ireland, SI 378 of 2006; SI 101 of 2009, SI 610 of 2010; SI 31 of 2014) commonly referred to as the Good Agricultural Practice (GAP) regulations. These gave statutory effect to Ireland's national ND National Action Programmes. The GAP regulations mandate a minimum slurry storage requirement for the housing of livestock over the winter period and closed periods for spreading organic and chemical fertilisers during autumn and winter months. Limits on livestock intensity are also implemented to indirectly constrain organic N use to 170 kg organic N ha^{-1} per annum and up to 250 kg N ha^{-1} per annum where a derogation has been granted[1]. This indirectly controls organic P application rates. The application limit of P chemical fertilizers is recommended by crop type at rates defined by crop demand (Coulter and Lawlor, 2008). A restriction on spreading according to a P limit is primarily related to a soil P index system which is based on the measured concentration of available P in soil as determined by the Morgan's P test (Morgan, 1941; Schulte et al., 2010). Total allowable chemical P fertiliser application limits is hence based on soil P status and crop demand with reductions for any organic manure or concentrate feedstuff imported.

Sub-optimal use of nutrients at farm and field level has significant economic and environmental implications (Oenema and Pietrzak, 2002; Buckley and Carney, 2013). Policymakers are ever more interested in the environmental efficiency of different farming systems and seek reliable indicators of sustainability (Brouwer, 1998; Halberg et al., 2005).

[1] This derogation was secured due to length of growing season in the Republic of Ireland. A total of 5,583 farmers secured Derogation in 2014, approximately 90% were dairy farmers (Nolan, 2014).

Farm-gate nutrient accounting systems have been proposed as a method of evaluating farm level nutrient use efficiency while also providing an indicator of pressure on environmental quality (Jarvis and Aarts, 2000; Schroder et al., 2004). Nutrient accounting systems account for nutrient inputs onto a farm, mainly through imported fertilisers and feedstuffs, and subtract nutrients exported from the farm through outputs such as milk, meat, cereals, wool and organic manures (Huhtanen et al., 2011; Gaj and Bellaloui, 2012; Gourley et al., 2012). The farm gate approach restricts analysis to imports and exports of nutrients over which the farmer has direct control. Typically P imports exceed exports in a dairy farm system (Van Keulen et al. 2000) and the excess results in surplus P that is either accumulated in the soil or lost from the system (Arriaga et al. 2009). In contrast to a farm gate balance, nutrient use efficiency examines the ratio of exports to imports and is an indicator of resource use efficiency and agronomic performance (Halberg 1999; Oenema et al. 2003; Gourley et al. 2012).

Milk production across the Republic of Ireland totalled 5.65 billion litres in 2013 (CSO, 2014a) and a national target of a 50% increase in dairy production by 2020 has been set by policymakers post abolition of the EU milk quota regime in 2015 (Department of Agriculture, Fisheries and Food 2010). In contrast to most EU countries, milk production across the Republic of Ireland is based on a grazed grass low-cost, low-input, seasonal (compact spring calving) model that seeks to maximise the utilization of grass grown on-farm and minimise the proportion of imported feed in the cow’s diet (Dillon and Delaby, 2009). Dairy farms tend to have the highest stocking densities and fertilizer inputs of grassland systems in the Republic of Ireland (Hennessy et al., 2013) and are therefore perceived as being of some concern in terms of pressures on the environment.

This study explores that use of P on specialist dairy farms since the implementation of EU Nitrates Directive based GAP regulations in 2006. This assessment is based on the estimation of farm-gate P balance and use efficiency across 147 specialist dairy farms taking part in a national farm survey over a 7 year period (2006-2012). Additionally, this paper uses a panel data model analysis to explore environmental and managerial factors which influence these P use sustainability indicators over the study period.

2.0 Methodology

2.1 Data

The data source for this analysis is the Teagasc National Farm Survey (NFS). The Teagasc NFS is collected annually as part of the EU Farm Accountancy Data Network (FADN) requirements (FADN, 2005). A detailed set of farm accounts and enterprise level transactions are recorded on a random representative sample of farms across the Republic of Ireland. This analysis focuses on 147 specialist dairy farms that remained in the Teagasc NFS over a 7 year period from 2006 to 2012. The average farm profile of the sample over the period is summarised in Table 1. Average population weights over the period were used and the sample is hence representative of 8,490 dairy farms nationally over the study period. It's estimated that there were approximately 15,654 specialist dairy farmers in the Republic of Ireland in 2012 (NFS, 2013).

Population weights are for each farm based on data provided by the Central Statistics Office of Ireland (see Teagasc National Farm Survey 2010 for a full description). Statistics presented in this analysis are population weighted unless otherwise stated. The analysis excludes farmer who reported importing or exporting organic manures as no data were available on volumes imported or exported. Data on the import and export of organic manures was only available from 2008-2012, hence if a farm was not importing/exporting over these 5 years then it was assumed this held for 2006 and 2007.

A specialist dairy farm is defined as a system where a minimum of two-thirds of farm standard output is from grazing livestock and dairy cows are responsible for a minimum of three-quarters of the grazing livestock output. Although labelled specialist dairy farms, these farms tend to have other farm enterprises also. This is noticeably illustrated in Table 1, where 35% of total livestock were non-dairy cows, although some of these livestock are replacement animals for the dairy herd. Farm gate balances presented here are for the whole-farm and not just for the dairy enterprise only. Hence, some of the nutrient imports and exports included in the balances will be associated with other non-dairy on-farm enterprises such as livestock rearing or arable crops grown for sale. Some of the dairy farms grew arable crops for the market, but the area devoted to this was not significant averaging 1.7 hectares across the sample. This would be typical for Irish dairy farms as milk production in Ireland is predominantly grass-based. Average P loading based stocking rate was 23.4 kgs ha^{-1} organic P per hectare and milk production on the portion of the farm devoted to dairying averaged 9,652 litres ha^{-1} with production per cow averaging 5,008 litres over the period.

Table 1: Sample profile 2006-2012

Production Profile	Mean (standard deviation)	Range
Farm size (ha)	47.7 (25.7)	8 – 161
Grassland (ha)	45.0 (23.1)	8 – 155.0
Cereals or root crops (ha)	1.7 (5.3)	0 – 56.3
Total livestock units	86.7 (47.3)	13.2 – 313.8
Dairy livestock units	56.2 (29.3)	8 – 186.0
Other livestock units	30.5 (21.9)	0 – 177.5
Stocking rate (organic P ha^{-1})	23.1 (5.5)	6 – 40.7
Milk (l ha^{-1})(land in milk production)	9,652 (3,262)	2,371 – 32,976
Milk (l cow^{-1})	5,008 (993)	1,878 – 8,308

2.2 P balance and use efficiency derivation

Average farm gate nutrient balances were derived from subtracting the total quantities of P exported from total quantities imported while nutrient use efficiencies were calculated by dividing P exports by imports and expressing as a percentage. The following section described derivation of P imports and exports.

2.1.1 Phosphorus imports

The main farm gate based P imports include chemical fertilisers, concentrate feeds, forage feeds, milk replacer (for feeding calves) and purchased livestock. Chemical fertiliser composition and quantities purchased are recorded as a matter of course in the Teagasc NFS. Actual quantities of fertiliser applied to land was used in the analysis and were calculated from opening stocks plus purchases less closing stock. Phosphorus imported in concentrate feeds was established from quantities of each feed type purchased and average P composition using standard values (Ewing, 2002). This approach was also adopted for other imported forage crops. A wide range of forage crops were imported onto these specialist dairy farms, such as silage, straw, cereals and root crops. These were converted to kgs of P based on quantities imported and standard P contents (Ewing, 2002). Milk replacer is a calf nutrition product sometimes fed to calves on dairy farms as a substitute for raw milk. Milk replacer imported was converted to kgs of P using standard P contents (Tikofsky et al., 2001). Imports of P through livestock was estimated based on the purchase price of the animal dividing by the prevailing prices (cent per kg) for the type and age of animal (Bord Bia, 2012; CSO, 2012) and applying standard co-efficients (McDonald et al. 1995).

3.1.2 Exports

Exports of P included milk, livestock, cereal crops, forage crops and wool as many farms had a second farm enterprise (beef, sheep, tillage) in conjunction with the dominant dairy enterprise. Phosphorus in milk-based farm gate exports were calculated by applying standard co-efficients (McDonald et al. 1995) to quantities of milk sold. Exports of P in liveweight sale was estimated based on the sale price of the animal dividing by the prevailing prices (cent per kg) for the type and age of animal (Bord Bia, 2012; CSO, 2012) and applying standard co-efficients (McDonald et al. 1995). A minority of farms in the sample had a cereal crop or root crop enterprise where crop outputs were exported post-harvest. The P content exported in the crop products were established from the quantities of each crop type sold and applying a standard co-efficient (Ewing, 2002). Finally, where farms had a sheep enterprise, P exported in wool was estimated from quantities sold and a co-efficient as estimated by Jarvis et al. (2002).

3.2.1 Modelling approach

P balance and use efficiency are expected apriori to be influenced by a range of observable and unobservable factors. A panel data model is employed to examine these relationships. The dependent variable Y_{it} (either P balance or P use efficiency) takes a value for individual farm *i* at time *t*. X denotes a vector of independent variables and β is a vector of parameter coefficients to be estimated and ε_{it} represents the random error term.

(1) $$Y_{it} = X_{it}\beta + \varepsilon_{it}$$

To take account of unobserved heterogeneity, the error term, ε_{it} can be decomposed into two components; an unobserved individual specific effect μ_i , which captures the time invariant unobserved heterogeneity and a random component, ν_{it} which is assumed to be independently and identically distributed over time and individuals. So that equation (1) becomes:

(2) $$Y_{it} = X_{it}\gamma + \nu_{it}$$

If it is believed that μ_i is not correlated with the explanatory variables, then a random effects estimator can be adopted. However, this assumption is quite strong and if it is violated random effects estimates will be biased. The modelling approach adapted by Mundlak (1978) and Chamberlain (1984) relax this assumption, allowing for a correlated random effect, by specifying that the unobserved effect for individual *i* is randomly distributed conditional on a function of X_{it} such as the average for the individual, X_i ($\mu_i = X_i\alpha + \zeta_i$). Although the Chamberlain approach is more flexible, using the average as proposed by Mundlak conserves degrees of freedom and is generally found to perform well empirically. The Mundlak approach is adopted in this analysis as it allows for account to be taken of the potential correlation between time invariant unobserved farm heterogeneity and included farm characteristics. By adopting this approach, bias due to correlation between the included variables and the omitted time invariant variables can be largely avoided.

3.2.2 Explanatory variables

A priori a number of farm level and environment variables are expected to influence P balance and use efficiency and these are discussed below.

Chemical fertiliser is a major input across specialist dairy farms due to the grass based nature of milk production across the Republic of Ireland. Application of fertiliser in excess of the optimum are often attributed to factors such as risk aversion to lower yields, information asymmetry or incentive incompatible fertiliser pricing (Scott, 2004; Buckley and Carney, 2013). The lower the price of fertiliser the greater the incentive to apply chemical fertiliser to excess to offset potential risk and uncertainty related to weather and yields. While farmers in the Republic of Ireland are volume limited under the EU Nitrates Directive, it is expected that higher fertiliser prices increase incentives for optimal use of fertiliser and may lead to lower P balances and higher use efficiencies (Scott, 2004). Annual average P fertiliser prices (€/kg) were derived from prices published by the Central Statistics Office of Ireland (CSO, 2014b).

The positive impact of farm size on efficiency is established in the literature (Latruffe et al., 2008; Buckley & Carney, 2013) so a variable reflecting area farmed in hectares is included in the analysis. A land use potential variable was derived based on a soil classification system. This system divides soils into six different classes based on soil quality, altitude, topography and drainage as set out in the National Soil Survey of Ireland (Gardiner and Radford, 1980). The good land use potential category consists of soil classes 1 and 2. Soil class 1 has no limitation and soil class 2 has minor limitations on land use due to soil texture, altitude or climatic conditions. These soils tend to be freer draining. The average land use potential category consists of soil classes 3 and 4. Soil class 3 has more significant use limitations associated with soil texture, altitude or climatic conditions, while soil class 4 has limitations associated with poor drainage. A poor land use potential category in the analysis was based on soil class 5 which has a very limited use range. Risk of P loss tends to be associated with heavier, more clay rich soils were P tends to be lost due to overland flow (Fealy et al., 2010).

A variable labelled organic P (OP) ha^{-1} is included in the analysis; this is a measure of livestock farming intensity and is measured in kg OP ha^{-1}. This variable is derived based on average numbers and types of animal held on the farm and applying standard coefficients (e.g. 1 dairy cow is equivalent to 13 kg OP) for different livestock types as set out in Nitrates Directive regulations (Government of Ireland, 2014). Higher rates of production intensity would be expected aprioi to influence P balances and use efficiencies.

Farmers with off-farm employment tend to have less time to dedicate to on-farm management and this may affect nutrient management efficiency. Prokopy et al., (2008) found that labour availability tended to increase adoption of best management practices. Off-farm employment in this instance is measured through a binary yes/no variable, where the variables takes a value of 1 if the farmer has off-farm employment.

In contrast to nitrogen, P is largely an immobile element and the majority of P applied to grassland is either utilised by the grass crop or bound to the soil. In grassland, most P is absorbed in the upper few centimetres of the soil and only a small proportion of the total soil P is available to plants, as measured by Morgan's P based soil test (Lalor and Culleton, 2009). Hence, a soil test is necessary to determine the optimal rate of P application. No data was available on whether farmers in the sample were basing nutrient management decisions on a soil test. However, it's hypothesised that farmers engaging with extension services were more likely to be encouraged to soil test and would have access to information and advice on appropriate rates of chemical P application. While more efficient farmers may in the first instance be more likely to engage with extension services, it is hypothesized that information and knowledge transfer around optimal nutrient management prescriptions is most likely to come from contact with an agricultural advisor and participation in a farmer network such as a discussion group. Farmer discussion groups are facilitated by an agricultural advisor; hence farmers in these groups would by definition have regular contact with an agricultural advisor. Consequently, two dummy variables were derived for this analysis, the variable contact with an advisor took a value of 1 if a farmer had engaged an agricultural advisor in the previous 12 months and the variable advisor and discussion group took a value of 1 if the respondent is a participant in a farmer discussion group.

As illustrated in Table 1 there is a wide variation in milk output per cow across farms in the sample. This variation may in part be explained by the genetic merits of individual herds. Higher genetic merit herds are potentially achieving higher levels of output which can reduce the amount of P lost per hectare or unit of output. To capture this effect a variable labelled milk recording was included in the analysis. Farmers who engage a milk recording service receive a performance report on each individual cow and can cull underperformers and promote high performers in terms of breeding herd replacements. This variable took a value of 1 if the farmer was milk recording.

Each farm in the NFS is assigned a regional code based on the NUTS (Nomenclature of Territorial Units) classification used by Eurostat. The NUTS 3 regions correspond to the eight Regional Authorities established under the Local Government Act, 1991 (Regional Authorities) (Establishment) Order, 1993. The national weather service Met Eireann has weather stations in each of these regions. While individual farms may be located significant distances from these weather stations, average rainfall and temperature from the nearest station was used as a proxy for these climatic variables for each farm over the study period (CSO, 2014; Met Eireann, 2014). However, in this context Kerebel et al. (2013) showed that results from regional stations correlate with local stations in the region for broad data patterns. Under Irish conditions, it might be expected that years of higher rainfall and lower temperatures might be associated with higher P balances and lower P use efficiencies due to decreased grass growth rates, decreased grazing days and increased requirements for feed imports, particularly on more poorly drained soils. Table 2 provides summary statistics for the explanatory variables included in the analysis

Table 2: Explanatory variables included in the regression analysis

*Variables***	*Mean*	*Std. Dev.*	*Min*	*Max*
P Fertiliser price (€/kg)	2.59	0.62	1.79	3.47
Organic P kgs ha^{-1}	22.8	5.6	6.0	40.7
Farm Size (hectares)	56.3	27.3	8.0	161.0
Off-farm employment	0.11	0.31	0	1
Contact with farm Advisor (yes/no)	0.53	0.50	0	1
Contact with farm advisor & discussion group (yes/no)	0.35	0.48	0	1
Milk recording (yes/no)	0.37	0.48	0	1
Good land use potential (yes/no)	0.58	0.49	0	1
Average land use potential (yes/no)	0.37	0.48	0	1
Poor land use potential (yes/no)	0.05	0.21	0	1
Annual rainfall (millimetres)	1126.5	272.2	691	1875
Average annual temperature (˚C)	10.4	0.6	8.3	11.3

** Unweighted in regression

4.0 Results

4.1 P Balance and use efficiency

Total P imports declined over the study period (2006 to 2012) by 6.6 Kgs Ha^{-1} from 21.7 to 15.1 Kgs Ha^{-1} as outlined in Table 3. This was almost exclusively driven by a decline in chemical P fertiliser imports which fell by 6.5 Kgs Ha^{-1} during the period from 13.3 to 6.8 Kgs Ha^{-1}. All other P imports remained relatively stable. Concentrate feedstuff was the other major source of P imports and fluctuated between 6.3 and 7.8 Kgs Ha^{-1} over the period. However, at the end of the study period in 2012, concentrates (6.9 Kgs Ha^{-1}) had taken over from chemical fertiliser (6.8 Kgs Ha^{-1}) as the main source of P imports. Other more minor sources of P imported include forage feeds (0.7- 0.9 Kgs Ha^{-1}) and livestock (0.3-0.4 Kgs Ha^{-1}), these imports remained relatively static over the period.

Total P exports declined slightly by 0.7 Kgs Ha^{-1}over the period from 9.8 in 2006 to 9.1 Kgs Ha^{-1} in 2012. This was mainly due to decreased livestock based P exports of 0.6 Kgs Ha^{-1}(4.0 to 3.4 Kgs Ha^{-1}). As expected milk was the dominant P export and accounted for approximately 60 per cent of total P farm gate exports. Due to the EU milk quota regime, P based milk exports remained static over the period and was the same in 2012 as 2006 at 5.5 Kgs Ha^{-1}. The other minor source of P export was crops based and this remained stable over the period at 0.2-0.3 Kgs Ha^{-1}.

Average P balance declined by 5.9 Kgs Ha^{-1}over the study period from 11.9 to 6.0 Kgs Ha^{-1}. This 50% decline was driven by a reduction in imports of chemical fertilisers (declined by 6.5 Kgs Ha^{-1}). P balance followed a declining trend over the study period and the lowest P balance was recorded in 2011 at 4.6 Kgs Ha^{-1}. Phosphorus use efficiency also improved over the study period from 59.6 in 2006 to 78 per cent in 2012, peaking in 2011 at 88.4 per cent.

Table 3: Phosphorus balance and use efficiency 2006-2012

Imports	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
P Fertilisers Kgs Ha^{-1}	13.3	8.8	7.4	6.5	7.0	6.7	6.8
P Concentrates Kgs Ha^{-1}	7.2	6.4	7.8	6.3	6.6	5.8	6.9
P Forage Feeds Kgs Ha^{-1}	0.8	0.8	0.7	0.9	0.9	0.9	0.9
P Livestock Imports Kgs Ha^{-1}	0.4	0.3	0.3	0.3	0.3	0.4	0.3
P Other Imports Kgs Ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total P Imports Kgs Ha^{-1}	21.7	16.3	16.2	14.0	14.8	13.8	15.1
Exports							
P Milk Kgs Ha^{-1}	5.5	5.6	5.4	5.2	5.5	5.7	5.5
P Livestock Exports Kgs Ha^{-1}	4.0	3.8	3.5	3.3	3.4	3.3	3.4
P Crops Kgs Ha^{-1}	0.3	0.2	0.2	0.2	0.2	0.2	0.2
P Wool Kgs Ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total P Exports Kgs Ha^{-1}	9.8	9.6	9.2	8.7	9.1	9.2	9.1
P Balance Kgs Ha^{-1}	**11.9**	**6.7**	**6.9**	**5.3**	**5.7**	**4.6**	**6.0**
P use efficiency	**59.6**	**73.5**	**77.8**	**80.0**	**80.2**	**88.4**	**78.0**

4.2 Results of regression analysis

An inverse relationship was found between fertiliser price and P balance (significant at the 1% level). Results indicate that a 1 unit increase in fertiliser price (€1/kg) leads to an estimated 1.736 kgs ha^{-1} decline in P balance ha^{-1}. However, it should be noted that such an increase would have the effect of increasing the average price of P fertiliser by 40%. Fertiliser price was found to have a positive and significant effect (also at the 1% level) on P use efficiency. Results show a 1 unit increase in fertiliser price predicting a 6.441 percentage point increase in P use efficiency. This is in line with expectations a priori as higher fertiliser price leads would be expected to reduce farmer demand.

A positive and significant relationship was found between stocking rate as measured by organic P based stocking rate and P balance (significant at the 5% level). Results indicate a 1 unit increase in organic P kgs ha^{-1} leads to a 0.192 P kgs ha^{-1} increase in P balance. While the relationship is significant the leakage from the system is significantly less than nitrogen at about 20%. There was no statistically significant relationship found between P use efficiency and organic P based stocking rate.

After controlling for correlation between time invariant unobserved variables via the inclusion of a Mundlak term, farm size was found to be only variable affected and no statistically significant relationship was found between farm size and either P balance or use efficiency. Off-farm employment was associated with a lower P balance and lower N use efficiency but again the effect was not found to be significant.

Farmers who were in contact with an agricultural advisors or had contact with farm advisor and a discussion group had significantly lower P balances (1% level) and higher P use efficiencies (5% level). Farmers with these extension contacts tended to have a P balance of 4.2-4.7 kgs ha^{-1} lower than the base category of no extension contact. Conversely, farmers in contact with the aforementioned extension contacts had 13-14% higher P use efficiency. Additionally, farmers who engaging with milk recording had also significantly lower P balances and higher P use efficiencies (both at 1% level). Farmers using this technology indicated a lower P balance by 2.34 kgs ha^{-1} and a higher P use efficiency of 14 per cent.

Given that heavier soils tend to be associated with greater P loss, results here are in line with expectations in that farmer on land of average (significant at the 10% level) and poor use potential were associated with higher P balances than those on good soils. A statistically significant relationship (1% level) was found between P use efficiency and land use potential. Phosphorus use efficiency was 17.2 per cent lower for farms of average land use potential and 21.6 per cent lower for farms of poor land use potential compared to the base category of good land use potential farms.

Rainfall was found to have a significant effect on both P balance and use efficiency at the 1% level. Higher annual rainfall was associated with higher P balances and lower use efficiencies. No significant effect was found between temperature and P balance or use efficiency.

Table 4: Results of regression analysis

Variables	*P Balance Ha^{-1}*	*P Use Efficiency*
Fertiliser price	-1.736*** (0.435)	6.441*** (2.373)
Organic P kgs ha^{-1}	0.192** (0.089)	0.077 (0.385)
Farm Size	-0.043 (0.041)	0.070 (0.249)
Mundlak – Farm Size	0.064 (0.0458)	-0.258 (0.242)
Off farm-employment	-0.422 (1.255)	2.863 (5.810)
Contact with farm Advisor	-4.171*** (1.191)	13.01** (5.459)
Contact with farm advisor & discussion group	-4.651*** (1.236)	14.258** (6.708)
Milk recording	-1.901*** (0.673)	13.64*** (4.382)
Average land use potential	1.521* (0.882)	-17.241*** (4.781)
Poor land use potential	0.537	-21.629***

	(1.569)	(7.484)
Rainfall	0.0034***	-0.0187***
	(0.001)	(0.0065)
Temperature	0.160	1.005
	(0.335)	(2.244)
Constant	3.339	69.53***
Observations	1,028	1,028
Number of farms	147	147
*** p<0.01, ** p<0.05, * p<0.1		

5.0 Discussion

Results from this study indicate that P balances declined by 50% (5.9 kgs ha^{-1}) and P use efficiency has increased by 19 per cent across the sample over the study period. This P balance reduction is equivalent to 281 kgs of P across the average farm and 2,392 tonnes of P across the weighted sample. This corresponds to a reduction of 1.76 tonnes of the main P based chemical fertiliser granular superphosphate (16% P) across the average farm and 14,951 tonnes cumulatively across the weighted sample of specialist dairy farms represented. As P exports per hectare remained relatively stable over the period (declined by 0.7 kgs ha^{-1}, but milk based output remained static), this reduced chemical fertiliser use is equivalent to a cost saving of €812 per annum[2] across the average farm and €6.89 million for the weighted sample.

The application of P in quantities excessive of crop requirement inherently leads to nutrient surpluses in soils and increases the risk of nutrient transfer to the aquatic environment. However, transfer of P to the aquatic environment ultimately depends on the characteristics of the landscape and soil as well as the type of rainfall prevalent. Results from this analysis indicate declining P balances and increasing P use efficiency across the most intensive cohort of farmer between 2006 and 2012. Concurrently, Environmental Protection Agency river monitoring over the study period indicates a general declining trend in P concentration, albeit with annual variations. The proportion of river monitoring locations with P concentrations of greater than 0.05 mg l^{-1} declined from 25.5% in 2007 to 14.6% in 2012 (Environmental Protection Agency, 2013). Phosphorus levels in lakes also declined where 62.5% of the lakes monitored in 2007 were below 0.025 mg l^{-1} total phosphorus while in 2012 this figure has

[2] Based on average price of €462 per tonne of Granular Superphosphate (16% P) in 2012 (CSO, 2014b)

increased to 71.4%. This decline is attributed to a number of factors including several agriculture related changes such as reduced chemical fertiliser applications; improved manure storage facilitates; and spreading practices associated with the implementation of Good Agricultural Practice (GAP) (Environmental Protection Agency, 2013). Lag times between policy implementation and effect in the aquatic environment are expected (Schulte et al, 2010; Fenton et al., 2011) however, these monitoring trends seem reflective of changes in agricultural production as found in this study.

The average farm-gate P surplus at the end of the study period is considerable lower and P use efficiency considerable higher than values reported nationally and internationally heretofore for smaller scale studies of dairy farm systems (Aarts 2003; Neilsen and Kristensen, 2005; Raison et al. 2006; Fangueiro et al. 2008; Gourley et al. 2012). In a study across 9 EU Atlantic regions and 139 pilot farms, Raison et al., (2006) found participating farms in southern Ireland had the lowest P balance (7.9 kgs P ha^{-1}) and highest P use efficiency (62 per cent) or any region. Results at the end of the study period here for P balance are considerable lower than the result (18 kgs P ha^{-1}) found in earlier smaller scale studies of intensive Irish dairy farms (Mounsey et al. 1998). The aforementioned studies and results were pre-implementation of the EU Nitrates based GAP regulations (SI 610 of 2010) in 2006 and while these studies are not directly comparable (not nationally representative) this result would suggest that P surpluses are declining and P use efficiency is increasing across Irish dairy farms. A more recent analysis (Mihailescu et al. – forthcoming) of P balances and use efficiency across 21 intensive grass-based specialist dairy farms in the south of Ireland 2009-2011 indicated an average P balance of 5.1 kgs P ha^{-1} and a P use efficiency of 70 per cent. This is in line with results from this study over the period 2009-2011.

As outlined by Lalor and Culleton (2009) a soil P Index system (based on a Morgan's P soil test) is used as an indicator of background soil P fertility levels in the Republic of Ireland generally. The target level for optimum grass production is Index 3 (between 5 and 8 mg/l soil test P) and this is associated with minimal risk of P loss in run-off. Index 1 and 2 soils are defined as agronomically deficient in P while Index 4 soils are enriched and generally show no response to P fertilizer and are more at risk of P loss to the aquatic environment. Results from a national soil analysis database (based on 38,000 non random samples per annum taken by Teagasc across the Republic of Ireland between 2007-2012) show that the percentage of Index 4 soils has fallen from 30% in 2007 to 18% in 2012 (Murphy, 2013). These trends indicate a decline in the pressure from diffuse agricultural P sources over time. However, this decline in the prevalence of Index 4 soils has been accompanied by an unintended sharp increase in Index 1 and 2 soils at the expense of Index 3 soils, which are in the target index. This increased prevalence of P-deficiency (index 1 and 2) from c. 40% in 2007 to c. 59% in 2012 and reduction in Index 3 from 30% to 23% over the same period maybe due to low uptake of soil testing, increased fertiliser prices or potentially non-optimal P allowances in the regulatory framework.

Results from this study indicate that fertiliser prices and contact with extension services significantly influence P balance and use efficiency. Chemical P fertiliser prices increased on average by over 50% (94% between the years 2006-2009) over the study period (CSO, 2014), hence farmer may have responded with sub optimal application of P fertiliser due to cost. Where fertiliser prices are incentive incompatible (associated with lower prices) farmers may apply an excess over crop requirement to offset risk of lower yields. At higher fertiliser prices there are greater incentives for farmers to use optimal quantities. However, previous research has found that regulatory limits on fertilisers compared to a pricing based policy instrument such as tax could achieve compliance more effectively and equitably for those farms already operating at optimal rates (Lally et al., 2007; 2014).

In the absence of a soil test and advice thereon, asymmetric information will pertain to the P status of soils and may lead to inappropriate levels of P fertiliser application. Farmers availing of an EU Nitrates Derogation are required to perform a periodic soil test; otherwise no data was available on whether farmers in the sample had performed a soil test. However, results did indicate that farmers in more regular contact with extension services and using milk recording technology had lower P balances and higher P use efficiencies. Farmers engaging with these aforementioned extension contacts are encouraged through these forums to soil test and are likely to have access to information on optimal fertiliser application schedules. Access to information, contact with extension agents and participation in a farmer network have previously been found to influence best practice adoption (Rahelizatovo and Gillespie 2004; Prokopy et al., 2008; Ghazalian et al., 2009; Lemke et al., 2010; Baumart-Gert et al., 2012). Farmers engaging in milk recording have access to the performance ratings of individual dairy cows and can make management decisions on this basis with a view to increasing the genetic merit of their herd. Production of a given level of milk from a reduced number of animals inherently improves nutrient use efficiency and has a knock effect of lower P balances as found in this study.

Results from this study indicate that higher stocking rates (as measured by Organic P ha^{-1}) are associated with higher farm gate P balances. With the abolition of EU milk quotas regime due in 2015 a national target of a 50% increase in milk production by 2020 has been set by policymakers in the Republic of Ireland (Department of Agriculture, Fisheries and Food 2010). This will place increased pressure in this area going forward and put an increased emphasis on nutrient management efficiency. As P is pre-dominantly an immobile element and can be tested for this, nutrient management planning based on a soil test where application are applied in optimal quantities and spatial location will help offset risk in this area. Additionally, it maybe that critical source areas where the risk of P transfers from agricultural production to the aquatic environment is greatest are identified and adaptive management strategies are implemented on these land parcels to manage this risk. However, it must be acknowledged that even with strict nutrient management factors beyond a farmers such as rainfall patterns influence P balance and use efficiency as results show deterioration in this metrics in higher rainfall years.

Conclusion

The Republic of Ireland was one of a minority of EU member states to include direct controls on chemical P fertilisers in its EU Nitrates Directive National Action Plans. Results from this study of specialist dairying systems indicate P balances declined significantly (50%) and P use efficiencies improved significantly (20%) over the period since the Directive implementation. While the imposition of regulations is likely having a significant effect on these indicators other non-regulatory based factors were found to be influential. Fertiliser prices, contact with extension and technology adoption such as milk recording of the dairy herd, stocking rates, rainfall patterns, and land use potential was generally found to affect P balance and use efficiency. Phosphorus is increasingly becoming a scarce resource and optimal application has implications for returns to agricultural production as well as reducing risk of nutrient transfer to the aquatic environment. Results from this study indicate dairy farmers have improved P management since the EU Nitrates Directive measures were introduced in 2006.

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