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# Farm-gate phosphorus balances and soil phosphorus concentrations on intensive dairy farms in the south-west of Ireland

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**Phosphorus (P) loss to water is a significant threat to water quality in Ireland. Agriculture is an important source of this P. There is concern about balancing agronomic requirements and environmental protection in regulations prescribing P management on farms. This study examined farm-gate (P) balances and soil test P (STP) concentrations on 21 dairy farms in the south west of Ireland over four years, from 2003 to 2006 inclusive. Stocking density on the farms averaged 2.4 (s.d. = 0.4) livestock units (LU) per ha. Annual mean import of P onto farms was 21.6 (1.9) kg P/ha. Fertilizer P accounted for 47% (0.041), concentrates 35% (0.060) and organic manures 18% (0.034) of imported P. The mean annual P balance per farm was 9.4 (1.2) kg/ha, ranging from –3 to 47 kg/ha and mean P use efficiency was 0.71 (0.05) ranging from 0.24 to 1.37. The mean STP per farm following extraction using Morgan's solution was 8.15 (2.9) mg/L of soil and ranged from 4.4 (2.2) to 14.7 (6.4) mg/L. There was a positive relationship ($R^2 = 0.34$; $P < 0.01$) between STP and P balance; farms with a deficit of P tended to have agronomically sub-optimal STP and vice versa. The high between- and within-farm variation in STP indicates that farmers were either unaware or were not making efficient use of STP results, and consequently there was agronomically sub-optimal soil P status in some fields and potentially environmentally damaging excesses on others (often within one farm). There was considerable potential to improve P management practices on these farms with clear agronomic and environmental benefits.**

*Keywords*: dairy farm-gate balance; nutrient management; phosphorus, phosphorus surplus; soil test phosphorus

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## Introduction

Phosphorus is an important input for profitable intensive grass-based dairy farming and an essential nutrient for the production of economically viable herbage yields. Agriculture is the single biggest contributor of P to Irish waters and eutrophication remains Ireland's most serious environmental pollution problem (McGarrigle, Lucey and Cinnéide 2010). This pollution is associated with high soil P levels and the excessive and the inappropriate timing of fertiliser and slurry applications (Kurz *et al.* 2005; Watson, Smith and Matthews 2007; Regan *et al.* 2010).

Phosphorus inputs to grassland in Ireland have been regulated since 2006 by Statutory Instruments (SI) (Anonymous 2006). The introduction of SI Number 378 of 2006 superseded the 2004 edition of the Teagasc recommendations for the management of P in grassland (Coulter 2004). The first SI 378 2006 was superseded by SI 101 2009 (Anonymous 2009) and by SI Number 610 of 2010 (Anonymous 2010; hereafter referred to as SI). The introduction of the SIs has resulted in the use of P on farms being stringently curtailed. Parameters for the use of manufactured fertilizer P on farms are delineated with the objective of achieving a zero balance on farms. The import of P onto farms (manufactured fertilizers, concentrates and other animal feeds, organic manures etc.) should not exceed export of P (products, organic manures exported from the farm etc.) from the farm (Tunney and Culleton 1995; Haygarth *et al.* 1998; Brogan 2001). In some cases where there is a need to increase the concentration of P in soils with very low or low soil P status P, imports are permitted to exceed P exports.

In both the 2004 Teagasc recommendations and in the SI (Table 9 in SI 610 2010), soil P concentrations in grassland soils are divided into four categories: Indices 1 to 4. The P index system depends on the concentration of plant-available P in mineral soils, which is determined by extraction using the Morgan's soil test for P (0.72 *M* $CH_3COONa$ + 0.52 *M* $CH_3COOH$, pH 4.8) (STP; Morgan 1941; Byrne 1979; Coulter 2004). A comparison of the index description of soil P ranges, as defined in the Teagasc recommendations and the SI, is presented in Table 1. In general the quantities of P inputs allowed under the SI are lower than that in the 2004 Teagasc recommendations.

Soils in index 1 and index 2 are deemed to be agronomically deficient in P and require a build up of soil P reserves (Schulte and Herlihy 2007). The optimum P index, known as the target index, is index 3, at which the soil is deemed able to provide sufficient P for crop uptake without negatively affecting the environment (Daly, Jeffrey and Tunney 2001; Jordan *et al.* 2005; Kurz *et al.* 2005). Soils

**Table 1. Index system 1 to 4 for soil P and actual Morgan soil test range for P in the Teagasc Recommendations in 2004 (Coulter 2004) and Statutory Instruments (SI) 378 2006, SI 101 2009 and SI 610 2010 (Anonymous 2006; 2009; 2010)**

| Soil Index | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Soil P status | Very low | Low | Sufficient | Excess |
| Response to fertilizers | Definite | Likely | Unlikely | None |
| | Soil P ranges (mg P/L) | | | |
| Teagasc Recommendations (2004) | 0.0–3.0 | 3.1–6.0 | 6.1–10.0 | >10.0 |
| SI 378 (2006); 101 (2009); 610 (2010) | 0.0–3.0 | 3.1–5.0 | 5.1–8.0 | >8.0 |

in index 4 have elevated P reserves, and do not exhibit justifiable responses to additional fertiliser P. Since there is a strong linear relationship between STP and P loss (Tunney *et al.* 1998; Buckley, Murphy and Wall 2013), soils in index 4 pose the greatest risk to water quality. For this reason it is desirable to allow the P level of these soils to decrease over time.

The implementation of these regulations is the culmination of a review of the national recommendations for P use on farms that commenced in the early 1990's motivated by concern about increasing incidences of eutrophication of inland surface waters. The initial consequence of this review was the introduction of revised recommendations in 1996. Prior to these 1996 recommendations, national use of manufactured fertilizer P was reasonably consistent from year to year at approximately 62,000 tonnes per annum (Figure 1). Following the 1996 recommendations, national fertilizer P use fell to 54,000 tonnes in 1997 and to approximately 50,000 tonnes per year between 1998 and 2000. Since 2000 there has been a steady decline in fertilizer P use nationally to 28,775 tonnes in 2010/11 due to a combination of further adjustments to the recommendations, rising fertilizer costs, increasing efficiency of P use on farms and falling livestock populations. Fertilizer P use in 2011 was approximately 46% of pre-1996 levels.

It is likely that the above changes in recommendations and regulations have had a substantial impact on P use, P balances and P use efficiency on dairy farms. However, there has been little or no reported research of this topic on dairy farms in Ireland and there is a dearth of reported research on this topic internationally (Nielsen and Kristensen 2005; Virtanen and Nousiainen 2005; Raison, Pflimlin and LeGall 2006; Fangueiro *et al.* 2008; Gourley *et al.* 2011). The present study examines soil test P levels, P use and farm-gate P balances on a group of 21 intensive dairy farms located in the south

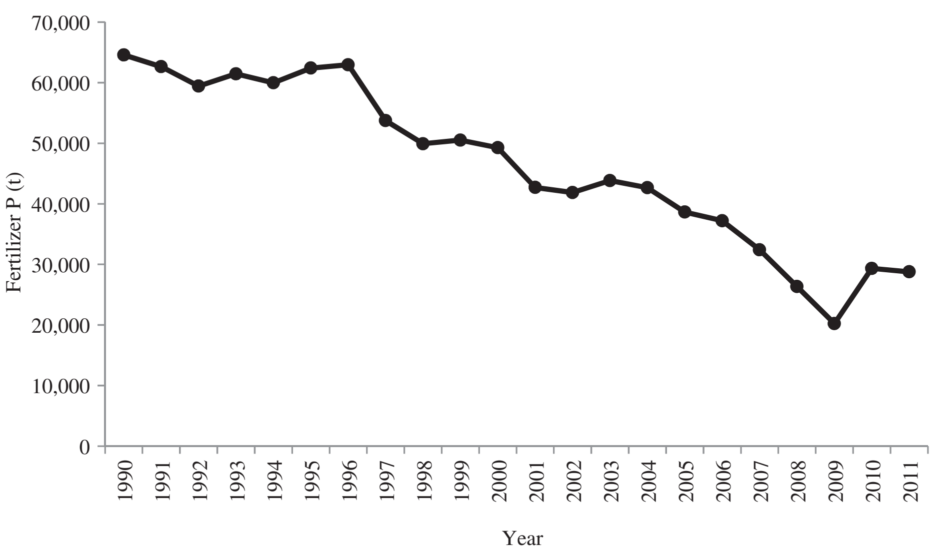


*Figure 1. Trends in national fertilizer phosphorus (P) use from 1990 to 2011 (Source: Anonymous 2013).*

west of Ireland for the years 2003 to 2006 inclusive. The study investigated whether farmers were using organic and chemical P in accordance with the agronomic requirement of soils.

Statutory Instruments (SI) 378 2006 was implemented in Ireland in September 2006, which was near the end of the present study. The objective of this study was to investigate the extent to which the farms in the present study complied with the limits on P use in the run up to the implementation of these new regulations. To this end, we collected data on P use on 21 farms collected over the four years from 2003 to 2006.

## Materials and Methods

### *Farm selection and on-farm recording*

Both the selection of the farms involved and methods for much of the on-farm recording have been already described by Treacy *et al.* (2008). Permanent grassland-based milk production from spring calving cows was the main enterprise on all the selected farms. All farms in this study were involved in the Dairy Management Information System (DAIRYMIS) programme run by Teagasc (Crosse 1991). This is a computerised recorder-based system designed to capture detailed information on farm inputs, livestock production and reproduction. The selected farmers had a history of accurate record keeping. During the study, all nutrient applications on each paddock were recorded by the farmer on purpose built recording boards. The data collected was validated by follow-up interviews with the farmers and by cross checking with the DAIRYMIS data to eliminate errors.

Livestock density was expressed as the quantity of N excreted by resident livestock relative to the area of the farm used for agricultural production (utilised agricultural area). This was calculated using the standard values for annual N excretion for the different categories of livestock in the SI (e.g. one dairy cow excretes 85 kg per year of N, one bovine less than one year old excretes 24 kg per year of N). The same criteria were used to define a livestock unit (LU), with one dairy cow equivalent to one LU and one bovine less than one year old equivalent to 0.28 LU. As the emphasis in this study was on intensive dairy farms, the majority of farms selected had livestock densities of between 2 and 3 LU per hectare. Milk output from the area used for milk production was estimated to facilitate comparison with specialised dairy farms in other countries. This area was the proportion of the utilised agricultural area that was equivalent to the proportion of the total LU on the farm represented by dairy cows (Treacy *et al.* 2008).

### *Soil Analysis*

A total of eight soil samples were taken on each of the farms during the study period (two samples per year during each of the four years). Samples were taken from different areas each year using a standard soil corer (100 mm in length and 10 mm in diameter), sampling to a depth of 100 mm. Sample areas evenly distributed across each of the farms to represent blocks of land that were managed in the same way, which and on average represented areas of 7 ha. The sample areas were selected to ensure areas used for grazing and silage production were both represented. At least 50 soil cores were taken from each sample area, in a zig-zag pattern. Care was taken to avoid unusual spots in the sample area, such as old fences, ditches, and around gateways and feed troughs. Each sample was carefully mixed, before smaller representative samples were extracted and sent for analysis to Teagasc, Johnstown Castle, Co. Wexford. Soil samples were dried for sixteen hours at 40 °C in a forced draught oven with moisture extraction. Samples were analysed for soil pH and Morgan's soil P as described by Byrne (1979). Soil pH was determined by mixing 10 mL of dried sieved (2 mm) soil with 20 mL of $H_2O$ and, after being allowed to stand for ten minutes, measuring the pH of the suspension using a digital pH meter with glass and calomel electrodes. For soil P concentrations, soil samples were extracted in a one part soil to five parts solution ratio with a 10% sodium acetate solution buffered at pH 4.8 (Morgan's solution): 6 mL of dried soil was extracted using 30 mL of Morgan's solution using a Brunswick Gyratory shaker for 30 minutes at constant temperature (20 °C). The suspension was then filtered using No. 2 Whatman filter paper. P concentrations in the clear extract were measured spectrophotometrically at 880 nm using the phosphomolybdate method (Murphy and Reilly 1962). Concentrations were expressed on a soil volume basis (mg $L^{-1}$ of air-dried soil).

*Calculation of farm-gate P balance*

Farm-gate P balances were calculated for each calendar year taking account of P imported onto and exported from farms. All imports and exports of P were expressed relative to the utilised agricultural area. Imports included fertilizer, concentrates and organic manures. Exports of P include the recovery of P in agricultural products such as milk and animals. The farm-gate balance was the difference between imports of P onto the farm and export of P in agricultural products. Phosphorus use efficiency (PUE) was calculated as the proportion of imported P recovered in agricultural products. The quantity of P imported in concentrate feed was calculated assuming 5 kg per tonne in concentrate feed (Anon 2006). The quantity of P imported in pig slurry was estimated to be 0.8 kg/$m^3$ of P (Anonymous 2006). Phosphorus exported in milk sold was calculated assuming P content in milk of 0.0009 kg P per kg of milk (Lynch and Caffrey 1997; McDonald *et al.* 2010). Phosphorus exported in livestock sold was calculated by multiplying the total live weight sold by the P content, estimated as 0.01 kg P per kg live weight (McDonald *et al.* 2010).

*Limits on imported P under Statutory Instruments*

For the purposes of investigating the extent to which the farms in the present study complied with limits on P use in the SI, each of the 8 soil samples from each farm were assumed to represent one-eight of the farm area. Therefore on this basis, the soil test results were used to categorise the soils on each farm into one of the four indices in the SI (Table 1). The appropriate P fertilization rate for each section of the farm was determined based on soil P indices and the farm livestock density using Table 13 in the SI 610 2010 and summed to give the maximum quantity of P that is permitted to be imported onto each farm under the SI. As stipulated in the SI, the amount of P imported in feed was deducted to give the quantity of P that could be imported onto each farm in fertilizer or in organic manures. This was then compared with the actual average annual quantity of P imported onto the farms in fertilizer and organic manures.

*Statistical analysis*

Statistical analyses were carried out using MSTAT-C (Freed *et al.* 1991). Data were subjected to analyses of variance to compare differences between years in production factors. Farms were considered as replicates in the model. The relationships between stocking density, milk output (milk sold) per hectare of the farm area used for milk production, soil P concentrations and (i) P inputs, (ii) P outputs, (iii) P balance and (iv) PUE were examined using linear regression.

## Results

### *Utilised agricultural area, livestock density, concentrate use and milk production*

Production data for the four years on the 21 farms is shown in Table 2 and further details are available in Treacy *et al.* (2008). The utilised agricultural area per farm ranged from 25 to 130 ha. The livestock density per farm ranged from 162 to 246 kg/ha and the mean livestock density across all farms was 202 kg/ha each year for the duration of the study. The mean number of cows per farm increased ($P < 0.001$) from 85 (range 45 to 183) in 2003 to 93 (range 44 to 190) in 2006 with the increase in dairy cow numbers offset by decreases in other livestock numbers (mainly beef), which decreased ($P < 0.05$) from 53 LU in 2003 to 48 LU in 2006. Mean milk output per hectare used for milk production ranged from 11,667 L in 2005 to 13,087 L in 2003. The mean concentration of protein in milk was 34.1 g/kg and remained the same throughout the duration of the project. The fat concentration of the milk differed between years ranging from 38.0 g/kg in 2003 to 39.1 g/kg in 2005. Mean concentrate feed ranged from 529 kg/LU in 2004 to 808 kg/LU in 2006. The high input of concentrate in 2006 ($P < 0.001$) was the result of a period of below average grass growth due to exceptionally dry weather. Between February and August of 2006 there was an average of 54.9 mm of rain per month compared with 75.6 mm/month in 2003, 83.4 mm/month in 2004 and 67.1 mm/month in 2005 for the same period of months.

### *Soil pH and soil P status*

Soil pH for the entire set of soil samples from the 21 farms over the four years ranged between 4.9 and 7.2 with a mean and median value of 6.0 (Figure 2). Approximately 37% of soil samples had pH values in the recommended range of 6.2 to 7.0 for optimum response to applied P in grassland (Coulter and Lalor 2008). Likewise, soil P concentrations (mg $L^{-1}$) ranged between 1.6 and 26.2; mean 8.1 and median 7.1. The distribution of samples in the Teagasc 2004 and SI 610 2010 indices

**Table 2. Mean values for utilised agricultural area, stocking density (excreted N per ha), mean number of dairy cows, mean number of other livestock per farm, annual concentrate feed use, annual fertilizer N use, annual milk sales from the area used for milk production, annual mean milk protein and fat concentrations**

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

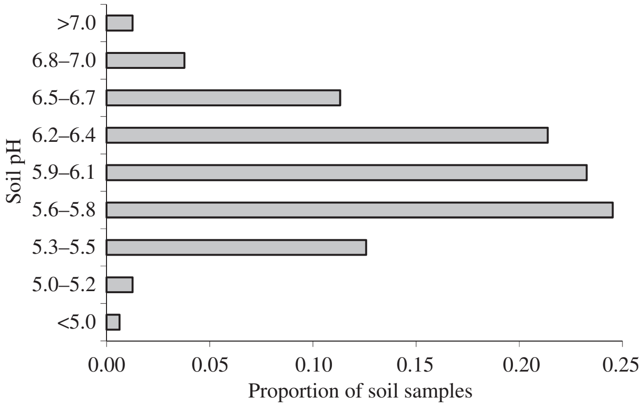


*Figure 2. Distribution of pH values in soils of 21 intensive dairy farms.*

are shown in Figure 3, with 0.05 of samples in index 1, which spans the same range in both classifications. Approximately 0.36 of the samples were in index 2 (3.1–6 mg/L P) and index 3 (6.1–10 mg/L P) with respect to the Teagasc 2004 recommendations and 0.26 of samples were in index 2 (3.1–6 mg/L P) and index 3 (3.1–5 mg/L P) with respect to the SI 610 2010 classification. The remainder of the samples, 0.26, were in index 4 (>10 mg/L P) as specified in the Teagasc recommendations in 2004 compared with 0.42 of the samples falling within the index 4 range (>8 mg P/L) specified by SI 610 2010.

*Farm-gate P Balances*

The overall mean annual quantities of fertilizer P imported across all 21 farms decreased from 12.0 to 8.9 kg/ha between 2003 and 2006, although this decrease was not significant (Table 3). Mean annual quantities of fertilizer P imported on individual farms ranged between 0.0 and 35.1 kg/ha. Fertilizer P accounted for 0.47 of imports onto farms. Fertilizer P was

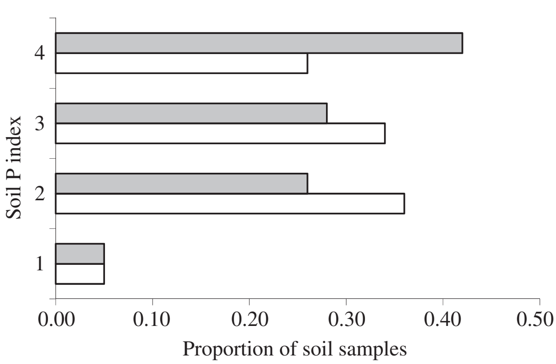


*Figure 3. Distribution of phosphorus (P) concentrations in soils of 21 intensive dairy farms in index systems used by Teagasc in 2004 (□ Coulter 2004) and in Statutory Instruments 610 2010 (▨ Anonymous 2010).*

**Table 3. Mean values for soil pH and soil phosphorus (P), imports of P in fertilizer, concentrates and organic manures, exports of P in milk and livestock, farm-gate P balances and P-use efficiency for 21 dairy farms over 4 years**

| | Year | | | | s.e. | F-test |
|---|---|---|---|---|---|---|
| | 2003 | 2004 | 2005 | 2006 | | |
| Farm-gate P imports (kg/ha) | | | | | | |
| Fertilizer | 12.0 | 10.7 | 9.3 | 8.9 | | |
| Concentrate | 8.4 | 6.3 | 6.3 | 9.3 | 0.42 | *** |
| Organic Manures | 4.1 | 3.6 | 4.5 | 3.1 | | |
| Total | 24.4 | 20.6 | 20.2 | 21.3 | | |
| Farm-gate P exports (kg/ha) | | | | | | |
| Milk | 7.4 | 7.2 | 7.2 | 7.7 | 0.14 | * |
| Livestock | 5.8 | 4.7 | 4.5 | 4.4 | 0.35 | * |
| Total | 13.2 | 11.8 | 11.7 | 12.1 | 0.38 | * |
| Farm-gate P surplus (kg/ha) | 11.2 | 8.8 | 8.5 | 9.2 | | |
| P-use efficiency | 0.65 | 0.77 | 0.74 | 0.68 | | |

generally applied as N, P and K compounds such as 27:2.5:5 and 24:2.5:10. Imports of concentrates accounted for 0.35 of imports and varied ($P < 0.001$) from year to year reflecting different annual requirements for concentrates on farms during the study. Imports of organic manures were mostly as pig slurry imported onto seven of the farms during the study. There was no significant difference between years in total quantity of P annually imported onto farms (21.6 kg/ha).

Highest ($P < 0.05$) exports of P were recorded in 2003 and 2006, although the relative contribution of P exports in milk and in livestock changed during the study. Milk accounted for 0.56 of total export in 2003 and 0.64 in 2006, reflecting the trend for higher dairy cow numbers and fewer beef cattle on farms during the study.

There was no significant difference between years in the mean annual P balance during the study, averaging at a surplus of 9.4 kg/ha. The minimum and maximum P balances on the individual farms, averaged over the four years, ranged from a deficit of –3.0 to a surplus of 22.2 kg/ha. Mean PUE over the four year study was 0.71 with no difference between years. Mean annual PUE on individual farms ranged from 0.24 to 1.37.

Relationships between stocking density, milk output per hectare, STP and P inputs, P balance, P outputs and PUE are presented in Table 4. There were ($P < 0.01$) correlations between soil P concentrations and (i) P balance ($R^2 = 0.34$; Figure 4) and (ii) PUE ($R^2 = -0.31$; Figure 5). The data analysed included one outlier, a farm with an extremely high soil P concentration

**Table 4. Correlations ($R^2$) between stocking density, milk output and soil test phosphorus (STP) concentrations and phosphorus (P) inputs, balance, outputs and P-use efficiency (PUE) for 21 dairy farms over four years. Correlations were not significant unless otherwise indicated**

| | P input | P balance | PUE | P output |
|---|---|---|---|---|
| Stocking density | 0.02 | 0.0082 | 0.0096 | 0.675*** |
| Milk output | 0.0077 | 0.0223 | 0.0206 | 0.69*** |
| STP | 0.25* | 0.34** | –0.31** | 0.121 |

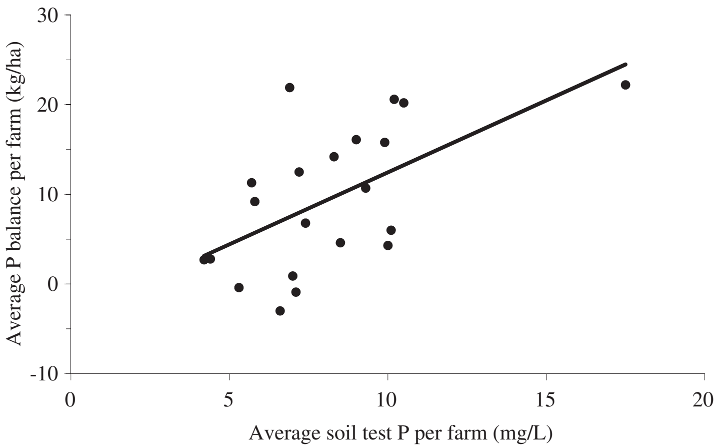


*Figure 4. Relationship between average phosphorus (P) balance per farm and the average soil P concentration per farm. Data are the mean of four years. The line was fitted using the following linear regression equation: $Y = -3.71 + 1.61x$, $R^2 = 0.34$, $P < 0.01$.*

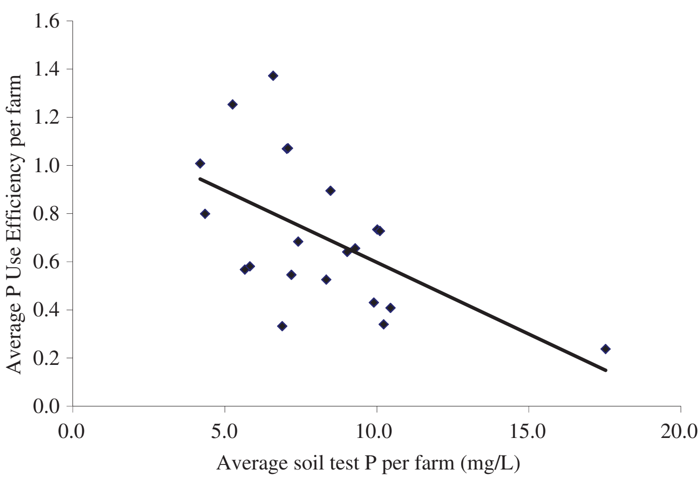


*Figure 5. Relationship between average phosphorus (P) use efficiency per farm and average soil P concentration per farm. Data are the mean of four years. The line was fitted using the following linear regression equation: $Y = 1.19 - 0.06x$, $R^2 = 0.0313$; $P < 0.01$.*

(17.5 mg $L^{-1}$). Analysis of the farm data both with the outlier included and the outlier excluded found that the relationships between stocking density, milk output per hectare, STP and P inputs, P balance and PUE were not significant. For all of the above calculations of significance, the inclusion or exclusion of the outlier did not affect the significance of either relationship; for P balances ($R^2 = 0.25$) or PUE ($R^2 = 0.23$).

*Limits on imported P under Statutory Instruments*

Seven farms imported lower quantities of P on average between 2003 and 2006 than allowed in the SI 610 2010 (Figure 6), and on most of these farms the quantity of imported P was substantially lower than allowed in the SI. Three farms imported quantities of P more-or-less (±1 kg/ha) in line with that allowed in the SI. The remaining eleven farms imported higher quantities of P than allowed in the SI and on most of these farms the quantities imported were substantially higher than the quantity that would be allowed under the SI.

## Discussion

*Soil pH, soil P status, and P imported onto farms*

Almost two thirds (62%) of soil samples in this study had pH values below the lower optimum limit generally recommended by Teagasc at the time this study was conducted (Coulter 2004). This was similar to national averages based on soil samples submitted to the Teagasc soil laboratory at Johnstown Castle for analyses. Part of the reason for the high proportion of low soil pH values in this study can be attributed to approximately one third of the farms being in areas with high soil molybdenum (Mo) concentrations. In such soils it is recommended not to raise the pH above 6.2 to avoid inducing Cu deficiency in livestock (Coulter 2004). Furthermore, one farm had a high proportion of peaty soils. The recommended pH for peat soils is 5.5 (Coulter 2004). Nevertheless, 39% of soil samples had pH values ≤5.8 indicating that in many instances best practices were not in place for maintaining soil pH at optimum levels. The farmers in this study had regular close contact with Teagasc advisors

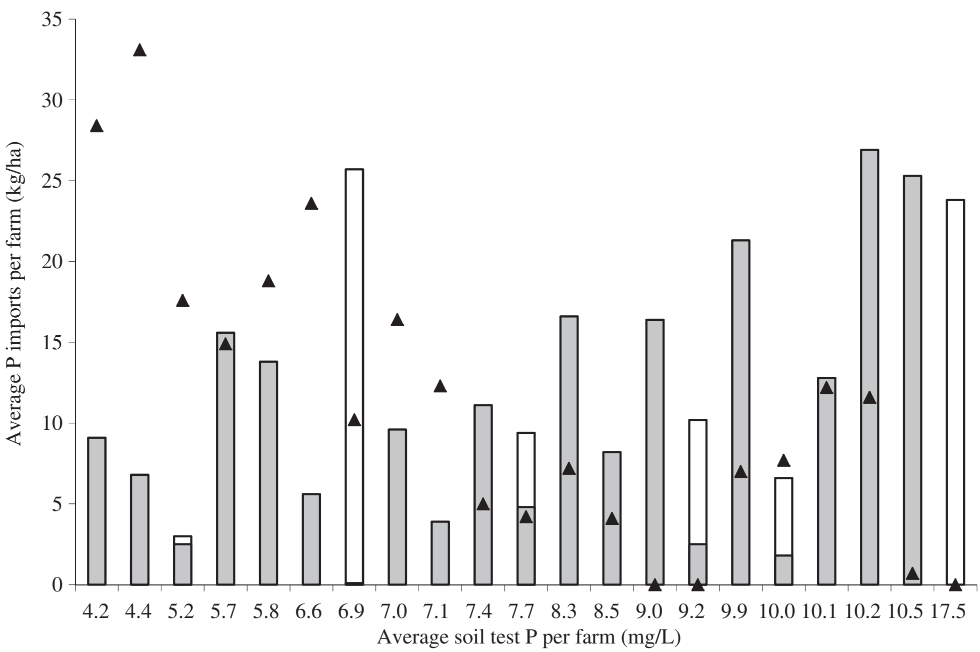


*Figure 6. Average annual imports (over four years) of phosphorus (P) in fertilizer (▢) and in manure (□) per farm relative to the amounts (▲) allowed under Statutory Instruments 610 2010 (Anonymous 2010), after deducting P in concentrates imported onto farms.*

and researchers for many years prior to and during this study. It is to be expected that these farmers would be much better informed about this important aspect of sustaining high productivity from grassland than the general population of farmers. It is apparent that this was not the case on many of these farms. This is a matter of concern given the important role that soil pH plays in ensuring optimum response to the major soil nutrients and the rapidly escalating cost of fertilizers in recent years (CSO 2010).

Only 5% of samples in this study were in soil P index 1 (Figure 3). This is substantially different from the national average at that time. Culleton, Coulter and Liebhardt (2002) reported that 22% of samples taken on farms across Ireland were in soil P index 1. In the present study, one third (34%) of samples had soil P concentrations in the recommended index 3 according to the Teagasc recommendations in 2004 (Coulter 2004). This was higher than the national average at the time; Culleton *et al*. (2002) found 25% of samples were in soil P index 3. The higher proportion of samples in Index 3 may be attributed to the close contact that the farmers involved in the study had with Teagasc advisors and researchers. The national average figure for soil samples includes soil samples from other farming enterprises, such as beef and tillage. Therefore, a direct comparison between the soil samples on the farms involved in this study and the national average figures presented should be considered with these factors in mind.

However, it is evident that best practices were not being implemented with regard to the overall management of fertilizer P and P in organic manures imported onto farms. On the one hand, there were farmers with low soil P concentrations that were importing relatively little P; the farmers with lowest soil P concentrations were also the ones most likely to be in P deficit (Figure 6). On the other hand there were farmers with high soil P concentrations importing excessive amounts of P. Hence, there was a positive relationship ($R^2$ = 0.34) between soil P concentrations and P balance. In contrast, if the recommendations were being followed, an inverse relationship would be expected: Farms with high soil P status should import less P and vice versa. This is also evident in Figure 6 which shows the farms with high P inputs were in fact the farms that would have been allowed little or no P imports under the SI. No additional pasture production would be expected from excessive imports of P and therefore no associated increase in milk production (Coulter and Lalor 2008). On one farm, it was apparent that pig slurry was being imported for the purposes of disposing of the slurry rather than for agronomic reasons, given that the mean STP level across the farm was 17.5 mg $L^{-1}$, which is in excess of agronomic requirements.

The general explanation for the use of P on the farms in the study may be attributed to farmer preferences. A substantial proportion of these farmers have historically been low P users and hence have low soil P concentrations, whereas there was another proportion of high P users with obvious consequences for soil P concentrations. The overall indication is that these farmers, in general, were not paying close attention to soil test results for P or for soil pH. Many of the farmers were importing quantities of P in excess of what they required based on soil test results. This would imply that pig manure was being imported as a method of disposal as opposed to viewing it as a source of nutrients. This study highlights the need for improvements in nutrient management planning on farms.

*Comparison with P surplus and P use efficiency in other studies*

Farm gate balances are considered a useful tool in terms of evaluating the nutrient flows at a farm scale, for improving nutrient management and for comparing and contextualising different farming systems. Several studies have been carried out on dairy systems across Europe on P balances although little or no data exists on the relation between STP and P balance. However, it is important to consider the relative difference in dairy systems between Ireland with its pasture-based system and most other European countries that employ a high-input high-output indoor system.

Several studies have found a poor relationship between P surplus and milk output per hectare (Raison *et al.* 2006; Fangueiro *et al.* 2008; Gourley *et al.* 2011). This relationship is associated with the high STP levels on some farms and the excessive amounts of P that were being imported in the present study (Figure 6). The relationship between P inputs and pasture growth is not a linear relationship therefore input of P in excess of what the soil requires to produce grass will not result in additional pasture production (Gourley *et al.* 2011).

A study was conducted on 319 Finnish dairy farms in 2002 stocked at an average of 0.88 LU/ha (Virtanen and Nousiainen 2005). Average inputs of P as fertilizer and concentrate feed were 9.1 kg/ha and 7.3 kg/ha. The average milk output per cow was 7,311 L. The average P surplus was calculated as 11.7 kg/ha and the average PUE was calculated as 0.36. This study found, however, that there was a tendency for P balances to increase with increasing milk output per cow. The relationship between P balance and milk output in the Finnish study occurred due to a positive association with the input of concentrate. There was no such relationship in the present study which is mostly likely as a result of the relatively low level of concentrates fed to livestock.

In the Netherlands, P balances and PUE were calculated for 25 conventional diary farms with an average herd size of 107 cows stocked at 1.54 LU/ha (Nielsen and Kristensen 2005). Concentrate accounted for 61% of total P inputs at 22 (±9) kg/ha and milk and manure made up the majority of P outputs at 7 (±2) and 5 (±8) kg/ha respectively. The average P balance was 16 kg/ha and PUE was calculated at 0.52. The P surplus was found to increase with increasing stocking density. The P balance from the study in the Netherlands was found to be similar with P balances and PUE from similar studies in Germany, Sweden and Belgium (Flanders).

The intensive dairy systems used in many European countries results in a higher P surplus than the pasture based system of dairying used in Ireland. All of studies have a lower PUE than the present study, which was 0.71, indicating that the high-input high-output systems commonly used on mainland Europe are not as efficient at converting P inputs into P outputs. The difference in P balances and PUE between the intensive indoor systems and pasture based systems is primarily as a result of the indoor system relying on a high input of concentrate feed which typically has 50% more P content than grass herbage (Withers, Edwards and Foy 2001).

Further studies by Mihailescu *et al.* (2014) were carried out in Ireland between 2009 and 2011 (inclusive) and investigated P balances on 21 Irish farms (a number of the farms in the present study were involved in the newer study). The study by Mihailescu *et al.* (2014) found a mean P surplus of 5.1 kg/ha compared with 9.4 kg/ha in the present study. The overall average input of inorganic fertilizer

P amounted to 7.6 kg/ha in the study by Mihailescu *et al.* (2014) and was 10.2 kg/ha in the present study. The average STP level across all the farms in the study by Mihailescu *et al.* (2014) was 5.6 mg/L compared with an overall average of 8.2 mg/L in the present study. The STP levels in the study by Mihailescu *et al.* (2014) followed a reduction in the inputs of P and reflected a return to an average STP level that would be considered optimal for pasture yield. However, future work is required to investigate whether those STP levels would continue on a downward trajectory or remain consistently in index 3 (5.1–8.0 mg/L). External factors, such as the price of fertiliser P and the effect of improved advice as a consequence of advancing research will undoubtedly have influenced the overall drops in STP levels and P surpluses between the two studies. This drop in STP levels and P surpluses on farms is indicative of the impact of the introduction of the SI.

## Conclusions

This study investigated farm-gate P balances and STP levels on 21 dairy farms in south west Ireland in the years preceding the introduction of the SI. Although the farmers involved in this study had regular close contact with Teagasc farm advisors, it is evident that best practises were not always followed. Over half of the farmers involved in the study were importing amounts of P over and above the amounts recommended by the SI. Eight farmers were importing less than the amount recommended by the SI which could lead to a reduced amount of grass growth due to sub-optimal STP levels. Only three farms imported quantities of P more-or-less (±1 kg/ha) in line with that allowed in the SI. With the cost of P likely to keep rising due to falling stocks of the world's reserves, it is of utmost importance that P amendment of the soil is clearly targeted at agronomic requirements. This study has highlighted the need for educating farmers on the correct use of P, which is likely to have positive impacts on profitability and the environment.

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