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McDonald, N. T., Wall, D. P., Mellander, P. E., Buckley, C., Shore, M., Shortle, G., Leach, S., Burgess, E., O'Connell, T., & Jordan, P. (2019). Field scale phosphorus balances and legacy soil pressures in mixed-land use catchments. *Agriculture, Ecosystems and Environment*, *274*, 14-23. https://doi.org/10.1016/j.agee.2018.12.014

Published in:
Agriculture, Ecosystems and Environment

Publication Status:
Published (in print/issue): 15/03/2019

DOI:
10.1016/j.agee.2018.12.014

Document Version
Publisher's PDF, also known as Version of record

Agriculture, Ecosystems and Environment 274 (2019) 14–23

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Field scale phosphorus balances and legacy soil pressures in mixed-land use catchments

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ARTICLE INFO

Keywords:
Soil test phosphorus
Field balances
Fertilizer use
Agricultural catchment
Nutrient management

ABSTRACT

Reducing legacy soil phosphorus (P) is recognised as an effective measure to mitigate diffuse P losses from agricultural landscapes and alleviate trophic pressure to freshwaters systems. Accounting for the distribution of P within farms is critical in identifying fields of agronomic underperformance and/or environmental risk to water as a consequence of inadequately managed re-cycling of P. There is also a need to understand how P use and legacy soil P evolves under the Nitrates Action Programme (NAP) regulations from the European Union (EU) Nitrates Directive. In an Irish case study the aim was to provide a systematic and detailed audit of P balance and soil P responses and trends in two mixed land use agricultural catchments (Arable A and B) across a four year study period. Driven by increased mineral P inputs the field balances in the Arable A catchment had an average surplus P, ranging from 1.9 to 7.5 kg ha^{-1} yr^{-1}. However, between the study period 2010 to 2013, the average soil test P (STP) levels declined, with the area of excessive soil P concentrations decreasing by 8%. Similarly, in the Arable B catchment the average annual P inputs increased the surplus field P from -0.42 to 25.5 kg ha^{-1} yr^{-1}, but the area of excessive soil P concentrations increased by 4%. In part, this increase is attributed to some fields receiving excess applications of organic nutrient forms above crop requirements. Whilst, the legacy soil P declined in the Arable A catchment indicating a response to NAP, for both catchments it is evident that the distribution of P sources within farms was poor and P inputs often did not match crop and soil P requirements at the field scale. This study highlights the need for improved support to knowledge transfer mechanisms that can deliver better farm and soil specific nutrient management planning strategies. Without this consideration, achieving the dual benefits of improvement to water quality and increased crop output from agricultural landscapes will be restricted.

1. Introduction

Legacy soil phosphorus (P), the residual store of P accumulated in soils above agronomic requirements (Kleinman et al., 2015), is recognised as prolonging the agricultural source pressure to freshwater quality (Tunney, 2002; Cassidy et al., 2017; Withers et al., 2017). The impacts can offset and overwhelm catchment mitigation measures to reduce P input loads to agricultural systems due to the highly adsorptive capacity of some soils to retain P and which, in small amounts, is released slowly to natural runoff (Sharpley et al., 2013). Small P fluxes from land relative to P inputs are, however, known to account for water quality pressures and especially related to the eutrophication of water resources (Withers et al., 2014a). Managing legacy P, therefore, remains a challenge to both water quality and to catchment mitigation measures that are often expensive to implement and carry an economic burden (Buckley et al., 2012; Sharpley, 2016).

There is a recognition that further soil P accumulation to legacy stores adds to environmental risk without benefitting agricultural output and that, in areas of existing legacies, soil P mining is required (Schulte et al., 2010; Sattari et al., 2012; Withers et al., 2014b). In these scenarios, soil P drawdown is induced over time so that soil P concentrations become agronomically optimum but less environmentally risky. This type of soil P management planning is written into guidelines and regulations where agricultural production is industrialised but

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https://doi.org/10.1016/j.agee.2018.12.014
Received 24 July 2018; Received in revised form 17 December 2018; Accepted 24 December 2018

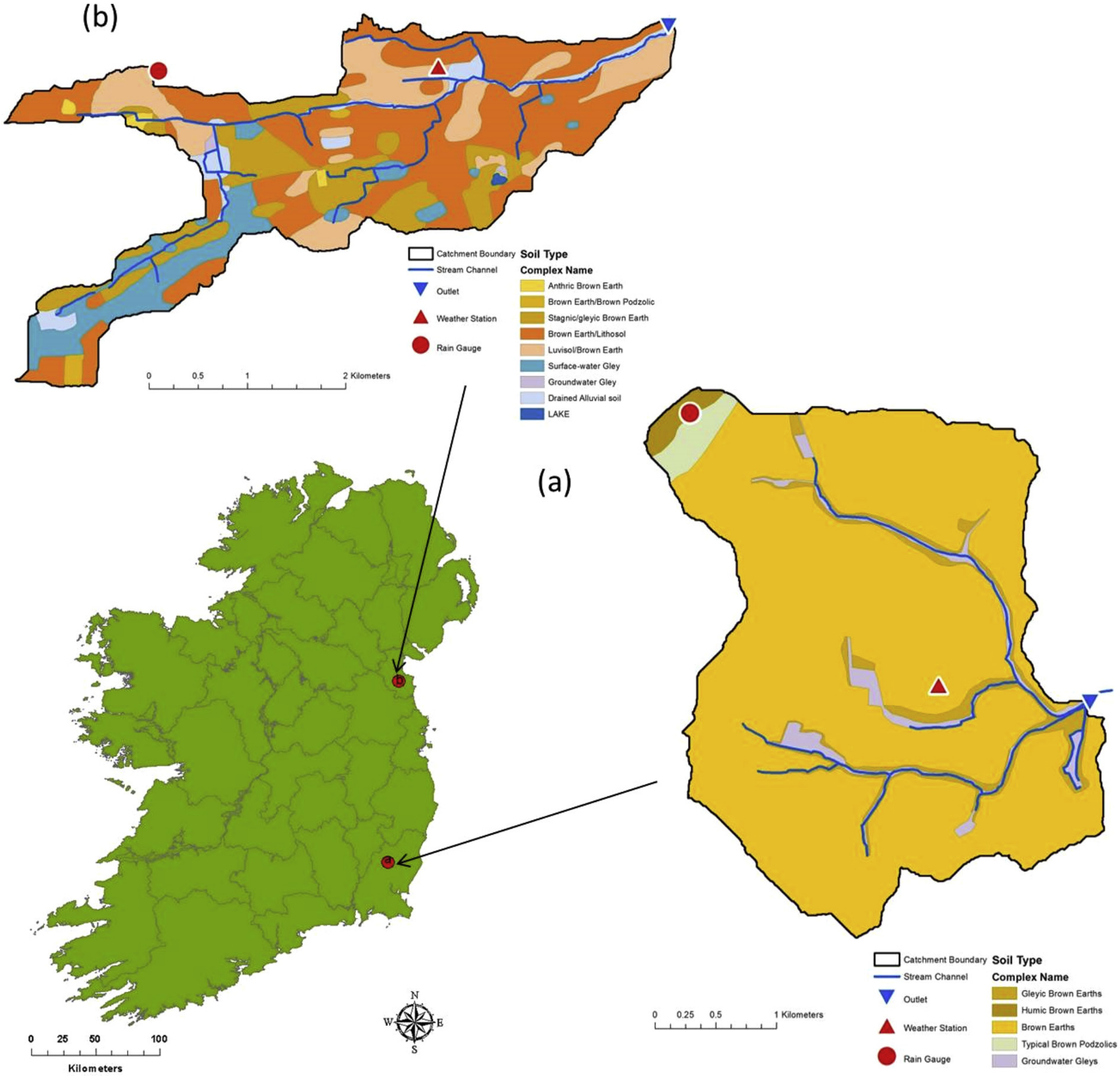

Fig. 1. Location of study catchments in Ireland and the soil types, stream network and monitoring stations for Arable A (a) and Arable B (b) catchments.

is explicit as part of some member states' Nitrates Action Programmes (NAP) following the European Union (EU) Nitrates Directive (OJEC, 1991).

In Ireland, the NAP (Statutory Instrument (SI) 610 of 2010, 31 of 2014 and 605 of 2017) sets limits on agricultural nitrogen (N) use and also includes regulations on nutrient P inputs to soils using a soil test P index system based on soil Morgan P (Morgan, 1941) extraction (soil test P (STP)). The inclusion of P in this NAP recognises the role this nutrient has on eutrophication processes in Ireland's extensive freshwater resource (Fanning et al., 2017). The Morgan STP index system for grassland and arable soils in Ireland differs slightly in the ranges for Morgan extractable P (mg l^{-1}). For grassland soils P index 1 soils (very low) have STP concentrations between 0–3.0 mg l^{-1}, P index 2 soils (low) between 3.1–8 mg l^{-1}, index 3 (agronomic optimum STP range) between 5.1–8.0 mg l^{-1} and P index 4 soils (high/increased environmental risk) > 8 mg l^{-1}. For arable soils P index 1 soils are 0–3.0 mg l^{-1}, P index 2 soil are between 3.1–6.0 mg l^{-1} P index 3 soils are between 6.1–10 mg l^{-1} and P index 4 soils are > 10 mg l^{-1} (Wall and Plunkett, 2016). Since there is a strong linear relationship between STP and P loss (Tunney et al., 1998), soils in index 4 are considered to 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.

In addition to soil chemistry processes, an important mechanism by which a soil builds-up, maintains or draws-down a soil P legacy is related to the P balances operating at the farm scale (Wall et al., 2012). Phosphorus inputs to the farm system includes inorganic fertilizers and concentrates (for animal production), and imported manures and slurries for recycling. Outputs include meat and milk (for animal production), crop removal (for arable land). To maintain optimum P status in soils, P removed in outputs must be replaced through further inputs. Soil P status and farm P balance information are also important for identifying potential opportunities for arable spread-lands to be used by third-party intensive housed animal enterprises (Schröder et al., 2016). In Ireland, increased P inputs to agricultural soils (up to + 5 kg ha^{-1}) from pig, poultry manure and spent mushroom compost (SMC) sources have been allowed under the NAP regulations, with only pig manure allowed under recent NAP revisions (SI 605, 2017). These transitional arrangements promote recycling of P from intensive housed animal and horticultural enterprises specifically onto arable land. This enables farmers receiving P from organic sources to use a positive P balance over the defined transitionary period, usually 4 years.

Despite the importance of farm scale P balances for managing optimum soil fertility, Wall et al. (2012) noted how scale can hide important management processes and trends when reporting on soil P states and balances. For example, fields as hotspots of agronomic underperformance and/or environmental risk may be hidden if data are averaged out at the farm and catchment and ultimately national scale. When considering the disproportionate risk that hotspots of field-scale high soil P may have on the environmental burden if they are hydrologically connected (Thomas et al., 2016), it is important to demonstrate how these soil P phenomena develop and especially when influenced by international policies such as EU NAPs.

Ireland has a small but important arable production system covering approximately 7% (CSO, 2012) of all agricultural land and largely concentrated on the eastern side of the island. Farms rarely operate on a wholly arable system and, when scaled up to small catchments (ca. 10 km^2), the total arable cover rarely exceeds 50% (Melland et al., 2012) with the remainder under some type of grassland management. Nevertheless, this mixed land use type has the potential for large variations in field scale soil P state, balance and subsequent agronomic/environmental risk hotspots due to large differences in P input and offtake.

To understand how P use and legacy soil P evolved under NAP regulations, this study aimed to provide a systematic and detailed audit of P balance and soil P responses and trends in mixed land use agricultural catchments. The context was to determine the magnitude of these pressures alongside water quality status and the objectives were two-fold:

1 Using continuous and repeat surveys to determine P balance, as a measure that would influence P use efficiency and soil P mobilization potential across mixed land-use landscapes.
2 Using repeat soil surveys to monitor the distribution of soil P trends where the primary policy directions were to decrease excessive soil P status towards at least optimum for agronomy.

2. Materials and methods

2.1. Study Areas and water quality context

The two mixed land use study catchments are described in detail elsewhere (Fealy et al., 2010; Wall et al., 2012) and summarised here. As in previous publications these catchments are referred to as Arable A and B (Wall et al., 2012; Melland et al., 2012; Sherriff et al., 2015). The Arable A catchment is 11.2 km^2 and located in the south-east of Ireland (Fig. 1a) and has a cool temperate maritime climate with a mean annual rainfall of 1060 mm (1981–2010, Met Éireann, Table 1). The bedrock geology underlying this catchment consists of Ordovician volcanic slate of reddish-purple buff-coloured mudstone inter-bedded with green-grey mudstone and thin silt-stone defined as the *Oakland* formation (Mellander et al., 2012). The soil is mostly a well-drained, Brown Earth soils (Cambisols) (88%), with the lesser proportional areas of gleyic Brown Earths, Brown Podzolics (Cambisol) and Groundwater Gleys (Gleysol). Arable production was the principle land management use between 2010 and 2013 (average 61% area), dominated by spring barley (c. 563 ha). A smaller proportion (average 27% area) was grassland utilized by mostly beef and sheep enterprises, at average stocking intensity of the grazed areas of 0.83 livestock units (LU) ha^{-1} (ranging from 0.18 to 2.1 LU ha^{-1}).

Arable B catchment is 9.5 km^2, located in the north-east of Ireland (Fig. 1b), and also has a cool temperate maritime climate but with a lower mean annual rainfall of 758 mm (1981–2010, Met Éireann, Table 1). The bedrock geology consists of Ordovician-Silurian calcareous greywacke and dark-grey to black banded mudstone defined as the *Salterstown* Formation (Sherriff et al., 2015). Approximately one-third of the catchment is made up of a mixture of poor to moderately drained Surface-water, Groundwater Gley soils (Gleysol), stagnic/gleyic Brown Earth soils (Cambisol) with the remaining proportion of the catchment of moderately drained Luvisols and well drained Brown Earth soils, Brown Podzolics (Cambisol) and Lithosols (Leptosol). A large proportion of the Arable B catchment was in grassland (average 44% area) utilised by dairy, beef and sheep enterprises with an average stocking intensity of the grazed areas of 1.04 LU ha^{-1} (ranging from 0.07 to 3.9 LU ha^{-1}). Due to the high density of arable winter-sown production (average 34%) on poor to moderately drained soil this catchment is hence defined as an arable catchment. The characteristics of both catchments are summarised by Melland et al., 2012 and in Table 1.

The water quality context for this study was based on results from previously published work. Arable A has reported mean annual total reactive P (TRP) concentrations in streamwater below the Environmental Quality Standard of 0.035 mg/l and Arable B at least three times this threshold (Melland et al., 2012). Jordan et al. (2012) described Arable B as providing conditions for fast runoff pathways and hence being more vulnerable to P runoff during storm events. Shore et al. (2017) supported this, showing P from organic sources was present at both high flows and for considerable periods during low flows from both agricultural and domestic sources.

Table 1
Characterises of the study catchments.

Total area (km^2)	Arable A 12.2	Arable B 9.5
Climate	Cool temperate maritime	Cool temperate maritime
Topography	Rolling with a steep-ridge to flat (0-16°)	Rolling to flat (0-22°)
Bedrock geology	Ordovician volcanic slate inter-bedded with mudstone and thin siltstone	Ordovician-Silurian calcareous greywacke and banded mudstone
Dominant soil type	Well-drained typical brown earth (Cambisols)	Poor-moderately drained gley (surface water and groundwater) soils (Gleysols)
Land-Use	61% arable, 27% grassland, 1.5% habitat & 10.5% other or non-agricultural	34% arable, 44% grassland, 1% habitat or forestry & 21% other or non-agricultural
Elevation (m AOL)	20-210	30-220
Mean annual air temperature 2010-2013 (°C)	9.6	9.4
Mean average soil temperature 2010-2013 (°C)	10.6	10.3
Mean annual rainfall* (mm)	1060	758
Mean annual catchment rainfall 2010-2013 (mm)	945	880
Mean annual runoff coefficient 2010-2013	0.50	0.49
Mean annual stream runoff 2010-2013 (mm)	474	431
Stream order	3	3

Annual average over the 4 year study period 2010 to 2013.
* 30 year average (1981–2010) from Johnstown Castle the nearest synoptic station to Arable A and Dublin Airport the nearest synoptic station to Arable B.

Table 2
Field P inputs, removal, balances, soil P build up and soil P balance in Arable A and B catchment in 2010–2013.

	Arable A					Arable B				
Area represented (ha)	1043.57					750.45				
Number of fields (sub-fields)	401					341				
Year	2010	2011	2012	2013	All years	2010	2011	2012	2013	All years
Inputs										
Mean total fertilizer P applied (kg ha^{-1} yr^{-1})	25.0	26.0	28.8	32.2	28.0	23.1	33.8	37.5	39.3	33.4
Min total fertilizer P applied (kg ha^{-1} yr^{-1})	0	0	0	0	0	0	0	0	0	0
Max total fertilizer P applied (kg ha^{-1} yr^{-1})	74.1	87.0	67.1	108.8	84.3	170.5	205.6	186.2	173.0	183.8
Standard Deviation total rate of P applied	16.2	17.4	14.8	18.1	16.6	32.1	43.9	47.3	41.3	41.2
Total fertilizer P applied to the catchment (kg)	26116	27633	31333	34317	29850	18912	28448	31473	32606	27860
Mean mineral fertilizer P applied (kg ha^{-1} yr^{-1})	21.5	23.4	25.2	28.2	24.6	8.13	9.28	10.93	17.71	11.5
Min mineral P applied (kg ha^{-1} yr^{-1})	0	0	0	0	0	0	0	0	0	0
Max mineral P applied (kg ha^{-1} yr^{-1})	74.1	74.1	49.4	98.8	74.1	170.5	55.6	55.6	170.5	170.5
Standard Deviation total rate of mineral P applied	14.1	15.7	13.5	14.6	14.5	14.30	11.5	13.9	22.18	15.5
Total chemical P applied to the catchment (kg)	22204	24916	27290	29994	26101	5787	7158	8652	12999	8649
Mean organic fertilizer P applied (kg ha^{-1} yr^{-1})	3.51	2.65	3.56	4.00	3.43	15.0	24.5	26.5	21.6	21.9
Min organic P applied (kg ha^{-1} yr^{-1})	0	0	0	0	0	0	0	0	0	0
Max organic P applied (kg ha^{-1} yr^{-1})	48.0	35.6	35.6	53.2	43.1	118.6	185.3	186.2	156.6	161.7
Standard Deviation total rate of organic P applied	9.72	8.09	9.54	10.6	9.49	31.8	42.9	46.7	37.8	39.8
Total organic P applied to the catchment (kg)	3911	2717	4042	4323	3748	13125	21290	22821	19607	19211
Mean concentrate P fed at grazing (kg ha^{-1} yr^{-1})	2.22	1.09	1.29	1.32	1.48	1.61	1.57	1.07	3.39	1.91
Min concentrate P fed at grazing (kg ha^{-1} yr^{-1})	0	0	0	0	0	0	0	0	0	0
Max concentrate P fed at grazing (kg ha^{-1} yr^{-1})	14.1	3.7	4.0	3.9	6.42	10.0	8.0	7.9	14.5	10.1
Standard Deviation concentrate P fed at grazing	3.7	1.5	1.5	1.5	2.04	3.0	2.3	1.2	4.0	2.6
Total concentrate P fed at grazing to the catchment (kg)	828	295	325	319	442	647	653	419	1,349	767
Removal										
Mean crop P removal (kg ha^{-1} yr^{-1})	23.1	24.0	23.3	25.1	23.9	24.5	25.3	21.7	24.2	23.9
Min crop P removal (kg ha^{-1} yr^{-1})	0	0	0	0	0	0	0	0	0	0
Max P crop removal (kg ha^{-1} yr^{-1})	45.5	42.8	42.8	48.7	44.9	56.4	51.0	42.6	58.8	52.2
Standard Deviation of crop P removal	10.0	10.6	9.4	9.4	9.9	15.0	14.8	11.9	15.5	14.3
Total crop P removal from the catchment (kg)	24748	26227	25409	27342	25932	19440	19847	17291	19358	18984
***Mean stocking rate change kg P ha^{-1} yr^{-1}**	–	−1.17	0.95	0.49	0.09	–	2.67	1.18	2.99	2.28
***Min stocking rate change kg P ha^{-1} yr^{-1}**	–	−14.7	−17.3	−14.1	−15.4	–	−18.0	−24.8	−21.2	−21.3
*** Max stocking rate change kg P ha^{-1} yr^{-1}**	–	13.8	13.4	9.90	12.4	–	34.5	36.8	50.0	40.4
*** Standard Deviation of stocking rate change**	–	4.7	4.4	4.1	4.4	–	10.8	6.4	9.0	8.7
Total stocking rate change in the catchment (kg)	–	−468	230	155	−28	–	1585	547	1152	1095
Mean soil P Build-up required (kg ha^{-1} yr^{-1})	8.7	8.6	8.6	8.6	8.6	9.7	9.5	9.8	9.4	9.6
Min soil P Build-up required (kg ha^{-1} yr^{-1})	0	0	0	0	0	0	0	0	0	0
Max soil P Build-up required (kg ha^{-1} yr^{-1})	30	30	30	30	30	50	50	50	50	50
Standard Deviation soil P Build-up required	8.3	8.2	8.2	8.2	8.2	9.3	8.7	9.6	8.9	9.1
Total soil P Build-up required in the catchment (kg)	8665	8720	8703	8648	8684	7048	7061	7098	6834	7010
***Mean NAP-P limits (kg ha^{-1} yr^{-1})**	26.3	27.5	26.5	26.8	26.8	28.8	26.6	27.3	24.6	26.4
***Min NAP-P limits (kg ha^{-1} yr^{-1})**	0	0	0	0	0	0	0	0	0	0
***Max NAP-P limits (kg ha^{-1} yr^{-1})**	70	75	60	70	68.8	125	125	125	100	118
Standard Deviation NAP-P limits	16.2	16.6	15.8	16.5	16.3	20.3	18.0	20.2	17.6	19.0
Total NAP-P limits of the catchment (kg)	26793	28361	27296	27916	27591	19,943	20,418	20,274	18,780	19,854
Balances										
Mean P balance (kg ha^{-1} yr^{-1})	2.67	1.89	6.14	7.54	4.56	−0.59	13.9	19.0	25.5	14.5
Min P balance (kg ha^{-1} yr^{-1})	−37.8	−35.8	−30.4	−36.5	−35.1	−46.3	−42.5	−33.5	−41.9	−41.1
Max P balance (kg ha^{-1} yr^{-1})	55.3	69.2	76.2	80.0	70.2	148.9	181.6	166.4	166.6	165.9
Standard Deviation P balance	16.9	18.3	14.9	18.1	17.1	30.0	46.3	44.5	47.0	42.0
Total P balance of the catchment (kg)	2196	1233	6478	7448	4339	119	13507	16844	21390	12965
Mean Soil P Balance(kg ha^{-1} yr^{-1})	−6.06	−6.74	−2.48	−1.05	−4.08	−10.3	4.43	9.23	16.1	4.87
Min Soil P Balance(kg ha^{-1} yr^{-1})	−43.3	−65.8	−38.5	−38.5	−46.5	−60.0	−67.8	−50.0	−81.4	−64.8
Max Soil P Balance(kg ha^{-1} yr^{-1})	39.4	65.7	76.2	77.3	64.6	148.9	171.9	166.4	166.6	163.5
Standard Deviation of Soil P Balance	16.9	18.8	15.1	18.4	17.3	33.2	48.1	47.4	50.7	44.9
Total soil P balance of the catchment (kg)	−6469	−7487	−2225	−1200	−4345	−6928	6446	9746	14556	5955

*Difference between the current year and previous year's stocking rates (in the form of total P per kg), using 2010 as the baseline year.

2.2. Field P inputs, removal and balances

Using a nutrient management recording (NMR) system, nutrient P inputs as mineral and organic fertilizer (rate and form) were captured by agricultural advisors from farms within both catchments between 2010 and 2013. This included the quantity and type of supplementary concentrate feed available for re-distribution at grazing, annual animal stocking rates, grazing duration and nutrient P removal in grain, straw and grass forage. These data were captured continuously across the 4 year study period for individual fields representing 92% and 73% of the soil sampled area within Arable A and Arable B catchments respectively.

2.2.1. Phosphorus inputs

Using the NMR, annual fertilizer P input loads were estimated for each catchment using a structured query reporter (SQL) data base system (Oracle, CA, USA). The main imports of P onto these farms were in the form of mineral fertilizers, concentrate feedstuffs and livestock. Where data were provided for the whole farm, the total available P in the annual concentrate feedstuffs was distributed over the farms' grazing areas, following a standard deduction of 300 kg of feed per 85 kg livestock manure N (i.e. per LU) assumed to be fed over the winter housing period (SI 31, 2014). This ensured that the P in feedstuff consumed by the livestock during the winter housing period was not double counted in the organic manure collected and stored over the same period and later applied to the land. Standard P concentrations were applied to different feed types using reported values (Ewing, 2002; Kavanagh, 2011). Changes in organic P loading (excreted P) from grazing livestock on each field were calculated as the difference between the current year and previous year's stocking rates (in the form of total P per kg), using 2010 as the baseline year.

2.2.2. Phosphorus outputs

The main outputs of P from these farms were in crops, meat and milk removal. For calculating the P removal from fields, P concentrations for the different crop types and animal outputs were used based on standard and reported values (McDonald et al., 1995; Ewing, 2002; Jarvis et al., 2002; Kavanagh, 2011; CSO, 2012; Wall and Plunkett, 2016).

2.2.3. Phosphorus balances

Three P balance calculations were developed from these data: (i) *field P balance*, (ii) *optimum soil P balance* and (iii) *regulated Irish NAP-P allowance balance*. The *field P balances* were calculated by subtracting the total P outputs from the total P inputs for each field each year. The *optimal soil P balances* were calculated by subtracting the total P outputs plus the soil P build-up requirement from the total P inputs for each field. Based on soil test analysis for each field the recommended soil P build-up rates used were 10 kg ha^{-1} and 20 kg ha^{-1} for cereal and grassland soils defined as index 2 (deficient) and index 1 (extremely deficient), respectively (Wall and Plunkett, 2016). The *regulated NAP-P allowance balances* were calculated by subtracting the total maximum P limits set out in the NAP that are crop type or stocking rate and soil test P specific (SI 610, 2010) from the total fertilizer P inputs (mineral and organic).

2.3. Soil P analysis

Using spatially identical sampling areas typically < 2 ha, the STP status across Arable A was assessed by soil sampling each field (1134 ha) in 2009 and again in the autumn-winter of 2013. Similarly in Arable B, all fields were sampled in 2010 and again in 2014 (1030 ha). The sampled fields were within and joining the catchment boundaries. These soil samples were collected to the standard agronomic depth of 0–10 cm, with at least 20 sub-sample cores (2.5 cm diameter) per sample, taken in a W pattern from each sampling area, bulked, oven-dried (40 °C), sieved (< 2 mm) and analyzed for Morgan extractable soil P (Morgan, 1941). Results were area weighted and comparisons made between the two sample periods as percentage changes between STP concentration and index categories over the catchment areas.

3. Results and discussion

3.1. Field P management practices

3.1.1. Fertilizer P inputs

From the records provided by the landowners, most of the P inputs to the land in both catchments was total fertilizer P (99% in Arable A and 94% in Arable B). In Arable A the mean annual total fertilizer P applied increased from 25.0 to 32.2 kg ha^{-1} yr^{-1} between 2010 and 2013, which equates to an increase of 8201 kg P in total P fertilizer loading within the catchment over the study period (Table 2). In comparison, in Arable B the mean annual total P fertilizer inputs increased from 23.1 to 39.3 kg ha^{-1} yr^{-1} between 2010 and 2013, (consistently higher from 2011 to 2013) which equates to an increase of 13,694 kg P loading within the catchment over the 4 year study period (Table 2). Between 2010 and 2013 the average P inputs for the dominant catchment cereal crops of spring barley (29 kg P ha^{-1} in Arable A) and winter wheat (16 kg P ha^{-1} in Arable B) were for most years comparable with typical P input levels to cereal crops nationally (Dillon et al., 2018). Of this total fertilizer P applied in each of these catchments, mineral P was the dominant form (87%) in Arable A where 53% of this mineral P was applied in the compound N-P-K fertilizer formulation of 10-10-20, whereas in Arable B the mineral P (42% of the total P fertilizer applied) was applied in the form of two N-P-K compounds 10-5-25 (22%) and 10-10-20 (20%). Where organic P was applied in Arable A it constituted mostly of farmyard manure (FYM) with smaller quantities of cattle and pig slurry. In Arable B 69% of P applied was organic P in the forms of cattle slurry and FYM, with some applications of imported poultry manure and spent mushroom compost from outside the catchment area.

3.1.2. Phosphorus removal

The mean P removal in crops (i.e. cereals, roots, pulses and grass forage) for the fields in both catchments remained relatively similar across the study period (23.9 kg P ha^{-1} yr^{-1}; Table 2). However, the untypically wet summer of 2012, where the average rainfall of 533 and 489 mm between May and August for Arable A and Arable B, respectively, contributed to lower crop yields and hence P removal in this year. This impact was most apparent in the moderate to poorly drained Arable B catchment, where mean crop P-offtake was at its lowest level (21.7 kg P ha^{-1}; Table 2) over the study period.

In Arable A, a small proportion of the land area was used for grazing, typically at low stocking densities, and P recycled by grazing livestock across this catchment was low (Table 2). In contrast, in Arable B, the average P cycling from grazing livestock increasing on the grazed grassland area over the study period, due primarily to increasing livestocking densities, especially in 2013 (Table 2). This increase originated from land-use change from tillage to dairy production systems and from the increase in dairy cow numbers on existing dairy farms as they intensified in preparation for post milk quota in 2015, in line with the national strategy to increase milk production targets (DAFM, 2015). The Irish national average stocking density of c. 1.2 LU ha^{-1} on grassland is relatively low (EUROSTAT, 2017).

3.2. Phosphorus balances

3.2.1. Field and optimum soil P balances

Reflecting the increasing trends in P fertilizers inputs to each catchment, the average *field P balance* within the Arable A catchment increased from 2.7 kg ha^{-1} in 2010 to 7.5 kg ha^{-1} in 2013, and similarly, in Arable B increased from -0.6 kg ha^{-1} in 2010 to 25.5 kg ha^{-1} in 2013 (Table 2). Over the 4 years of this study the average P balance was, on average, 9.9 kg ha^{-1} higher in Arable B compared to Arable A.

The average *optimum soil P balance* for fields in Arable A, which includes P build-up requirement for low soil P fields (STP index 1 and 2), showed a P deficit each year over the 4 year study period. Moreover, despite the overall increase in P inputs into Arable A and the average concurrent soil P deficit decrease from -6.1 kg P ha^{-1} in 2010 to -1.1 kg P ha^{-1} in 2013 (Table 2), the data indicate that these levels of fertilizer P input were insufficient to satisfy the P build-up requirement of the catchment soils. In Arable B, the average *optimum soil P balance* was in deficit in 2010, however, as the P inputs increased substantially between 2011 and 2013, an average soil P surplus occurred in these years (Table 2), indicating that soil P build-up and surplus P above crop requirement was occurring in a proportion of these fields.

Knowledge of the average P balance according to the cropping systems within these agriculturally dominated landscapes can inform the speed at which legacy soil P build-up or draw down may occur (Wall et al., 2013). In this study the largest mean field P balance and optimum soil P balance were 73.3 kg ha^{-1} yr^{-1} and 59.7 kg ha^{-1} yr^{-1}, respectively, in fields occupied by maize crops. In contrast, the lowest

Table 3
Mean, Min, Max and standard deviation field and soil P balances per crop type across the study period (2010–2013) for Arable A and B catchments combined. Included are crops that represented no less than 3 farmer mangers and from at least 3 of the study years.

*(kg ha^{-1} yr^{-1})	Grass: Silage only (1 cut)	Grass: Silage only (2 cut)	Beans	Winter Oilseed Rape	Winter Wheat	Spring Oats	Spring Barley	Grass: 1 Cut (Hay) + Grazing	Winter Barley	Spring Wheat	Grass: 1 Cut + Grazing	Winter Oats	Grass: 2 Cut + Grazing	Grass: Grazing only	Swedes/ Turnips	Potatoes (Maincrop)	Beet	Maize
Mean P balance	−14.6	−14.0	−7.6	−6.8	−5.5	1.8	2.8	3.4	9.3	9.4	10.0	16.1	17.7	22.8	38.3	41.8	46.7	73.3
Min P balance	−33.1	−37.8	−40.3	−32.4	−46.3	−27.7	−36.5	−8.0	−33.5	−35.2	−24.0	−19.4	−32.5	−21.0	25.4	−17.8	29.9	18.1
Max P balance	−6.4	20.8	22.6	83.3	157.7	75.2	90.6	21.8	145.9	136.3	171.9	84.0	146.1	166.6	43.4	148.9	77.3	181.6
sd P balance	8.4	15.2	21.6	22.9	34.1	26.6	15.5	9.6	33.7	36.5	25.3	41.3	45.5	39.0	8.7	42.9	13.5	49.2
Mean soil P Balance	−26.3	−26.2	−25.5	−12.3	−15.5	−9.3	−6.2	−12.9	−3.1	0.7	2.8	10.1	10.3	15.7	25.8	19.5	34.6	59.7
Min soil P Balance	−43.1	−81.4	−65.8	−41.7	−61.1	−37.7	−40.5	−28.0	−49.3	−45.0	−44.0	−38.4	−52.5	−41.0	13.4	−67.8	11.1	−11.9
Max soil P Balance	−12.6	20.8	22.6	73.3	147.7	75.2	90.6	6.6	135.9	126.3	171.9	84.0	136.1	166.6	41.1	148.9	77.3	151.6
sd soil P balance	7.8	20.6	22.2	21.8	36.6	29.8	15.1	10.6	33.9	35.9	27.0	44.0	47.0	41.9	11.4	57.1	17.0	44.6
n, fields	23	71	28	65	305	43	887	35	156	39	285	30	149	667	4	28	21	36
n, farm mangers	4	8	7	5	22	11	39	4	13	7	30	4	15	43	3	4	7	17
n, study years	4	4	3	4	4	4	4	4	4	4	4	4	4	4	3	4	4	3

*sd-Standard Deviation.

mean field P balances (-14.6 kg ha^{-1} yr^{-1}) and optimum soil P balance (-43.1 kg ha^{-1} yr^{-1}) were in grassland fields where herbage was removed as first cut silage (Table 3). Regardless of the number of fields occupied by individual crops and the number of farm managers, there was large variability in field and optimum soil P balances most notably for the following crops; winter barley, winter wheat, spring wheat, grass: grazing only, winter oats, potatoes (maincrop), grass: 2 cut + grazing and maize, as indicated by their high standard deviations (Table 3). This highlights the large variability of P management even within crop type.

The main crops in Arable A catchment were, spring barley, winter wheat, grass: 1 cut silage + grazing and grass: grazing, and represented 80% of the land area. In contrast, in Arable B, the main crops were winter wheat, winter barley, grass: 2 cut silage + grazing and grass: grazing, and represented 70% of the area. Comparing all of the dominant crops in both catchments the range of the P balances (field and optimum soil P) were on average 1.6 times higher in Arable B. There was a larger range in field P balances across Arable B compared to Arable A, for example 187.6 kg P ha^{-1} on the grazed grass and 204.1 kg P ha^{-1} yr^{-1} in winter wheat fields in Arable B (Fig. 2b), compared to 93.4 kg P ha^{-1} on spring barley fields in Arable A (Fig. 2a). This indicates that nutrient (P) management of the specific crops types or grassland stocking rates in each catchment are the main source of dissimilarity in their P balances.

3.2.2. Regulated NAP-P allowance balances

In Ireland maximum P fertilizer application limits were set out in the NAP (SI, 610 of 2010) according to crop type, stocking rate and within STP indices. The mean NAP-P limits per hectare were similar for both Arable A and Arable B catchments across the study periods (26.8 and 26.4 kg ha^{-1} yr^{-1}, respectively, Table 2). However, for individual fields the highest crop specific NAP-P limit of 125 kg ha^{-1} yr^{-1} was within the Arable B catchment where maincrop potatoes (*Solamum tuberosum*) on STP index 1 soils were grown (Table 2). In Arable A and Arable B 56.1% and 50.2% of the area respectively received P fertilizer applications less than the NAP-P limits in accordance to crop type and stocking rate (Fig. 3a). This equated to an annual average shortfall of 5047 kg and 8503 kg in total P applied according to the recommended P limit across this area of Arable A and Arable B, respectively. Similarly, in both catchments these lower P applications occurred mainly on the P deficient soils (index 1 and 2) (Fig. 3b and d).

In Arable A, a further 7.5% of the catchment area had P fertilizer applications equal to the NAP-P limits, mostly in fields with zero P applications due to high STP levels (P index 4) where no additional P inputs are allowed (Fig. 3a and b). In Arable B, 16.9% of the catchment area had P fertilizer applications equal to the NAP-P limits (Fig. 3c). However, 11.0% of this balanced area had received SMC and poultry manure applications, under transitional provisions of the NAP (SI, 2009 and 2010) where P application levels could be in excess of crop P removal, up to until a maximum of 5 kg ha^{-1} in excess limit was introduced in 2013. If these transitional arrangements were not in effect during the study period then, on average, only 5.5% of this area would have had P applications equal to the NAP-P limits (Table S1).

On average, one-third of both catchment areas (36% of Arable A and 33% of Arable B) received P fertilizer inputs in excess of the NAP-P limits. The annual average surplus in total P that exceeded the recommended P limit across this area in Arable A and B was 7306 kg and 8688 kg, respectively. The majority (> 53%) of the P application excesses were represented by the index 4 soils (Fig. 3b and d) ranging from 11 to 67 kg P ha^{-1} yr^{-1} in Arable A and 3.71 to 151.5 kg P ha^{-1} yr^{-1} above the NAP allowance in Arable B. If the transitional provisions for the increased application of poultry manure and spent mushroom compost were removed this area of exceedance of the NAP-P limits across the four year study period increases by 11% (i.e. up to 44%, Table S1).

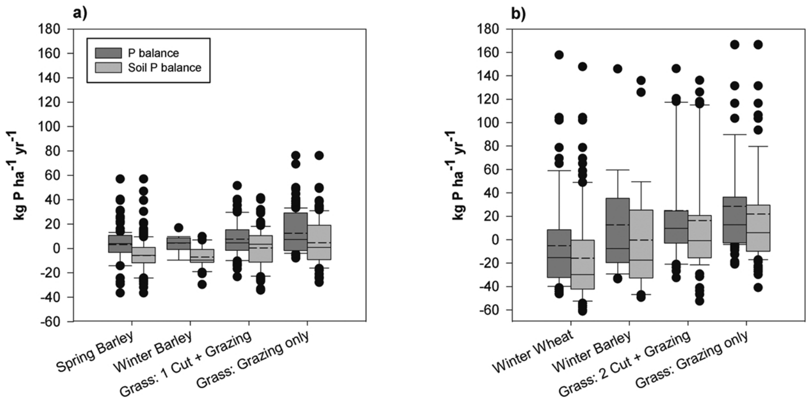

Fig. 2. Field P (dark grey boxes) and optimal P (light grey boxes) balances of the four dominant crops types in the Arable A (a) and Arable B (b) catchments, across the study period 2010–2013. The dotted line represents the mean.

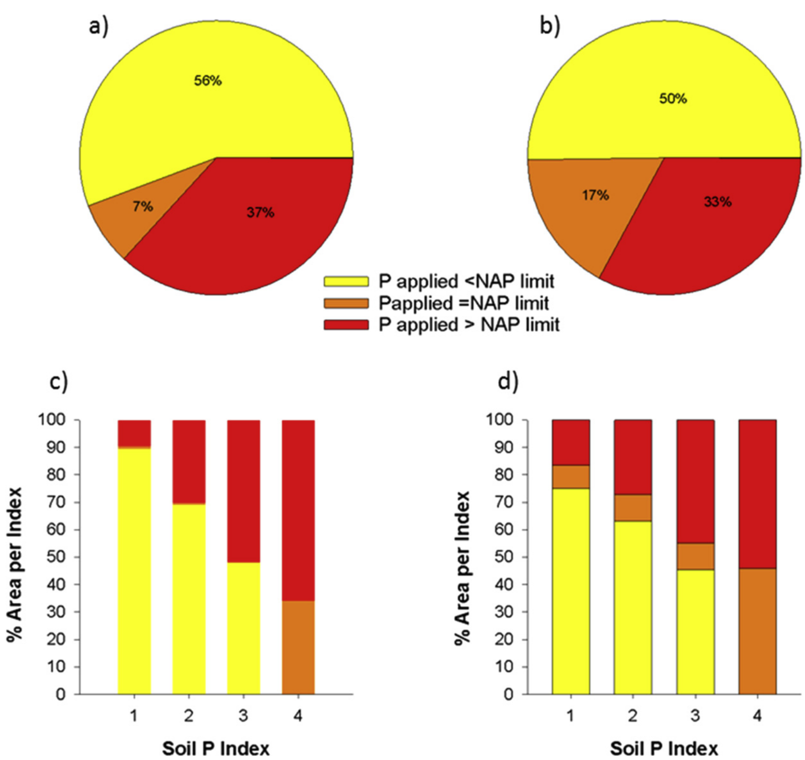

Fig. 3. The average across four study years (2010–2013) areal proportion of P applied (as fertilizer) that was less than (P applied < NAP), equal to (balanced P applied) and/or exceeded (P applied > NAP) crop and/or animal requirement allowances as set out in the national action programme (NAP) SI, 106 of 2010 in within (a) Arable A and (b) the Arable B catchments and within each baseline soil test P index for (c) Arable A and (d) Arable B.

3.3. Trend in soil test P (STP)

While source P inputs increased in both catchments, the direction of change in area-weighted mean STP concentrations upon resampling in 2013/2014 differed between the catchments. In Arable A soils declined from 6.19 mg l^{-1} in 2009 to 5.22 mg l^{-1} in 2013 (n = 401 fields). The area of Arable A with soil P in excess of agronomic optimum (P index 4) decreased by 4% (17% to 13%; Fig. 4a) over this period. The area with soil P levels within the agronomic optimum range (P index 3) decreased by 3% (23 to 20%) and there was a subsequent increase in area with P deficient soils, where the area of P index 2 increased from 35% to 36% and the area of P index 1 soils from 25 to 31% over the 4 year period. In contrast, across Arable B the area of soil P index 4 soils increased by 4% (22% to 26%; Fig. 4b), the area within P index 3 and 2 remained relatively constant at 17% and 34% respectively. There was a 5% decrease in the area of very low P index 1 soils (28 to 23%; Fig. 4b). These changes in STP across the farmed land within Arable B indicate a convergence of STP towards the optimum and above (i.e. P index 3 or 4), as the area-weighted mean STP increased from 6.71 mg l^{-1} in 2010 to 9.10 mg l^{-1} in 2014 (n = 341 fields). However, the median STP remained relatively constant at 4.20 mg l^{-1} in 2009 and 4.65 mg l^{-1} in 2014, indicating that this increase in STP was occurring in a relatively small proportion of the Arable B catchment.

Within fields with very low P soils (P index 1) in both catchments there was an increase in mean STP concentrations, but the mean change in STP concentration was approximately 4 times higher in Arable B (1.60 mg l^{-1}) compared to Arable A (0.30 mg l^{-1}) (Fig. 5a). Within the other three soil P index ranges (2–4) the STP concentrations decreased in Arable A and increased in Arable B (Fig. 5b). Fields with STP levels above the agronomic optimum (P index 4) showed the largest mean reductions in STP of 4.08 mg l^{-1} for the Arable A soils and the largest increases in the mean STP of 5.51 mg l^{-1} for Arable B.

This variability in STP concentrations across these catchments, and other similarly monitored catchments (Wall et al., 2012; Murphy et al., 2015) and across farms nationally (Plunkett and Wall, 2016), is a continuing issue. At a European scale, the LandUse/LandCover Area Frame Survey (LUCAS) of 2009 and 2012, reported large differences in STP levels between croplands within and between 27 EU member states

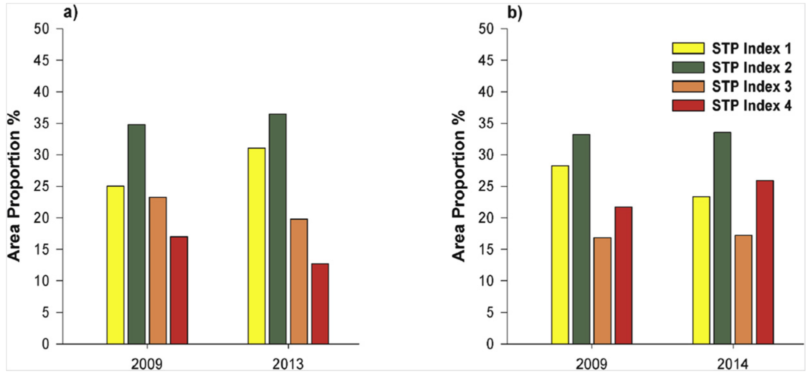

Fig. 4. The area weighted proportion of soils in each soil P index for a) Arable A and b) Arable B in 2009 and.2013–2014.

(Tóth et al., 2014). Approximately half the samples collected in this EU wide study had high to very high STP levels, with larger STP levels observed in the North-West regions of Europe due to higher expected crop yields, fertilizer inputs, and probable livestock densities under favourable climatic conditions (Tóth et al., 2014). In this current study, annual P balance provided an indication of how P inputs may change STP over time. The cumulative P balance over the 4 year soil census period did not necessarily provide further information, as many other soil, management and climatic factors also affect soil P pools.

While nutrient management planning by farmers in conjunction with their local farm advisor in Arable A appears to have influenced redirecting P inputs from high STP soils (index 4) to lower soil P fields, the increasing areas of index 1 and 2 soil up to 2013 indicates that increased P inputs will be required (according to farm planning) to correct the imbalances in the future. However, in Arable B the advice to distribute P inputs across the low STP fields and away from the high STP soils (index 4) within farms and across the catchments is a continual challenge, especially on farms where organic manures are being imported.

3.4. Implications for future nutrient management planning

Both Wall et al. (2012) and Roberts et al. (2017) have associated the over application of P inputs, above the P requirement of the soil and crop, with lack of farmer knowledge of the soil test results, soil type, and poor or absent nutrient management planning (NMP) at the field scale on farms. The N to P ratios within organic manure sources are often mismatched with the N and P requirements of crops (Withers et al., 2014b) and, hence, situations of over-application of P may result as a consequence of fulfilling the N requirement of a crop first. Therefore, the awareness by farmers of the P contribution by organic manure inputs are often overlooked (Murphy et al., 2015). Manures such as poultry litter typically have relatively high available N (11.0 kg N t^{-1}) and P (6.0 kg P t^{-1}) concentrations compared to cattle or pig slurries (Wall and Plunkett, 2016). A high density of poultry enterprises are located in the north-east of Ireland and are in close proximity for land spreading to Arable B. For farmers within this catchment and similar catchment types, importation of this poultry manure in accordance with the NAP allowances (i.e. not exceeding 170 kg N ha^{-1} limit) provides a cheaper alternative source of N compared to mineral fertilizer N inputs. Increased awareness of the value of P from poultry and pig manures has not been assisted by the transitional provisions. In some cases the objective of the NAP measures to reduce legacy P within soils has become ineffective where transitional manures have been applied, for example on some Arable B fields, as soil build-up to excessive levels has occurred.

Part of this study was to understand the change in legacy soil P under the NAP regulations, where reduced area of P risky index 4 soils was shown in the Arable A catchment while a trend for increased index 4 soils was shown in the Arable B catchment, linked specifically to the importation of organic manure P. However, there was also evidence that greater than 50% of both catchment areas had P deficient soils, i.e. below the agronomic optimum level (index 3). There was evidence of mismatches between P inputs and outputs for certain crop types and farming systems, especially where transitional arrangements for the import and application of poultry manure and SMC was being utilised. While NMP is being conducted at the whole farm scale on these farms this study also indicates that better nutrient management is required within farms at field scale, in order to maximise nutrient P efficiency, and reduce the potential for P loss risk. In particular better spatial targeting of organic manure inputs towards low STP fields is needed and this is incentivised under new NAP arrangements (SI 605, 2017) where farmers can assume 50% availability of manure P when calculating application rates for soils with low STP, compared to 100% availability if manure is applied on soil with high STP.

Overall the findings from this study highlight the need for improved

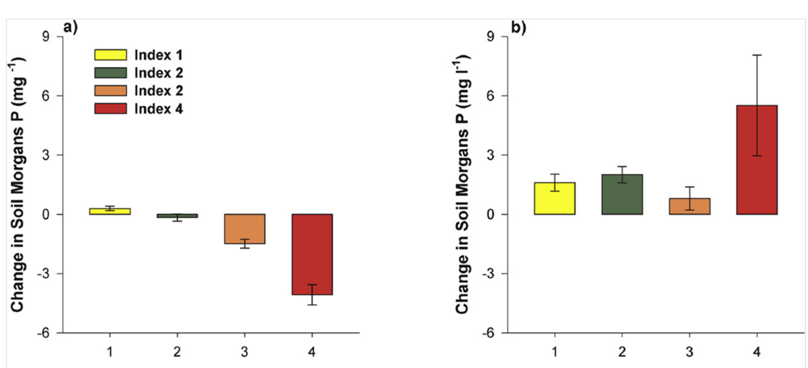

Fig. 5. Mean change in the Morgan P concentration over 4 years by initial soil P index in both in a) Arable A and b) Arable B catchments. Error bars indicate standard deviation.

engagement with NMP. Among farmers and experts, NMP is perceived as one of the most effective measures towards improving P use efficiency on farms and has production and economic benefits for farmers while simultaneously helping to reduce landscape diffuse P loss over time to local watercourses (Beegle et al., 2000; Darby et al., 2013; Micha et al., 2018). While NMP has been a mandatory measure via NAP regulations on a whole territory basis in Ireland since 2006, the effectiveness of this measure for P source risk mitigation has been slow and variable to date (Schulte et al., 2010; Murphy et al., 2015). Reasons for sub-optimal NMP implementation on farms have been shown to include inclement weather, associated economic costs (i.e. soil sampling, fertilizer prices), farmer age, time restrictions due to off-farm employment, farm size and enterprise type, (Beegle et al., 2000; Newell Price et al., 2011; Darby et al., 2013; Buckley et al., 2015), with more extensive farms being less likely to have a NMP (Roberts et al., 2017). Other barriers to full implementation of NMP are lack of availability to local advisory services to provide one to one planning and guidance for farmers (Micha et al., 2018) and lag-times between advisory intervention and full implementation of the NMP on the farm (Hodge and McNally, 1998).

However, Buckley et al. (2015) reported that NMP was not popular with only a 27% level of adoption when Irish farmers that were surveyed about nutrient management related practices on their farms. Information burden and lack of practicality in NMP general implementation are cited as the main issues (Beegle et al., 2000; Buckley et al., 2015). More focused education and technical assistance via knowledge transfer services and via online NMP software tools (Wall and Plunkett, 2016), especially when delivered by farm advisory services, are seen as the most effective means of providing successful implementation of NMP (Darby et al., 2013). Intervention by advisory services is required to guide correct fertilizer inputs, to increase nutrient efficiency, and to achieve balanced soil fertility over time while improving on-farm productivity and reducing the risk of P loss to surface waters.

Linked to this final point is the overall need to consider the absolute water quality risk of high soil P conditions in individual fields and where these may or may not be coincident with zones of high runoff vulnerability (Thomas et al., 2016). This is particularly important where fields are slow to draw down legacy P and/or which have and are being subjected to high P balances but where the runoff risk may actually be more benign (Shore et al., 2016). Nevertheless, notwithstanding runoff risk between the fields and the catchments, the results of this study indicate that Arable B presents the highest overall P source risk from fields with high soil P states, trends and P balances. This finding, combined with P contributions from agricultural and domestic faecal matter (Shore et al., 2017) and a higher surface runoff risk, provides a strong evidence base explaining the high and low flow P concentrations patterns observed in this river catchment and likely similar catchments.

4. Conclusions

In two mixed land use agricultural catchments (c.10 km^2), where P management has responded to EU regulations, and with P balance data on a c.2 ha basis over four year periods, this study found that:

- Mean nutrient P inputs per ha increased over the study period resulting in positive field P balances in both catchments.
- Within one predominantly spring cereal cropping dominated catchment (Arable A) this increase was mostly due to increased mineral P applications. However, on average, the P fertilizer inputs did not fulfil the P build-up requirements of the soils across this catchment.
- In contrast, the predominantly winter cereal catchment (Arable B), mainly had increased nutrient P inputs from organic sources i.e. cattle slurries and manures, over the period, as a result of increased livestock densities coupled with an existing reliance on imported manures from land-limited poultry and mushroom enterprises.

These trends in fertilizer P inputs were further assessed by the results of a c.2 ha soil P audit taken at the start and end of the study period. Overall the soil audit showed that:

- Up to 67% of the predominantly Arable A area and 57% of Arable B had STP levels that were below the agronomic optimum (i.e. P deficient) in 2013. The majority of soils in both catchments of low P status and this is of concern from agronomic and economic perspectives of the farmers in both catchments.
- In contrast, the area of each catchment with high P status and hence higher P loss risk potential (i.e. STP index 4) declined in the Arable A catchment by 8% over the study period, but increased in the Arable B catchment by 4%.
- These results indicate that the distribution of P across the fields was sometimes poor within farms and in particular, the distribution of imported manures to the Arable B catchment often did not match crops and soil requirements at the field scale.
- More than one-third of the land area in both catchments received fertilizer P inputs on a field scale in excess of those required to replace crop removal or above that allowed for STP build up, where required on low STP soils. However, the majority of these farms were compliant with the P limits specified in the NAP which are assessed on a whole farm basis.

While farm-gate P balances can provide essential indictors of source pressure changes at the farm-system scale, this study demonstrates the need to account for the actual field scale P balances to indicate where pressures of P attenuation, and hence enhanced or maintained legacies, may occur within the agricultural landscape. To support regulations on soil nutrient management in the EU and beyond the EU, policy assisted schemes and/ or increased knowledge transfer initiatives are required for farmers to assist and ensure better distribution of organic nutrients within farms especially in catchments neighbouring confined animal production units.

Acknowledgements

This study was made within the Teagasc Agricultural Catchments Programme (ACP) that was funded by the Department of Agricultural, Food and the Marine in Ireland. We acknowledge the work by past and present Teagasc and ACP advisors, technical, research and data management staff in supporting data collection and laboratory analysis for this project. We would like to thank the catchment farmers and their representatives for participation through contribution of farm management information and allowing access onto their farmlands.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2018.12.014.

References

Beegle, D.B., Carton, O.T., Bailey, J.S., 2000. Nutrient management planning: justification, theory, practice. J. Environ. Qual. 29, 72–79.
Buckley, C., Hynes, S., Mechan, S., 2012. Supply of an ecosystem service—farmers' willingness to adopt riparian buffer zones in agricultural catchments. Environ. Sci. Policy 24, 101–109.
Buckley, C., Howley, P., Jordan, P., 2015. The role of differing farming motivations on the adoption of nutrient management practices. Int. J. Agric. Manag. 4, 152–162.
Cassidy, R., Doody, D.G., Watson, C.J., 2017. Impact of legacy soil phosphorus on losses in drainage and overland flow from grazed grassland soils. Sci. Total Environ. 575, 474–484.
CSO, 2012. Census of Agriculture 2010-Final Results. Central Statistics Office Stationery Office, Dublin, Ireland, pp. 129.

DAFM, 2015. Local roots global reach. FoodWise 2025: a 10 year vision for the Irish agri-food industry. Department of Agriculture Food and the Marine, pp. 108. (Assessed 20 July 2018). https://www.agriculture.gov.ie/foodwise2025/foodwise2025report/.

Darby, H., Halteman, P., Heleba, D., 2013. The effectiveness of nutrient management plans on vermont dairy farms. J. Ext [On-line].

Dillon, E., Buckley, C., Moran, B., Lennon, J., Wall, D., 2018. Teagasc National Farm Survey Fertiliser Use Survey 2005-2015. Teagasc.

EUROSTAT, 2017. Agri-environmental Indicator-livestock Patterns. (Accessed 26 June 2018). http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_livestock_patterns/.

Ewing, W.N., 2002. The Feeds Directory: Branded Products Guide. Context Publications Ltd.

Fanning, A., Craig, M., Webster, P., Bradley, C., Tierney, D., Wilkes, R., Mannix, A., Treacy, P., Kelly, F., Geoghegan, R., Kent, T., Mageean, M., 2017. Water Quality in Ireland 2010–2015. Environmental Protection Agency, Wexford, Ireland, pp. 68.

Fealy, R.M., Buckley, C., Mechan, S., Melland, A., Mellander, P.E., Shortle, G., Wall, D., Jordan, P., 2010. The Irish Agricultural Catchments Programme: catchment selection using spatial multi-criteria decision analysis. Soil Use Manage. 26, 225–236.

Hodge, I., McNally, S., 1998. Evaluating the environmentally sensitive areas: the value of rural environments and policy relevance. J. Rural Stud. 14, 357–367.

Jarvis, P.J., Boswell, C.C., Metherell, A.K., Davison, R.M., Murphy, J.A., 2002. A nutrient budget for the Meat and Wool Economic Service of a New Zealand Class 1 high--country farm model. New Zealand J. Agr. Res. 45, 1–15.

Jordan, P., Melland, A.R., Mellander, P.E., Shortle, G., Wall, D., 2012. The seasonality of phosphorus transfers from land to water: implications for trophic impacts and policy evaluation. Sci. Total Environ. 434, 101–109.

Kavanagh, S., 2011. Feeding the dairy cow. In: Moore, M. (Ed.), Teagasc Dairy Manual: A Best Practice Manual for Ireland's Dairy Farmers. Teagasc, Teagasc, Oakpark, Ireland, pp. 310.

Kleinman, P.J.A., Sharpley, A.N., Withers, P.J.A., Bergström, L., Johnson, L.T., Doody, D.G., 2015. Implementing agricultural phosphorus science and management to combat eutrophication. Ambio 44, 297–310.

McDonald, P., Edwards, R., Greenhalgh, J., Morgan, C., 1995. Animal Nutrition, 5th edn. Longman Scientific and Technical, Harlow, UK.

Melland, A., Mellander, P.-E., Murphy, P., Wall, D., Mechan, S., Shine, O., Shortle, G., Jordan, P., 2012. Stream water quality in intensive cereal cropping catchments with regulated nutrient management. Environ. Sci. Policy 24, 58–70.

Mellander, P.-E., Melland, A.R., Jordan, P., Wall, D.P., Murphy, P.N.C., Shortle, G., 2012. Quantifying nutrient transfer pathways in agricultural catchments using high temporal resolution data. Environ. Sci. Policy 24, 44–57.

Micha, E., Roberts, W., Ryan, M., O'Donoghue, C., Daly, K., 2018. A participatory approach for comparing stakeholders' evaluation of P loss mitigation options in a high ecological status river catchment. Environ. Sci. Policy 84, 41–51.

Morgan, M.F., 1941. Chemical Soil Diagnosis by the Universal Soil Testing System. Connecticut Agricultural Experimental Station Bulletin 450. New Haven Connecticut, USA. .

Murphy, P., Mellander, P.-E., Melland, A., Buckley, C., Shore, M., Shortle, G., Wall, D., Treacy, M., Shine, O., Mechan, S., 2015. Variable response to phosphorus mitigation measures across the nutrient transfer continuum in a dairy grassland catchment. Agric. Ecosyst. Environ. 207, 192–202.

Newell Price, J., Harris, D., Taylor, M., Williams, J., Anthony, S., Duethmann, D., Gooday, R., Lord, E., Chambers, B., Chadwick, D., 2011. An Inventory of Mitigation Methods and Guide to Their Effects on Diffuse Water Pollution, Greenhouse Gas Emissions and Ammonia Emissions From Agriculture. Food and Rural Affairs, UK.

OJEC, 1991. Council Directive 91/676/EEC Concerning the Protection of Waters Against Pollution Caused by Nitrates From Agricultural Sources.

Plunkett, M., Wall, D.P., 2016. Soil Fertility Trends-latest Update. The Fertilizer Association of Ireland. Walsh Printers Roscrea, Horse and Jockey, Co. Tipperary, pp. 3–11.

Roberts, W.M., Gonzalez-Jimenez, J.L., Doody, D.G., Jordan, P., Daly, K., 2017. Assessing the risk of phosphorus transfer to high ecological status rivers: integration of nutrient management with soil geochemical and hydrological conditions. Sci. Total Environ. 589, 25–35.

Sattari, S.Z., Bouwman, A.F., Giller, K.E., van Ittersum, M.K., 2012. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proc. Natl. Acad. Sci. 109, 6348–6353.

Schröder, J.J., Schulte, R.P.O., Creamer, R.E., Delgado, A., Leeuwen, J., Lehtinen, T., Rutgers, M., Spiegel, H., Staes, J., Tóth, G., Wall, D.P., 2016. The elusive role of soil quality in nutrient cycling: a review. Soil Use Manage. 32, 476–486.

Schulte, R.P.O., Melland, A.R., Fenton, O., Herlihy, M., Richards, K., Jordan, P., 2010. Modelling soil phosphorus decline: expectations of water framework directive policies. Environ. Sci. Policy 13, 472–484.

Sharpley, A., 2016. Managing agricultural phosphorus to minimize water quality impacts. Sci. Agric. 73, 1–8.

Sharpley, A., Jarvie, H.P., Buda, A., May, L., Spears, B., Kleinman, P., 2013. Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J. Environ. Qual. 42, 1308–1326.

Sherriff, S., Rowan, J., Melland, A., Jordan, P., Fenton, O., O hUallachain, D., 2015. Investigating suspended sediment dynamics in contrasting agricultural catchments using ex situ turbidity-based suspended sediment monitoring. Hydrol. Earth Syst. Sci. Discuss. 19, 3349–3363.

Shore, M., Jordan, P., Melland, A.R., Mellander, P.-E., McDonald, N., Shortle, G., 2016. Incidental nutrient transfers: assessing critical times in agricultural catchments using high-resolution data. Sci. Total Environ. 553, 404–415.

Shore, M., Murphy, S., Mellander, P.-E., Shortle, G., Melland, A.R., Crockford, L., O'Flaherty, V., Williams, L., Morgan, G., Jordan, P., 2017. Influence of stormflow and baseflow phosphorus pressures on stream ecology in agricultural catchments. Sci. Total Environ. 590, 469–483.

SI, 31, 2014. European Union (Good Agricultural Practice for Protection of Waters) Regulations.

SI, 605, 2017. European Union (Good Agricultural Practice for Protection of Waters) Regulations.

SI, 610, 2010. European Union (Good Agricultural Practice for Protection of Waters) Regulations.

Thomas, I.A., Mellander, P.E., Murphy, P.N.C., Fenton, O., Shine, O., Djodjic, F., Dunlop, P., Jordan, P., 2016. A sub-field scale critical source area index for legacy phosphorus management using high resolution data. Agric. Ecosyst. Environ. 233, 238–252.

Tóth, G., Guicharnaud, R.-A., Tóth, B., Hermann, T., 2014. Phosphorus levels in croplands of the European Union with implications for P fertilizer use. Eur. J. Agron. 55, 42–52.

Tunney, H., 2002. Phosphorus needs of grassland soils and loss to water. In: Steenvoorden, J., Claessen, F., Willems, J. (Eds.), Agricultural Effects on Ground and Surface Waters: Research at the Edge of Science and Society. International Association of Hydrologic Sciences, Centre for Ecology and Hydrology. IAHS Publ, Wallingford, United Kingdom, pp. 63–69.

Tunney, H., Carton, O., O'Donnell, T., Fanning, A., Ireland, 1998. Phosphorus Loss From Soil to Water: End of Project Report, ARMIS 4022. page 11. Available online:. Teagasc (Accessed 20 July 2018). www.teagasc.ie/research/reports/environment/4022/eopr-4022.pdf.

Wall, D.P., Murphy, P.N.C., Melland, A.R., Mechan, S., Shine, O., Buckley, C., Mellander, P.E., Shortle, G., Jordan, P., 2012. Evaluating nutrient source regulations at different scales in five agricultural catchments. Environ. Sci. Policy 24, 34–43.

Wall, D.P., Jordan, P., Melland, A.R., Mellander, P.E., Mechan, S., Shortle, G., 2013. Forecasting the decline of excess soil phosphorus in agricultural catchments. Soil Use Manage. 29, 147–154.

Wall, D.P., Plunkett, M. (Eds.), 2016. Major and Micro Nutrient Advice for Productive Agricultural Agricultrual Crops. Teagasc, Johnstown Castle, Environment Research Centre, Wexford. Available online: Teagasc https://www.teagasc.ie/media/website/publications/2016/soil-fertility-green.pdf (assessed 20 July 2018).

Withers, P., Neal, C., Jarvie, H., Doody, D., 2014a. Agriculture and Eutrophication: Where Do We Go from Here? Sustainability 6, 5853.

Withers, P.J.A., Sylvester-Bradley, R., Jones, D.L., Healey, J.R., Talboys, P.J., 2014b. Feed the crop not the soil: rethinking phosphorus management in the food chain. Environ. Sci. Technol. 48, 6523–6530.

Withers, P.J.A., Hodgkinson, R.A., Rollett, A., Dyer, C., Dils, R., Collins, A.L., Bilsborrow, P.E., Bailey, G., Sylvester-Bradley, R., 2017. Reducing soil phosphorus fertility brings potential long-term environmental gains: a UK analysis. Environ. Res. Lett. 12, 063001.