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The influence of phosphorus application and varying soil pH on soil and herbage properties across a range of grassland soils with impeded drainage

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Abstract

On soils dominated by high proportions of clay and organic matter, soil acidity and poor nutrient use efficiency have a major impact on output potential. Due to the inherent chemical properties of these soils, reducing soil acidity and the prevalence of undesirable metallic cations poses challenges. As a result, these soils have a large capacity for phosphorus (P) fixation, therefore reducing plant P availability. Limestone ($CaCO_3$ or $MgCO_3$) is applied to agricultural soils to counteract soil acidity and reduce P fixation. The current study investigates the effects of four contrasting annual P application rates (0, 50, 100, 150 kg P/ha); split (50:50) between spring and summer, across soils with a range of soil pH values from a previous liming trial. The effect of soil pH ranges and P treatment rates on seasonal herbage growth and herbage P concentration was investigated over three years. Soil nutrient status was also investigated. Soil pH had a significant impact on the rate of mineralization and soil P concentration across each site. A soil pH of 6.2 caused a 1.8 mg/l increase in soil test P. An annual P application was necessary to maintain sufficient herbage P concentration for animal dietary requirements (0.35% DM), however there was no effect of P application or liming rate on herbage productivity across the three sites as all sites possessed sufficient soil P reserves. The current experiment has shown that despite optimal soil fertility status, ensuring sufficient plant available P is a problem on these particular soils.

Introduction

Phosphorus is an essential nutrient, both for herbage production and for grazing animals. Phosphorus is a key component in every living cell and plays a critical role in many physiological and biochemical properties (Westheimer, 1987). It is a critical nutrient in milk and meat production, constantly being removed from the soil and converted into animal products in grazing systems. It is therefore essential that offtakes are replaced and soil P concentration is maintained for healthy plant growth and sufficient animal P availability. Due to the temperate climate in Ireland, grass is easily grown and is the cheapest form of feed available (Finneran *et al.*, 2011). Dillon *et al.* (2005) showed that the increased proportion of grass in the diet of a grazing cow resulted in a lower cost of production.

Soil acidity is a major problem in Ireland due to the inherently acidic nature of Irish soils (Wall and Plunkett, 2020). Achieving optimum soil pH (≥6.3) through the application of limestone ($CaCO_3$ or $CaMg(CO_3)_2$) is critical. Soil pH has a major influence on soil and plant processes. Liming improves nutrient availability for plant uptake (McDowell *et al.*, 2002) and removes undesirable metallic cations that largely affect plant growth and development, increasing grassland yield and quality (Stevens and Laughlin, 1996).

Overall soil fertility is poor in Ireland, the most recent national soil fertility statistics for dairy farms in Ireland show that 41% of soils are suboptimal for pH, 48% suboptimal for P and 41% suboptimal for potassium (K) (Teagasc, 2021). Of the soil samples analysed by Teagasc in 2020, only 21% of soils had optimum soil pH, P and K. Soil fertility has a major impact on overall farm production and profitability as well as the efficient use of nutrients, particularly nitrogen. The EU Green Deal and Farm to Fork strategy aim to reduce fertilizer use by 20% by 2030 (EU, 2021). The average nitrogen use efficiency on Irish dairy farms was 24.4% in 2019 (Donnellan *et al.*, 2020). Achieving optimum soil fertility (pH, P and K) on-farm will help reduce the N input required, aid in its utilization and recycling.

As a result of the negative effects of the overuse of P on water quality and also the uncertainty of remaining P reserves, much focus has been put on increasing P efficiency and reducing its potential environmental impact (Dawson and Hilton, 2011). Recycling organic forms of P on farm efficiently and using effective P management practices can help ensure maximum

Table 1. Initial soil properties (chemical and physical) across all three sites

Site	1	2	3
Soil pH	6.6	6.2	6.4
Soil phosphorus (mg/l)[a]	5.1	6.9	6.7
Soil phosphorus index	3	3	3
No. grazing's	8	8	9
CEC (meqv/100 g)	25.7	25.7	16.5
Ca BS (%)[b]	84	80	77
Mg BS (%)	6	10	11
Na BS (%)	5	7	9
K BS (%)	4	3	3
Ca:Mg ratio	14:1	8:1	7:1
Sand (%)	15	29	26
Silt (%)	49	43	47
Clay (%)	36	28	27
Organic matter (%)	15	18	12
Soil texture	Silty clay loam	Clay loam	Loam
Drainage	Moderately	Poorly	Imperfectly
Soil classification	Brown Podzolic	Stagnic/Gleyic Luvisol	Humic SW Gley
Bedrock	Shale	Limestone	Shale
Soil series[c]	Cupidstownhill	Ballygree	Crosstown/Crossabeg

[a]Morgan's soil test extractable concentration.
[b]Base saturation (BS) percentage of base cations.
[c]A group of soils with similar profiles developed from similar parent material under comparable climatic and vegetational conditions.

P uptake and reduced losses (Grant *et al*., 2001); as well as reducing chemical P requirements (McDonald *et al*., 2019). In Ireland, early (spring) and late (autumn) herbage production is restricted due to poorer climatic conditions, nutrient availability and also the supply of mineralized nutrients. Therefore during periods when herbage production is greater than animal requirement, surplus grass is preserved as silage to supplement the diet during periods of deficit (Finneran *et al*., 2010). Increasing early and late seasonal grass growth reduces the requirement for supplementary, increasing production efficiencies on farm (O'Donovan *et al*., 2011). Saunders *et al*. (1987) showed a yield response to P fertilizer application in periods of low herbage production.

Awareness of seasonal fertilizer application and its impact on herbage growth, animal dietary P and P loss is of considerable importance. Studies have been carried out to assess the effects of P application across contrasting soils in Ireland (Sheil *et al*., 2016), however more research is required to assess the impact of P application across a broader range of Irish soils. Much research carried out to date involves a cut (mechanical harvesting) system which does not take into account the large variability within and across seasons (2–4 cut systems) (Schils and Snijders, 2004; Power *et al*., 2005; Schulte and Herlihy, 2007). Due to current national soil P fertility levels and the recent decline in P fertilizer input, herbage P concentrations may be below dietary requirements. It is widely known that herbage P concentration varies largely during the grass-growing season. Sheil *et al*. (2016) showed large variation in herbage P concentration between periods of high and low herbage production; it was also observed that no trend exists in herbage P concentration throughout the grazing season (Cotching and Burkitt, 2011).

The objective of the current study is to assess the effects of four annual chemical P input rates on herbage production and herbage nutrient content over a 3-year sampling period across existing liming plots with varying soil pH values. Furthermore, it set out to determine the level of P input required to ensure sufficient dietary P in herbage for grazing animals.

Materials and methods

Site description

A site was selected on each of the three commercial dairy farms, dominated by soils with high proportions of fine soil particles (silt and clay), high levels of rainfall (1298–1622 mm annually) and poor soil fertility in southwest Ireland (Table 1). Each site was in a continuous grazing system by dairy cows for milk production (Byrne *et al*., 2018). Grazing frequency was uniform on each individual site with each site being grazed at 20–30 day intervals during the grazing season. All farms are participants in the Teagasc 'Heavy Soils Program', which aims to demonstrate methods to improve grassland productivity and utilization and sustain viable farm enterprises on poorly drained soils (O'Loughlin *et al*., 2012). Site 1 was located in Kiskeam, Co. Cork (52°12′N 9°08′W), Site 2 was located in Athea, Co. Limerick (52°27N 9°19W) and Site 3 was located in Castleisland, Co. Kerry (52°13N 9°28W).

Experimental treatments and design

In 2018, the phosphorus plot trial was superimposed onto an existing historic liming plot trial, which had previously been

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established in 2015. This provided a range of soil pH values within three distinct trial sites. In 2015, a randomized complete block design was established on each of the three sites with four blocks, each having seven treatment plots. Treatment plots were 6×6 m (36 m^2) in size. The experimental set up was a 2×3 factorial design + 1, namely; ground limestone at three rates (7.5, 5 and 2.5 tonnes/ha), granulated limestone at three rates (7.5, 2.5 and 1.5 tonnes/ha) plus a control. Both limestone products were derived from calcitic limestone ($CaCO_3$). Ground limestone had a neutralising value ≥50% and granulated limestone had a neutralising value ≥90%. At site 1, limestone treatments were applied in March 2015 and at sites 2 and 3, limestone treatments were applied in September 2015. Limestone application treatments were applied in a single application at the experimental set-up stage and no additional liming product was applied over the duration of the experiment.

In March 2018, the original 28 plots (6×6 m) at each site were subdivided into 56 plots at 6×3 m in size (18 m^2). Phosphorus treatments were super-imposed onto the existing liming plot study (2015–2018) which resulted in soil pH ranges. The P trial was carried out for a 3-year trial period (2018–2020). The experimental set up was a 4×3 factorial design + 2, namely the four phosphorus treatment rates (0, 50, 100 and 150 kg P/ha – using 16% triple super phosphate), the three limestone rates (high, medium and low) plus two controls. Each of the three trial sites had four blocks; each having 14 treatment plots. The phosphorus treatment rates were applied in a split application each year, the first split was applied in spring (March) and the second split applied in summer (May).

Nitrogen (N), potassium (K) and sulphur (S) were applied uniformly across the trial plot area after each grazing. An annual application rate of 300 kg N/ha was applied in the form of chemical nitrogen (calcium ammonium nitrate plus sulphur) throughout the grazing season and after each grazing event. Potassium was applied at an annual rate of 80 kg/ha as a split application in April and August. Nitrogen, K and S were applied using a hand help fiddle spinner fertilizer spreader (Earthway Products, Inc. Bristol, Indiana).

Grass varieties were sown at a seeding rate of 34.5 kg/ha. Each site was reseeded with a 100% perennial ryegrass mix; 70% tetraploid, 30% diploid. Site 1 was reseeded in 2014, site 2 was reseeded in 2009 and site 3 was reseeded in 2014.

Soil analysis

Soil chemical analysis was carried out pre-phosphorus treatment application in March 2018 to determine a baseline for each treatment plot. Soil chemical analysis was carried out at 6-month intervals until March 2020. Twelve soil cores were taken at random from the surface layer to 10 cm to form one composite sample from each plot using a 4 cm radius × 10 cm height soil corer at each time point. Soil core samples were taken from the central 5 × 2.5 m area of the plot to negate edge effects. The soil cores were prepared by oven drying at 40°C for 1 week and sieving through a 2 mm sieve. All soil samples were analysed at Teagasc, Johnstown Castle, Co. Wexford. Soil organic matter was determined using a 5-gram (g) subsample of the original soil samples taken across each individual experimental site by the loss on ignition method. This method quantifies the proportion of oxidizable organic matter by weight, determined as the weight loss of a given sample following high temperature oxidation in a muffle furnace at 500°C (Gavlak *et al*., 2003). Soil texture analysis was determined using the pipette method (British Standard, 1989), and soil pH using a ratio 1:2 (soil: water) with a pH probe (WTW, Germany).

Morgan's test was carried out using Morgan's extracting solution (Morgan, 1941). A 3 g subsample of each soil sample was added to a round bottom flask and Morgan's reagent (a buffered acetate-acetic acid reagent) was added in a 1:5 (soil: solution) ratio and extracted on a gyratory shaker for 30 min at 180 rpm. The solution was filtered through a Whatmann no.2 filter paper and the filtrate were analysed by a Lachat continuous flow analyser for extractable P. Morgan's test gives an indication of plant and crop nutrient availability. Morgan's extraction test is the recognized soil test in Ireland to test for soil P availability. Morgan's soil test is categorized into a 1–4 index system. The aim is to achieve index 3 (5.1–8.0 mg/l) to ensure sufficient plant available P and also ensure sufficient P for animal production in perennial ryegrass swards (Wall and Plunkett, 2020). Cation exchange capacity and percentage base saturation were determined on initial soil samples, pre-limestone treatment application from March 2015. Cation exchange capacity was determined using the ammonium acetate method, which measures a soils ability to retain exchangeable cations, neutralising the negative charge of soil (Gavlak *et al*., 2003). Percentage base saturation was calculated based on the percentage of CEC occupied by base cations. Base cations are distinguished from acid cation at a soil pH of 5.4 or less (Mehlich, 1984).

Herbage analysis

Herbage production was assessed at frequently scheduled intervals, pre grazing (7–10 annual grazings) over the grass growing season. Herbage nutrient content was analysed seasonally for N and P. Pre grazing sampling dates and rotation length are outlined on Table 2. Herbage production was measured as compressed sward height (Murphy *et al*., 2018) by conducting 10 measurements on each plot using a Jenquip rising plate meter (Jenquip Rising Plate Pasture Meters, New Zealand; diameter 355 mm and 3.2 kg/m^3) (Jenquip, 2021). This measures the quantity of grass accumulated and is presented in centimetres as grazing sward height (GSH). Compressed sward height was measured as a function of sward height and density. PostGSH was measured in the same manner to determine the residual sward height post grazing. Herbage grown was calculated as the difference between PreGSH and the previous PostGSH.

Herbage chemical analysis was carried out pre-phosphorus treatment application in March 2018 to determine a baseline for each treatment plot. Herbage samples were obtained before each grazing event and herbage mineral analysis was carried out seasonally for each year of the trial period (Table 2). Six random grass snips were collected from each plot in order to obtain a representative sample. Samples were oven dried at 60°C for 48 h and milled. Herbage N and P concentration was obtained using colorimetric analysis following hot acid digestion using sulphuric acid (Byrne, 1979). Herbage mineral analysis was analysed seasonally over the trial period by bulking dried and milled herbage samples from each rotation (Table 2). Herbage samples were bulked based on season and considerable differences in growth rates between sampling dates throughout the grazing season. Bulking was also dependant on the application date of P treatment rates, with each spring and summer bulked sample containing one annual split of P application. Schulte and Herlihy (2007) recommend that a minimum herbage P concentration of 0.35% DM is

Table 2. Sampling dates and rotation length (days) across each year within each farm

Season		Winter	Spring		Summer					Autumn			
	2018	6 Mar	25 April (50)	23 May (28)	11 June (19)	3 July (22)	27 July (24)			21 Aug (25)	21 Sept (31)	6 Nov (47)	
Site 1	2019	7 Mar (121)	30 Mar (23)	2 May (33)	27 May (25)	17 June (21)	8 July (21)	29 July (21)	21 Aug (23)	26 Sept (36)			
	2020	4 Mar (159)	21 April (48)	13 May (23)	4 June (22)	30 June (26)	20 July (20)	18 Aug (29)		21 Sept (34)	25 Oct (34)		
	2018	13 Mar	3 May (51)	25 May (22)	12 June (18)	3 July (21)	27 July (24)			17 Aug (21)	17 Sept (31)	18 Oct (32)	
Site 2	2019	1 Mar (134)	19 Mar (18)	9 May (51)	27 May (18)	17 June (21)	4 July (17)			16 July (12)	21 Aug (36)	1 Oct (41)	
	2020	4 Mar (153)	28 April (55)		22 May (24)	10 June (19)	30 June (20)			15 July (15)	6 Aug (22)	28 Aug (22)	21 Sept (24)
	2018	7 Mar	23 April (47)	24 May (31)	12 June (19)	5 July (23)	28 July (23)			21 Aug (24)	14 Sept (24)	16 Nov (64)	
Site 3	2019	27 Feb (103)	29 Mar (31)	25 April (27)	13 May (18)	31 May (18)	21 June (21)	16 July (25)	30 July (14)	23 Aug (24)	9 Oct (46)		
	2020	5 Mar (148)	28 Mar (23)	5 May (38)	26 May (21)	13 June (18)	6 July (23)			4 Aug (29)	4 Sept (31)	28 Sept (24)	

required to supply sufficient P to a grazing animal. Soil P index 4 however results in an oversupply of soil P and therefore increases the risk of loss to waterbodies (Tunney, 2002).

Meteorological data

Meteorological data [air and soil temperature (10 cm) (°C), rainfall (mm), solar radiation (J/m^2), wind speed and direction (m/s) and relative humidity (%)] were measured on each site by an automated weather station at 15 min intervals.

Statistics

The data were analysed by multiple analysis of variance using mixed models, implemented using PROC MIXED and GLM procedures in the statistical analysis systems (SAS) version 9.3 (SAS inst. 2011). The dependant variables were analysed using a linear mixed model (PROC MIXED). The model for soil test results included the factors of site, sampling date, season, liming rate and phosphorus rate and included interactions between factors. Site, site sampling date, season, liming rate and phosphorus rate were included as fixed effects. The model for change in soil test included the factors of site, sampling date, season, liming rate and phosphorus rate. The interaction between factors was also included. Liming products were grouped together in the current analysis and classified as high (H), medium (M) and low (L) liming rates.

Soil pH and Morgan's soil test were analysed and presented as the change in soil test. Change in soil test is defined as the difference between the initial soil sampling test (T_0) and the final soil sampling test (T_f): T_f–T_0. Mean change in soil test is defined as a mean of the difference between the initial soil sampling test (T_0) and the soil sampling test at each individual sampling date (T_{1-6}):

$$\text{Mean}\,[(T_1 - T_0) + (T_2 - T_0) + (T_3 - T_0) + (T_4 - T_0) + (T_5 - T_0) + (T_6 - T_0)]$$

Results

Herbage production

There was no effect of liming or P treatment rate on herbage growth. Sites showed a significant interaction between year (F = 31.8; $P < 0.001$), sampling date (F = 245.1; $P < 0.001$) (Fig. 1*b*) and season (F = 355.1; $P < 0.001$) (Fig. 1*b*) in mean herbage production. Site 2 grew 14 and 25% more herbage than sites 1 and 3, respectively. Year 1 grew 9 and 14% more herbage than year 2 and 3, respectively. The summer daily grass growth rate was 28 and 20% greater than spring and autumn, respectively; and a large variation existed between herbage grown across sampling dates (Fig. 1*a*).

Herbage phosphorus concentration

There was no effect of liming rate on herbage P concentration at the initial sampling date (March 2018), pre-phosphorus application. Herbage P concentration however was significantly different across all three sites. Initial herbage P concentration was 0.35, 0.31 and 0.38% at sites 1, 2 and 3, respectively.

There was a significant interaction between site, season and P rate (F = 26.7; $P < 0.001$) in mean herbage P concentration over

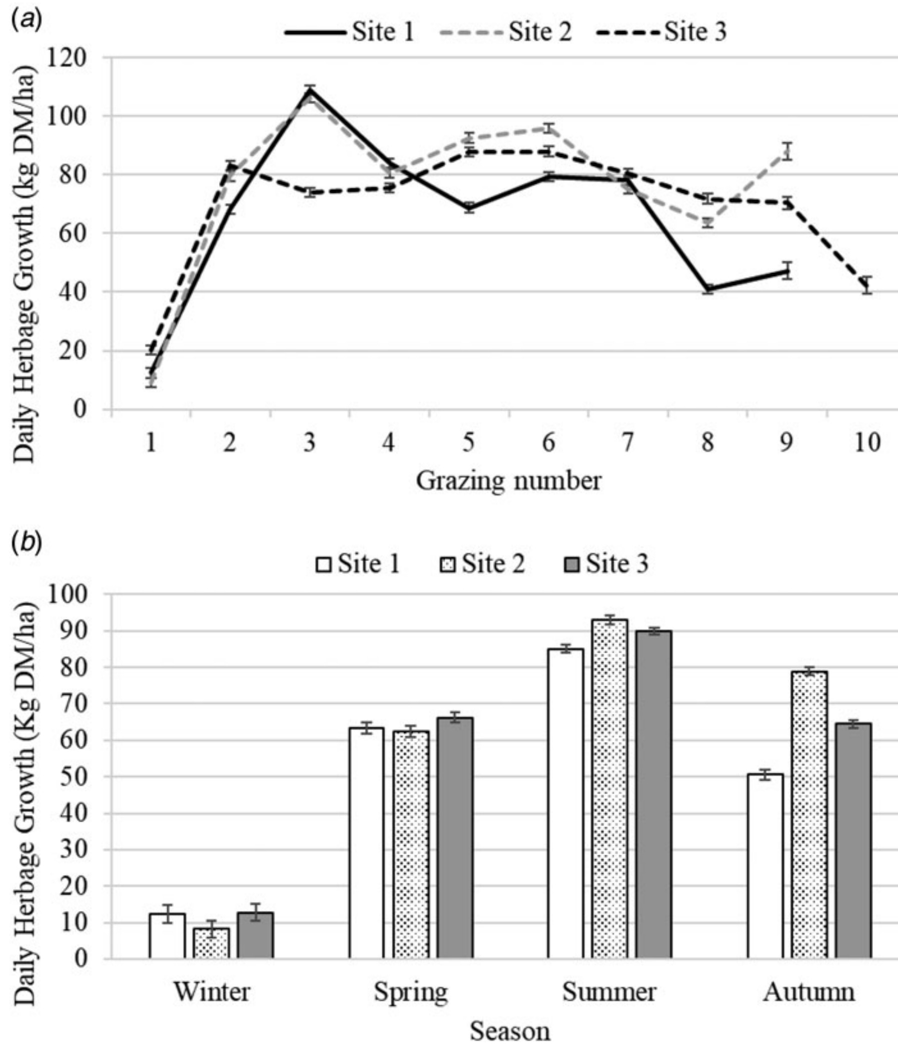

Fig. 1. (a) Daily herbage growth between individual sites across grazing dates; (b) daily herbage growth between individual sites across seasons.

the trial period (Table 3). Sites 1 and 2 were significantly greater than site 3 in herbage P concentration. Herbage P concentration was 9.6 and 7.6% lower in summer and winter, respectively, in comparison to the other two season that had the highest seasonal herbage P concentration and were not significantly different. Responses due to no supply in winter and high growth in summer. There was a 0.03, 0.07, 0.07 and 0.06% difference in herbage P concentration between the 0P and 150P treatment rates within the winter, spring, summer and autumn seasons, respectively (Table 3 and Fig. 2). There was a significant difference between all P treatment rates with a strong correlation between P treatment rate and mean herbage P concentration ($r^2 = 0.99$) (Fig. 2). As an average across all sites, an initial soil test phosphorus (STP) concentration of 6.2 mg/l (index 3) was adequate in achieving sufficient herbage P concentration across winter, spring and autumn. The variation between farms and seasons is shown in Table 3, highlighting the seasons where P input is necessary to achieve sufficient herbage P concentration.

Herbage nitrogen concentration

There was a significant singular effect of season, sites and years on herbage N concentration. Lime rate and P rate had no significant effect on herbage N concentration. Winter and autumn herbage N concentration did not differ, however they were significantly higher than spring and summer, spring being significantly lower than all seasons. Herbage N concentration was 3.71, 3.23, 3.41 and 3.70% across winter, spring, summer and autumn, respectively. Years 1 and 2 were not different in mean herbage N concentration; however, they were significantly higher than year 3. All sites differed significantly in mean herbage N concentration with values of 3.44, 3.73 and 3.37% herbage N across sites 1, 2 and 3, respectively.

Soil test phosphorus

There was no significant difference between trial plots in the initial STP concentration, therefore no effect of liming rates on soil P availability was found. There was, however, a significant difference between sites, site 1 being significantly lower than sites 2 and 3 with initial STP concentrations of 5.0, 6.8 and 6.8 mg/l recorded across sites 1, 2 and 3, respectively. Over the trial period there was a natural increase in STP across the control plots (mean: 1.8 mg/l). The natural (control plots) change in STP over the experimental period was 0.7, 1.3 and 3.3 mg/l across sites 1, 2 and 3, respectively.

There was a significant interaction between liming rate, sampling date and site in the change in STP (Table 4); and also a

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Table 3. Seasonal herbage phosphorus concentration (%) across P treatment rates and sites

Season	P rate	Winter	Spring	Summer	Autumn	S.E.M.[a]
Site 1	0 P	0.36	0.37	0.34	0.36	0.005
	50 P	0.38	0.39	0.36	0.38	0.007
	100 P	0.39	0.42	0.37	0.39	0.007
	150 P	0.40	0.43	0.39	0.41	0.007
Site 2	0 P	0.39	0.35	0.32	0.35	0.005
	50 P	0.38	0.40	0.35	0.38	0.007
	100 P	0.40	0.42	0.37	0.40	0.007
	150 P	0.42	0.43	0.39	0.41	0.007
Site 3	0 P	0.33	0.34	0.31	0.37	0.005
	50 P	0.34	0.38	0.36	0.40	0.007
	100 P	0.35	0.40	0.37	0.41	0.007
	150 P	0.36	0.43	0.39	0.43	0.007

Herbage P concentrations marked with box are low in ruminant P dietary requirement (<0.35%).
[a]Standard error of mean.

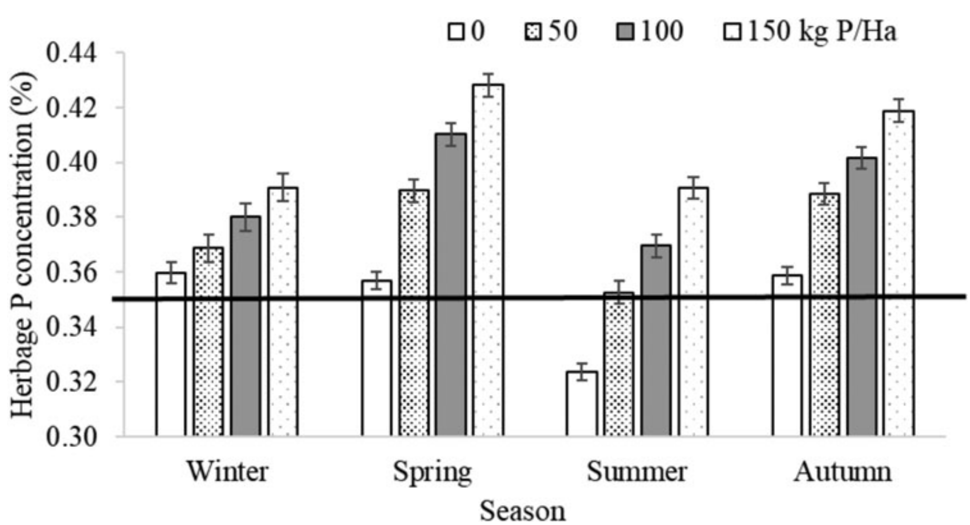

Fig. 2. Average herbage P concentration over the trial period across P treatment rates within each season – average across all sites (line on figure represents herbage critical P threshold for animal dietary requirements – 0.35%).

significant interaction between P rate, sampling date and site (Table 4). Liming rate, P rate and site also showed a significant interaction in the mean change in STP across the trial period (Table 4 and Fig. 3).

Change in STP was significantly greater (34%) at the high liming rate than the medium and low liming rates as a mean across all sampling dates and sites (Table 4 and Fig. 3). All P rates were significantly different in mean change in soil STP. There was a strong correlation between P treatment rate and its respective change in STP ($r^2 = 0.98$) across sampling dates and sites. Sampling date 2 (Mar-2019) was significantly greater than sampling date 1 (Sept-2018) in the mean change in STP. Sampling dates 3, 4 and 5 were significantly lower in their change in STP. All farms were significantly different from each other in the mean change in STP with site 3 2.8 times greater than site 1 and 1.8 times greater than site 2 in the change in STP at comparable P treatment rates.

Soil pH

Initial soil pH was 6.7, 6.4 and 6.3 across the high, medium and low liming rate plots, respectively; with the control plots (no liming application) having a soil pH of 6.1. Initial soil pH across sites 1, 2 and 3 was 6.5, 6.2 and 6.4, respectively; site 2 experiencing a significantly lower initial soil pH in comparison to sites 1 and 3.

Site showed a significant interaction with liming rate and sampling date ($F = 4.7$; $P < 0.001$) regarding the change in soil pH over the trial period (Fig. 4). All sites were significantly different in the mean change in soil pH, site 1 experiencing the

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Table 4. Change in soil test phosphorus across sites, sampling dates and phosphorus treatment rates

Effects (initial STP mg/l)	Treatment	Avg.	Sep 2018	Mar 2019	Sep 2019	Mar 2020	Sep 2020	S.E.M.[a]
Site 1 (5.0)	Control	0.7	1.0	1.9	0.2	0.5	−0.4	0.96
	0 P	0.3	0.4	2.8	−0.3	0.2	−1.5	
	50 P	1.8	0.9	4.2	1.7	1.5	0.6	0.78
	100 P	4.8	4.0	6.7	4.5	4.6	4.3	
	150 P	6.8	4.5	7.9	8.8	6.0	7.0	
	High lime	4.7	3.7	7.1	5.2	4.3	3.5	0.98
	Medium lime	2.5	1.8	4.7	2.7	2.1	1.4	
	Low lime	3.0	1.9	4.4	3.2	2.9	2.9	
Site 2 (6.8)	Control	1.3	1.6	3.1	0.4	1.0	0.7	0.96
	0 P	2.0	3.1	5.1	0.8	0.7	0.6	
	50 P	3.7	4.3	5.5	2.4	3.1	3.3	0.78
	100 P	6.1	6.0	8.4	4.7	5.1	6.3	
	150 P	8.1	6.2	10.0	7.1	7.5	9.5	
	High lime	5.2	5.1	8.6	3.7	3.8	4.9	
	Medium lime	5.0	5.4	6.6	3.7	3.8	5.3	0.98
	Low lime	4.7	4.2	6.5	3.8	4.6	4.6	
Site 3 (6.8)	Control	3.3	5.5	8.7	1.4	0.1	0.8	0.96
	0 P	4.2	6.9	9.1	2.1	1.3	1.8	
	50 P	5.9	9.3	10.6	3.4	1.8	4.2	0.78
	100 P	10.0	12.2	14.9	8.1	4.7	9.8	
	150 P	14.5	16.6	17.1	13.8	8.2	16.8	
	High lime	10.6	13.2	15.7	8.5	5.8	9.8	
	Medium lime	7.9	11.3	12.4	6.1	2.7	6.7	0.98
	Low lime	7.4	9.3	10.7	5.9	3.5	7.9	
All Sites (6.2)	Control	1.8	2.7	4.6	0.7	0.5	0.4	0.75
	0 P	2.2	3.5	5.6	0.9	0.7	0.3	
	50 P	3.8	4.8	6.8	2.5	2.1	2.7	0.61
	100 P	7.0	7.4	10.0	5.8	4.8	6.8	
	150 P	9.8	9.1	11.7	9.9	7.2	11.1	
	High lime	6.8	7.3	10.4	5.8	4.7	6.0	
	Medium lime	5.1	6.2	7.9	4.2	2.9	4.5	0.75
	Low lime	5.1	5.1	7.2	4.3	3.7	5.1	

[a]Standard error of mean.

greatest reduction in soil pH, exhibiting a 2.5 times greater pH reduction than site 2 and 8.7 times greater reduction than site 3. There was a large variation between liming rates in the rate of change in soil pH across the trial period (Table 5). The first two sampling dates post P treatment application (Sept-18 and Mar-19) experienced an increase in soil pH (mean across sites) and were not significantly different. The remaining sampling dates experienced a reduction in soil pH, sampling date 4 (Mar-20) being significantly lower than all other sampling dates in soil pH levels. There was a large variation in the change in soil pH over sampling dates and across individual sites (Fig. 4).

Discussion

Herbage growth

Previous research has shown significant increases in herbage production following the application of P fertilizer (Schulte and Herlihy, 2007; Sheil *et al.*, 2016). Differences in herbage production were observed in the studies mentioned above as initial STP concentrations were suboptimal, therefore restricting sufficient plant P availability and plant growth. Schulte and Herlihy (2007) showed a large variation in P requirement, particularly across low soil P indices among a range of soils. Spring P application resulted in significantly more herbage production in the

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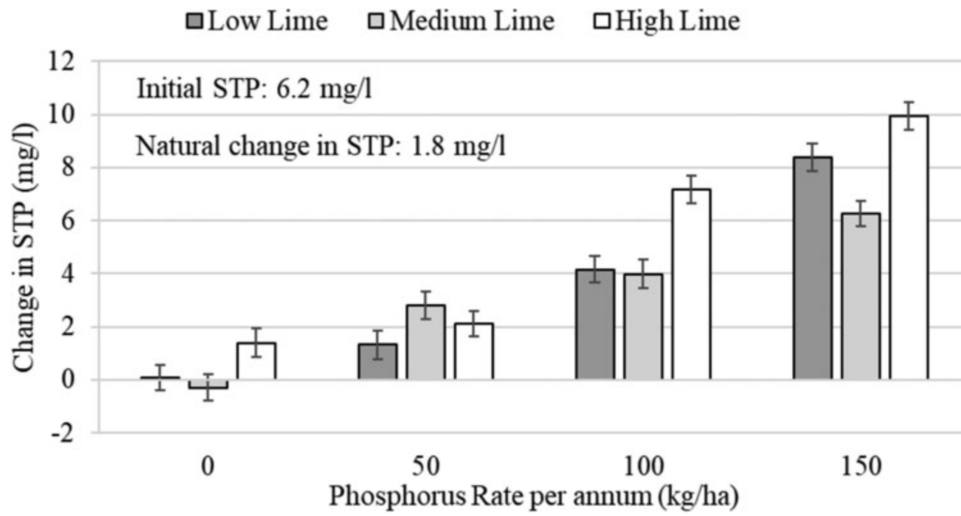

Fig. 3. Average change in Morgan's STP concentration across all sites over the trial period as a result of P and lime treatment rates (results presented are the change in addition to control) – STP refers to Morgan's P soil test.

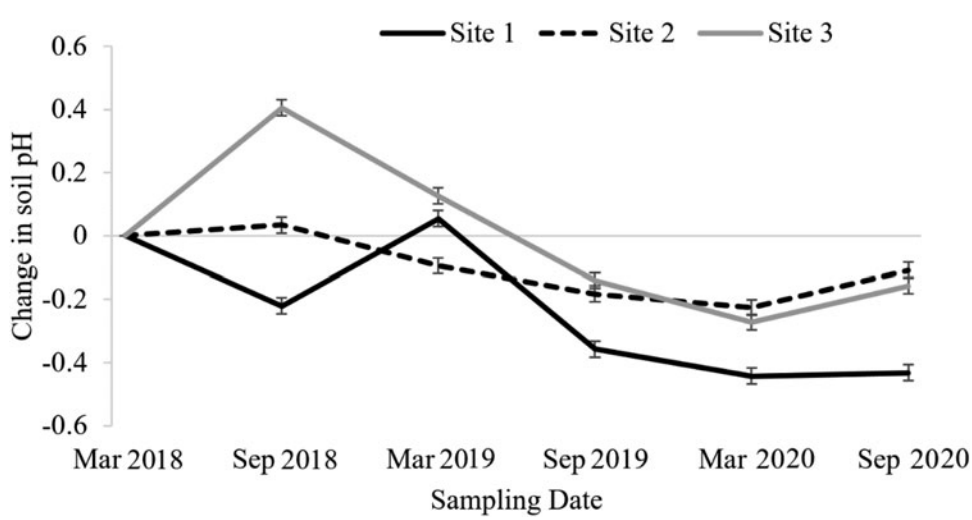

Fig. 4. Average change in soil pH across sites and sampling dates over the trial period.

first two seasonal harvests (average: +332 kg DM/ha each) in a cutting trial carried out by Sheil *et al.* (2016). Phosphorus demand is increased during early spring growth, as plants have a poor ability to utilize soil P (Sheil *et al.*, 2016), this was also demonstrated by Burkitt *et al.* (2010) by achieving increased herbage yield following early P application.

In the current study however there was no effect of P input rate on early spring growth or overall growth. Each site had an initial soil P index of 3, which is recognized as the optimal index for maximising herbage growth (Wall and Plunkett, 2020). Grant *et al.* (2001) stated that low soil temperatures in spring affect plant nutrient uptake, with plants being more readily able to uptake available soluble P as opposed the existing P already held in soil that is represented in the soil fertility P concentration. From the current study, the mean first grazing date across all farms and years was 5 April, suggesting that the potential grass growth effect of early P application may be reduced due to later defoliation and a relatively dormant plant until post grazing. Average pre grazing covers in spring in the current study were 2302 kg DM/ha, suggesting that reduced grass growth was as a result of high pre grazing covers. Laidlaw and Mayne (2000) showed that in grass covers >2000 kg DM/ha, shading caused poor tiller production, establishment and survival, and therefore reduced overall grass production. The average soil temperature across the study farms remained below 6°C for the months of January to March, increasing to approximately 10°C in April. Grass growth requires a soil temperature of 6°C, therefore little response would be evident over the January to March period. It can be seen that once the first defoliation occurred, average daily growth increased from 29 kg DM/ha per day for spring growth (March–April) to 89 kg DM/ha day from April to May (grass growth rate between first and second grazing). It could be suggested that a combination of low soil temperatures, poor soil conditions and late grazing dates was a result of poor spring growth. A simulated cutting trial may be required on these farms to assess the effect P fertilizer application on early grass growth

Table 5. Change in soil pH across sampling dates and liming rates within each individual site

Season	Lime	Average	Sep 2018	Mar 2019	Sep 2019	Mar 2020	Sep 2020	S.E.M.[a]
Site 1	Control	−0.26	−0.25	0.05	−0.34	−0.40	−0.37	0.063
	High	−0.38	−0.29	−0.01	−0.45	−0.57	−0.58	
	Medium	−0.25	−0.18	0.09	−0.33	−0.41	−0.43	0.045
	Low	−0.22	−0.16	0.09	−0.32	−0.39	−0.35	
Site 2	Control	−0.12	−0.01	−0.11	−0.19	−0.21	−0.06	0.063
	High	−0.14	0.05	−0.09	−0.19	−0.29	−0.19	
	Medium	−0.08	0.10	−0.06	−0.14	−0.21	−0.09	0.045
	Low	−0.12	−0.01	−0.11	−0.20	−0.19	−0.09	
Site 3	Control	−0.03	0.38	0.14	−0.18	−0.31	−0.20	0.063
	High	0.05	0.47	0.17	−0.08	−0.19	−0.10	
	Medium	0.00	0.43	0.12	−0.13	−0.28	−0.15	0.045
	Low	−0.04	0.35	0.08	−0.17	−0.31	−0.18	

[a]Standard error of mean.

and also across soils with suboptimal soil P concentrations in early spring. Also, due to poor ground conditions as a result of field saturation and consequently later turn out to grass in the spring, the necessity of early spring P and its efficiency is questionable. Therefore research is required into developing a more calculated approach around specific timing of spring P application in such circumstances.

Herbage nutrient concentration

The optimum herbage P concentration for grazing ruminants is 3.0–4.0 g/kg DM, the variation largely being dictated by the maturity of the animal, stage of production and whether the animal is lactating or not (Karn, 2001). The requirement by the growing plant however is much lower; herbage yield will only be significantly affected when herbage P concentration is less than 2.1 g/kg DM (0.21%) (Smith *et al.*, 1985). Therefore the P concentration required to grow grass is much lower than that required to maximize animal performance. The desired soil P concentration in Ireland is 5.01–8.0 mg l (index 3) Morgan's P (Wall and Plunkett, 2020), with the aim of achieving a herbage P concentration of between 3.0 and 3.5 g/kg DM (Schulte and Herlihy, 2007).

Across a long-term experiment carried out by Sheil *et al.* (2016), it was found a higher P input was required to achieve optimum herbage P concentration than was required for herbage growth. Sheil *et al.* (2016) showed that a minimum of 45 kg P/ha was required to achieve sufficient herbage P concentration throughout the grazing season. This was similar to the current study where 50 kg P/ha was required to achieve optimal herbage P concentration, despite a greater initial STP concentration in the current study. Soils dominated with higher rates of organic matter have shown to have greater moisture retention ability (Murphy, 2015), therefore over the summer period these particular soils have an increased grass growth potential in comparison to freely drained/loamy soils as they do not experience severe soil moisture deficits and as a result have higher herbage growth rates and greater P requirement (Teagasc, 2021).

Phosphorus input rate had no impact on herbage production as optimum soil P concentration was achieved. However variation was seen in the seasonal P input requirement to achieve sufficient herbage P requirement, particularly across individual farms. Despite a lower initial STP on site 1, it had a greater initial soil pH, therefore increasing plant P availability and uptake potential, also demonstrated by Ryant *et al.* (2016), and as a result a lower P requirement to achieve optimal herbage P across seasons. It could be suggested that the Mehlich 3 soil test would be a more suitable soil test in determining plant P availability due to the larger quantity of elements being tested and therefore attaining a better understanding of nutrient availability based on the presence of soil P antagonists such as Al and Fe (Corbett *et al.*, 2021). Nitrogen mineralization varies greatly throughout the year. Mineralization is closely linked to soil temperature and water status. Nitrogen availability is a major limiting factor restricting winter and spring growth due to the reduced mineralization potential (Whitehead, 2000). This was clearly observed in the current study as chemical N input was the same at each grazing event throughout the three-year trial period. Winter and autumn had the highest herbage N concentration, which was as a result of high N availability and also low or declining herbage growth rates. This supports work carried out by Marino *et al.* (2004) which showed lower N concentration at higher herbage production levels. The nitrogen dilution curve was a concept developed by Lemaire *et al.* (1984) which accounted for variations in herbage nitrogen concentration based on growth rates and N input rates. Due to there being no differences in herbage growth between treatment rates, and no differences in N input rates throughout the study, developing a nitrogen dilution curve was not necessary. It is evident that differences in N concentration in the current study were derived from seasonal effects.

Soil test phosphorus

A large variation existed between sites and P rates in the level of change in STP. Site 1 experienced a much lower change in STP in comparison to sites 2 and 3, this was largely attributed to soil composition and initial STP levels. This was clearly evident in the previous study where there were differences in initial soil Al and Fe concentration, and also differences in the change in soil test P across sites despite similar treatment rates (Corbett *et al.*, 2021). Site 1 had a significantly lower initial STP concentration, therefore more P was required to experience an equivalent change in STP in comparison to sites 2 and 3. This reduced ability to change STP at lower STP concentration was observed in a farm data study across these particular soils which showed larger P inputs were required to achieve equivalent changes in STP. It was previously shown by Daly *et al.* (2015) that above a certain Al to P ratio change point, Al had a significant impact on plant P availability. This suggests that increasing P input is required on soils with large Al and Fe content in order to reach optimum P availability for plant uptake (Quintero *et al.*, 1999).

Much work has been carried out showing the factors effecting P availability. Clay content has also been shown to play a major role in P availability (Gérard, 2016). Work carried out by Cui and Weng (2013) has shown Fe oxides to have a much greater effect on P sorption than clay minerals. However, research has also shown small differences between clay minerals and Fe and Al oxides in a soils P sorption capacity (Wei *et al.*, 2014). Site 1 contains significantly more clay content than the other two sites, resulting in greater P sorption and reduced plant P availability. In the previous liming study carried out on these particular sites (between 2015 and 2018), similar trends were observed across individual sites with site 1 experiencing a significantly smaller change in STP. It was also noted that site 1 experienced a significantly lower reduction in soil test aluminium concentration (Corbett *et al.*, 2021). Aluminium has previously shown to significantly reduce P availability due to its high P fixation capacity (Daly *et al.*, 2015).

Climate played a major role in STP concentrations across the current study. There was a considerable increase in STP as a result of the drought situation in 2018 (Falzoi *et al.*, 2019). The two consecutive sampling dates post P treatment application (Sept-2018 and March-19) experienced extremely high STP concentration, which reduced drastically thereafter. The legacy effect of the drought continued into the autumn period in 2018 (post Sept-2018 soil sampling). The greatest change in STP was experienced in Mar-2019, suggesting the effect of mineralized nutrients was carried into 2019. The soils in question experience large stores of plant unavailable P in labile and organic P pools. Increased mineralization after the rewetting of the sites following rainfall in autumn 2018 in conjunction with elevated soil temperatures caused excess plant available P and an increase in STP concentrations (Bünemann, 2015). Research has shown that environmental factors such as soil moisture, season and fertilizer application have a profound impact on P availability from organic sources (Butterly *et al.*, 2009). As well as this, there was no organic manure addition to these plots over the 3-year trial period, this would have caused a potential reduction in the carbon (C):P ratio which would have caused P mobilization and an increase in available P (Richardson and Simpson, 2011). As well as the process of mineralization, it is possible that P was made available through dissolution. Due to the continuous increase in soil pH to optimum levels over the trial period, it is possible that the increased P availability was also as a result of the dissolution of P from Al and Fe oxides and clay particle surfaces (Devau *et al.*, 2011). The level of mineralization or dissolution caused a 1.5, 2.4 and 7.1 mg/l increase in STP on the control plots across sites 1, 2 and 3, respectively. This highlights the increased potential of soils less confounded by high Al and Fe and clay content to increase mineralization of dissolved P into plant available forms. It can also be noted that the level of increased P availability was linked directly to liming rate in the current study and also the original liming study carried out at these sites (Corbett *et al.*, 2021). The use of the Mehlich soil test in the original liming study allowed a better understanding of P dynamics and soil elements dictating P availability.

Soil pH

Soil pH and reducing soil acidity are imperative to ensure sufficient P availability and efficiency (Ryant *et al.*, 2016). As soil acidity is reduced through liming (addition of calcium carbonate), so too is the concentration and abundance of metallic cations (Al and Fe), with metallic cations replaced by base cations (Corbett *et al.*, 2021). Holland *et al.* (2018) has reviewed the impact liming and shown that it increased nutrient availability and biota, which is important for the mineralization process.

The previous trial that was carried out on the particular sites in question experienced a continuous increase in soil pH over the 3-year trial period post liming application, reaching a maximum soil pH potential in March-2018. Soil pH continued to increase on site 3, it maintained on site 2 and reduced in soil pH on site 1, thereafter continuously decreasing in soil pH for the remainder of the experimental period. This highlights a 3-year effect of liming in increasing and maintaining soil pH, reducing significantly thereafter. Increased P availability was experienced on the previous liming trial carried out on these specific plots, with increased soil pH post liming application resulting in a significant increase in STP (Corbett *et al.*, 2021). In addition to the increased mineralization in year one of the current study, soil pH has also caused a large variation in STP throughout the experimental period. Soil pH reduced significantly after the first two sampling dates, resulting in reduced P availability across all sites. This is due to the high sorption capacity of P by sub-optimal soil pH and a potential increase in the concentration of metallic cations (Al and Fe) that were previously reduced with a reduction in soil acidity. In a review paper carried out by Barrow (2017), it was shown that maximum P availability occurs at a near neutral soil pH (6.5). The current study supports this as P availability began to reduce as the trial progressed due to a reduction in soil pH across each site. The reduced P availability is a result of P fixation.

Conclusion

The high initial soil P and pH levels offered a limitation to the current study. Further investigation into the herbage growth response to applied P at lower initial soil P indices would be particularly interesting. A minimum annual P application of 50 kg P/ha (50% spring and 50% summer) was required to achieve sufficient herbage P concentration throughout the grazing season, particularly in summer when growth rates were high and plant available P was restricted due to elevated P uptake. Despite sufficient P being naturally available in the spring where no P was applied to plots, the spring P application was crucial in minimising the extent and longevity of summer herbage P deficiency. Spring offers an ideal opportunity to increase STP through P application as soil conditions begin to improve and growth rates are relatively low in comparison to summer, therefore allowing P reserves be built in the soils fertility. Soil pH played a key role in maximising soil mineralization potential. Mineralization potential varied at contrasting soil pH levels. The greater the change in soil pH, the more P that becomes available through the process of mineralization.

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