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Effects over time of fertiliser P and soil series on P balance, soil-test P and herbage production

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Quantification of the balance between P input and offtake (P balance), and the consequent effect on soil-test P, is essential for management of sustainable soil and fertiliser nutrient supply. Results of measurements on 31 cut swards showed that change in P balance over 4 years was significantly affected by both P treatment and soil series. The more negative P balances were in high-P soils, and in soils of non-limestone parent material compared with limestone parent material. Initial mean Morgan P of 4.3 and 12.6 mg/l, in low and high index groups (0 to 6.0 and ≥6.1 mg/l) decreased to 1.7 and 4.4 mg/l after 4 years with no P treatment, in response to annual changes of *ca.* 25 to 35 kg/ha in P balance. Decreases were progressively smaller with increased P input, and smaller in non-limestone than limestone soils. The ratio of negative P balance to change in Morgan P varied from 20:1 to 70:1 depending on soil P index and parent material. Five sites gave a response to P in the final year following annual P inputs of 20 and 40 kg/ha, although Morgan P was ≤3.0 mg/l at 12 sites in the preceding autumn and 3.1 to 6.0 at nine sites. The results showed that both P balance and soil series should be taken into account in efficient fertiliser management, and that data from cut swards can be extrapolated to grazed swards when adjusted for P offtake. However, the results did not support the assumption that inputs balance offtakes in direct proportion.

Keywords: Grassland; phosphorus balance; soil-test P; sustainability

Introduction

In soils of low fertility, application of fertiliser P in excess of crop requirements may be used to build up available soil-P to levels that are perceived either to sustain higher levels of production, or to reduce the margin of error due to variability in large field areas. In more fertile soils with

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high levels of available P, and little or no fertiliser application, depletion of available P occurs over time. In either case, quantification of the difference between fertiliser input and offtake in herbage or animal product (P balance), and the consequent effect on soil-test P, is essential for efficient management of fertiliser use and of sustainable soil nutrient supply. There is inadequate information, however, on the range of variation in P balance and the extent to which variation in soil series, soil-P status and fertiliser application affect the relationship between P balance and soil-test P over time.

The assumption that inputs effectively replace offtakes commonly constitutes the basis of agronomic advice. Although there is some evidence for this (Zhang, MacKenzie and Liang, 1995; Schmidt, Buol and Kamprath, 1997), there can be wide differences between soils (Bertilsson and Forsberg, 1997), and within soils of different soil-P status (McCollum, 1991). Thus, the assumption of a 1:1 ratio between inputs and offtakes may not take into account the differential effects of soil series, soil-P status and fertiliser application on the resultant level of soil-test P. Soils vary in the extent to which the more labile, available, P is buffered or sustained by release from less available sources, and in their ability to retain added P or increase the available pool over time with fertiliser application. Differences associated with soil constituents occur both in short-term reactions, such as sorption characteristics (Evans and Smillie, 1976), and in longer term availability to crops (Adepoju, Pratt and Mattigod, 1982). Also, conversion of P to unextractable forms appears to be more evident on soils of high P status, which cannot be maintained by annual replacement of crop-removed P (Kamprath, 1999). Much of the available data on change in P balance and associated effects on soil-test P are based on arable crops (Sharpley and Rekolainen, 1997), with less information from field trials on grassland soils. Our objective was to evaluate the balance between fertiliser-P input and P offtake in grassland herbage and its effect on sustainability and depletion of available soil P, and on herbage production i.e. dry matter (DM) yield, for a range of soil series, P inputs and soil-test P categories.

Materials and Methods

Initially, 32 field sites were selected for this study over the 4 years (1997 to 2000). They consisted of four sites, with a range of soil-test P, on each of eight soil series or associations. Four of the soils are of limestone parent material (soils 30, 33, 34, 39) and four are from non-limestone parent material (soils 14, 22 and soil associations 13 and 15) (Gardiner and Radford, 1980). Mean clay concentration (g/100 g) varied from 18 and 19 for soils 13 and 30, respectively, to 41 for soil 39; values for other soils were in the range 21 to 28. Depth of the A1 soil horizon typically varied between 25 and 40 cm, except for the shallow soil 33 (9-cm depth). The soils are described in Table 1. The soil pH range of the non-limestone and limestone groups did not differ markedly, because pH at the 0 to 10-cm depth was affected by agronomy, i.e. fertiliser and lime use, as opposed to parent material.

Sites were categorised according to Morgan P and assigned to low and high index groups by combining the normal index categories 1 and 2 (0 to 3.0 and 3.1 to 6.0 mg/l P) and 3 and 4 (6.1 to 10.0 and >10 mg/l P), since there were insufficient sites for analysis of variance within individual categories for all soil series. One site was subsequently omitted, to give a total of 124 site years, because of on-site problems. Sites were selected on swards from which silage harvests had been taken and which

Table 1. Classification and characteristics of the soils

Series/association[†]	Soil series	Parent material	Drainage	pH range	Location
Association-13	13	Sandstone-limestone diamicton	Well drained	5.0–6.4	Waterford
Clonroche	14	Ordovician shale diamicton	Well drained	5.8–6.5	Wexford
Association-15	15	Sandstone-shale diamicton	Well drained	5.7–6.6	Cork
Castlecomer	22	Upper Carboniferous (Silesian) shale diamicton	Poorly drained	5.2–6.0	Kilkenny
Baggotstown	30	Calcareous fluvio-glacial gravel	Well drained	5.6–6.9	Offaly
Kinvara	33	Limestone diamicton (shallow)	Well drained	5.6–7.3	Galway
Elton	34	Limestone diamicton	Well drained	4.8–6.5	Tipperary
Howardstown	39	Limestone diamicton	Poorly drained	4.9–6.3	Limerick

[†]Source: Gardiner and Radford (1980)

were free from clover. The project comprised part of a separate large-scale experiment where plots were re-randomised on a new location within each site each year to calibrate soil tests with the optimum fertiliser P for grass production. For the present study, selected plots from year one (1997) were maintained to evaluate changes in P balance and provide a more extended measure of input-offtake relationships. For this, the plots were given repeated annual applications of P similar to their 1997 treatment. The treatments were two replicates of 20 kg P per ha (P_{20}) and 40 kg P per ha (P_{40}) annually, a once-off application in year one of 60 kg P per ha (P_{60}), and two replicates of a zero P control (P_0). The experimental inputs of P were applied at various dates in February each year, generally within a 2-week period. Basal fertiliser inputs (kg/ha) were applied in February and after each harvest. Total annual basal inputs varied in successive years, as follows: N 290, 150, 200 and 200; K 300, 300, 380 and 380; S 54, 28, 37 and 37. In 1997, basal inputs were aligned with those of the main experiment. In 1998, it was decided to reduce the N input, to which the S was linked, to facilitate comparison with the lower levels of offtake found in grazing trials. Inputs were revised upwards, subsequently, because 1998 yields were deemed inadequate.

Herbage was cut four times annually at each site to a height of *ca.* 6 cm on duplicate plots of 8 m × 1.5 m. Cuts 1 and 2 were combined in one instance (soil 22, low index group, 1998) because of difficulty of access on the impermeable soil. Also, one site was cut three times only, because animals accessed the site prior to one cut (soil 14, low index group, 2000). In all cases, herbage yields were combined to give a value for total annual production. DM (%) was determined by drying at 100 °C for 16 h. The sample was ground to less than 1 mm for Kjeldahl digestion, and P concentration was determined by measuring the colour of the phosphate-molybdate-vanadate complex at 420 nm (Byrne, 1979). DM yield (t/ha), P offtake (= uptake) (kg/ha) and P balance (kg/ha) were calculated. A composite soil sample (20 subsamples) was taken from the experimental area in spring 1997, at the beginning of the trial, and subsequently from individual plots each October. All samples were taken at the standard 10-cm depth used in soil testing with a core sampler (diameter 3.5 cm in spring 1997 and 1.5 cm subsequently). Prior to analysis, soils were dried at 40 °C. Available soil P was measured after extraction for 30 min at 180 rpm using Morgan's solution at a ratio of 30 ml to 6 ml of <2 mm soil (Peech and English, 1944).

The variables examined were P balance, Morgan P and DM yield. Morgan P and DM yield values were transformed using the natural logarithm to normalise the data. Due to the fact that the same plots were revisited each year, repeated measures ANOVA (SAS, 2001) was applied within the two index groups to reveal interactions between the factors, P treatment and soil series, over time. Combined analysis of results of relevant interactions are presented where the effects were significant. P recovery in herbage over 4 years was also calculated on the basis of the difference between cumulative P uptake in the control and each individual P treatment, and the values were analysed using PROC GLM of SAS (2001). The change in P balance per unit change in soil-test P (unit change ratio) was evaluated for each P treatment, both index groups, and soil groups categorised on the basis of limestone and non-limestone parent materials.

Results and Discussion

Statistical analysis demonstrated consistent two-way, but no three-way, interaction effects for P treatment × time and soil series × time on P balance, soil-test P and DM yield. The data from individual years were consistent in not showing a significant P treatment × soil interaction.

P balance

The magnitude and trends in P balances indicate the extent to which soil-P reserves may be enriched or depleted as a result of variation in either farm management or soil characteristics. In this study, depletion was the operative effect, since P input generally did not exceed offtake. Significant ($P < 0.001$) two-way interactions with time were observed for both P treatment and soil series. Irrespective of P treatment, there was a more negative P balance over 4 years in the high index group, consistent with higher uptake and availability of soil P (Table 2). Over the 4 years, the offtake in the P_0 treatment resulted in cumulative P balances of –99.5 and –143.5 kg/ha in the low and high index groups, respectively, which reflected cumulative DM yields of 38.5 *v.* 42.2 t/ha and mean P concentrations of 0.26 *v.* 0.34 g/100 g, respectively. These are comparable to changes in P balance observed elsewhere (Picone *et al.*, 2003), and provide an estimate of the availability and uptake of soil P for herbage production. The soil-P uptake on the P_0 plots declined significantly between 1997 and 2000 and, by 2000, was 65% and 75% of the 1997 value in the low and high soil-P index groups. In both groups, the cumulative P balance was similar in the P_{20} and P_{60} treatments over the first 3 years, when the cumulative P input was the same, indicating that any rapid initial adsorption of the higher once-off P input did not diminish its subsequent availability, as reflected in crop performance. This result may be consistent with the observation that slow formation of compounds rather than initial sorption by Fe and Al oxides, or other constituents, is responsible for the decrease in uptake and recovery of soil and fertiliser P in crops (Barrow, 1980), particularly where uptake in herbage is high compared with systems where long-term residual effects are observed (Malhi *et al.,* 2003). There was a substantial positive P balance only for the P_{60} treatment in the year of application. Overall, there were minimal effects on P balance in the P_{40} treatment in both index groups, which implies that this level of P input may generally approximate the maintenance requirement.

P balance varied widely in individual soils, and was in a higher range than noted in earlier work on grassland soils (Ryan and Finn, 1976), which had a higher frequency of very low-P responsive sites than reported here, or elsewhere (Tunney, Carton and O'Donnell, 1999). Generally, the more negative P balance values in the high compared with the low index group, when combined

Table 2. Effect of fertiliser P input (kg/ha) on P balance (kg/ha) combined over soil series†

Morgan-P index	Annual P input	Year				Cumulative balance
		1997	1998	1999	2000	
1+2	0	–31.7	–23.4	–24.0	–20.5	–99.5
	20	–15.7	–9.0	–13.6	–9.8	–48.1
	40	0.3	7.2	1.2	3.8	12.5
	60‡	18.7	–27.9	–27.2	–23.3	–59.7
3+4	0	–42.2	–33.9	–35.8	–31.5	–143.5
	20	–25.7	–18.3	–20.9	–17.2	–82.0
	40	–6.8	0.3	–4.1	–0.2	–10.7
	60‡	11.3	–37.2	–37.9	–32.9	–96.7

†LSD values for P treatment × time were 4.2 for index 1+2 and 3.3 for index 3+4.
‡Once-off application in 1997.

over P treatments (Table 3), reflected mean P concentrations of 0.38 and 0.31 g/100 g, respectively, and mean DM yields of 10.7 and 10.1 t/ha. Other than soil 22, which had very low values because of low yield and low P concentration, the range in P balance in the low group was from –38.3 kg/ha in soil 30 to –79.9 kg/ha in soil 33. However, there was no evident effect of soil parent material. In contrast, non-limestone soils had consistently more negative values than limestone soils in the high index group, although initial Morgan P was broadly comparable in both, possibly indicative of the effect of other soil constituents (Sample, Sopher and Racz, 1980). Values were generally negative for all soil series, showing that offtake was greater than applied P averaged over the range of P inputs. The wide range in values is indicative of the widely-contrasting effects of inputs and offtakes between soils.

Soil-test P

Soil-test P can be expected to decline in the absence of fertiliser P input, although the

Table 3. Effect of soil series on P balance (kg/ha) combined over P inputs†

Morgan-P index	Soil series	Year				Cumulative balance
		1997	1998	1999	2000	
1+2	13	–5.7	–18.0	–17.8	–13.2	–54.8
	14	–8.9	–14.3	–14.9	–10.7	–48.9
	15	–6.6	–17.3	–20.8	–21.1	–65.8
	22	–0.3	1.1	–6.4	–1.9	–7.6
	30	–4.3	–12.4	–15.6	–5.9	–38.3
	33	–16.8	–16.2	–22.9	–24.0	–79.9
	34	–7.0	–15.7	–12.9	–10.1	–45.7
3+4	13	–24.0	–31.0	–29.3	–25.2	–109.4
	14	–16.5	–25.9	–30.7	–21.8	–94.8
	15	–12.2	–27.2	–31.0	–32.1	–102.6
	22	–18.5	–22.5	–26.1	–21.9	–89.0
	30	–11.1	–17.4	–21.0	–6.2	–55.6
	33	–13.9	–17.2	–21.4	–18.2	–70.8
	34	–15.2	–23.2	–22.2	–24.9	–85.5
	39	–15.4	–13.7	–15.7	–13.3	–58.1

†LSD values for soil series × time were 6.5 for Index 1+2 and 5.0 for Index 3+4.

extent of decline is likely to reflect the initial P status. Figure 1 shows the change in P_0 plots after 4 years. It is evident that the magnitude of change was greatest where initial Morgan P was high. For example, initial levels of 10 and 20 mg/l would decrease by approximately 6.2 and 12.7 mg/l P in 4 years if no fertiliser P was applied. Expressed as Olsen P, on the basis of a conversion equation for the same range of grassland soils (Herlihy, M., unpublished), the decrease as a proportion of the relevant P balance, –143.5 kg/ha (Table 2), is 6% and 13%, respectively. This compares favourably with a value of 8% for a corresponding P balance of –153 kg/ha over 13 years, based on Olsen P in the UK (Johnston, Poulton and Syers, 2001). Generally, the relationship reflects what might be expected in terms of abatement of soil-P levels following increase due to loadings of high-P wastes or other products. Although these changes are broadly indicative of the potential for decline in soil P, more specific information is required for the effects of variation due to P treatment and soil series.

Figures 2 and 3 show the trends in soil-test P over 4 years with respect to differences in P treatment and soil series, respectively, for the two index groups. In both groups, significant two-way interaction effects ($P < 0.001$) with time were observed for P treatment and soils, and soil P decreased in the order $P_0 > P_{60} > P_{20} > P_{40}$ over the 4 years. The once-off P_{60} input caused an initial increase in the first year (Figure 2), but its subsequent decline was more comparable with the P_0 control than with other levels of input. There was no significant decrease in soil-test P for the P_{40} treatment in either group, although there was a declining trend in the high index group. High soil-test-P levels may not be maintained by annual replacement of P offtake, because of possible chemical conversion of fertiliser P to unextractable forms (Kamprath, 1999), or losses to surface and groundwater. In contrast, replacement may be more effective at sites of lower soil P (McCollum, 1991).

Generally, soil-test P declined more rapidly in the high index group, in agreement with the findings of Barber (1979). Combined over the range of soils in our study, Morgan P of 4.3 and 12.6 mg/l, in the low and high groups, respectively, decreased to 1.7 and 4.4 mg/l after 4 years of cutting with no fertiliser application (P_0). The corresponding cumulative P balances were –99.5

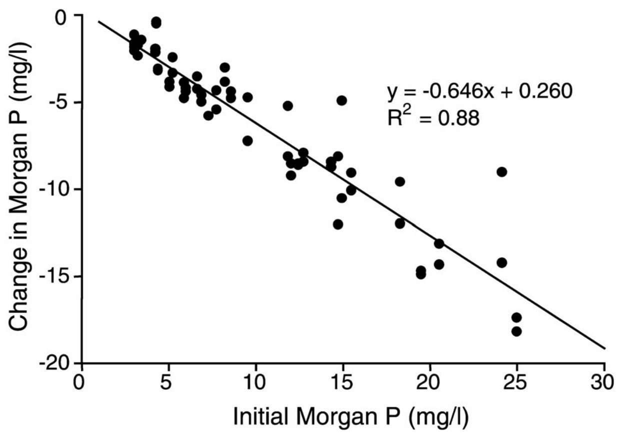

Figure 1: Relationship between initial Morgan P (x; Spring 1997) and the change (1997 to 2000) in Morgan P (y) in the absence of fertiliser P.

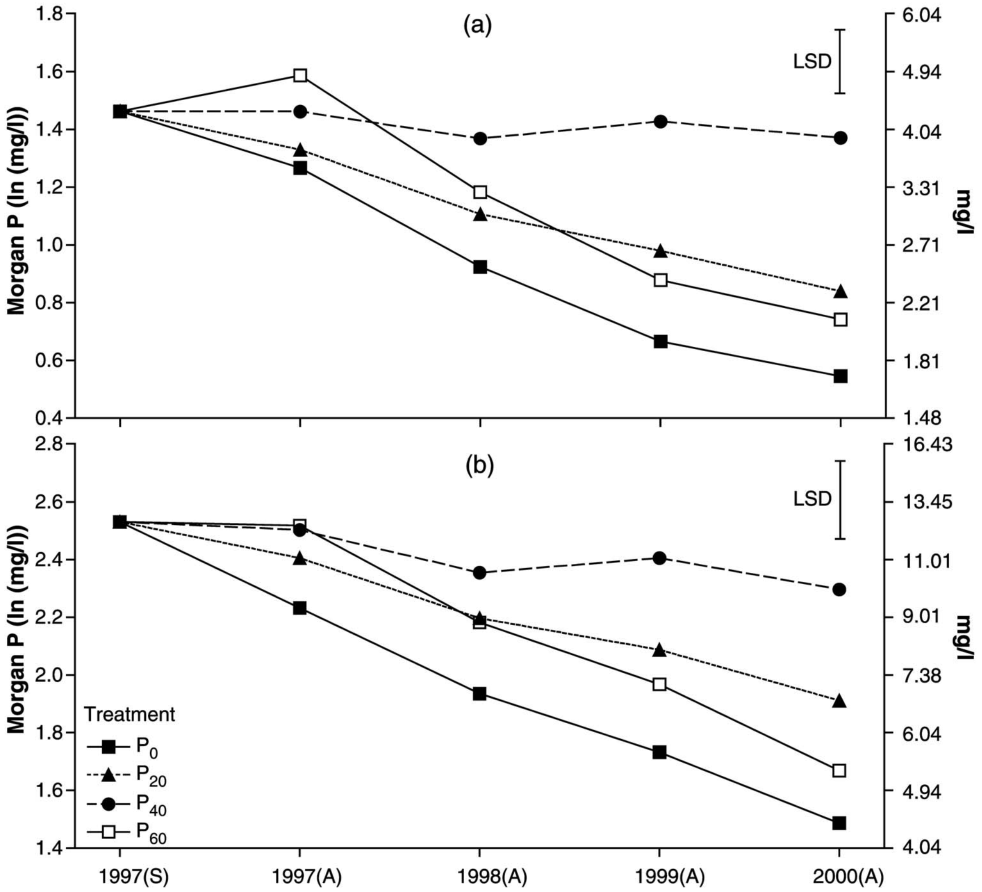

Figure 2: Variation in Morgan P (mg/l) with P treatment and time (S = spring; A = autumn): (a) Index 1+2 (LSD 0.2), (b) Index 3+4 (LSD 0.3).

and –143.5 kg/ha (Table 2). There were progressively smaller decreases in soil P with increased levels of fertiliser input. With the once-off 60 kg/ha P application, soil-test values decreased to 2.1 and 5.3 mg/l in the low and high index groups, with cumulative P balances of –59.7 and –96.7 kg/ha, respectively. When P was applied annually at 20 kg/ha, soil-test P decreased to 2.3 and 6.7 mg/l in the low and high index groups, respectively, with corresponding cumulative P balances of –48.1 and –82.0 kg/ha. There was effectively no decrease in soil P over the 4 years on the P_{40} treatment in the low index group, with a small positive P balance of 12.5, consistent with other results (Schmidt *et al.*, 1997) and with results in grazed grassland over 30 years when input marginally exceeded animal offtake (Culleton, Coulter and Liebhardt, 2002). Others (Tunney *et al.*, 1999) have shown that annual inputs of 40 to 50 kg/ha maintained Morgan P over 10 years in loams with soil-test P of 5 to 11 mg/l, but levels were halved in a sandy loam with an initial soil-test P of 40 mg/l. The cumulative P balance for P_{40} in the high index group was –10.7 kg/ha with a trend in soil P from 12.6 to 9.9 mg/l, which was not significant.

Soil-test P declined over time for all soils

(Figure 3), except for soil 22 in the low index group. The mean decline over all soils was 3.2 and 9.0 mg/l in the low and high index groups, respectively, consistent with other observations (Barber, 1979; McCollum, 1991). Limestone soils had the most consistently rapid decline in the low group, with decreases of 65%, 59% and 55% in soils 33, 34 and 30, respectively. Although soil 33 had the most negative P balance (–79.9 kg/ha, Table 3), and a sharp decline in soil-test P, the decline was not always consistent with the magnitude of the change in P balance. Soil 22 sustained P levels, with minimal changes in P balance (–7.6 kg/ha, Table 3). However, soil 30 had relatively low P-balance changes also (–38.3 kg/ha), but depleted rapidly in soil-test P, from 3.9 to 1.8 mg/l over the 4 years (55% decrease). Of the non-limestone soils, the relatively smaller decline in soil-test P for soil 14, from 3.2 to 2.3 mg/l (30%), is consistent with anecdotal observations of its slow reaction to P inputs. There was no evident effect of soil texture, but the magnitude of decline in the various soils was consistent with lower buffering in the limestone soils and with soil 14 having the highest buffering capacity of all the soils (McGrath, D. and Herlihy, M., unpublished). Although the soil series × time interaction was also significant for the high index group, the decline in soil P was more broadly comparable between soils. These trends reflect the combined P treatment effects (18.75 kg/ha P), whereas more usually no P is applied to high P soils. Consequently, we also determined the effects where no P was applied. In this case there was no soil series × time interaction, and mean soil P decreased from 12.6 to 4.4 mg/l, compared with 12.6 to 6.3 mg/l in the combined treatment (Figure 3).

Cumulative effects

There has been much emphasis on the environmental impact of excessive build up of P, and its implication for P application. However, it is also essential from an agronomic viewpoint to monitor change in soil-test P over time for various levels of P input. At low index levels, in particular, depletion of P is undesirable if it impacts on production, because of the associated low environmental risk. Although annual trends in soil-test P can be informative, year-to-year change is often small and inconsistent (Kamprath, 1999), and may be difficult to detect, because of soil sampling and analytical errors (Gallagher and Herlihy, 1963). Consequently, the application of results from studies on P balance is enabled by aggregation of the quantitative effect on soil-test values over discrete time intervals. The advantage of measuring changes in soil P in long-term studies, in order to overcome risks of large annual fluxes, has been noted (Schmidt *et al.*, 1997). In farming practice, soil-test P is often monitored in the medium term by repeat sampling within a 3- to 5-year cycle. Determination of cumulative effects over a similar time-span results in more measurable change in soil-test P and its relationship with P balance.

For the current data, the change in P balance per unit change in soil-test P, i.e. unit change ratio, was evaluated for each P treatment and for both index groups (Figure 4). Generally, the ratio was significantly higher in the low compared with the high index group for non-limestone soils, and higher in non-limestone compared with limestone soils in the low group. Effectively, in the latter a large P offtake was required to reduce soil-test P, in the absence of fertiliser P. The relevant unit change ratios were 70:1 on non-limestone and 30:1 on limestone soils. In a grazed sward, P offtake in beef, over 30 years, induced comparable levels of change in soil-test P where no P was applied (Culleton *et al.*, 2002), which would result in ratios of 55 and 66 at low and high stocking rates, given the P offtake for beef and minimal loss to the environment. In the low

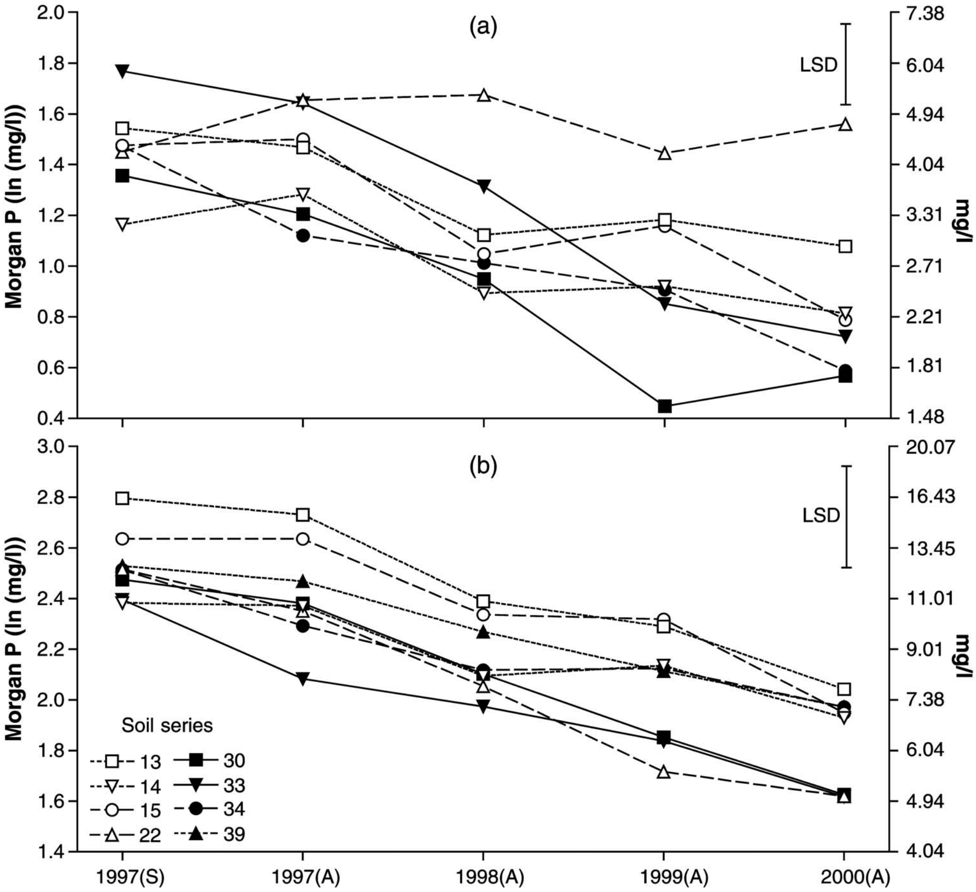

Figure 3: Variation in Morgan P (mg/l) with soil series and time (S =spring; A= autumn): (a) Index 1+2 (LSD 0.3), (b) Index 3+4 (LSD 0.4).

index group, the non-limestone soils had significantly higher ratios with all P inputs other than P_{40}, generally consistent with higher buffering in these shale- and old-red-sandstone-derived soils. The effect of the P_{20} and the once-off P_{60} treatments was to narrow the ratio, which would be expected with the enhanced availability of P. Differences due to soil parent material were not significant in the high index group. The P_{40} data were erratic, because this treatment was more closely matched to offtake, so that marginal differences could result in both positive and negative balances. Similarly, the P_{40} treatment had marginal effects, positive and negative, on the change in soil-test P, in contrast to more consistent effects where P input was limited.

Overall, the mix of ratios between parent-material groups and P treatments only partially supports the common assumption that inputs directly replace offtakes on all soils, one requirement of which is that soils behave similarly in terms of P fluxes that involve simultaneous input and offtake. The indication that it may have some validity for soils of high P status may be concealed, however, by the size of the available pool in such soils, which mitigates the effects of different bonding energies. Also, in the more simple system

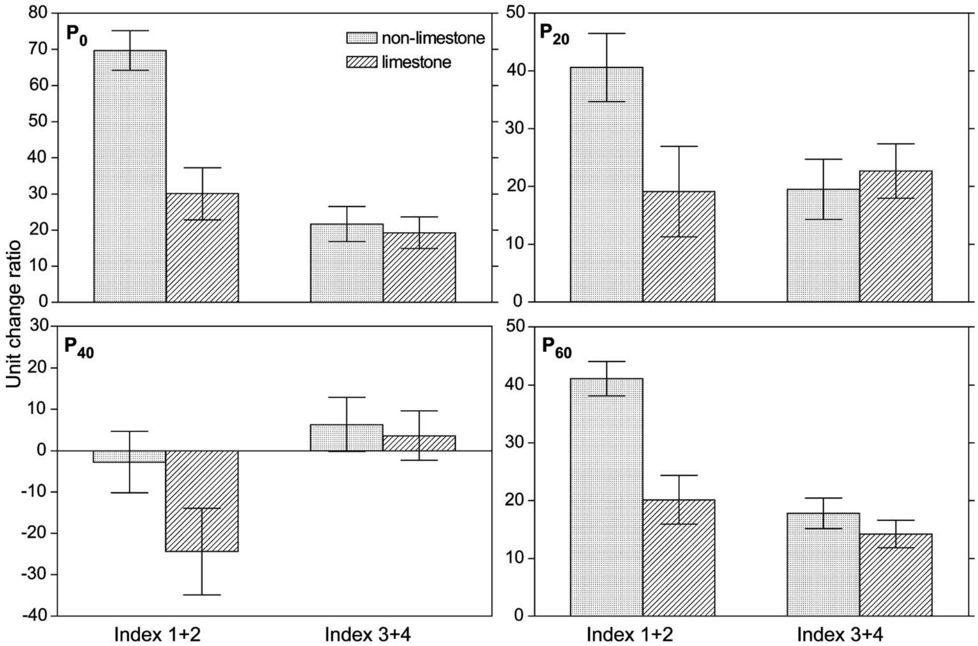

Figure 4: Variation in the unit change ratio (change in P balance per unit change in soil-test P (1997 to 2000)) with P treatment and P index.

of build-up of P in the absence of concurrent offtake, large differences between soils were evident in the input needed to increase soil-test P, irrespective of P status (Power, 1992).

Effects on herbage production and P recovery

Ultimately, changes in nutrient balance and soil-test P need to be assessed in terms of their effect on production, especially where the soil-P status is depleted and unlikely to be a risk to the environment. Combined analysis of sites within soil series showed only a significant interaction effect of P treatment with time ($P < 0.01$) for the low index group. The results indicated no response to P within years, rather a difference in yield between years, probably because of different levels of basal N applied. In any case, combined analysis of sites within soil series is not necessarily indicative of variation between individual sites, given the wide scatter in response to P observed at similar soil-test levels (Herlihy *et al.*, 1996). Consequently, we also tested the effects of P treatment within sites, particularly to determine the sustainability of DM yield in the context of the significant decline in soil-test P (Figures 2 and 3). On this basis, there was no DM yield response to P in 1997. In 1998, one site (site 24) gave a DM yield response to P, although anomalously, with Morgan P of 19.8 mg/l, and subsequently gave no response. The results in Table 4 for the end years of the experiment (1999 and 2000), and the relevant preceding autumn soil tests, provide a measure of the sustainability of herbage production as Morgan P progressively declined from the levels observed in spring 1997.

Although Morgan P (mg/l) was ≤3.0 in 10 sites in autumn 1998 and 3.1 to 6.0 in 9 sites (corresponding numbers were 12 and 9 in autumn 1999), only five sites in each of the following years gave a significant response to

Table 4. Effect of P treatment on herbage production (dry matter (DM) yield) in 1999 and 2000

Morgan-P index†	Soil series	Site no.	Morgan P (mg/l, P_0 treatment)			DM yield (t/ha) 1999				F-test	DM yield (t/ha) 2000				F-test
			Spr‡ 97	Aut‡ 98	Aut‡ 99	P_0	P_{20}	P_{40}	P_{60}		P_0	P_{20}	P_{40}	P_{60}	
1+2	13	1	5.2	2.2	2.6	11.4	11.1	10.3	11.8		8.4	9.8	9.4	8.5	
		2	4.2	2.6	2.6	9.4	10.1	10.2	9.3		10.1	10.6	10.1	10.0	
	14	5	3.4	2.2	2.0	8.9	10.7	10.3	9.7		9.9	11.3	11.1	10.0	
		6	3.0	2.3	1.9	10.3^{b}	10.7^{c}	10.8^{c}	9.9^{a}	*	7.8	7.5	7.8	8.2	
	15	9	3.2	1.4	1.6	9.9	11.0	10.7	10.8		10.3	11.2	12.3	11.4	
		10	6.0	2.8	2.8	11.3	12.0	12.2	11.7		12.2	12.9	13.2	12.7	
	22	13	4.3	4.3	3.3	7.0^{a}	8.7^{c}	8.9^{c}	7.6^{b}	**	6.1^{a}	8.9^{c}	9.0^{c}	7.0^{b}	***
	30	17	3.0	1.9	0.8	9.3	10.3	10.8	10.1		7.6^{a}	10.2^{c}	9.6^{c}	8.4^{b}	**
		19	5.0	1.9	1.0	9.7^{a}	10.4^{c}	10.4^{c}	10.0^{b}	**	9.5	10.3	10.8	9.2	
	33	21	5.9	3.1	1.8	9.9	10.9	11.1	10.3		12.3	13.2	13.5	12.6	
	34	25	4.4	2.5	2.1	9.5	10.3	10.2	9.5		8.9^{a}	10.3^{b}	10.9^{c}	8.8^{a}	***
3+4	13	3	14.7	8.9	6.9	12.4	12.3	12.2	12.8		11.8	11.1	11.7	12.4	
		4	18.3	10.4	9.8	11.1^{bc}	10.6^{b}	11.3^{c}	10.0^{a}	*	9.6	9.5	9.5	9.4	
	14	7	8.2	4.9	5.1	11.8	12.1	12.4	12.1		12.1	11.7	11.7	12.1	
		8	14.3	9.1	7.6	10.6	10.5	10.7	12.4		11.2	10.1	10.7	11.2	
	15	11	9.5	6.1	6.2	13.2	13.2	12.3	12.8		13.3	14.1	12.9	12.8	
		12	20.5	12.9	10.1	10.5	10.5	12.4	11.3		12.4	11.8	12.1	12.8	
	22	14	12.7	7.4	4.8	10.0	10.8	10.7	10.1		11.4	12.6	11.6	12.4	
		15	12.0	4.8	3.3	9.2	9.5	10.3	9.4		10.5	11.2	11.2	11.0	
		16	12.4	5.9	4.4	12.1	11.9	11.6	12.1		14.1	13.0	12.8	12.8	
	30	18	7.3	2.3	1.4	9.5	9.9	10.1	9.9		8.9	10.1	9.5	9.3	
		20	19.5	11.0	8.6	8.8	8.8	9.2	8.4		7.7	8.4	8.2	7.5	
	33	22	7.7	5.1	4.4	9.4	10.3	10.4	10.1		9.8^{a}	10.4^{ab}	11.1^{c}	10.5^{b}	*
		23	6.9	3.2	2.5	9.4	9.6	10.3	10.3		10.1	11.8	11.8	10.2	
		24	25.0	13.7	9.8	10.4	10.0	9.7	10.1		11.3	11.7	11.9	11.3	
	34	26	11.8	6.9	5.6	11.2	12.1	11.5	11.3		12.9	14.4	14.1	13.3	
		27	6.6	4.2	3.4	11.2	9.9	10.5	10.5		12.4	12.2	12.3	12.2	
		28	24.1	13.2	16.1	10.1^{ab}	9.9^{a}	10.4^{b}	11.1^{c}	*	11.3	11.3	11.2	10.8	
	39	30	8.6	5.9	4.2	8.2	8.1	8.6	8.2		10.2	11.1	9.5	10.7	
		31	15.5	8.2	7.6	9.5	10.0	11.0	9.3		9.8^{a}	10.6^{a}	12.1^{a}	10.4^{a}	*
		32	14.9	12.7	9.7	8.5	8.9	8.5	7.5		7.9	9.2	8.6	9.3	

† Spring 1997. ‡Spr = Spring, Aut = Autumn.
abc Means, within a row, without a common superscript are significantly different.

P. Of the total of 10, two of the three that were then at higher soil-P levels (>6 mg/l) in fact gave no response to the annual P_{20} and P_{40} inputs, but differed inconsistently from the P_{60} treatment. No consistent pattern was evident across either soils or years, or between sites of contrasting levels of DM yield. It should be noted that basal fertiliser N was constrained in order to avoid excessive levels of P offtake, which were nonetheless high in the context of grazed swards. Consequently, DM yield does not necessarily reflect the production potential of the various soils, but it was generally similar to or exceeded that observed in previous studies (Tunney *et al.*, 1999), in one of which greater frequency of response was noted on sites that were of lower initial P status (Ryan and Finn, 1976). Others observed no effect on DM yield of withholding fertiliser P for 3 years on soils of moderate P fertility, and no significant change in P status, as indicated by the Olsen test (Withers *et al.*, 1999). These various results need to be interpreted in the context of the wide range of spatial, seasonal and sampling variation that imposes constraints on interpretation of soil-test values at the field scale (Herlihy *et al.*, 1996), and in terms of environmental thresholds. These latter are also qualified by a great deal of uncertainty, and cannot be defined in terms of a critical limit imposed by a specific soil-test value (Kurz *et al.*, 2004). However, there may be a critical limit of Morgan P (Kleinman *et al.,* 2000), or other tests, beyond which the potential for loss of soluble P is accelerated.

Fertiliser P recovery in herbage over 4 years was calculated as the difference between cumulative P uptake in the control (P_0) and each individual P treatment. There was no significant effect of P treatment on recovery, or of a P treatment × soil series interaction, although effects of soil series and initial soil-P status were highly significant ($P<0.001$). Mean recovery was 33.1% in the low index group compared with 20.8% in the high group, over all soil series and P treatments (Table 5). The limestone soils tended to have higher recovery than non-limestone soils, consistent with the latter having buffering capacity values more than twice as high (McGrath, D. and Herlihy, M., unpublished). Overall, there was a wide range in values, from 19.4% to 47.5% and 11.6% to 32.9% in the low and high index groups, respectively. In the low group, recoveries were lowest in soils 13 and 14 (20.9% and 19.4%), and highest in soils 30 and 33 (47.5% and 46.5%). In the high group, less than 21% of applied P was recovered by soils 13, 14, 15, 34 and 39. Generally high P reversion has been noted on soils of high P status (Kamprath, 1999). More usually, crop recovery of 25% or less

Table 5. Effect of soil series on cumulative P recovery (%) in 2000†

Soil series	Morgan-P index	
	Index 1+2	Index 3+4
13	20.9	15.4
14	19.4	14.4
15	29.3	11.6
22	33.5	30.5
30	47.5	32.9
33	46.5	27.4
34	34.7	13.3
39	–	20.5
Mean	33.12	20.8

†LSD values were 20.9 for Index 1+2 and 14.8 for Index 3+4.

of fertiliser P is observed in the year of application (Read *et al.*, 1973), which increases with time to 40 or 50% (Halvorson and Black, 1985). Thus, many of our 4-year values may underestimate those attainable in the longer term, in the absence of further P inputs, i.e. by determination of residual effects.

Overall perspective

Although soil tests can be an imperfect basis for assigning P inputs, even in the short-term, they are also employed to monitor changes induced by soil and crop management over more extended periods of time. The observed changes in soil-test P may appear to be rapid, but are in agreement with those of other studies when related to the relevant crop and animal offtakes. Comparable changes in both P balance and soil-test P occur over a longer duration in grazed grassland, but measurements are difficult to replicate because of the time-scale and cost. Short-term studies on cut swards enable replication across soils, and the derived soil-test and unit change ratios provide a basis for extrapolation to grazed swards for which offtakes can be derived for a range of management and environmental conditions. The assumption that inputs directly replace offtakes (1:1) under all conditions may not be sustainable, given that our results showed that all soils do not behave similarly in terms of P fluxes that involve simultaneous input and offtake. The variability in response to P, following rapid depletion of soil-test P, also emphasises the lack of consistency between soils, and even between years for individual sites. The question is whether inputs can, or need to, replace offtakes, except in circumstances where the implied equilibrium may not be measurable in any case by soil tests. If such a strategy is employed, it likely provides only a crude approximation that needs regular monitoring of soil P. Alternatively, the proviso is that the input should be aligned with the optimum P established for a particular soil and soil-test value. Fertiliser P had no effect on herbage yield for many low-P sites on which a response might be expected. Confirmation of a similarly low proportion of responsive sites in specifically designed calibration-experiments is required to indicate whether agronomic needs can be achieved within environmental guidelines.

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