



SOIL ANALYSES AND COMPARISON OF SOIL PHOSPHORUS TESTS FOR THE BELLSGROVE CATCHMENT, CAVAN



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END OF PROJECT REPORT

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SUMMARY

The Bellsgrove catchment is located in the south-east of County Cavan, on the north-west border of Lough Sheelin and is approximately 9.2 km² in size. The Bellsgrove stream feeds into Lough Sheelin. Phosphorus loss from agricultural soils to water is perceived as an important water quality issue in the region.

① Soil P concentrations in the Bellsgrove catchment

Soil samples were sampled from 184 sites throughout the catchment to a depth of 10 cm. Mean soil Morgan P concentration in the catchment was 10.1 mg l⁻¹ which is slightly higher than the mean concentration of samples received at the soil testing laboratory at Johnstown Castle, *i.e.* 8.3 mg l⁻¹. 28.4% of samples were in soil P index 4. Soil P concentrations in index 4 are not of economic benefit to the farmer and represent relatively high potential risk of dissolved P loss from soils.

② Comparison of soil tests

Three procedures for extraction of soil P: Morgan (Na acetate + acetic acid, pH 4.8), Olsen (NaHCO₃, pH 8.5) and 0.01 M CaCl₂ solutions were compared. Soil P concentrations ranged from very low to very high (0.7 mg l⁻¹ to 405.2 mg l⁻¹ (Morgan test)). There was a linear relationship between Morgan P and 0.01M CaCl₂ P: $\text{CaCl}_2 \text{ P} = -0.66 + (\text{Morgan P} \times 0.235)$ [$r^2 = 0.97^{***}$]. However, the relationships between Morgan P and Olsen P and between 0.01 M CaCl₂ P and Olsen P were not linear: $\text{Morgan P} = 5.5 + (\text{Olsen P} \times -0.22) + (\text{Olsen P}^2 \times 0.008)$ [$r^2 = 0.94^{***}$]; $\text{CaCl}_2 \text{ P} = 1.48 + (\text{Olsen P} \times -0.088) + (\text{Olsen P}^2 \times 0.002)$ [$r^2 = 0.93^{***}$].

③ Comparison of P fertilizer recommendations

52 sites with a range of soil P concentrations were sampled to depths of 7.5 cm and 10 cm. In the comparison of these two sampling depths, there tended to be higher soil P concentrations in the samples taken to a depth of 7.5 cm compared to samples taken to a depth of 10 cm for each of the three soil tests although differences between the two sampling depths were very variable. Fertilizer P recommendations for grassland in the Republic of Ireland generally exceeded those of Northern Ireland at similar levels of soil P depending on the system of management.

④ Comparison of the ability of soil tests to predict plant available P

The three above soil testing procedures were correlated with perennial ryegrass dry matter (DM) yields and P uptake in the grass DM. 56 soils were selected on the basis of their Morgan P test results to give a range of soil P levels (2.5 to 33.8 mg l⁻¹). 200 g of each soil (dry weight) were weighed into plastic pots (9 cm surface diameter). Ten perennial ryegrass seeds were sown per pot in May. Herbage was harvested six times over the growing season at approximately three week intervals. Grass DM yields were significantly ($P \leq 0.001$) correlated with the three soil tests: Morgan, $r^2 = 0.786$; Olsen, $r^2 = 0.651$; CaCl₂, $r^2 = 0.569$. Total P uptake in the grass DM during the experiment was also significantly ($P \leq 0.001$) correlated with the results of the three soil tests: Morgan, $r^2 = 0.897$; Olsen, $r^2 = 0.817$; CaCl₂, $r^2 = 0.806$. Of the three soil P tests examined, the Morgan test best estimated the availability of soil P to perennial ryegrass .

⑤ Evaluating potential P loss from soil to water

This study was concerned with loss of dissolved P from soils in surface runoff from grassland soils. Loss of dissolved P takes place from the upper 3 mm of soil and therefore soil samples were taken from the upper 1 cm of soils and compared to concentrations of samples taken to the standard depth of 10 cm. The P concentrations of samples taken to a depth of 1 cm were substantially higher than the P concentrations of samples taken to a depth of 10 cm indicating

that much of the P in grassland soils is concentrated in the upper layers of the soil which increases potential risk of P loss. Soil Morgan P concentrations and P desorption were closely and linearly correlated when both analyses were carried out on samples taken to a depth of 1 cm ($r^2 = 0.95^{***}$). However, when the Morgan test results for samples taken to a depth of 10 cm were compared to P desorption in samples taken to 1 cm, this latter comparison resulted in a relatively lower r^2 value ($r^2 = 0.62^{***}$). Nevertheless, potential dissolved P loss at the soil surface increased with increasing soil Morgan P concentrations sampled to the standard depth of 10 cm. Background Morgan P concentrations (sampled to 10 cm) were around 2 to 2.5 mg l^{-1} , and at this level there was very little potential P loss. However, potential P loss, measured as P desorption, increased exponentially with increasing P sorption index. Therefore to minimise the potential risk of dissolved P loss from soils, soil P concentrations should be the minimum necessary to maintain optimum levels of agricultural production.

CONCLUSIONS

- Soil P concentrations in the Bellsgrove catchment were not greatly different from the average concentrations of samples received at Johnstown Castle soil testing Laboratory, although there were some samples with very high soil P concentrations.
- 28.4% of samples were in soil P index 4. Soil P concentrations in index 4 are not of economic benefit to the farmer and represent relatively high potential risk of dissolved P loss from soils.
- The Morgan and CaCl_2 tests were closely ($r^2 = 0.97^{***}$) and linearly correlated. However, the Olsen test was not linearly correlated with the Morgan test ($r^2 = 0.94^{***}$) or with the CaCl_2 test ($r^2 = 0.93^{***}$) indicating that the Olsen test tended to provide relatively lower estimates of soil P at the higher soil P concentrations
- P fertilizer recommendations for grassland, based on samples from the Bellsgrove catchment, were, in general, substantially higher in the Republic of Ireland compared to those in Northern Ireland.
- The Morgan test provided the best estimate of P availability to grass in terms of grass DM yield and P uptake in the grass DM over 6 harvests compared to the Olsen and CaCl_2 tests.
- Although the Morgan and CaCl_2 test results were closely correlated, this did not mean that one test could replace the other in terms of predicting P availability to grass.
- Soil P concentrations decreased with increasing sampling depth indicating that there was much higher levels of P concentrated in the upper 1 cm of soils compared to the 10 cm sampling depth.
- Soil P concentrations sampled to 1 cm were not very closely correlated with soil P concentrations sampled to 10 cm ($r^2 = 0.68^{***}$, Morgan test).

- The Morgan test results for samples taken to 10 cm do not provide a wholly accurate estimate of potential P loss at the soil surface because soil P concentrations of samples taken to the standard depth of 10 cm provides only a mediocre estimate of soil P concentrations at the soil surface.
- Nevertheless, potential dissolved P loss at the soil surface increased with increasing soil Morgan P concentrations sampled to the standard depth of 10 cm.

INTRODUCTION

Phosphorus (P) is an essential element for plant nutrition and its input is necessary to maintain profitable agricultural production. Phosphorus is generally added to agricultural soils as inorganic fertilizer or as organic manures. As there are generally no obvious adverse effects of high soil P concentrations on plant growth, farmers have frequently added P in amounts which exceed crop removal. This is particularly the case in regions with intensive pig, poultry or cattle production systems. As a consequence, P has accumulated in many intensively farmed agricultural soils (Tunney, 1990). In recent years, however, there is growing concern about phosphorus loss from agricultural soils to water and consequent eutrophication of surface waters. Eutrophication of lakes, associated with P enrichment, has become a problem in Ireland, and this includes many lakes which drain predominantly agricultural catchments (Clabby *et al.*, 1992; Gibson *et al.*, 1996). Attention is therefore being directed towards the contribution of P loss from agricultural soils to P in surface waters.

Generally, this loss of soil P in runoff is very small relative to total soil P reserves and P fertilizer inputs and is not of economic importance to the farmer. However, P is usually considered to be the nutrient which limits eutrophication in freshwater ecosystems. A critical P concentration for triggering eutrophic effects in lakes can be as low as 0.02 to 0.035 mg l⁻¹ (Vollenweider, 1975). Advanced eutrophication of surface water can lead to problems with its use for fisheries, recreation, industry, or drinking, due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by their senescence and decomposition (Sharpley and Rekolainen, 1997).

Therefore, reducing P loss from agricultural soils is of prime importance in controlling the accelerated eutrophication of fresh waters. This requires a greater understanding of how much P, in soil, is necessary for developing agricultural resource systems that can lead to a balance between agricultural production and environmental quality. Negative environmental effects are caused by

surface runoff from soils with high soil P levels (Sharpley, Sims and Pierzynski, 1994) and by leaching from P-saturated soils (Breeuwsma, Reijerink and Schoumans, 1995).

There is continuing concern over water quality in Lough Sheelin in Co. Cavan. The deterioration in water quality has coincided with large increases in catchment phosphorus (P) inputs arising from the general growth in agricultural output in the region since the 1970's. Phosphorus loss from agricultural soils to water is perceived as an important water quality issue in the region. The Bellsgrove catchment is located in the south-east of County Cavan, on the north-west border of Lough Sheelin and is approximately 9.2 km² in size. The Bellsgrove stream feeds into Lough Sheelin. This catchment was selected to study potential P losses from agricultural soils to water.

The specific objectives of the present study will be presented under the five following headings:

- ① Ascertain soil P concentrations in the Bellsgrove
- ② Compare soil P concentrations using three commonly used extracting solutions: Morgan, Olsen and 0.01 M Calcium
- ③ Compare fertilizer P recommendations in Ireland with
- ④ Evaluate the ability of the above three soil P tests to
- ⑤ Evaluate potential P loss from soils to water in the Bellsgrove catchment.

The present study was part of a more comprehensive project which involved drawing up a nutrient management plan for Co. Cavan with the objective of developing a spatial model using overlays of the factors relevant to stream phosphate concentration (rainfall, animal density, soils, land classification, soil nutrient levels, integrity of farmyard management facilities). This project was funded by InterReg through Cavan Co. Council.

SOIL P CONCENTRATIONS IN THE BELLSGROVE CATCHMENT

Soils of the Bellsgrove catchment

The soils in the catchment are predominantly Acid Brown Earths (75%) associated with Gleys (23%) and Peaty Gleys (2%). Topography generally is gently rolling with uniform slopes. The principle soil consists of a well-drained Acid Brown Earth of loam or clay loam texture. Base status is low to medium. The profile is characterised by a dark brown surface horizon about 30 cm deep, with a moderately strong medium crumb structure.

The principle associated soil is a ground water Gley with a clay loam texture and low to medium base status. At the surface there is a weak crumb structure, becoming massive at about 30 cm. Below this soil consistence is plastic and root penetration is poor. It occurs in the depressions and the poor drainage is due to the presence of a high water table and/or the heavy texture. Surface horizons have over 30% clay and 35% silt. The retentive nature of the sub-soil predisposes it to periodic water saturation (Gardiner and Radford, 1980).

Materials and Methods

Soil Sampling

Soil samples were collected from 184 sites selected at random on a 250 m² grid throughout the catchment to a depth of 10 cm during February and August 1996. Each site representing approximately 6 ha. Soil samples were taken from the field on which the point of an intersection of the grid occurred. If the field exceeded 3 ha, samples were taken in a 2 ha region under similar management, closest to the sample point. If a sample point fell on an unsuitable area (i.e. farmyard, road, river, lake, etc.) the soil sample was taken from the nearest representative 1 to 3 ha area in the field directly east of the sample point. One hundred cores were taken at random at each site (see: Byrne, Culleton and Coulter, 1996). After collection, soil

samples were placed in a forced draught oven and dried for 60 hours at 40 °C. Samples were rolled by hand, thoroughly mixed and passed through a 2 mm sieve. Soil P was extracted using Morgan, Olsen and CaCl₂ solutions. Soil Potassium (K) concentrations and soil pH levels were also measured.

Sampling depth

Fifty two selected sites were sampled to depths of 10 cm, 7.5 cm and 1 cm in August 1996. These sites were selected on the basis of having soil P concentrations ranging from very low (Morgan P sampled to a depth of 10 cm of approximately 1 mg l⁻¹) to very high (Morgan P sampled to a depth of 10 cm of over 80 mg l⁻¹). Twenty cores at both depths were taken at random at each site using the methods outlined by Byrne, Culleton and Coulter (1996). Morgan, Olsen and CaCl₂ P concentrations, for samples from the three sampling depths, were measured.

Results

Of the 184 sites sampled to a depth of 10 cm in this survey only one was cultivated, seven were under forestry and the remaining 176 sites were under grassland of varying degrees of intensity of agricultural production. The degree of intensity of production on these sites is likely to be reflected in the soil P concentrations recorded for each field sampled (Fig. 1).

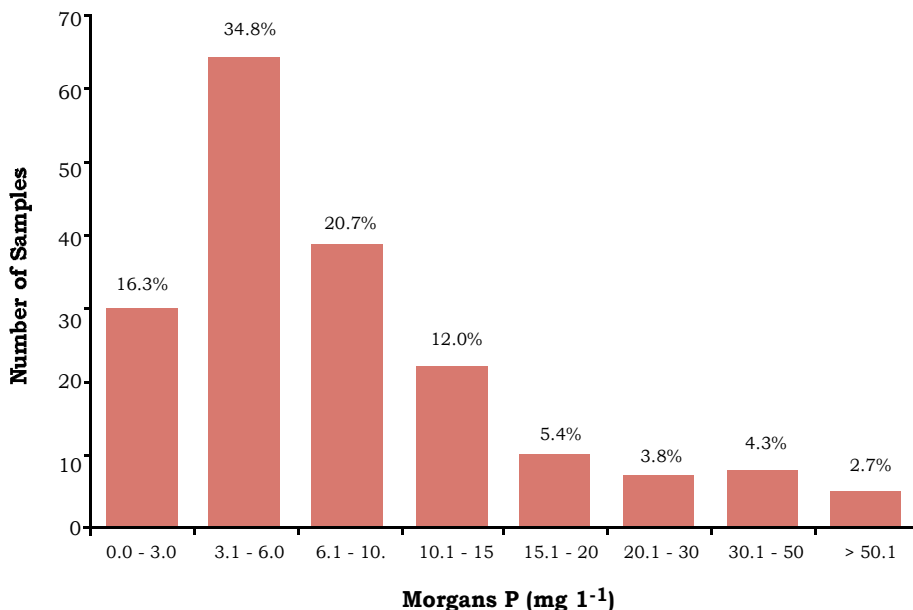


Figure 1. Distribution of soil P concentrations in the Bellsgrove catchment (n = 184)

Table 1. Teagasc index system (1 to 4) and actual Morgan soil test range for P and distribution of soil test P concentrations in the four Teagasc soil P indices and mean soil P concentrations in the Bellsgrove catchment compared to the National levels which are based on all soil samples received at Johnstown Castle.

Soil P	Index 1	Index 2	Index 3	Index 4	Mean soil P
(mg l ⁻¹):	0.0-3.0	3.1 -6.0	6.1 - 10	> 10	Concentration
	%	(%)	%	%	(mg l ⁻¹)
Bellsgrove Catchment	16.3	34.8	20.6	28.3	10.1
National Average	18	33	24	25	8.3

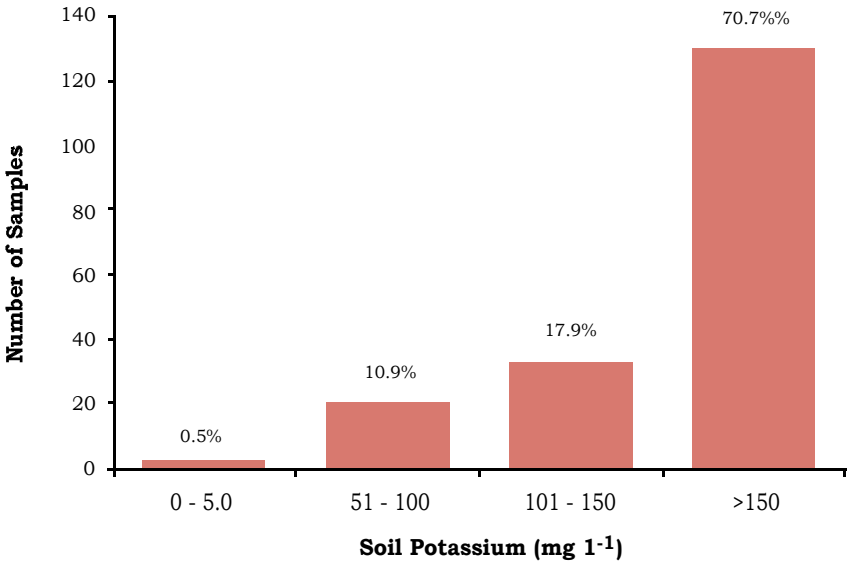


Figure 2. Distribution of soil K concentrations in the Bellsgrove catchment (n = 184)

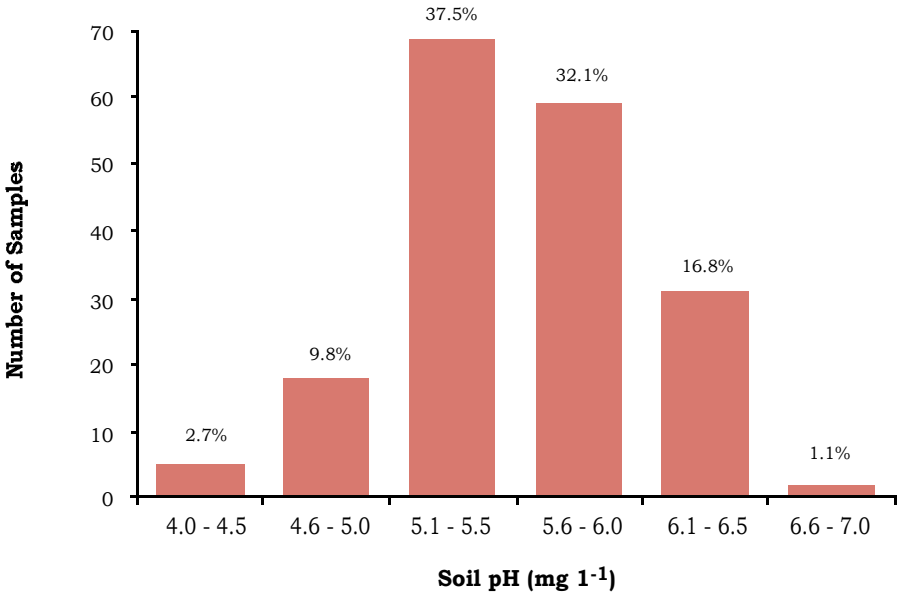


Figure 3. Distribution of soil pH levels in the Bellsgrove catchment (n =184).

There was a wide range of soil P concentrations recorded in the catchment (Fig. 1). Mean concentration was 10.1 mg l^{-1} which is slightly higher than the mean concentration of samples received at the soil testing laboratory at Johnstown Castle, *i.e.* 8.3 mg l^{-1} (Table 1). When classified in the Teagasc indices for soil P the distribution of samples in the Bellsgrave catchment was not greatly different from those received at Johnstown Castle (Table 1).

Soil K concentrations tended to be high with 70.7% of samples in Teagasc index 4 (Fig. 2), or in other words, in excess of that required for optimum production. In contrast, soil pH levels were low, only 17.9% of samples had soil pH levels between 6 and 7 (Fig.3), which is the optimum range for grassland production.

Discussion

The soils in index 4 have relatively high soil P concentrations. Such concentrations are not of economic benefit to the farmer. These sites are also likely to be more at risk of P loss from soil to water compared to sites in the lower index categories (Sharpley and Rekolainen, 1997).

COMPARISON OF SOIL TESTS

Introduction

There are more than 10 different extraction procedures used for estimating available soil P in the European Union (Tunney *et al.*, 1997). In Ireland, the Morgan P test (Morgan, 1941) has been used for almost 50 years, although it is the only country in Europe to use this test. A change was made from the Morgan test and other reagents to the Olsen test (Olsen *et al.*, 1954) in 1971 for England and Wales and in 1983 for Northern Ireland (Stevens, 1983). In the Netherlands recalibration of current fertilizer recommendations based on 0.01 M calcium chloride (CaCl_2) (Houba, Novozamsky and Temminghoff, 1994) is being investigated (Tunney *et al.*, 1997). One of the objectives of the present study was to compare the results of these three procedures for measuring soil P concentrations.

It is very difficult to estimate the ability of soil to supply plant available P due to the complex nature of soil P (Simonis and Setatou, 1996). Using one extractant does not necessarily mean that the analytical results of one method will give similar results to a different soil test procedure. The main extractant properties and experimental factors which can vary are: pH, nature and concentration of anions and cations, temperature, period of extraction, and the extractant to soil ratio (Williams and Knight, 1963; Houba, Novozamsky and Temminghoff, 1994). Various tests often result in widely different amounts of P extracted primarily due to their ability to dissolve different forms of soil P (Sen Gupta and Cornfield, 1963). Nevertheless, in comparing the three tests for soil P pointed out above, the hypothesis is that these three tests will provide comparable estimates of soil P concentrations, although the quantities measured may vary substantially.

Materials and Methods

The following comparison includes a total of 368 soil samples taken from the Bellsgrove catchment: 208 sampled to a depth of 10 cm, 52 sampled to a depth of 7.5 cm, 52 sampled to a depth of 1 cm and 56 soils which were depleted to low levels using perennial ryegrass in pots (see below).

Soil P concentrations were determined as follows:

Soil samples were extracted in a 1:5 (v/v) soil:solution ratio with a 10% sodium acetate buffered at pH 4.8 (Morgan solution): 6 ml of soil dried at 40°C was extracted using 30 ml of Morgan solution mechanically for 30 minutes at constant temperature (20 °C).

Soil samples were extracted in a 1:20 (v/v) soil:solution ratio with a 0.5 M sodium bicarbonate solution of pH 8.5 (Olsen solution); 4ml of dried soil was extracted using 80 ml of Olsen solution shaken mechanically for 30 minutes at constant temperature (20°C).

Soil samples were extracted in a 1:10 (v/v) soil:solution ratio with 0.01 M CaCl₂ solution; 4 ml of dry soil was extracted using 40.0 ml of 0.01 M CaCl₂ solution shaken mechanically for 2 hours at constant temperature (20 °C).

Following extraction with the above solutions, P concentrations in the extract were measured spectrophotometrically at 880 nm using the phosphomolybdate method (Murphy and Reilly, 1962). Concentrations were expressed on a soil volume basis (mg P l⁻¹ of dry soil).

Results

The range of P concentrations in soils ranged from very low to very high (Morgan P of 0.7 mg l⁻¹ to a Morgan P of 405.2 mg l⁻¹). There was a linear relationship between Morgan P and CaCl₂ P (Fig 3a). However, the relationships between Morgan P and Olsen P and between CaCl₂ P and Olsen P were not linear (Fig. 4b and 4c).

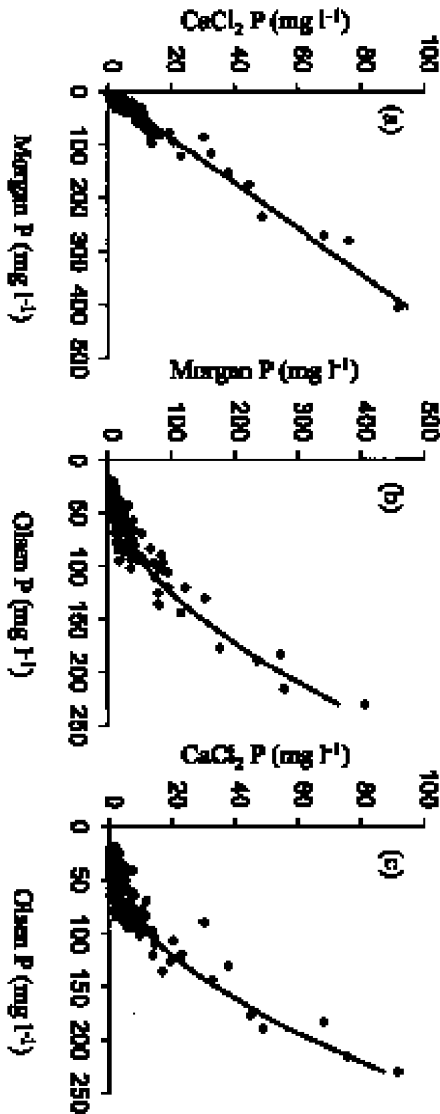


Figure 4. The relationship between (a) Morgan P and 0.01M CaCl₂ P test results, (b) Olsen P test and Morgan P test results and (c) Olsen P test and 0.01M CaCl₂ P test results (n = 368 in all cases). The best-fit regression equations were: (a) $y = -0.66 + 0.235 x$ ($r^2 = 0.97$, $P < 0.001$); (b) $y = 5.5 - 0.22 x + 0.008 x^2$ ($r^2 = 0.94$, $P < 0.001$); (c) $y = 1.48 - 0.088 x + 0.002 x^2$ ($r^2 = 0.93$, $P < 0.001$) where x = variable on abscissa and y = variable on ordinate axis.

Discussion

The linear relationship between CaCl_2 P and Morgan P indicates that both of these tests provide comparable results for the soil types examined in this experiment. In the UK, Williams and Cooke (1962) found that the Morgan and CaCl_2 tests tended to be closely correlated. The absence of a linear relationship between Morgan or CaCl_2 tests with the Olsen P test indicates that the Olsen test provided a comparatively low estimation of soil P levels at the higher soil P concentrations included in this study. The relationship between the CaCl_2 test and the Olsen test, presented in this study, is similar to that demonstrated by Johnston and Poulton (1993).

COMPARISON OF P FERTILIZER RECOMMENDATIONS

Introduction

Two soil tests are widely used by advisory services in Ireland. The Morgan test is employed by Teagasc in the Republic of Ireland while the Olsen test is used in Northern Ireland. The quantities of P fertilizer recommended for agriculture are recommended on the basis of an index of soil P concentrations which is usually divided into four or more categories such as described by Herlihy *et al.* (1996). The index system and recommendations for the Republic of Ireland were developed by Teagasc. The index system and recommendations employed in Northern Ireland were developed by the Ministry of Agriculture, Fisheries and Food (MAFF) in England, Wales and Northern Ireland. An objective of the present study was to compare P fertilizer recommendations for grassland in the Republic of Ireland with those of Northern Ireland.

While the difficulties in comparing soil tests are pointed out in section 2, the comparison of fertilizer recommendations is further complicated by the fact that soil samples are taken to a depth of 10 cm in the Republic of Ireland while samples are taken to a depth of 7.5 cm in Northern Ireland. Murphy and Culleton (1997) demonstrated that, in Irish grassland soils, the soil P concentrations tended to decline with increasing depth in the soil profile. The comparison of fertilizer P recommendations for grassland presented here is therefore concerned with two sources of variation: (1) the two soil P tests (Morgan and Olsen); (2) the two sampling depths (10 cm and 7.5 cm). These two sources of variation impact upon the estimation of plant available P and hence on fertilizer recommendations. These issues are examined in this study.

Materials and Methods

The comparison of P fertilizer recommendations involved 52 soil samples, described in section 1.2., which were sampled to depths of both 10 cm and 7.5 cm. The Morgan test values of the 52 samples sampled to a depth of 10 cm were classified into the Teagasc Index System (Table 2) and quantities of recommended P fertilizer were allocated for the following:

- ① Pre-1996 grazing recommendation (Gately, 1994);
- ② 1996 dairy grazing 2.5 LU ha⁻¹ full utilization required (Culleton *et al.*, 1996)
- ③ 1996 dairy grazing 2.0 LU ha⁻¹ full utilization required (Culleton *et al.*, 1996)
- ④ 1996 dairy grazing 2.0 LU ha⁻¹ full utilization not required (Culleton *et al.*, 1996)
- ⑤ Pre-1996 two-cut silage recommendation (Gately, 1994);
- ⑥ 1996 two-cut silage where cattle slurry is recycled (Tunney *et al.*, 1996);
- ⑦ 1996 two-cut silage where cattle slurry is not recycled (Tunney *et al.*, 1996).

The total quantities of P which would have been recommended by Teagasc in the Republic of Ireland for the 52 samples for each of these seven situations were each individually summed and mean quantities for each recommendation were calculated.

Table 2. Teagasc Index system 1 to 4 and actual Morgan soil test range for P and quantities of fertilizer P recommended for grassland under a range of different management practices

Index	Soil P (mg l ⁻¹)	Number of samples	P fertilizer recommendations (kg P ha ⁻¹)						
			Grazing situations*				Silage situations ^o		
			(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	0.0 - 3.0	14	40	33	30	20	70	20	50
2	3.1 - 6.0	17	30	22	20	12	55	10	40
3	6.1 - 10.0	7	20	13	10	0	45	0	10
4	>10.0	14	0	0	0	0	35	0	0

* (1) Pre-1996 grazing recommendation; (2) 1996 dairy grazing 2.5 LU ha⁻¹ full utilization required, (3) 1996 dairy grazing 2.0 LU ha⁻¹ full utilization required, (4) 1996 dairy grazing 2.0 LU ha⁻¹ full utilization not required;

^o (5) Pre-1996 two-cut silage recommendation, (6) 1996 two-cut silage where cattle slurry is recycled, (7) 1996 two-cut silage where cattle slurry is not recycled.

Similarly the Olsen test values of the 52 sampled to a depth of 7.5 cm were classified in the MAFF index system (Table 3) and quantities of recommended P fertilizer were allocated using this latter index (MAFF, 1994) for:

- (8) Grazed swards;
- (9) Multi-cut silage systems.

The total quantities of P which would have been recommend in Northern Ireland for the 52 samples for both of these situations were, similar to above, summed and mean quantities were calculated. These latter mean grazing re2commenda2tions were then compared to the relevant above mean Republic of Ireland fertilizer P recommendations.

Table 3. MAFF Index system 0 to 5 and actual Olsen soil test range for P and quantities of P recommended for grazing and multi-cut silage (from MAFF, 1994)

Index	Soil P (mg l ⁻¹)	Number of samples	P fertilizer recommendations (kg P ha ⁻¹)*	
			Grazing	Multi-cut Silage
0	0.0 - 9.5	6	26.2	65.2
1	9.6- 15.5	5	17.5	39.1
2	15.6 - 25.5	13	8.7	21.7
3	25.6 - 45.5	13	0.0	21.7
4	45.6-70.5	9	0.0	0.0
5	70.6- 100.5	5	0.0	0.0

*The levels of P fertilizer recommended by MAFF is usually expressed as diphosphorus pentoxide (P₂O₅) whereas the Teagasc recommendations are presented as elemental phosphorus (P). The MAFF recommendations were converted to elemental phosphorus (P) by multiplying by 0.4346 to facilitate comparison.

Results

Sampling depth

In general there tended to be higher soil P concentrations in the samples taken to a depth of 7.5 cm compared to samples taken to a depth of 10 cm for each of the three soil tests. The relationships between soil test results of samples taken to a depth of 10 cm and 7.5 cm are presented in Figure 5.

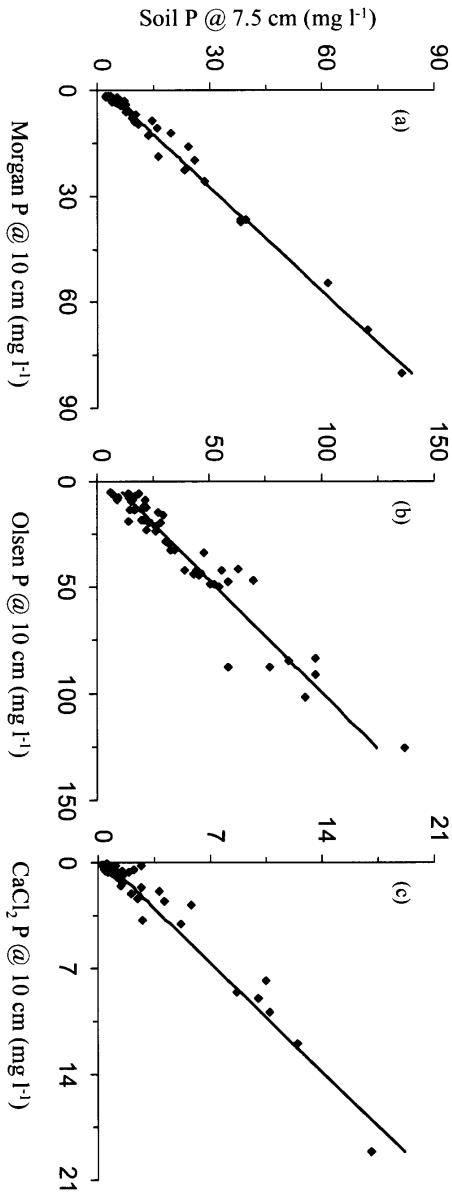


Figure 5. The relationship in soil P concentrations between soil sampled to a depth of 10 cm and 7.5 cm for (a) Morgan P, (b) Olsen P and (c) 0.01M CaCl₂ P. The best-fit linear regression equations were: (a) $y = 2.08 + 1.02 x$ ($r^2 = 0.99$, $P \leq 0.001$); (b) $y = 6.24 + 0.94 x$ ($r^2 = 0.92$, $P \leq 0.001$); (c) $y = 0.56 + 0.97 x$ ($r^2 = 0.95$, $P \leq 0.001$) where x = concentration at 10 cm and y = concentration at 7.5 cm.

Comparison of soil tests

The mean quantities of fertilizer P for a number of grassland management practices which would have been recommended in the Republic of Ireland and in Northern Ireland for the 52 fields involved in this study are presented in Table 4. In all the grazing situations the Teagasc recommendations exceeded the Northern Ireland recommendations. The pre-1996 Teagasc grazing recommendation was 3.38 times that recommended in Northern Ireland. The lowest Teagasc grazing recommendation (1996 dairy grazing 2.0 LU ha⁻¹ full utilization not required) was 1.35 times higher than the Northern Ireland recommendation for grazed swards.

Table 4. The mean quantity of P fertilizer required by the 52 soil samples from the Bellsgrove catchment as would be recommended in the Republic of Ireland (ROI) and in Northern Ireland (NI)

Recommendations	kg P ha ⁻¹	Relative to NI (%)
ROI Grazing		
Pre- 1996 grazing recommendation	23.3	338
1996 dairy grazing 2.5 LU ha ⁻¹ full utilization required	17.8	259
1996 dairy grazing 2.0 LU ha ⁻¹ full utilization required	16.0	232
1996 dairy grazing 2.0 LU ha ⁻¹ full utilization not required	9.3	135
ROI Silage		
Pre-1996 two-cut silage recommendation	44.9	203
1996 two-cut silage where cattle slurry is recycled	8.7	39
1996 two-cut silage where cattle slurry is not recycled	27.9	126
NI Recommendations		
Grazed swards	6.9	
Multi-cut silage systems	22.1	

The magnitude of difference between recommendations was not as great in the case of the silage recommendations. The pre-1996 Teagasc two-cut silage recommendation was 2.03 times that of the Northern Ireland recommendation, while the 1996 Teagasc two-cut silage where cattle slurry is recycled was only 39% of the Northern Ireland recommendation. Where cattle slurry is not recycled to silage areas, the Teagasc recommendation was 126% of the Northern Ireland recommendation.

Discussion

The higher concentrations of P in soil sampled to a depth of 7.5 cm compared to 10cm in uncultivated grassland soils encountered in this experiment can be accounted for as follows: P extracted by plant roots from subsurface layers is transferred to the herbage which, either decomposes directly returning P to the soil surface, or is eaten by livestock and most of P is returned to the soil surface in dung. Application of P fertilizers and animal manures further compound the build up of P in the upper layers of soil.

In the present study, quantities of fertilizer which would have been recommended following classification in the relevant indices in both countries were compared. Although this approach helps to minimise the variation associated with soil test and sampling depth, the results of the comparison can only be interpreted in a general way. The present comparison of fertilizer recommendations indicates that fertilizer P recommendations in Northern Ireland were substantially lower than corresponding recommendations by Teagasc in the Republic of Ireland in the past. Some of the difference in recommendations may be attributed to differences in soil type between Ireland and England and Wales. However, there are many similarities between the soils of Co. Cavan in the Republic of Ireland and those in Northern Ireland. Teagasc has recently adopted newer and lower P recommendations for grassland. Nevertheless, at present time, the fertilizer P recommendations for grazed grassland in the Republic of Ireland examined in the present experiment can still be said to be substantially higher than those employed in Northern Ireland.

COMPARISON OF THE ABILITY OF SOIL TESTS TO PREDICT PLANT AVAILABLE P

Introduction

Different extractants are used to extract what is often referred to as plant-available phosphorus (P) from soil. Such extractants have been selected because, in the results from field experiments where soil P concentrations are relatively low, extracted P was reasonably well correlated with dry-matter yield and crop response to added fertilizer P. Such studies were presented by Gallagher, Ryan and Brogan (1961) in Ireland and Williams and Cooke (1962) in England, Wales and Northern Ireland.

The empirical results obtained with a particular chemical extract are only of value in diagnosing the P status of soils if they are correlated with uptake of P by crops (Sen Gupta and Cornfield, 1963). The practical usefulness of methods for evaluating soil P status is determined by their ability to predict crop yields and responses to P under field conditions. However, numerous interrelated factors effect the delivery and uptake of P and regulate plant growth in the field. These include soil properties and profile characteristics, pH, temperature, moisture, aeration, biological activity, nutrient levels and interactions, cultural practices, the nature of the crop, and pests and diseases. Variations in these factors can severely upset correlations between soil P values and crop performance. In pot experiments such variations are either minimised or largely eliminated and hence soil P values are known to correlate better with pot than field data (Williams and Knight, 1963; Simonis and Setatou, 1996). The most reliable soil test methods for P account for about 60% of the variance in the P responses in field experiments and about 80% in glasshouse experiments, when the plants are grown under optimum fertilization conditions with all nutrients except for P (Simonis and Setatou, 1996).

In the present experiment perennial ryegrass herbage production, the P content of herbage and P uptake by the herbage were compared with the Morgan, Olsen and CaCl_2 tests for soil P in a pot experiment. Perennial ryegrass herbage was harvested six times over a growing season in order to measure the slow release of P from

labile pools. This slow release P is not readily available but becomes available over to time to crops which grow over an extended period and are repeatedly harvested, such as grass.

Materials and Methods

This experiment had 14 treatments (soil P concentrations) and replicated 4 times. A total of 56 soils out of the above 184 were selected on the basis of their Morgan P test results, soil K concentrations and soil pH levels to give 14 sets of four soils with a range of soil P levels (Figure 6).

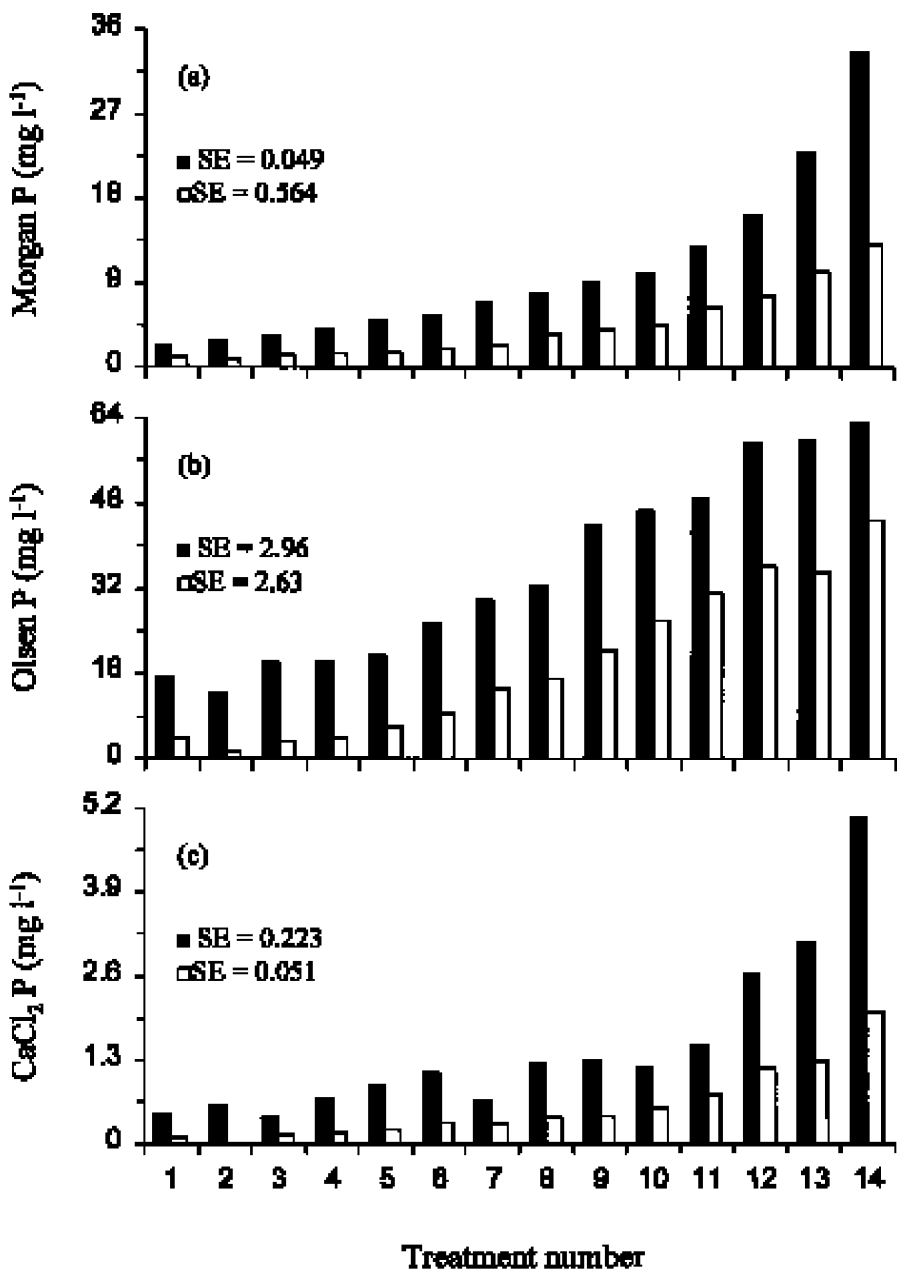


Figure 6. Mean soil Morgan (a), Olsen (b) and CaCl₂ (c) P concentrations at the beginning (■) and end (□) of the experiment.

200 g of each soil (dry weight) were weighed into plastic pots (9 cm surface diameter). Ten perennial ryegrass seeds were sown per pot (5 seeds c.v. Morgana and 5 seeds c.v. Talbot) on 10 May 1996. A nutrient solution of 1.56 g ammonium nitrate and 1.2 g calcium carbonate was made up to 3 l with distilled water and 50 ml was applied to each pot at regular intervals three times each week during June. During the remainder of the experiment a nutrient solution of 1.56 g ammonium nitrate and 0.72 g potassium nitrate was made up to 3 l with distilled water and 50 ml was applied to each pot at regular intervals three times each week. A second nutrient solution of 1.5 g magnesium sulphate dissolved in 3 l of distilled water was made up and 50 ml applied to each pot once a week throughout the experiment. All nutrient solutions were made up on the day of use during the experiment. Pots were also watered on a regular basis with distilled water as required.

Herbage was harvested as soon as it reached an average height of 15 cm across treatments. Herbage was harvested to a height of 4 cm on 24 June, 10 and 29 July, 26 August and 16 September and herbage was harvested level to the soil surface on 8 October (the final harvest). Herbage was dried at 100 °C for 16 hours and dry matter (DM) yields per pot were recorded.

At the end of the experiment the P content of herbage was determined for a sample of herbage from each of the 56 soils according to the methods described by Byrne (1979). Herbage from each treatment for all of the six harvests was bulked together, ground to pass through a 2 mm sieve and an aliquot was then taken to measure the P content of the grass DM. Total P uptake in grass DM was calculated by multiplying the P content of grass DM by the total grass DM yields for the six harvests throughout the experiment.

Results

Soil P concentrations, as measured following extraction using Morgan, Olsen and CaCl_2 solutions, at the beginning and end of the experiment are presented in Figure 6. Grass DM yields (Fig. 7), the P content of grass DM (Fig. 8) and P uptake in the grass DM (Fig. 9) were significantly ($P \leq 0.001$) correlated with the results of the three soil tests at the beginning of the experiment. For the three above parameters, the Morgan test gave higher r^2 values than the Olsen test. Both of these tests resulted in higher r^2 values than the CaCl_2 test.

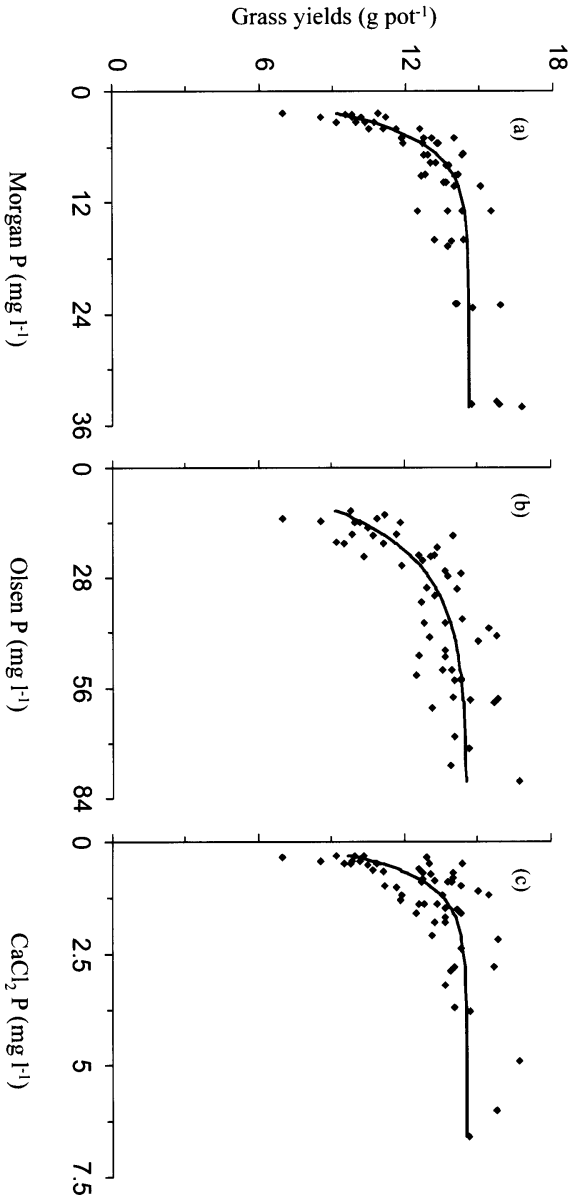


Figure 7. Grass dry matter production in relation to soil P concentrations at the beginning of the experiment: (a) soil Morgan P, (b) soil Olsen P and (c) soil CaCl_2 P. Lines are fitted using the following regression equations: (a) $y = 14.579 - 11.62 X 0.7269^x$ ($r^2 = 0.786$ $P < 0.001$); (b) $y = 14.557 - 12.04 X 0.9290^x$ ($r^2 = 0.651$ $P < 0.001$); (c) $y = 14.534 - 8.27 X 14.534^x$ ($r^2 = 0.569$ $P < 0.001$).

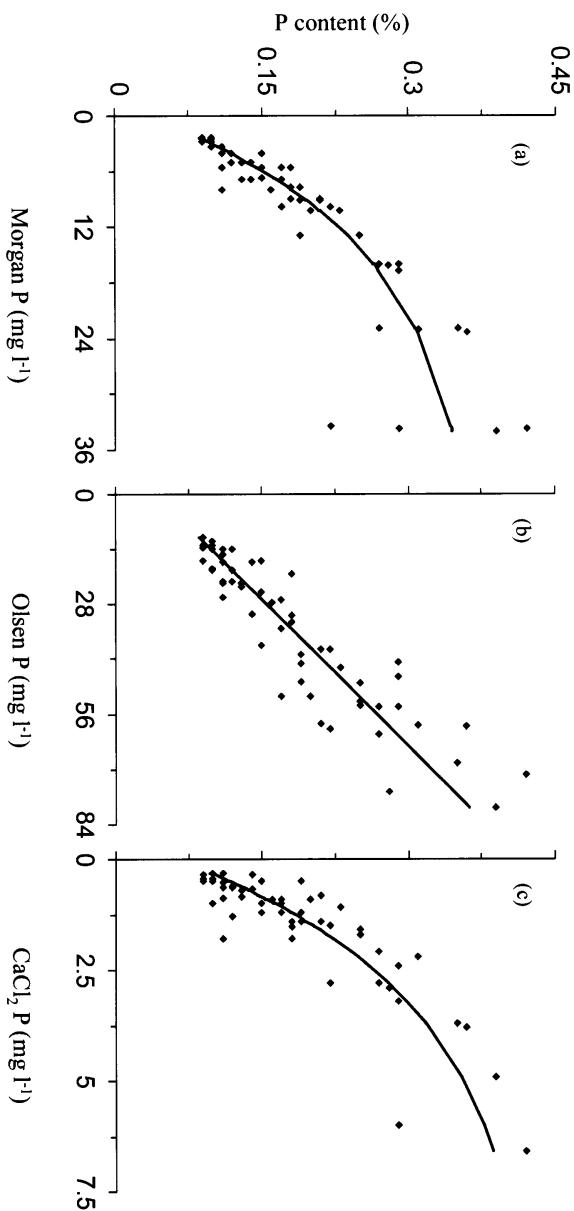


Figure 8. The P content of grass dry matter in relation to soil P concentrations at the beginning of the experiment: (a) soil Morgan P, (b) soil Olsen P and (c) soil CaCl₂ P. Lines are fitted using the following regression equations: (a) $y = 0.3766 - 0.3424 X 0.9329^x$ ($r^2 = 0.867$ $P < 0.001$); (b) $y = 0.0429 - 0.004x$ ($r^2 = 0.824$ $P < 0.001$); (c) $y = 0.4344 - 0.3719 X 0.7313^x$ ($r^2 = 0.803$ $P < 0.001$).

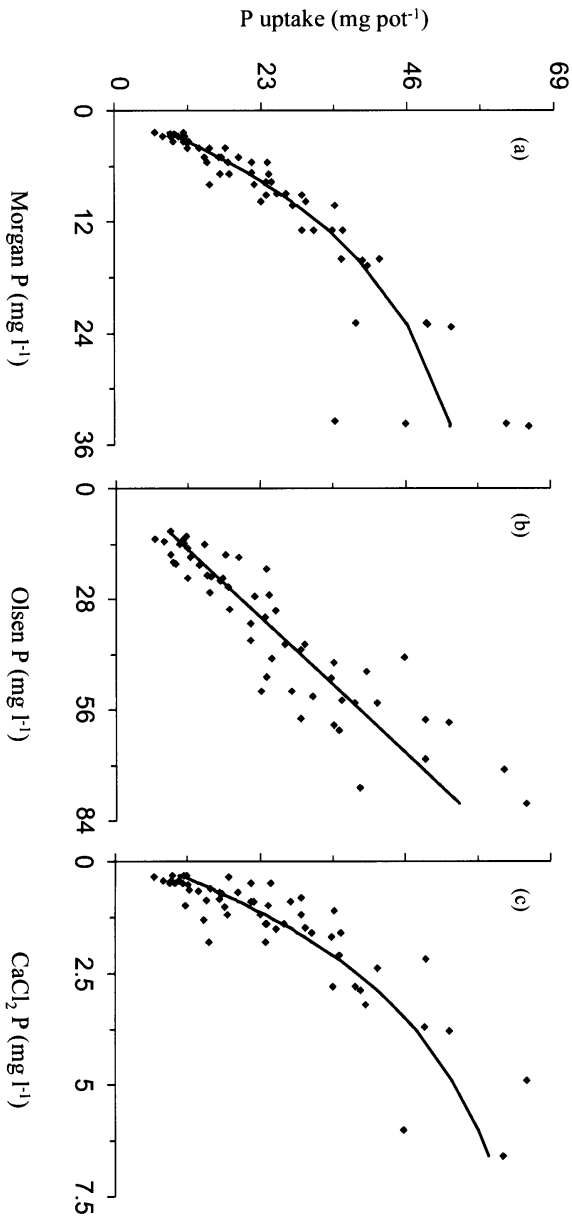


Figure 9. The P uptake in the grass dry matter in relation to soil P concentrations at the beginning of the experiment: (a) soil Morgan P, (b) soil Olsen P and (c) soil CaCl₂ P. Lines are fitted using the following regression equations: (a) $y = 59.65 - 59.64 \times 0.9384^x$ ($r^2 = 0.897$ $P < 0.001$); (b) $y = 1.12 - 0.67x$ ($r^2 = 0.817$ $P < 0.001$); (c) $y = 67.78 - 63.34 \times 0.7378^x$ ($r^2 = 0.806$ $P < 0.001$).

Discussion

Soil P concentrations at the beginning of the experiment exerted a substantial influence on grass DM yields, the P content of herbage and P content of the grass DM during this experiment. In previous comparisons of soil P extracting procedures in Ireland, Gallagher, Ryan and Brogan (1961) found that the Morgan method resulted in higher correlation coefficients than the Olsen test for yields of potatoes and swedes whereas the Olsen test resulted in a higher coefficient for yields of oats. Brereton and Hanley (1970) found that a modified Olsen P test (Olsen solution, 1:100 soil:solution ratio for 16 h) resulted in a higher correlation coefficient with DM yield of potatoes than the Morgan P test. Herlihy (1986) demonstrated that the Morgan test resulted in a higher correlation coefficient than the Olsen test when related to DM yields of sugar beet.

P uptake in the crop is often taken as a more accurate measure of soil P concentrations than crop yield (Sen Gupta and Cornfield, 1963, Williams and Knight, 1963; Simonis and Setatou, 1996). In the present experiment the Morgan test resulted in a higher correlation coefficient between soil P concentration and P uptake in the grass DM than the Olsen and CaCl_2 tests (Fig. 9). While the relationships between P uptake in the grass DM and the Morgan P and CaCl_2 P tests results were non-linear asymptotic relationships, the relationship with the Olsen test was linear. It is difficult to account for this linear relationship between Olsen P concentrations and P uptake in the herbage when both grass DM yields and the P content of the grass DM will eventually reach maximum values which would suggest an asymptotic relationship.

The relationships between the Morgan and CaCl_2 P test results and the P content of grass DM were not linear. It was pointed out in section 2 that there was a linear relationship between Morgan and CaCl_2 P test results, however, the relationship between both of these latter P tests and the Olsen P test were not linear. This was attributed to the Olsen P test providing a relatively low estimate of soil P concentrations at the higher soil P concentrations due to extraction of differing quantities of P from the various P fractions in the soil. In the present experiment the linear relationship between the Olsen P test and the P content of grass DM and total P uptake in

the herbage may also be attributed to the Olsen test providing a relatively low estimate of soil P at the higher soil P concentrations. Therefore, although the Olsen test results were significantly correlated with grass DM yields and total P uptake in grass DM in the present experiment, the Olsen test may provide relatively low estimates of soil P concentrations at high soil P concentrations and this may lead to a certain degree of inaccuracy in recommendations relating to the use of P amendments to soil at the higher soil P concentrations.

Furthermore, in section 2, it was demonstrated that the Morgan and CaCl_2 test results were closely correlated, however, in the present experiment the Morgan test provided a better estimate of grass response, in terms of DM yield and P uptake in the grass DM, than the CaCl_2 test. This points to the danger of replacing one chemical analysis method by another, merely because the new method correlates well with the old.

EVALUATING POTENTIAL P LOSS FROM SOIL TO WATER

Introduction

Although P is strongly fixed on clay particles, it is evident that P may move from agricultural soils to the aquatic environment in three ways: (1) as water-soluble and/or particulate P in surface runoff (over land flow), referring to P picked up by rainwater which flows over land surfaces to streams or rivers; (2) as water-soluble and/or particulate P in subsurface runoff, referring to P picked up by water which enters the soil profile and moves through the soil to streams or rivers without ever reaching the main water table; (3) as water-soluble and/or particulate P in flow to groundwater, referring to P picked up by the water that passes to the water-table and which is subsequently discharged to streams, rivers or lakes as seepage (Miller *et al.*, 1982; Isermann, 1990; Vighi *et al.*, 1991). Generally the P concentration of water percolating through the soil profile is low due to adsorption of P by P-deficient subsoils and therefore P leaching is generally relatively low on mineral soils, although significant quantities of P may be lost to drainage water by preferential flow through the soil (Breeuwsma and Silva, 1992). Exceptions occur in acid organic or peaty soils, where the adsorption affinity and capacity for P is low due to the predominantly negative charged surfaces and the complexing of Al and Fe by organic matter (Duxbury and Peeverly, 1978; Miller, 1979; White and Thomas, 1981). In general, it is considered that the greater part of P export from mineral soils occurs in surface rather than subsurface runoff. In such soils particulate P includes P adsorbed by soil particles and organic matter eroded during flow events and constitutes the major proportion of P transported from cultivated land (Pietilainen and Rekolainen, 1991; Sharpley and Rekolainen, 1997). Runoff from grassland generally carries little sediment, and is, therefore, dominated by the dissolved P form.

The study presented here is primarily concerned with grassland mineral soils and therefore focuses on loss of dissolved P from soils in surface runoff. Dissolved P is, for the most part, immediately available for biological uptake (Nurnberg and Peters, 1984; Walton and Lee, 1972) and can increase the biological productivity of surface waters. There are three important issues to consider: (1) the concentration of soil P and (2) the capacity of soil to retain P, or the sorption capacity of the soil, and (3) the interaction between rainfall and the depth of soil from which dissolved P is removed in runoff water.

Soil P concentration

Several studies have reported that the loss of dissolved P in runoff is related to soil P concentrations (Romkens and Nelson, 1974; Schreiber, 1988; Olness *et al.*, 1975; Yli-Halla *et al.*, 1995; Sharpley and Rekolainen, 1997). Sharpley and Rekolainen (1997) stated that as soil P concentrations increase, the potential for dissolved P transport in runoff increases. This can be attributed to the fact that more P is released from soil to the soil solution as the degree of P saturation increases and hence is more easily lost to surface runoff during runoff events (Breeuwsma and Silva, 1992). The process of P desorption from surface soil under rainfall involves a continuous application and removal of water at the soil surface. This process involves the release of dissolved to runoff water. However, as dissolved P is removed in runoff it does not slow down further dissolved P release from labile P fraction in the soil. Further dissolved P can therefore become available from the labile P fraction through desorption.

P sorption capacity

The ability of a particular soil to adsorb P is dependent on differences in P buffering capacity between soils caused by varying levels of clay, Fe and Al oxides, carbonates and organic matter. However, for a particular soil type, the greater the degree of P saturation the less well able that soil is able to adsorb P from the soil solution and the greater is its capacity to release P into the soil solution. Soils with a high degree of P saturation and a low ability to

adsorb P therefore have greater potential to lose P to water through the process of desorption.

Bache and Williams (1971) tested several single-point methods by statistical correlation against phosphate sorption isotherms and found that the sorption x , from one addition of 150 mg P per 100 g soil gave $r = 0.974^{**}$ when the equilibrium concentration was also taken into account in the quotient $x/\log c$. This quotient, the P sorption index, was therefore suggested as a simple yet adequate way of indicating a fundamental soil property, its phosphate sorption isotherm. This method is used in the following experiment as a rapid method of estimating the degree of P sorption capacity of soils with different soil P concentrations. A low P sorption index value for a soil indicates a high ability to absorb P or, on the other hand, a low degree of P saturation. Increasing P sorption index values indicate an increasing degree of P saturation.

Soil depth

The transport of dissolved P in runoff is initiated by the processes of desorption, dissolution, and extraction of P by water from soil. In practice desorption of soil P by rainfall and subsequent runoff is brought about by the interaction of rainwater with a thin layer of surface soil, caused by the impact of raindrops and the flow of runoff water. Sharpley *et al.*, (1981) found that the average depth of runoff-surface soil interaction ranged from 1.5 to 3.0 mm and that mean dissolved P concentrations of individual runoff events increased linearly with the amount of desorbable P in the surface soil. In the following experiment estimation of the potential dissolved P loss from soils and the sorption capacity of soils were measured on soil samples were taken from the upper 1 cm of soils.

Materials and Methods

Soil P desorption and the P sorption index were determined for the 52 soil samples sampled at 1 cm depth. The amount of desorbable P was measured in water (soil:water 1:40) shaken mechanically for 30 minutes at constant temperature (20°C) according to Sharpley et al. (1981) and Yli-Halla *et al.* (1995). Soil P sorption was measured by contact of 1.5 g P l⁻¹ soil shaken mechanically for 40 h at constant temperature (20 °C) in 0.01 M KCl solution at a soil to solution ratio of 1:40 according to Simard *et al.* (1994). Solution P concentrations were measured spectrophotometrically at 880 nm using the phosphomolybdate method and soil concentrations were extrapolated from standard curves (Murphy and Reilly, 1962). The P sorption index was calculated using the quotient X/Log₁₀ C, where C is the solution P concentration (Bache and Williams, 1971; Simard *et al.*, 1994).

Results

The P concentrations of samples taken to a depth of 1 cm were substantially higher than the P concentrations of samples taken to a depth of 10 cm indicating that much of the P in grassland soils is concentrated in the upper layers of the soil. In general, soil P concentrations sampled to 1 cm were not closely correlated with soil P concentrations sampled to 10 cm, as measured by the Morgan, Olsen and CaCl₂ tests (Fig. 10) compared to the correlations for these three tests between samples taken to 7.5 cm and 10 cm (Fig. 5). Soil Morgan P concentrations and P desorption were closely and linearly correlated when both analyses were carried out on samples taken to a depth of 1 cm (Fig. 11). However, when the Morgan test results for samples taken to a depth of 10 cm were compared to P desorption in samples taken to 1 cm, this latter comparison resulted in a relatively lower r² value (Fig. 12).

Phosphorus desorption for samples taken to 1 cm and Morgan P for samples taken to 10 cm in relation to P sorption index of samples taken to 1 cm are presented in Figure 13. Background Morgan P concentrations were around 2 to 2.5 mg l⁻¹, and at this level there was very little potential P loss. However, potential P loss, measured as P desorption, increased exponentially with increasing P sorption index.

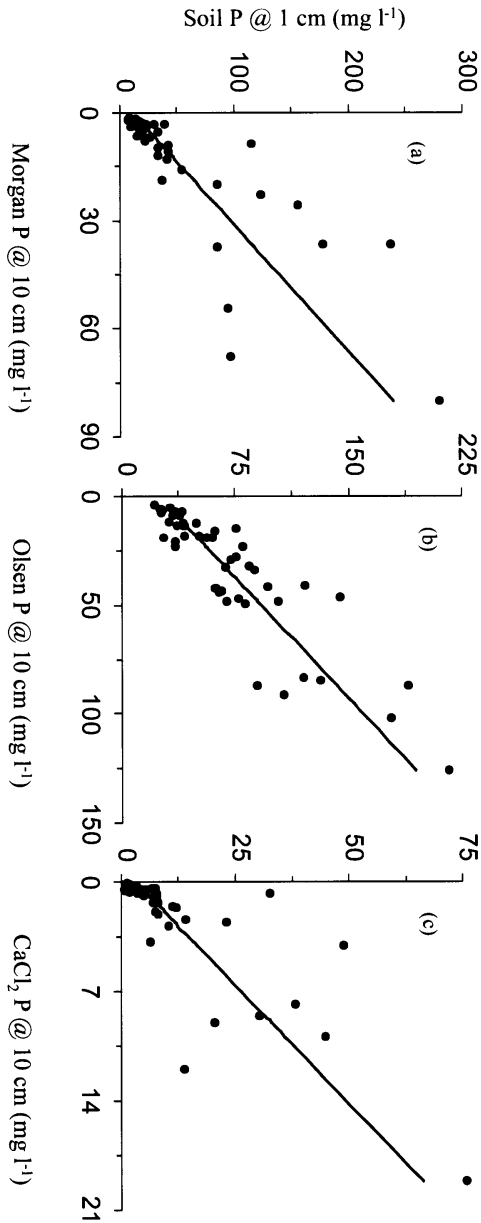


Figure 10. The relationship in soil P concentrations between soil sampled to a depth of 10 cm and 1 cm for (a) Morgan P, (b) Olsen P and (c) 0.01M CaCl₂ P. The best-fit linear regression equations were: (a) $y = 11.48 + 2.83x$ ($r^2 = 0.679$, $P \leq 0.001$); (b) $y = 24.41 + 1.35x$ ($r^2 = 0.798$, $P \leq 0.001$); (c) $y = 3.29 + 3.29x$ ($r^2 = 0.681$, $P \leq 0.001$) where x = concentration at 10 cm and y = concentration at 1 cm.

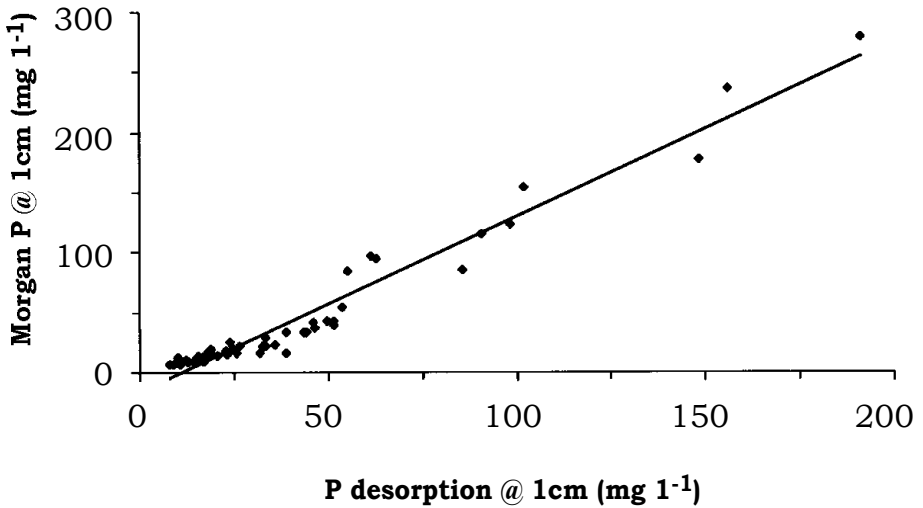


Figure 11. Soil Morgan P concentrations in relation to P desorption for samples taken to a depth of 1 cm. The line was fitted using the following linear regression equation: $y = -16.31 + 1.461x$ ($r^2 = 0.954$, $P < 0.001$).

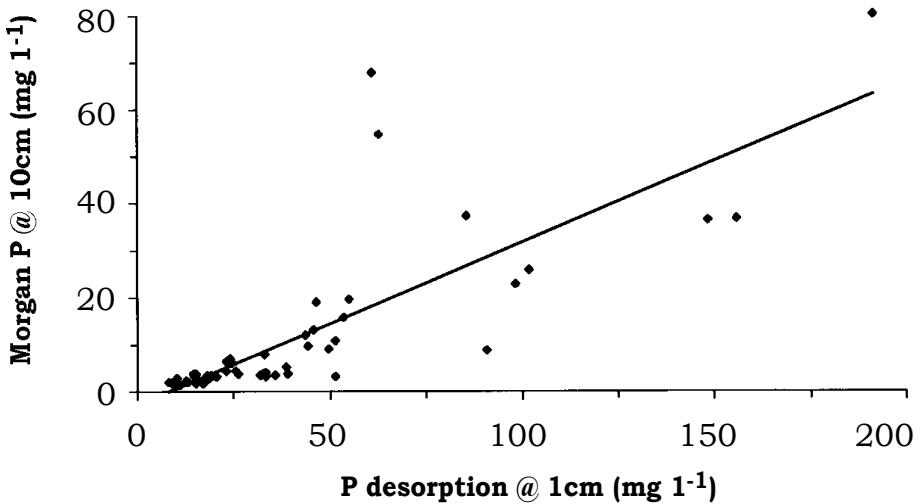


Figure 12. Soil Morgan P concentrations for samples taken to a depth of 10 cm in relation to P desorption for samples taken to a depth of 1 cm. The line was fitted using the following linear regression equation: $y = -2.67 + 0.344x$ ($r^2 = 0.623$, $P < 0.001$).

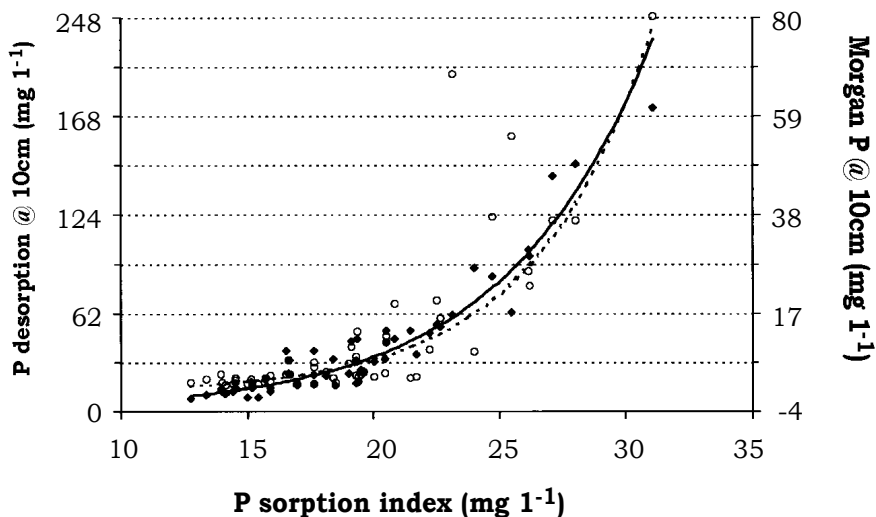


Figure 13. P desorption for samples taken to a depth of 1 cm (◆) and soil Morgan P concentrations for samples taken to a depth of 10 cm (○) in relation to the P sorption index for samples taken to a depth of 1cm. Lines were fitted using the following exponential equations: desorbed P @ 1 cm, $y = 1.124 \exp^{0.172x}$, ($r^2 = 0.871$, $P < 0.001$); Morgan P @ 10 cm, $y = 0.095 \exp^{0.216x}$, ($r^2 = 0.733$, $P < 0.001$).

Discussion

The degree of P saturation is dependent on the amount of dissolved and labile P in the soil. At low soil P levels, such as soils which would be considered deficient from an agricultural production point of view, the soil is at a low degree of P saturation and much of the P is strongly absorbed by the soil, resulting in relatively low levels of dissolved P in the soil solution. There is therefore insufficient dissolved P in the soil to meet the requirements of crops and/or livestock leading to P deficiency in the production system. Phosphorus amendments, either in organic (animal manures) or inorganic form, are therefore supplied to maintain agricultural production. Once applied, P is either taken up by the crop, incorporated into organic P (McLaughlin *et al.*, 1988), or becomes weakly (physisorption) or strongly (chemisorption) adsorbed onto Al, Fe and Ca surfaces (Syers and Curtin, 1988). As the quantity of adsorbed P increases, the degree of P saturation in the soil also increases. The extent of the degree of saturation is a function of

certain physical and chemical soil properties, such as clay, organic C, Fe, Al, and CaCO₃ content (Mengel and Kirkby, 1987). The continual application of P inputs will eventually increase the degree of soil P saturation and hence the dissolved P concentration in soil which is the objective of P inputs in agricultural production. However, excessive P applications can lead to soil P levels above that required for optimum yields. This intensifies the degree of soil P saturation and simultaneously reduces the P retentive capacity of soils, thus increasing potential dissolved P loss in surface runoff.

In the present experiment, soil P concentrations as measured by the Morgan test were closely correlated with P desorption when sampled to the same depth of 1 cm. This is similar to that found by Romkens and Nelson (1974), Schreiber (1988), Olness *et al.* (1975), Yli-Halla *et al.* (1995) and Sharpley and Rekolainen (1997). However, P desorption at the soil surface (*i.e.* 1 cm samples) was not as closely correlated with soil Morgan concentrations for samples taken to the standard depth of 10 cm. This indicates that Morgan test results for samples taken to 10 cm do not provide a wholly accurate estimate of potential P loss at the soil surface because soil P concentrations of samples taken to a depth of 10 cm provides only a mediocre estimate of soil P concentrations at the soil surface. Nevertheless, potential dissolved P loss at the soil surface will increase with increasing soil Morgan P sampled to a depth of 10 cm. Furthermore, once soil P concentrations in the upper 1 cm of soils increased above background concentrations, potential dissolved P loss increased exponentially with increasing P sorption index. This indicates that there is no basis for establishing thresholds which can be applied to soil P concentrations in order to categorise potential dissolved P loss within a single soil series because every increment in soil P concentration will result in an exponential increase in potential loss. Therefore to minimise the potential risk of dissolved P loss from soils, soil P concentrations should be the minimum necessary to maintain optimum levels of agricultural production. However, it must also be taken into account that actual amounts of dissolved P transported from catchments are a function of catchment hydrology (Sharpley and Rekolainen, 1997).

Reasons for the higher concentrations of P in the surface of uncultivated grassland soils have been pointed out in section 3. In order to facilitate both agricultural production and protection of surface waters, infrequent shallow ploughing or other surface cultivations (e.g. Rotavation) which invert or mix the upper layers of the soil profile may offer one solution. If the upper 10 to 15 cm of soils are inverted and thoroughly mixed, the resultant upper surface would have lower soil P concentrations compared with an unmixed soil, although soil P concentrations in the upper 10 cm in both situations would be the same. Plant roots would be able to penetrate to the buried P resource facilitating agricultural production while minimising potential dissolved P loss in runoff water. Such a strategy along with good farm practices should greatly reduce potential dissolved P losses from agricultural soils.

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