Modelling phosphorus for grassland: agronomically and environmentally sustainable advice.

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Introduction

In 2006, the Nitrates Directive (through S.I. 378 (Anon, 2006)) was implemented in Ireland, aimed at reducing nutrient losses from agriculture to water bodies, i.e. surface waters, groundwater and estuarine waters. This legislation introduced strict regulation of nutrient management on Irish farms. Thus far, nutrient management had largely been based on Teagasc advice (Coulter, 2004). However, in the new policy climate, in addition to advice, compliance with legal limits is also required.

This significant change in the practicalities surrounding nutrient management led to a review of Teagasc nutrient (phosphorus and nitrogen) advice, based on the following considerations:

Traditionally, nutrient advice had largely been based on fertiliser rates for economically optimal productivity, i.e. rates at which further fertiliser applications would not result in higher economic returns. Now, SI 378 of 2006 demands that nutrient application rates do not exceed crop (grass) demand, nor result in nutrient losses that may have a negative impact on water quality.

Previous phosphorus (P) advice (Coulter, 2004) was similar for all soil types, and did not account for potentially different P-requirements, or indeed potentially different risks of P-loss to water between soils.

Previous P advice was based on returning optimum crop yields. However, grassland management in Ireland is increasingly focussed on maximising the amount of herbage grazed *in situ*. With extended grazing seasons and an increasing share of the animal diet consisting of grazed herbage, the scope and flexibility of diet supplementation through straights and concentrates is reduced. An increasing proportion of dietary P must be obtained from this grazed herbage as a result. Therefore P fertiliser strategies should no longer be based on yield responses alone, but in addition sustain adequate herbage P-concentrations in order to ensure that the dietary P requirements can be met on a non-supplemented diet of grazed herbage.

Against this background, Teagasc, Johnstown Castle Environment Research Centre, undertook a major research programme, reviewing both agronomic and environmental aspects of P-advice for grassland.

Phosphorus agronomy

Rationale

P advice for grassland in the Republic of Ireland was based on a soil P-index system (Table 1), defined by soil-test P (STP) using Morgan’s extractant. Soils in Index 1 are P-deficient, and require build-up of soil P-reserves. The optimum soil-test P (“target index”) depended on farm intensity. A target Index of 3 was recommended where early grass was required and where herbage production is fully utilised. A target Index of 2 was recommended where the stocking rate was below the stock carrying capacity of the land. Soils in Index 4 have elevated P-reserves, and do not exhibit responses to additional fertiliser P.

Table 1. P Index system for grassland prior to SI 378 of 2006.

P Index	Soil Test P (mg/l, Morgan's)
1	0 – 3.0
2	3.1 – 6.0
3	6.1 – 10.0
4	Above 10.0

Phosphorus fertiliser advice for grassland has been based on:

1 Building up soil P reserves to the target index;
2 Maintaining soil-test P at the target index by replacing off-take of P in meat and milk;
3 Frequent (every 4-5 years) soil tests to ensure STP levels are maintained at the target index.

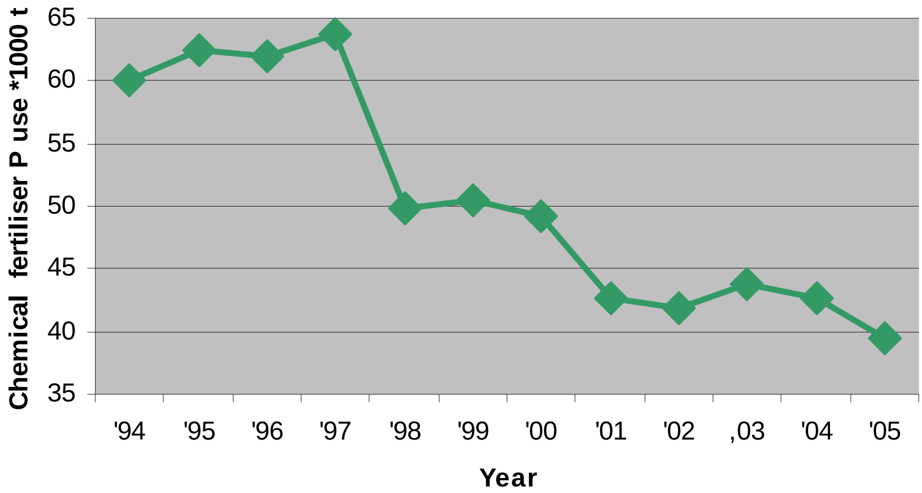

Figure 1. Usage of chemical fertiliser P from 1994 to 2005.

At the time, the introduction of this advice led to a marked reduction in fertiliser use, from *c.* 60,000 tonnes in 1994 to less than 40,000 tonnes in 2004, a reduction of a third over a decade (figure 1).

However, a review of soil test P levels revealed that up to 25% of samples received at Johnstown Castle laboratories were of soils in Index 4. This means that these soils had elevated soil P levels, i.e. levels at which fertiliser P application do not yield economic returns, yet at which risks of P-loss to the environment are considered to be increased. On these sites, agronomic and environmental management are synergistic, since withholding fertiliser P on index 4 soils saves both money for farmers and reduces risks of P-loss to water.

Materials and methods

In order to establish soil-specific responses of herbage production and herbage P concentration to fertiliser P applications and to STP, a large-scale agronomic experiment was carried out from 1997 to 2000. The experiment was conducted on eight contrasting soils (associations 13 and 15, series 14, 22, 30, 33, 34, 39 of the General Soils Map (Gardiner and Radford, 1980)), see Table 2 and Figure 2. The objective of the experiment was to establish fertiliser P-application rates that return 95% of potential maximum yield and herbage P-concentrations of 0.30-0.35%.

Table 2. Classification and selected characteristics of the soils used in this study (Gardiner and Radford, 1980; Herlihy *et al.*, 2004).

Series / association	No.	Principle soil	Parent material	Drainage	pH range	Location
Association 13	13	Acid brown earths	Sandstone-limestone diamicton	Good	5.0-6.4	Waterford
Clonroche	14	Acid brown earths	Ordovician shale diamicton	Good	5.8-6.5	Wexford
Association 15	15	Brown Podzolics	Sanstone-shale diamicton	Good	5.7-6.6	Cork
Castlecomer	22	Gleys	Upper Carboniferous (Silesian) shale diamicton	Poor	5.2-6.0	Kilkenny
Baggotstown	30	Grey brown podzolics	Calcareous fluvio-glacial gravel	Good	5.6-6.9	Offaly
Kinvarra	33	Shallow brown earths and rendzinas	Limestone diamicton (shallow)	Good	5.6-7.3	Galway
Elton	34	Minimal grey brown podzolics	Limestone diamicton	Good	4.8-6.5	Tipperary
Howardstown	39	Gleys	Limestone diamicton	Poor	4.9-6.3	Limerick

Within each soil series, sites were selected representing the P indices 1, 2, 3 and 4, and fertiliser P was applied at rates of 0, 10, 20, 30, 40, 50, 60, 75, and 100kg/ha with two replications (four for 0kg/ha control). At each site, herbage was cut four times annually, and herbage DM yield and P concentration was established for each treatment. After each year, the experimental plots were re-randomised on a new location within each site, in order to prevent residual effects. Composite soil samples (20 sub-samples per plot) were taken twice annually (spring and autumn) at a standard depth of 10cm, and dried at 40°C. STP was measured annually using Morgan’s extract (details in Herlihy *et al.*, (2004)). For each soil type, the annual herbage yield (kg DM/ha) and average herbage P concentration (g/kg DM) of each year were non-linearly related to the annual STP (mg /l) and fertiliser P rates (kg/ha) as analysed by multiple non-linear regression.

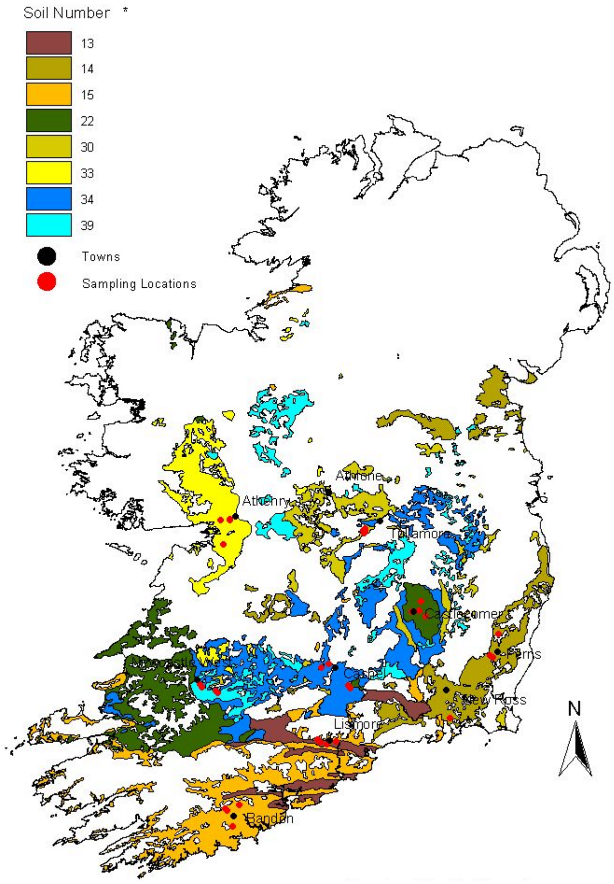

Figure 2. Map showing location of the soils represented by the experimental sites. Source: Gardiner and Radford (1980).

Results

Both fertiliser P and STP had a significant effect on both herbage yield and P-concentration ($P < 0.0001$). Together, STP, fertiliser P, and to a lesser extent year effects explained on average 34% (range: 9%-66%) of the variation in herbage yield, but more than double this percentage, i.e. 73% (range: 59%-86%) of the variation in herbage P concentration. This finding suggests that there is a strong relationship between soil P-levels and fertiliser P applications and the amount of P taken up by the grass. However, how this P-uptake is utilised and transformed into yield responses depends on additional external factors, e.g. meteorological conditions and botanical composition.

Figure 3a illustrates the P-fertilisation rates required to return a relative yield of 95% of potential yield. At Soil P Index 1, four soils required fertiliser rates between 10 and 40kg P/ha, with soils 34 and 22 requiring as much as 58 and 76kg P/ha, respectively. Soils 14 and 30 required only 3 and 0kg P/ha, respectively. At Soil P Index 2, the herbage yield responded to fertiliser P only on soils 22, 34 and 39, while at Soil P Index 3, substantial P-fertilisation was only required on soil 22.

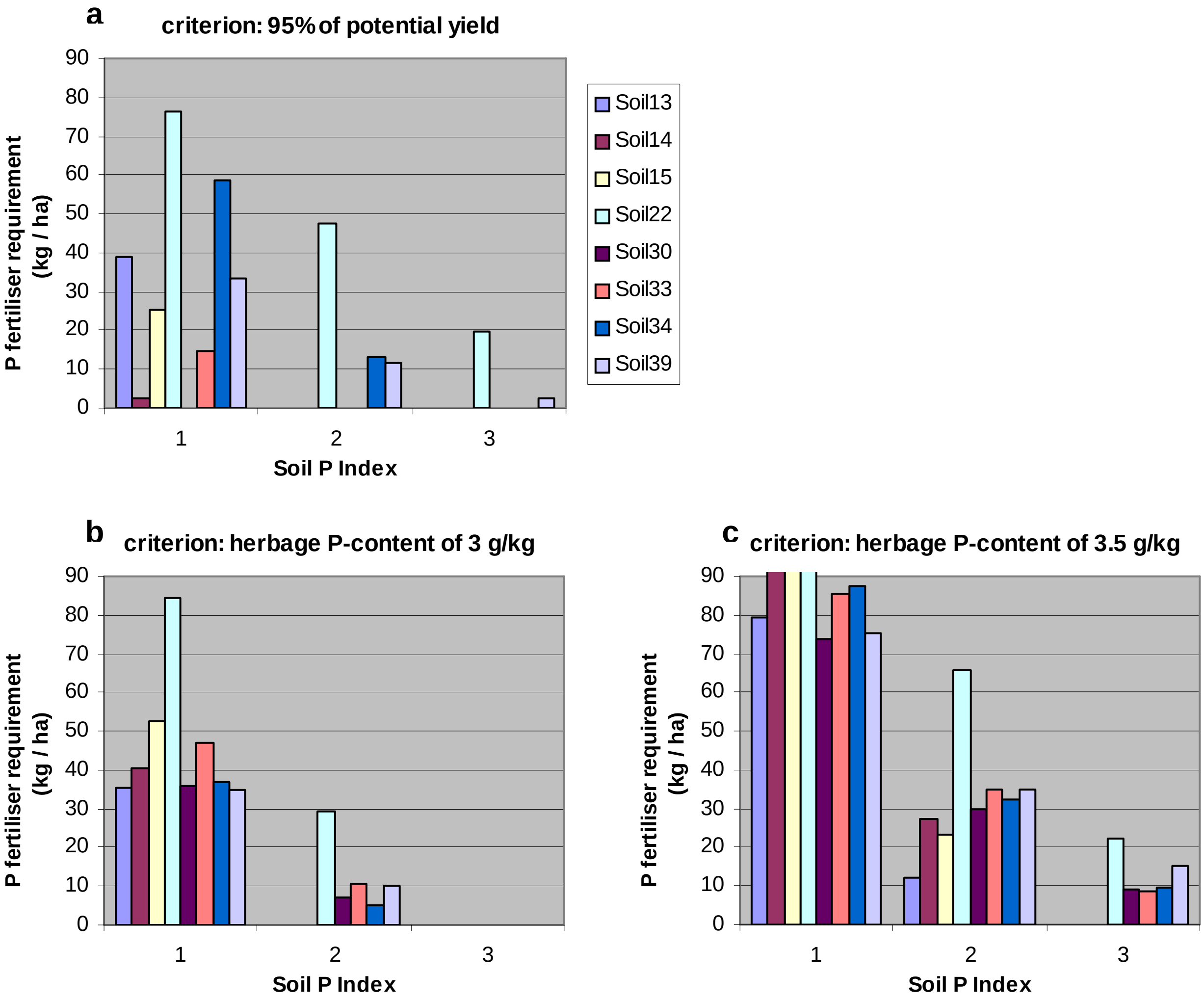

Figure 3: P fertiliser rates (kg /ha) required to produce a) 95% of potential yield; b) a herbage content of 3.0g /kg and c) a herbage content of 3.5g /kg for each combination of soil series and the "old" soil P index.

Figure 3b shows that for all soils, higher P fertiliser rates were required to reach herbage P contents of 3g/kg than for maximum yield. At Soil P Index 1, most soils required between 35 and 55kg P/ha, again with the exception of soil 22, on which as much as 85kg P/ha was required. At Soil P Index 2, these rates were reduced to less than 11kg P/ha on most soils, except for soil 22 which required 29kg P/ha. As with DM yield, no substantial fertilisation was required at Soil P Index 3.

Even higher rates were required to produce herbage P-contents of 3.5g/kg (Figure 3c), with all soils requiring over 70kg P/ha at Soil P Index 1, and between 12 and 35kg P/ha in Soil P Index 2, again with the exception of soil 22, which required as much as 65kg P/ha at Soil P Index 2. The 3.5g/kg P content target required modest fertiliser P inputs up to 15kg P/ha to be applied to Soil P Index 3 soils (22kg P/ha for soil 22).

The P-fertiliser requirements shown in Figure 3 are not to be equated to fertiliser P advice at farm scale; instead, these are the P-requirements under the experimental management regime imposed. The up-scaling of these experimental data to field and farm level should account for P cycling and P-dynamics at these higher scales, and in particular for the following:

The experimental plots in this study were cut four times annually. In practice, herbage is commonly defoliated either less frequently (silage) or more frequently (grazing). Cayley and Hannah (1995) showed that the responses of the relative yields to fertiliser P were identical for cut and grazed grass. However, herbage P content does decline with grass maturity. Data by Fleming and Murphy (1968) suggest that P contents remained high in herbage cut frequently (13 times annually), but declined by up to 2.5g/kg when grass was not cut until full maturity, though the precise quantification of this reduction in P contents is difficult to establish from their data. However, this suggests that in the current study, higher P contents may have been expected under more frequent defoliation.

The P requirements deduced in this study were total P-inputs. Since no organic P was applied to the experimental plots, these P-requirements equated to fertilizer P rates. However, at farm scale additional P is recycled, mainly in the form of manure and slurry produced over winter and dung deposited at grazing. To date, fertiliser P advice in Ireland has accounted for P in slurry and manure, by subtracting the latter from the total P requirements. P in dung, however, is deposited on only c. 5% of the grazing area each year, even on intensive dairy systems, and thus cannot be accounted for on the remaining 95% of the grazing area. Additional P may also be imported onto the farm in the form of concentrate feeds. However, from the above it follows only concentrate P fed during the housing period may be presumed available in the slurry.

For soils that have reached the target P index, P inputs should not be below maintenance rates, i.e. rates required to replace offtakes of P in the form of animal produce. Recently, Herlihy et al. (2004) showed that, on the soils used in their study, P application rates below maintenance requirements led to declining STP concentrations over time.

Implications for fertiliser P advice

Notwithstanding these uncertainties surrounding the up scaling of results to farm level, this experiment has produced the following consistent results:
In general, the fertiliser P rates advised by Coulter (2004) largely correspond to the P requirements observed in this experiment, with the exception of soil 22 (see point 3 below). The main discrepancy between current P advice and P requirements in this experiment involved the high P rates required to produce herbage P-content of 3.5g/kg on soils in Index 1 (Figure 3c). This warrants more detailed investigations into P chemistry at low indices, which is the subject of recent and ongoing studies
(e.g. Herlihy & McGrath, (2007)).

P-fertilisation rates required to produce herbage P contents of 3.0 and 3.5g/kg, exceeded rates required to produce a relative yield of 95% of potential yield. In other words, where average herbage P content in excess of 3.5g/kg is observed, this implicitly confirms that a relative yield of 95% has been reached, irrespective of soil type. As a result, P fertiliser requirements are primarily determined by the need for adequate herbage P-concentrations.

These P requirements for herbage quality exhibit similar patterns for most of the eight soil series and associations in this study, with the notable exception of soil series 22. This non-limestone soil is characterised by its very poor drainage characteristics and high organic matter content. Attempts were made to explain differences between soils by auxiliary soil parameters, i.e. parent material, Hedley fractions, sorption parameters, pH and soil texture fractions, but no straight-forward, unambiguous relationships were found. Therefore, the results of this study do not support soil-specificity in agronomic P advice.

No dry matter yield responses to fertiliser P were observed at STP levels between 3 and 6mg/l (Figure 3b). However, where high herbage P-contents are required, large responses were observed at these STP levels. At levels between 6 and 10mg/l, small additional P concentration responses were observed, largely corresponding to maintenance application rates (Figure 3c). This suggest that the agronomic optimum for herbage P-concentrations approximates 6mg/l for farming systems with a demand for high grass quality (in terms of herbage P content), irrespective of demands for overall grass quantity (i.e. stocking densities).

For soils that are above the target Index, applications of fertiliser P are not required. The STP can be allowed to fall until it reaches the target Index, at which point application of maintenance rates of fertiliser P should resume. Regular soil testing is required the rate of decrease of STP concentration.

Phosphorus and the environment

Background

In comparison to nitrogen, phosphorus is largely an immobile element. The majority of phosphorus applied to grassland is either utilised by the grass crop, or firmly bound to soil particles at so-called “binding sites” through a process called adsorption. In grassland, most P is adsorbed in the upper few centimetres of the soil profile, and only a small proportion of the total soil P is available to plants, as measured by Morgan’s P-test. However, at high soil P levels, the majority of high-energy binding sites may be utilised and further P additions may remain available in more labile forms. This phosphorus, when not taken up by the plant, is susceptible to being moved from soil to water by overland flow. Although quantities lost to water may be small in agronomic terms, losses of one or more kilograms of P per hectare may have undesired environmental side-effects and result in eutrophication of surface waters. Eutrophication is the process of nutrient enrichment of surface waters, which may lead to excessive growth of algae and produce algae mats. Rotting of this vegetation extracts oxygen from the water, which impacts negatively on the aquatic ecology and, in extreme cases, may lead to fish kills.

Water quality in Ireland

Compared to many parts of Europe, water quality in Ireland is generally good, with 88.3 % of river waters classified as “unpolluted” (70.2 %) or “slightly polluted” (18.1 %) by the EPA (Toner *et al.*, 2005). However, 30% of surface waters are subject to “moderate” or “severe” eutrophication. Recently, concerns are growing about the quality of our estuarine waters, with 22.4 % of our estuaries classified as “potentially eutrophic” or “eutrophic”. Both the Nitrates Directive and the Water Framework Directive require that all surface waters are restored to reach “good” water quality status.

There has been an ongoing debate on the relative contribution of agriculture to eutrophication in comparison to other sources such as losses from municipal discharges and septic tanks. The precise contribution from agriculture is very difficult to quantify, but has been estimated to be approximately 70% (Stapleton *et al.*, 2000; EPA, 2004).

Environmental research

Phosphorus loss from soil to water, as well as mitigation strategies to reduce these losses, have been the subject of a very large research programme at Johnstown Castle, in collaboration with many Irish universities, and co-funded by the EPA. The outcomes of this programme can be summarised by the pressure pathway concept (Schulte *et al.*, 2006) illustrated in Figure 4. In summary, risk of P-loss to water occurs in circumstances where “P pressures”, i.e. quantities of available P, coincide with transport mechanisms from soil to water.

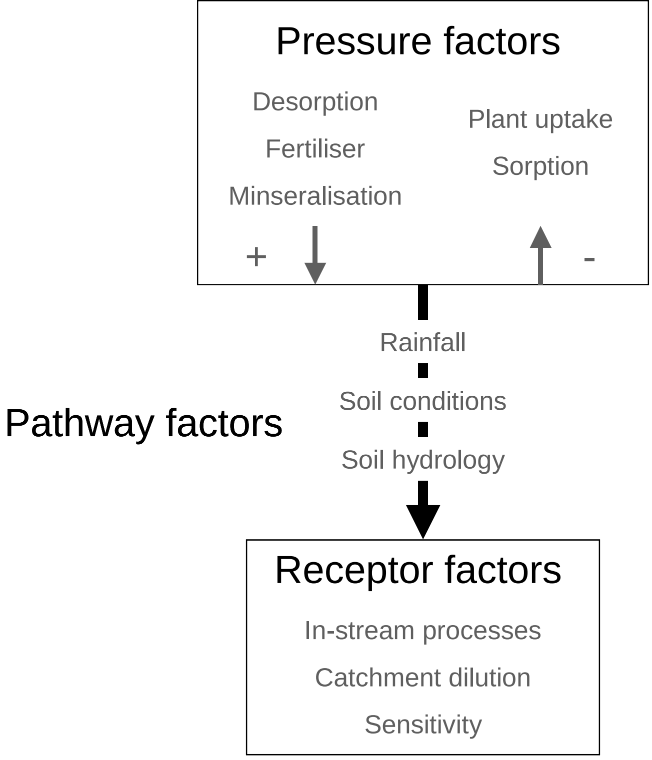

Figure 4 : A conceptual model of P loss to water (adapted from Schulte et al., 2006)

Pressure factors

Pressure may be defined as the balance between inputs and outputs of nutrients, i.e. inputs of fertiliser and organic nutrients, mineralisation and desorption on the one hand, and plant uptake and sorption on the other hand (Heathwaite *et al.*, 2003). Therefore, the pressure or the risk of nutrient P loss to water is determined by the size of the P surplus. The greater the surplus, the greater is the source pressure. It is now well established that soil P-levels are the main P-pressure factor. There is an unambiguous relationship between increasing STP levels in soils and increasing potential for P loss at plot scale (Sharpley *et al.*, 1981; McDowell and Condron, 2004), field scale (Kurz *et al.*, 2005a; Kurz *et al.*, 2005b) and sub-catchment scale (Daly *et al.*, 2002; Jordan *et al.*, 2005; Kurz *et al.*, 2005b) in Ireland. At high soil P levels, most of the high-energy binding sites have been utilised, and further P-additions are bound in more labile forms (Herlihy and McCarthy, 2006), which are more susceptible to desorption and transport through overland flow.

However, desorption processes are soil-type dependent, and the precise relationship between STP and risks of P-loss depends to a large extent on soil chemistry. In organic soils (peats and peaty soils), organic matter competes with P for binding sites. As a result, few binding sites are available for P (Daly and Styles, 2005), therefore the concept of “P build-up” is less applicable in these soils. On the other hand, increases in Fe^{2+}, Al^{3+} and Ca^{2+} concentrations in the soil generally favour P adsorption, so that soils with high concentrations of these ions have high capacities to bind and store P (Daly and Styles, 2005).

Pathway and Receptor factors

For high nutrient pressures to pose a significant risk to water quality, transport pathways have to be present in the form of surface overland flow that will transport the nutrients to water body receptor. Overland flow is generally caused by excess rainfall on saturated, poorly-drained soils (Diamond and Sills, 2001; Kurz, 2002; O'Reilly, 2006). Phosphorus can then become mobilised and transported. Since the soil surface has the highest concentrations of P (Ahuja *et al.*, 1981; Sharpley, 1985; Culleton *et al.*, 2000), few binding sites are available for resorption. Potential to contribute diffuse losses of P only exists if a source area is hydrologically linked to a receiving surface water body (Heathwaite *et al.*, 2005), and therefore, not all land has an equal risk of contributing P to receiving waters.

Some soil can be regarded as hydrologically inactive with respect to surface overland flow, and fall into low risk soil types. These are typically permanent pasture with deep soils and high infiltration rates that are not prone to rapid fluctuations in water table level in response to rainfall. In these soils, most excess rainfall is drained through infiltration. As P-concentrations decline rapidly through the profile, the quantity of binding sites available for resorption increases with depth.

Implications for nutrient advice: the new P index

The results from these agronomic and environmental studies presented difficulties for the implementation of legislation for sustainable nutrient management.

The agronomic studies showed that the agronomic optimum Soil Test P (i.e. the soil P level at which maintenance fertiliser P applications ensure 95% of potential yield, and satisfactory herbage P concentrations), is approximately 6mg/l (Morgan's P-test). This soil P level was exactly at the breakpoint of the old indices 2 and 3. Were the old index 2, ranging from 3-6mg/l, to be adopted as the target index, this would mean that at low STP levels of 3mg, fertiliser P could only be applied at maintenance levels, which would raise serious concerns about herbage productivity and quality at the soil P levels. On the other hand, were the old index 3, ranging from 6-10mg/l, to be adopted as the target index, this could result in STP levels building up as high as 10mg/l, well above levels at which fertiliser applications yield economic returns.

The environmental studies demonstrated that risk of P-loss to water is related to STP levels, though the precise relationship may differ significantly across soil types. On poorly-drained soils, on which overland flow occurs regularly, STP levels of 8mg/l were reported to result in unacceptable levels of P-loss to water. By contrast, on well-drained soils, on which overland flow occurs only infrequently, no significant losses were reported at STP levels below 10mg/l. This would imply that the Target Index would need to account of soil drainage capacity. Choosing the old Index 3 as the Target Index would be environmentally sustainable on well-drained soils, but not on poorly-drained soils. The drainage capacity of individual soils can only be established by direct observation at field-scale, and the designation of individual fields to Target Indices would indeed have been very challenging to implement.

The new P index

Therefore, the old P-index system was revised to take account of these concerns. The new P-index for grassland (table 3) uses new breakpoints, based on the research projects described above.

Table 3. The new P Index for grassland

P Index	Soil Test P (mg/l, Morgan's)
1	0 – 3.0
2	3.1 – 5.0
3	5.1 – 8.0
4	> 8.0

In this new P-index, Index 3 (5.1-8.0mg/l) represents a Target Index that is both agronomically and environmentally sustainable for all soils. With an agronomically optimum STP of 6mg/l, maintenance rates are applied only to soils with STP levels between 5 and 8mg/l. As soon as the STP drops below 5mg/l, build-up P may be applied. At the same time, the new upper limit of Index 3 ensures that STP levels will not be built up in excess of 8mg/l. As a result, soil in the new Index 3 should not be significantly at risk of P loss to water, even on poorly-drained soils.

On peat soils, where the concept of building up P-reserves does not apply in practice, fertiliser should be applied at maintenance rates only to all soils with a STP of Index 1-3. On these soils, P should be applied in synchronisation with crop demand, i.e. little and often over the growing season.

On non-grassland soils such as with tillage crops, the P Index system has not changed. The “old” P Index (table 1) is still to be used for nutrient management for non-grassland crops.

Otherwise, the basis of fertiliser P advice for grassland has remained the same in the new P-advice, due to be published in early 2008, i.e. build up STP levels to the Target Index, apply maintenance rates only when the Target Index has been reached, and conduct frequent soil testing to ensure the soil remains at Target Index. In the new policy climate, the new P-index ensures synergy between agricultural production and the environment, by facilitating optimum productivity and herbage quality, while minimising risks of P-loss to water.

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