FERTILIZER ASSOCIATION OF IRELAND

Proceedings of Spring Scientific Meeting 2019

5th February 2019

Horse and Jockey, Thurles, Co. Tipperary

Publication No. 54

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Identifying and managing soil compaction in agricultural soils

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Introduction

Maintenance of soils in good structural condition is fundamental to efficient crop production. Soil structure controls the way in which roots, water and air move through soils. Poorly structured and compacted soils are often associated with lower crop yields, higher inputs (nutrients, energy) and an increased risk of flooding, run-off and erosion, leading to sediment, nutrient and agrochemical losses to surface water.

Damage to soil structure largely arises due to compaction as a result of vehicle and livestock trafficking, particularly when soils are wet and not strong enough to withstand compressive pressures. Soil compaction often results in the formation of plough/traffic/tillage pans in arable systems or ‘cow pans’ in grassland systems where void space and particularly visible macropore space is significantly reduced. There is a strong link between soil type, land use practices, climate and the risk of soil compaction. Soil properties such as clay, calcium carbonate and organic matter content will determine a soils susceptibility to compaction, whereas its vulnerability to these processes depends largely on soil moisture content and cropping.

Identifying soil compaction

Soil bulk density has been identified as a useful indicator of soil physical condition, with changes in bulk density over time indicating a change in soil compaction or loosening and an associated decrease or increase in total porosity. However, bulk density measurements (and other methods for quantifying soil physical condition) can be time consuming and difficult to interpret. Semi-quantitative, visual soil evaluation is increasingly being used as a low cost, but effective field technique to assess soil condition. Rather than measuring one specific property, visual soil evaluation provides an overall assessment of the soil structural condition, providing an integrated assessment in three dimensions.

Strategies to maintain and restore soil structure

Successful soil management should avoid soil structural damage and alleviate severe compaction when it occurs. Moreover, any soil management strategy should include methods to improve soil condition as well as those that repair damage.

Key management practices that help minimise soil compaction include:

- timing operations to avoid travelling on and cultivating soils when they are wet
- limiting vehicle weight and carefully controlling tyre pressures
- avoiding growing root crops and late harvested crops on vulnerable soils
- enhancing soil organic matter (SOM) levels to improve soil structure and the stability and resilience of soils to degradation.

This paper considers the importance of soil structure to crop productivity and nutrient use efficiency and looks at the use of visual soil evaluation techniques for assessing soil structural condition. Methods for restoring and maintaining good soil structure are also discussed.

Challenges and opportunities for environmentally sustainable nutrient use

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Introduction

Global demand for livestock products is increasing, with an estimated increase of 70% by 2050, associated with growing populations, rising affluence and urbanisation (Gerber *et al*., 2013). As the agricultural land use area per person is declining, the accommodation of intensified production to satisfy global demands, such as that anticipated for livestock products, requires prudent management to guarantee the sustainability of the soil and land base. In Ireland, ambitious expansion of the agri-food sector under the governments Food Harvest 2020 strategy (DAFM, 2010) and reinforced by the Food Wise 2025 strategy (DAFM, 2015), encourages farmers to expand and intensify their grassland systems by increasing stocking rates and extending the grazing season. Since the abolition of the milk quota in 2015 the European dairy industry, which is the dominant farming system in a number of northern European countries, is challenged by these demands (Micha *et al*., 2018). However, while intensification will enhance production volume and economic growth, in the longer term it could also severely impact soils and environment if not managed carefully (Courtney, 2013).

Irish grass based farming systems

Grasslands make a significant contribution to food security through providing part of the feed requirements of ruminants used for meat and milk production. There is a renewed interest in grazing systems in many temperate and subtropical regions of the world and in Ireland, over 90 % of the agricultural area consists of pasture, grass silage or hay, and rough grazing (O'Mara, 2008). Dairy farms are anticipated to increase to 16,500, with 1,500 new entrants to milk production since EU milk quotas were abolished in 2015. In 2016, total milk output was estimated at 7.5 billion litres (Teagasc, 2016). Irish dairy farms are predominantly grass based and focus on increasing the conversion of grass into milk. To achieve this dairy cows are genetically selected to provide higher milk production from grass as the main feed input. The utilization of grass by grazing should provide a sustainable basis for livestock production systems as grazed grass is the cheapest source of nutrients for ruminants (O'Donovan *et al*., 2011). With feed cost, including the fertiliser cost for producing that feed, accounting for over 75% of total variable costs on these livestock farms (Connolly *et al*., 2010) the production of sufficient grass for the grazing herd has a significant impact on farm profitability (Shalloo *et al*., 2004; Finneran *et al.,* 2010). Farm and field level nutrient management best practice have been shown to significantly improve both farm level profitability (Buckley and Carney, 2013)

From 2013 to 2015 average levels of grass dry matter (DM) production on intensive dairy farms measuring grass in Ireland ranged from 8.0 to 18.5 t/ha (O'Leary *et al*., 2016). Dairy cows graze for on average of 280 days a year, with stocking rates of over 3 cows per hectare on the main grazing platform on more intensive dairy farms (Shalloo *et al*., 2011). However, grass production between and within farms can vary widely depending on a number of soil, climate and management related factors.

The Irish drystock and dairy farming systems are based on increasing the conversion of grass into meat and milk. Irish farms have expanded rapidly over the last number of years. Average dairy herd size in 2016 was approximately 93 cows/farm, which requires farms to increase the amount of grass grown to meet an increasing herd feed demand. Increasing stocking rates and more compact calving has resulted in increased spring feed demand on dairy farms. Extra grass must be grown and utilised in this period to avoid increases in supplementary feed use. With increasing herd size on dairy farms there is a significant growth in milk production and milk constituents (expected average protein of 3.56% and butterfat of 4.25%), through improved herd genetics and better grassland management and grazed grass utilization. Table 1 shows the future targets for manufacturing milk production in Ireland (Teagasc, 2016).

Table 1. Technical performance for manufacturing milk production herds (Teagasc, 2016)

Performance parameter	Current av. (2013-2015)	2025	Research Targets
Milk Delivered (kg/cow)	5,036	5,739	5,800
Milk Solids (kg fat plus protein/cow)	372	448	475
Calving Interval (days)	394	385	365
Herd Economic Breeding Index (€)	55	180	230
Stocking Rate (LU/ha)	1.96	2.15	2.94
Herbage Utilised (t DM/ha)	7.36	10.0	12.7
Concentrate per Cow (kg)	1,008	750	400

GHG (kg CO_{2e}/kg m^2)	1.10	0.97	0.83

However, these future production targets for dairy farming systems depend on a constant supply of high quality grass for the grazing cow, inevitably result in an increasing use of chemical fertilisers. Therefore efficient use of fertilisers is critical for sustainable intensification of dairy production systems. Identifying the optimum quantity of fertiliser to sustain grass growth over a long growing season will also minimise the potential for fertiliser losses and negative impacts of nutrients nitrogen (N) & phosphorus (P) in the environment.

Challenges for meeting environmental sustainability on farms

The Irish governments Food Harvest development plan has been further extended under the Food Wise (FW) 2025 Strategy, which envisages a further increase in dairy production as well as significant expansion of the arable, pig, poultry and forestry sectors. However, all future expansion of output will have to be carried out whilst maintaining environmental sustainability. Indeed, the strategy has adopted as a guiding principle that "… environmental protection and economic competiveness will be considered as equal and complementary, one will not be achieved at the expense of the other." Sustainability is understood to encompass economic, social and environmental attributes and the subsequent strategic environmental assessment of FW2025 proposed the need to embed sustainable growth into FW2025 plans. The definition of this sustainable growth recognises the need to achieve a balance between economic, environmental and social objectives and sustainable growth should seek to increase the value added by the sector per unit of emissions (GHG or ammonia) produced.

It is well known that adequate N and P fertilisation in particular are critical for achieving high levels of production (Wall and Plunkett, 2016), however, these nutrients can also have negative environmental consequences when N and, or P are lost to aquatic systems and or when N is lost in certain gaseous forms to the atmosphere.

Sources of N in agricultural systems are generally anthropogenic and with a heavy dependence on external addition of fertiliser (Van Grinsven *et al*., 2012). As nutrients cycle though the farm system, unavoidable losses occur (Hilhorst *et al.,* 2001). Losses of nitrogen (N) occur by three major loss pathways; nitrate (NO_3) leaching, denitrification as di-nitrogen gas (N_2) or nitrous oxide (N_2O), and ammonia (NH_3) volatilisation (Stark and Richards, 2008). Nitrate leaching leads to the enrichment of surface and ground waters causing the eutrophication of rivers, lakes and estuaries. Considering that cows are responsible for 62% and 64% of emissions of nitrous oxide (N_2O) and ammonia (NH_3) respectively (Steinfeld *et al*., 2006), from an intensification perspective, the increase in stocking rates will lead to higher N losses in water pathways due to the greater production of urine, slurry and dairy-soiled water (Selbie *et al*., 2015, Necpalova *et al*., 2012). An inefficient use of N will most likely compromise the natural N balance, leading to N contamination wherever soil attenuation capacity (or water attenuation function) does not support complete bioremediation. Increasing N use without a corresponding increase in efficiency therefore raises concerns about the achievement of sustainable intensification for Ireland's agricultural industry, especially considering that the ecological status targets set out for surface waters have not yet been achieved (EPA, 2016).

Phosphorus is considered the second most important nutrient for grass growth following nitrogen and a key nutrient that supports herbage yields (Sheil *et al*., 2016) and farm exports (Mihailescu *et al*., 2015). Phosphorus is applied on grassland mainly through chemical fertilisers and in organic manure applications (Heckenmüller *et al*., 2014; Micha *et al*., 2018). Plant available P in the soil is a much smaller proportion of the total P reserves with approximately 1% of P available for plant uptake (Schnug and Haneklaus, 2016). As drystock and dairy farming in Ireland is pasture based, use of P chemical fertilisers is part of the standard grassland management process (Micha *et al*., 2018). Some soils are more prone than others to "lock up" P and this will lead to difficulties on building up optimum P levels as per soil test. This can result in excessive use of P fertiliser which can lead to losses from soil into water bodies leading to eutrophication and ecosystem quality degradation (Gourley *et al*., 2012). Relatively small losses of P can be quite significant in terms of water quality (Jarvis and Aarts, 2000). Indeed, P loss to water is Ireland's greatest environmental concern (Toner *et al.*, 2005). Phosphorus loss is associated with high soil P levels and the inappropriate timing of fertiliser P applications, such as during periods of low crop demand or heavy rainfall. Phosphorus losses from agriculture have been reported to majorly contribute to the diffuse pollution of water bodies across Europe (Carpender, 2008), emphasizing the need for careful P fertiliser use. Given this, along with the finite nature of P resources, efficient P fertiliser use in dairy systems is of great concern (Mihailescu *et al*., 2015).

Green House Gas (GHG) emission targets 2021-2030

Ireland has been set targets of 30% reduction in GHG emission by 2030, to be achieved by linear reduction from 2021-2030 based relative to a 2005 baseline (
18.69 Mt CO_2-e). This equates to a total reduction of 5.6 Mt CO_2-e based on emission levels in 2005. However, GHG emission have increased since 2005, (19.24 Mt CO_2-e in 2016) which means that higher levels of reductions will be needed to reach this target.

Ireland has been offered flexible mechanisms, with 4% of the target achievable through the use of banking/borrowing of EU Emissions Trading Sector allowances and 5.6% achieved via offsetting emissions by sequestering carbon dioxide (CO_2) in woody perennial biomass and soils through land use management (of forestry, grasslands, wetlands and croplands) and land-use change (from cropland to forestry for instance).

Achieving 2030 climate targets as well as delivering carbon neutrality will be extremely challenging for the agriculture, forestry and land-use sectors. Mitigation of methane (CH_4) and nitrous oxide (N_2O) (1.85 Mt CO_2-e) , combined with carbon sequestration (2.97 Mt CO_2-e), and energy displacement delivers a 6.19 Mt CO_2e per annum saving for the periods 2021-2030 at a net cost (including efficiency savings) of circa €34 million per annum. When cost savings from efficiency measures are removed, the gross cost of measures is €223 million per annum (Lanigan and Donnelan, 2018).

Ammonia emissions targets

Aside from the pressures to reduce GHG emissions, the requirement to also reduce ammonia emissions is not only urgent in the context of the National Clean Air Strategy, but as a principal loss pathway for agricultural nitrogen, ammonia emissions reduction should be a key focus for improving farm efficiency and sustainability. This is particularly relevant in the context of the Food Wise 2025 Strategy. Similar to GHGs, by 2030 ammonia is projected to increase by 6% relative to 2005, with a 1% reduction target from 2020 to 2030 and a 5% reduction target set for 2030 onwards.

Teagasc analysis (Lanigan et al, 2018) has indicated that there is a maximum potential ammonia mitigation of 22 kt NH_3/yr by 2030 at a cost of €79M per annum, with most abatement achieved via the use of a urea fertiliser that is coated with a urease inhibitor, the adoption of trailing shoe/trailing hose technologies for slurry spreading and slurry amendments. These measures have the potential to reduce GHG emissions by 168.6 kt CO_2-e /yr mainly from measures including reducing crude protein in pig diets, the use of slurry amendments and the adoption of low-emission slurry spreading methods.

Ireland ammonia and GHG emissions profile is shown in figure 1. The majority of ammonia related emission originates from animal manure (housing, storage and spreading) with emissions during the grazing period being a smaller proportion. The GHG emissions profile is much different with manure management (~10% in total) being a relatively small percentage of total GHG emissions from agriculture. Methane emissions produced by enteric fermentation in ruminant animals is the largest contributor to GHG emissions and there is considerable debate surrounding magnitude of effect of this GHG source on global warming potential and climate change effects.

The next biggest contributor to GHG emissions is N_2O coming from managed soils mainly resulting from N inputs as chemical fertilisers. In terms of gaseous emission mitigation any management or option that improves N use efficiency will help to reduce the quantity of ammonia and GHG's from agriculture.

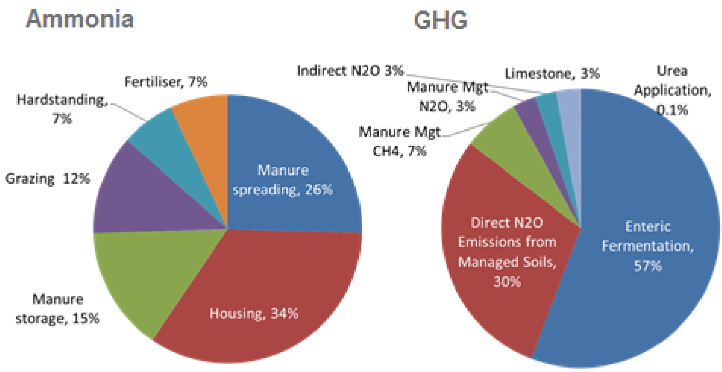

Figure 1. Irelands ammonia and green house gas (GHG) emissions profile (source Teagasc)

Realising the GHG mitigation potential of agriculture is ultimately dependent on farm-level decisions based on how adoption will benefit the individual farmer. Mitigation options that both reduce GHG emissions and increase farm productivity, i.e. cost- effective practices, are more likely to be adopted than practices which would negatively affect the farmer's income. Policy makers must therefore develop a better understanding of individual farmer's decisions and behaviours, in particular at a local level due to spatial heterogeneity, if policy is to be effective and encourage adoption of GHG mitigation practices (OECD, 2012).

Nutrient requirements of grass swards

Fertiliser use is projected to increase over the period 2016 to 2030. As the more fertiliser intensive dairy sector increases its production it is inevitable that more N fertiliser will be used to grow grass. Given the challenges outlined, it is of critical important that N and P fertilisers are used as efficiently as possible by the crops and grassland that receive them. Grass requires a continuous and balanced nutrient supply from the soil to achieve its production potential. Some well managed and fertile farms are capable of growing in excess of 16 t grass DM/ha annually. This level of grass production requires large quantities of nutrients, such as the major nutrients N, P, potassium (K), and sulphur (S) (Table 2). However, only a fraction of these quantities of nutrients are required as fertiliser inputs due to the continuous recycling of nutrients that occurs in grazing systems and nutrient cycling within the soil. These high nutrient uptake requirements by grass swards show the importance of having soils in optimum condition to supply a range of nutrients when required over a relatively long growing season (Figure 1).

Table 2. Typical concentrations of N, P, K and S in a tonne of grass DM, and the total uptake of each nutrient required in a full year by swards growing 16 t grass DM/ha

Nutrient	Typical nutrient concentration in grass (kg/t dry matter)	Total uptake required for 16 t grass DM (kg/ha)
N	34.9	558
P	4.1	67
K	29.7	475
S	2.9	46

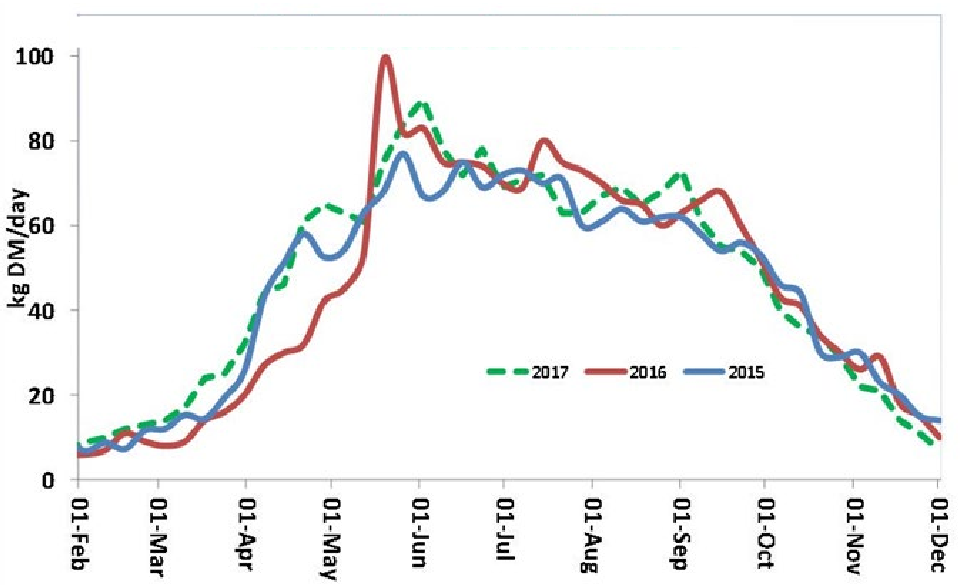

Figure 1. Average national grass growth, kg dry matter per day, across dairy farms measuring and recording grass growth in Ireland over the 2015, 2016 and 2017 growing seasons. Data source Teagasc Pasture Ireland.

Soil fertility status of grassland soils

Each year soil samples are taken on a sample of commercial grassland farms by Teagasc advisory services and submitted for soil test analysis. The standard soil test analysis includes soil pH and soil test P and K (in Morgan's extract). Soil fertility had been in decline since the mid-noughties, linked closely with lower lime and lower compound fertilizer use, and had reached very low status between 2013 to 2015 with just 10% of soil samples showing good overall fertility in terms of pH (>6.2), P and K (≥ index 3) status. Over the last decade in particular, a worrying trend of continuous mining of the native fertility of some soils may have eroded their grass and crop production potential limiting their ability to maximize grass as our main fodder source and to maximize the yield potential from new cereal varieties. However, the Teagasc soils data base now indicates large improvements in soil pH levels and early signs of improvements in both soil P and K levels on farms, although the rates of these improvements are enterprise specific.

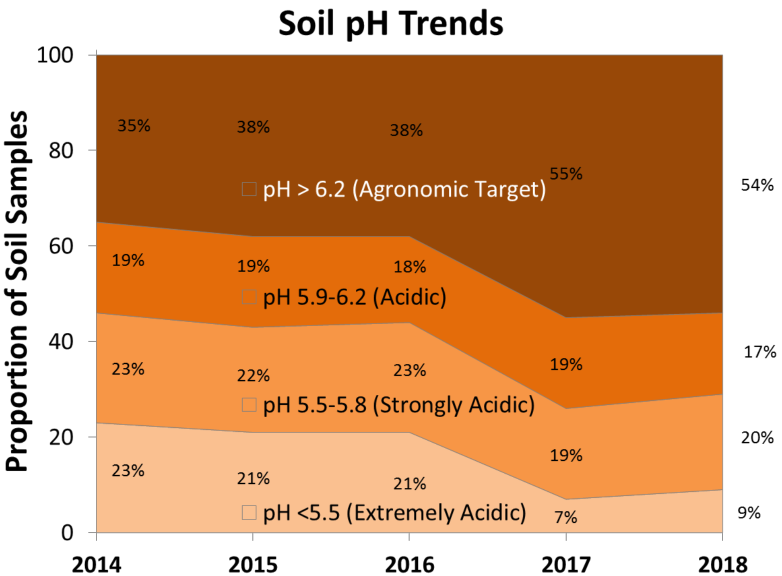

Figure 2. Proportion of soils analyzed which fall into each soil pH range across all farm types. Based on total of 223,000 soil samples analyzed by Teagasc between 2014 and 2018.

Soil pH levels on dairy and tillage farms have shown the greatest improvement since to 2016 and increased annual lime applications have contributed to a dramatic change in national soil pH status over the last five years with 64% soils below optimum pH in 2014-15 and just 46% in 2017-18 (Figure 2)

Declining trends in grassland soil fertility between 2006 and 2016 clearly indicated that the production potential of grassland soils in Ireland was being slowly eroded.

In particular the rate of decline in soil P and K levels were quite serious, and if allowed to continue may undermine the resilience of the grass based production systems and the expansion of our national livestock sector (dairy and meat output) and the achievement of both volume and value targets as set out in Food Harvest 2020 and the more recent Food Wise 2025 agri-sector growth strategies. Furthermore large additional costs for soil P build-up will be incurred by farmers in order to regain the production potential of their land in the future.

Since 2016 all farm enterprises have made progress in relation to soil fertility (Figure 3). Overall soil fertility on tillage farms had the largest increase with approximately 20% of soil samples with the optimum mix of pH, P and K for crop production. Dairy farms were next with approximately 15% of soils with good overall soil fertility. Drystock farms showed the least improvement with just 11% of samples with good overall soil fertility. These poorer results on drystock farms may be influenced by a number of factors such as lack of profitability, lower fertilizer use, lower feed demand and need to maximise grass production especially where stocking rates are low. While the majority of these overall soil fertility improvement has resulted from positive changes in soil pH across all farming enterprises there are also indications that soil K, and possibly P, are also improving.

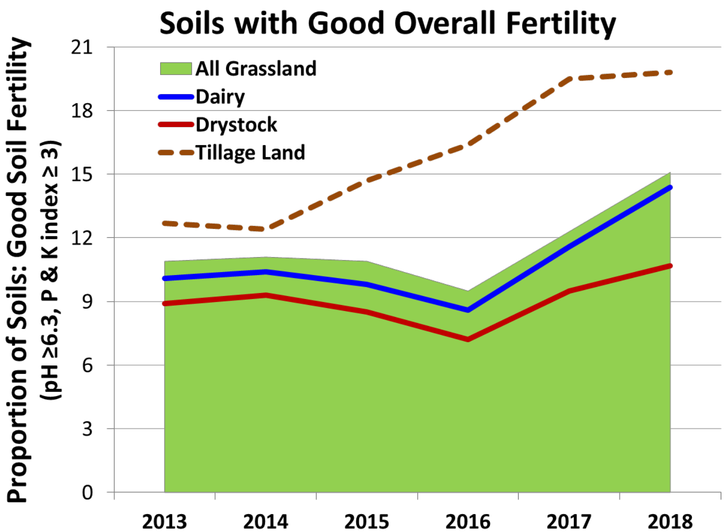

Figure 3. Proportion of soil samples analysed by Teagasc that had optimum soil fertility (pH ≥6.3 and P 7 K index ≥3) for tillage, drystock and dairy farms between 2013 and 2018.

These positive trends in national soil fertility represent a foundation to build on. While these trends represent a snapshot at a national scale, the real focus is needed at farm, and even field scale to develop a balanced fertilizer programme and to utilize organic manures resources where they are most beneficial on low soil P and K soils. Soil fertility is a cornerstone of our grass based animal production systems and critical for enhancing crop yields and quality into the future as well as achieving economic and environmental sustainability.

Long term fertiliser use in Ireland

Overall fertiliser N sales in Ireland have remained relatively constant since 1990, compared to fertiliser P and K which declined sharply from 1990 to 2009 (Figure 4). Over the past 10 years sales fertiliser P and K have recovered somewhat with current P and K use similar to that in the year 2000.

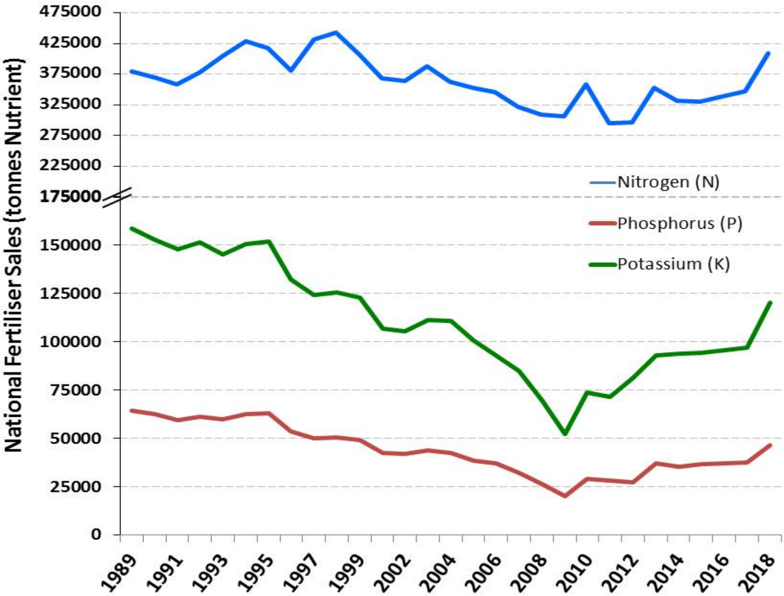

Figure 4. National fertiliser N, P and K sales (tonnes of nutrient)between 1989 and 2018. (source DAFM).

The national fertiliser use survey (Dillon *et al.*, 2018) examines long term developments in farm and crop scale fertiliser use across the Republic of Ireland. The analysis is based on data collected by the Teagasc National Farm Survey (part of the EU FADN network) covering the years 2005 to 2015. This is a period when fertiliser use on farms in the Republic of Ireland has been constrained by the EU Nitrates Directive regulations. This longer term study provides a better picture of fertiliser use trends at farm level than short term analysis. Data showing short term trends in fertiliser use can be affected by fertiliser price levels and weather variations and are a less reliable indicator of longer term changes.

The NFS is based on a nationally representative random sample of the farming population. The 2015 results are based on a sample of 898 farms which represents 84,259 farms nationally. Results are presented for average quantities of N, P and K and lime applied at farm level on grassland and arable farms between 2005 and 2015. Trends in fertiliser use by nitrates zone, land use class, farm system, stocking rate and agri-environmental scheme participation are provided (Dillon *et al*., 2018). These NFS data results close track annual sales data of N, P and K from the Department of Agriculture, Food and the Marine (DAFM).

Results indicate that average N, P, K, fertiliser application rates on grassland tended to be between 11-16% lower at the end of the study period compared to the start, with more dramatic declines in application rates noticeable in the mid-study period (23-52%) The years of lowest grassland fertiliser use (2008-09) coincided with the period of higher fertiliser prices, while higher than average fertiliser application rates in 2013-2014were associated with the aftermath of a national fodder shortage with similar higher fertiliser use trends in 2018 following a very wet spring and drought conditions in summer. Higher application rates of N, P and K on grassland were generally associated with farms in Nitrates zone A (longer growing period), farms of wide land use potential, dairy farms and farms with higher stocking rates.

Nutrient use efficiency on dairy farms

Farm and field level nutrient management best practice have been shown to significantly improve both farm level profitability (Buckley and Carney, 2013). Since the introduction of 1st EU Nitrates Directive – National Action Programme (NAP) in Ireland in 2006, there have been declines in farm-gate N and P surpluses and increases in N and P use efficiencies as was shown in a study carried out by Buckley *et al.* (2016a and 2016b) across 150 specialist dairy farms continuously participating in the National Farm Survey (NFS) between 2006 and 2012. The study showed that this efficiency increase is driven by efficient use of inorganic N and P fertilisers and organic nutrient sources on these farms.

Nitrogen balance declined by 25 kg/ha from 180 to 155 kg/ha over the study period, this was attributable to reduced chemical N fertiliser imports of 23 kg /ha. Nitrogen use efficiency (NUE) improved by 2.1% over the 2006-12 period from 20.8 to 22.9%. Phosphorus balance declined by 50% from 12 to 6 kg/ha between 2006 and 2012. This decline in P balance can be attributed to reduced chemical P fertiliser inputs of 7 kg /ha and has had a knock on effect in declining soil P (and K) fertility levels during this period While P use efficiency (PUE) was shown to improve by 18% over the study period from 60 to 78% this extra efficiency was gained from mining soil reserves and is not sustainable into the long run after soil fertility has declined. Over this period milk solids output increased from 405 to 450 kg/ha (at a stocking rate of 1.86 to 1.84 LU/ha) across these 150 specialist dairy farms indicating increased efficiency in cow productivity in the national herds (as indicated by increasing herd EBI over this period). Mihailescu *et al.* (2014, 2015a, 2015b) also reported notable shifts in farm practice aligned with utilizing organic manures according to their nutrient value (e.g. spring applications) citing the change to the "positive impact of NAP regulations".

High reliance on grazed grass and a low proportion of concentrate in the diet of dairy cows in Ireland is a key contributor to Irish dairy farms having the highest P use efficiency in the world (Figure 5, which is in sharp contrast to the situation in most other EU countries and even Northern Ireland, where concentrate inputs are higher. There have been substantial improvements in slurry storage and slurry and dirty water management on Irish farms over the past decade. Paradoxically, soil deficiencies of lime, P and K have been identified as a key area for improvement because declining soil fertility has a negative impact on grass growth and the economic performance of farms.

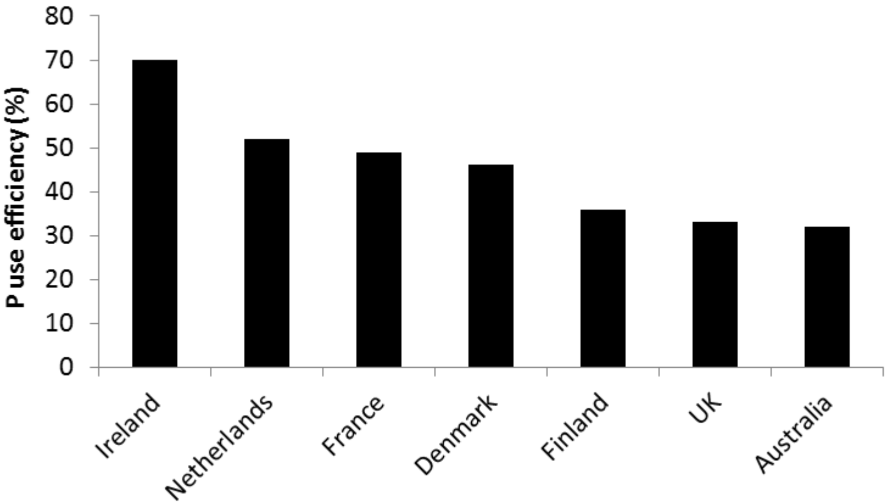

Figure 5. Phosphorus use efficiency (the ratio of P inputs to a farm that end up in products sold off the farm) on dairy farms in different countries (after Humphreys 2018).

Nutrient N, P and K balances at field scale on intensive dairy farms

A study of 21 dairy farms spread across the south of Ireland commenced in 2015 to evaluate nutrient management practices at the field and paddock scale. These farms were selected to represent different biophysical and management conditions across the south and south east of Ireland. All farms had grass based spring calving dairy systems and the total herd size ranged from 59 to 245 cows, with an average of 131 in 2016. The stocking rate on the milking platform ranged from 195.6 to 379.7 kg Org N/ha/year (2.3 to 4.5 cows per ha). All farms increased herd size by an average of 15 cows in the year following the EU quota abolition (2015). Holstein-Friesian was the predominant breed used on most farms. Most farms imported concentrate feed only to supplement the grazed grass diet for their cows; however, two farms grew maize as additional feed. Each farm was intensively soil sampled on a per paddock basis in 2015 and 2016. Grass growth was measured throughout each growing season in each paddock individually. These data were coupled with biophysical data including soil type, drainage, weather etc. and management data including fertiliser and slurry applications, grazing management etc. to evaluate nutrient flows, recoveries, losses and efficiencies within and between farms.

Results from these dairy farms highlight high spatial variability in soil fertility status within farms (Murphy *et al*. 2018). In particular, low pH levels are impeding grass production by reducing the nutrient availability of both stored nutrients in the soil and freshly applied nutrients. Current nutrient management practices do not address variability issues at the sub-field scale. The requirement for increasing applications of lime, P and K indicated that farmers were not prioritising nutrient management in line with increasing stocking rates. In 2015-16 the average grass nutrient uptake demand corresponding to grass production per paddock (n=384) was 356 kg /ha N, 37kg/ha P and 278 kg/ha K.

Nutrient balances were calculated at the farm scale and the field scale as follows:
Nutrient Balance = Nutrient Inputs - Nutrient Offtakes

Where nutrient inputs are: nutrient in fertiliser, manures and concentrate feed. And nutrient offtakes are: nutrients in milk, meat and silage/hay. The average nutrient balance per paddock across these intensive of these dairy farms were 133.60 kg/ha N, -1.6 Kg/ha P and 14.83 kg/ha K in 2016 (Table 3).

Table 3. Average nitrogen, phosphorus and potassium balance at the field and whole farm scale for intensive grass based dairy farms in this study (Murphy et al., 2018).

Average field/paddock scale nutrient balance (kg/ha)				
Sample size	Year	Nitrogen	Phosphorus	Potassium
n = 384	2015	**133.67**	**-4.52**	**9.29**
n = 384	2016	**133.60**	**-1.64**	**14.83**
Average farm scale nutrient balance (kg/ha)				
n = 10	2015	**75.47**	**2.41**	**18.25**
n = 10	2016	**67.34**	**1.03**	**12.32**

The OVERSEER™ model, developed for New Zealand conditions, was parameterised and calibrated for Irish grassland conditions in order to model the nutrient flows and to estimate nutrient balance, N leaching and P run-off within Irish dairy farming systems. Focussing on N leaching, the OVERSEER™ modal estimated on average 49kg/ha/yr N leached from the rootzone across these dairy farming systems. Although results for N balance at both scales indicate N surplus, the farm scale balance has a smaller range and also a smaller mean value. In contrast the field scale balance has a larger sample size and a bigger range in N surplus values indicating a large variability N use efficiency between fields due to difference soil type, soil fertility, sward composition, land use etc. However, the field scale approach proves its usefulness when the data is split into appropriate categories or groupings based on cropping type (Figure 6) or soil drainage class (Figure 7).

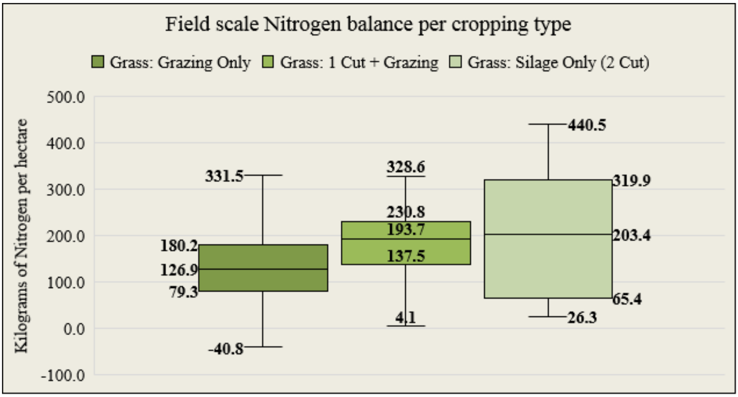

Figure 6. Average field nitrogen balance per grassland use and management type across dairy farms in 2016. (Murphy et al., 2018)

These results indicate that there are opportunities to reduce N surplus and losses on dairy farms at both farm and field scales. Overall, it may be necessary to reduce the total amount of N being imported to reduce N surpluses however; increased efficiency can be achieved by better distribution of N inside the farm boundary. For example, differences in N balance per field was affected by crop use: grazing only < grazing and 1st cut silage = 2nd cut silage (Figure 6). Another more common example of categorising fields for different management would be by function, such as "milking platform", "out-block" and "silage block". Nutrient management strategies across these groupings are often not optimised to match to the different grass production functions, as shown by the range in N balance values in figure 5. By categorising fields into groupings such as these improved targeting of N application (fertiliser and manure) can be achieved and result in economic and environmental benefit. The range in field scale nutrient balance results can be driven by a number of factors; from soil fertility differences and management factors to landscape factors including soil type, drainage class and slope. The fields can be categorised appropriately and matched to nutrient management plans according to desired outcome e.g. decrease P run-off loss risk by identifying fields that have steep slopes. In the case of N, the identification of fields that have a different drainage class can better inform fertiliser planners which fields pose the greatest risk of N leaching. Figure 6 highlight the effect soil drainage class on N balance. The average surplus is greatest on fields that are well-drained soils while the surplus is lowest on fields that are poorly drained. Well-drained fields require careful consideration when deciding on N rate, N type and N timing to minimise N leaching while poorly drain soils need similar consideration in relation to N loss through denitrification.

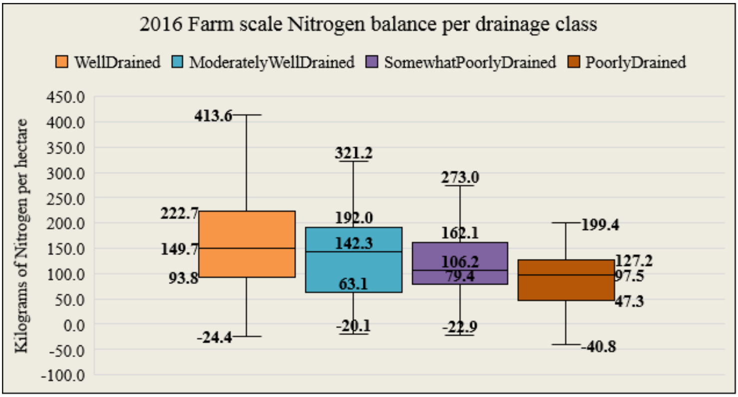

Figure 7. Average field nitrogen balance per drainage class across farms in 2016 (Murphy et al., 2018)

Modelling the N (and P) flows on these farms proved insightful and the development of nutrient management strategy that account for field scale nutrient balance differences and groups fields for more targeted nutrient managements strategies would be a progressive step towards improving the production, economic and environmental sustainability of Irish dairy systems. Understanding the field scale nutrient balance and the factors that affect them are critical information that can be used to enhance current fertiliser planning methodologies on grassland farms.

Nutrient management for achieving production and environmental targets.

Different soils have variable capacity to produce grass and crops due to their intrinsic physical and chemical characteristics, their biology and the climatic environment in which they occur. In Ireland the variability of soils is often very broad and soil characteristics can change dramatically over relatively small spatial areas, even within fields. This presents particular challenges when planning nutrients and fertilisers management strategies at farm level. The tendency is often to apply the same fertiliser plan to all fields that are perceived to have similar characteristics and similar grass growth potential. However, this type of blanket approach, where all fields are equally treated, does not reflect the real heterogeneity of soil characteristics and qualities. It is important to address nutrient application to specific soil type so that a correct nutrient balance is achieved (Wall and Plunkett, 2016). Teagasc has mapped our soils at regional scale with soils information available through the Irish Soil Information System (http://gis.teagasc.ie/isis/). Across 11 Great Soil groups identified in Ireland the more intensive and productive ones are Brown Earths, Brown Podzolics and Luvisols, which are considered well to moderately drained soils, sufficiently able to retain nutrients and for this reason more suitable for growing crops. These lighter and well-drained soil types are likely to be very responsive to nutrient inputs including N, K and S fertilisers. However, timing of fertiliser application is important on these soils as applications during wetter seasons increases the risk of nutrient, especially N, leaching with draining water. On the other hand, some wet soils such as Alluvial soils and drained Surface-Water and Ground-Water Gleys, usually considered less productive, often receive a more active management by farmers to influence their fertility status. When conditions are favourable, these soils can supply relatively high levels of N and P and other nutrients from their reserves of organic matter. These soils can be very acidic and often require high rates of lime on a regular basis. The main risk of nutrient loss with these soil types is the risk of denitrification for N and run-off for P which can happen if the soil is waterlogged for a certain period of time. Similar mechanisms occur when Gley soils are subjected to application of P fertilisers as they are more prone to P loss after heavy rainfall if water flows off the surface, which can represent a loss on investment (Wall and Plunkett, 2016).

Site-specific soil testing and soil-specific nutrient management planning

Experienced farmers will know that not all soils (or fields) have the same production potential (or suitability for certain crop types) or response in terms of their soil fertility status to the nutrients that are applied. This poses a challenge for individual farmers and their advisors when planning nutrient and fertiliser management strategies for their farms. Using a blanket fertiliser approach, where all fields, even with similar soil test results, receive and "are perceived to respond" to similar nutrient application rates may not achieve the desired outcomes in reality. This is because different soil types possess different characteristics and qualities to receive, store and supply nutrients for grass growth.

Soil testing and soil quality assessments are critical tools when fertiliser plans are being developed for farms. Recent studies showed that the risk of nutrient losses are site specific and can be due to several factors (Doody *et al.*, 2014, 2012;

Roberts *et al*., 2017). The quality of agricultural soils is deemed to play a role in the cycling of nutrients into residues and convert these nutrients in forms that can be used by crops (Wall and Plunkett, 2016; Schröder *et al.,* 2016). Farmers play a pivotal role in managing soil fertility by applying inorganic or/and organic fertilisers and build up or maintain the supply of nutrients required for grass production. However, if experienced farmers recognise differences in production potential of different soils, other farmers might not be aware about actual soil conditions/characteristics on each field within their own farm, due to lack of soil testing, and may overestimate or underestimate the nutrient application rate (Roberts *et al*., 2017). Increased farmer awareness and advice is required to address field scale soil fertility issues and to develop a specific suitable fertiliser plan (McDonald *et al*., 2018). However, the attention needs to shift from a quantitative approach based only on the evaluation of chemical features to a qualitative approach that considers also other factors such as: soil type, geographical position, hydrogeology and drainage characteristics, management and grass type (Brereton, 1995, Shalloo *et al*., 2011).

Conclusions

Fertiliser is an important investment on grass-based dairy farms and represents >25% of total variable production costs. On grassland farming systems, with one main crop type "grass" typically the only differentiation for fertiliser programmes is between the areas used for silage/hay and that continuously grazed. However, "one soil does not fit all" and developing fertiliser application strategies without appropriate field-by-field or paddock scale information on soil fertility, soil types and grass sward productivity levels is impossible and leads to poor return on fertiliser investment, resource use and potential losses of nutrients to the environment. Soil testing costs less than 1 kg of fertiliser P per ha per year (€2) and having up to date soil test results for the whole farm is essential when selecting the right <u>fertiliser type</u>, and deciding the right <u>fertiliser application rate</u> and right <u>fertiliser application timing</u> for the <u>right field/place</u>.

Although it costs money to increase soil fertility levels, the returns in terms of increased grass production from low fertility soils can be considerable (>2.0 tonnes grass dry matter per ha, worth approximately €362/ha), and can increase the livestock carrying capacity (i.e. stocking rate) of the farm, provide additional winter feed stocks (silage), improve animal health (nutrition value of the grass), increase milk and meat outputs and ultimately whole farm profitability.

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Smart Farming: reducing costs while taking climate action on farms

Andrew McHugh and Thomas Ryan

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Introduction - What is Smart Farming?

Smart Farming is a voluntary resource efficiency programme led by the Irish Farmers' Association (IFA), in conjunction with the Environmental Protection Agency (EPA).

The programme collates existing knowledge and expertise from Ireland's leading academic and advisory bodies, state agencies and technical institutions. It communicates this knowledge in a targeted way, to deliver on the *double dividend* of improving farm returns and enhancing the rural environment through better resource management.

The programme's scientific foundation is derived from Teagasc's *Marginal Abatement Cost Curve (MACC)* for Irish agriculture (Figure 1). This cost curve quantifies the opportunities to reduce agricultural greenhouse gases, as well as the associated costs or benefits.

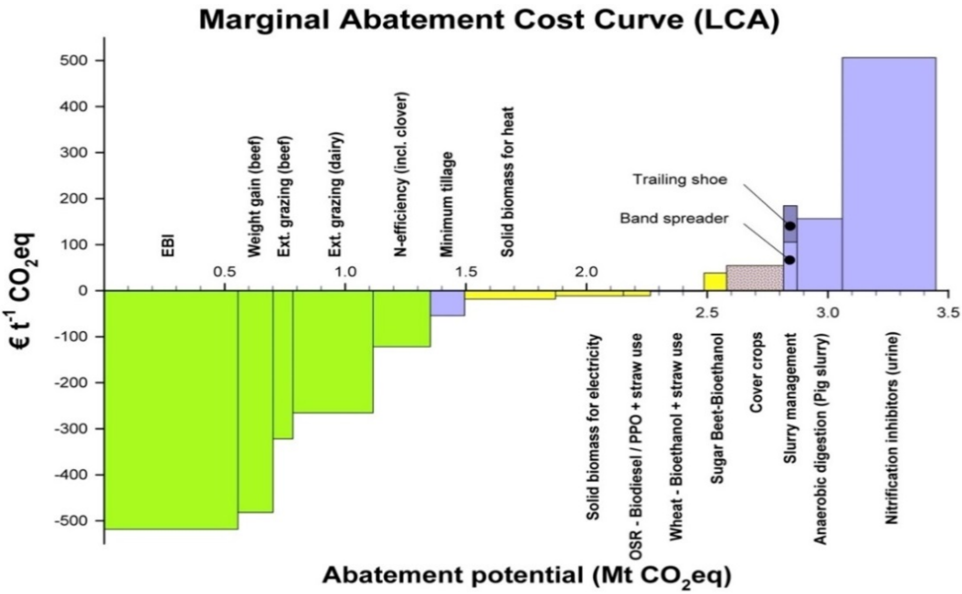

Figure 1.Marginal abatement cost curve, based on life cycle assessment analysis (Teagasc).

Over 80% (c.2.8 Mt CO_2eq.) of the measures identified are considered to be cost-efficient, i.e. the adoption of these measures is good for the environment and also saves farmers money.
The development of the Smart Farming programme and identification of the eight focus areas (Figure 2) of the programme were strongly influenced by this research.

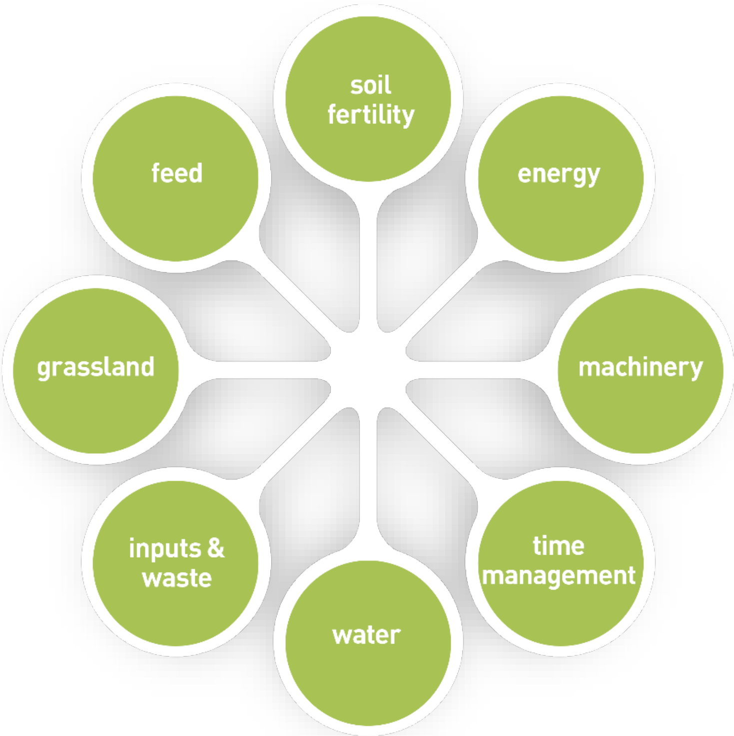

Figure 2. Smart Farming focus areas

The Teagasc *MACC* research and *Four Well-Beings of Community Sustainability* (Figure 3) continue to be at the centre of all Smart Farming's activities. This community sustainability model advocates that society can have a long-term positive impact on the wider environment and their own well-being when environmental needs are better aligned with the economic, social and cultural needs of individuals, in this case – farmers. Thus, Smart Farming is focused on improving farm returns and enhancing the environment by operating through accepted cultural communication norms such as discussion groups, IFA branches and purchasing groups.

Figure 3. Four Well-Beings of Community Sustainability

Smart Farming – improving farm returns

Each farmer who participates in the Smart Farming programme receives a resource efficiency assessment (REA) of their farm, which is also called a cost saving study. These REAs are completed by a qualified agronomist who has a minimum level 8 qualification and is an agricultural science graduate.

In preparation for the REAs, the participating farmers submit the following information to the Smart Farming agronomist:

- House & farm electricity & fuel bills (heating & diesel) for the previous 12 months.
- Results of any soil samples that may have been taken in recent years and the farm map showing where soil samples were taken.
- Any Nutrient Management Plan completed in the last 2 – 3 years.
- Copy of the most recent Basic Payment Scheme application form (without details of the value of the Basic Payment, as this is not required).
- Copy of BPS Maps sent from the Department of Agriculture, Food and the Marine.
- Land Parcel Identification numbers.
- Water:
    - Water bills for previous 12 months (if using water supply other than own well).
    - Results of any water quality tests.
- Feed - dockets for the previous 12 months.
- Results of the most recent silage tests.

Using this information, the Smart Farming agronomist prepares a draft desktop REA, which focuses on identifying average cost savings on each participating farm of €5,000. This is delivered by focusing on the eight themes of soil fertility, inputs and waste, grassland, feed, energy, machinery, time management and water - as identified in figure 1.2.

The net cost savings identified often require an initial investment. For example, an expenditure on lime may be required to address underlying soil pH issues, in order to maximise grass growth and reduce more expensive concentrate requirements. Therefore, the cost savings identified in the draft REA will also include the likely payback period, so that the farmer can determine whether it is reasonable when considered against the investment required.

The agronomist then completes a farm walk with each participating farmer. This is used to examine the information provided and to get a more complete understanding of particular areas of farm management including the grassland reseeding plan, approach to feed purchasing, energy management and nutrient management.

The REA is then finalised and discussed with the participating farmers in advance of the REA being disseminated to the host farmer's discussion group, IFA branch or purchasing group.

At the discussion group meeting, the completed REA is presented by the Smart Farming agronomist and the host farmer. Robust and challenging exchanges usually take place during which the recommendations in the REA are questioned and debated.

Smart Farming – enhancing the environment

As part of the REAs, participating farmers receive a suite of environmental indicators for their farms. A carbon reduction strategy for each farm is developed by using the Carbon Navigator (Figure 4) decision support tool developed by Teagasc and Bord Bia. The Carbon Navigator provides an estimate of greenhouse gas emission reductions that can be delivered on each participating farm, by achieving the targets which are set.

Soil tests are also taken and a nutrient management plan for each participating farm is completed, using the Teagasc Online Nutrient Management Planning tool. Maps are generated, which indicate the existing soil fertility levels as well as the liming and fertiliser requirements.

The quality of the water from the domestic water well and quality of the silage is also analysed. Recommendations are provided regarding feed management strategies based on the results of the silage tests.

Figure 4. Teagasc and Bord Bia Carbon Navigator

Smart Farming – stakeholders collaborating to make a difference

A unique aspect of Smart Farming is the enthusiastic willingness of farmers, representative organisations, academia, advisory bodies, technical institutions and state agencies (Figure 4.1) to collaborate and share their knowledge and expertise in a targeted way to deliver change. The focus of all this collaboration is a desire to improve farm incomes and enhance the rural environment, through better resource management.

Figure 5. The stakeholders that collaborate to make the Smart Farming difference

Experts from these organisations continue to significantly enhance the standard of resource efficiency messages communicated to farmers. These individuals devised and developed the scientific, agronomic and economic content of each of the eight themes on the Smart Farming website, *www.smarttfarming.ie*. They also contributed to a comprehensive Smart Farming guide, which provides top-tips on how to save money on feed, fertiliser, energy and water bills; as well as ideas on reducing waste and the environmental impact.

Smart Farming – farmers making the real difference

The most important part of the Smart Farming programme is that farmers themselves continue to lead the programme's evolution. The National Environment Committee (Figure 6) of the Irish Farmers' Association, which comprises of farmer representatives from every county in Ireland, has taken an *adaptive leadership approach* when developing this programme and dealing with the agri-environmental challenges facing the sector.

They recognise the issues in terms of air, water, soils, climate and other areas within farming and have moved beyond a standard enforcement and compliance approach. The Committee established the eight focus areas (Figure 2) of the Smart Farming programme; expanded the initial cost saving focus of the programme to incorporate environmental indicators; proofed the guide and all national communications; as well as participated in the studies. They also supported the Smart Farming Programme Leader and Manager in continuing the collaboration with others to deliver on better resource management, which will improve farm returns while enhancing the rural environment.

Figure 6. IFA National Environment Committee on water visit the Agricultural Catchments Programme study trip and planning meeting at Teagasc, Johnstown Castle, Co Wexford.

Smart Farming results for 2018

In October 2018, Smart Farming's results for 2018 were published. Figure 7 provides a summary of the results, with the average cost savings target of €5,000 being exceeded by 43% and the target to identify greenhouse gas emissions reductions of 5-7% also being exceeded.

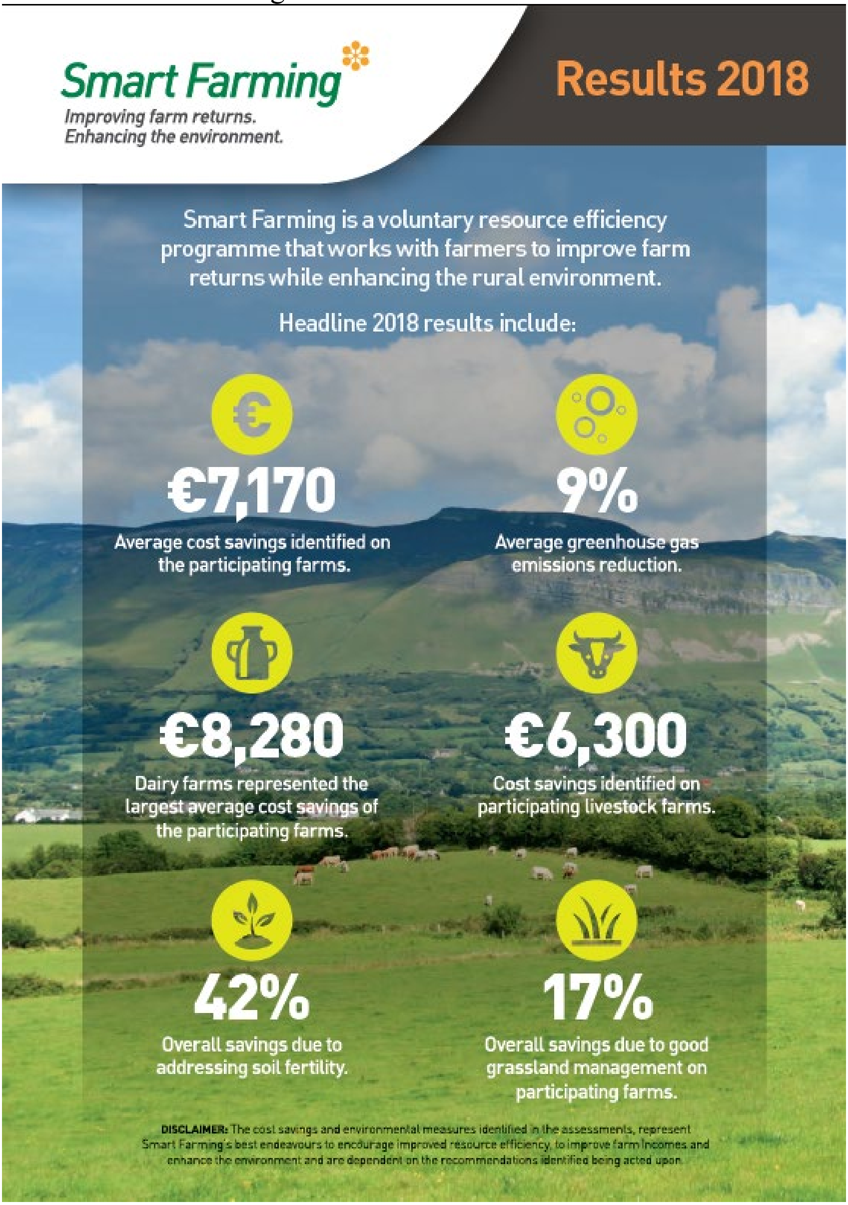

Figure 7. Summary of the results from the 2018 Smart Farming programme

Case study – Andrew McHugh

Andrew and his family are dairy farmers and live near Newtownforbes in County Longford. Andrew took part in the Smart Farming programme, which helped him to identify cost savings on his farm of over €9,000 (Figure 7.2). Andrew is also currently on a pathway to reduce his climate impact by 20% (Table 1).

Table 1. Greenhouse gas emissions reductions identified on Andrew McHugh's farm

Measure	Action	GHG Change
Grazing season length	Increased grazing season length in shoulders of the year	-0.8%
EBI	Scope to improve EBI by 55 points – breed for milk production and fertility	-15.0%
Nitrogen Efficiency	Reseeding and grassland management to allow greater kg solids output per hectare for similar inputs.	-2.9%
Slurry spreading timing	Spread slurry 70% in spring v's current 60%	-1.9%
Energy efficiency	Reduce energy consumption through increased plate cooler capacity	-0.8%
Total		**-21.3%**

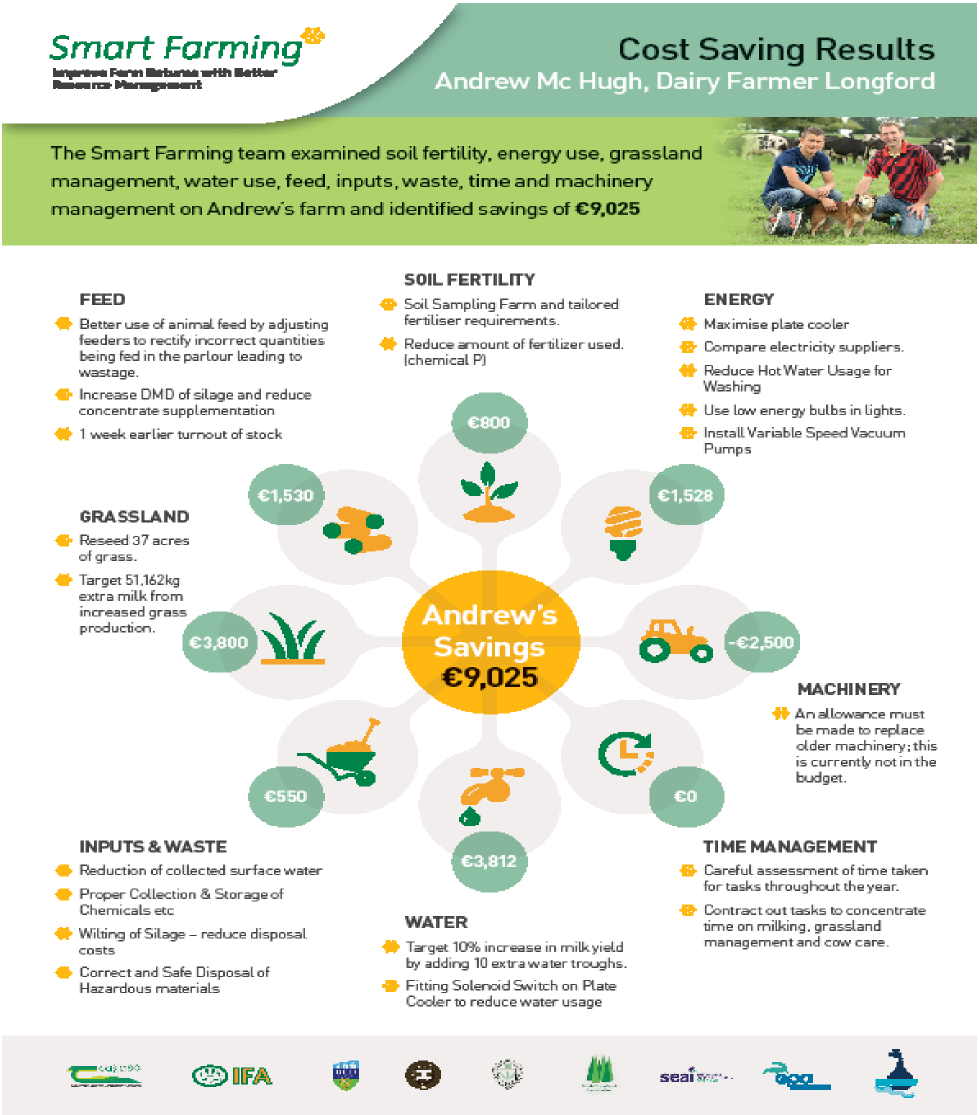

Figure 8. Smart Farming cost savings identified on Andrew McHugh's farm

Concluding comments

Smart Farming is one means by which the agriculture sector in Ireland, and in particular farmers themselves, is endeavouring to provide leadership in addressing climate change. The programme draws on the expertise of the sector and complements other knowledge transfer programmes such as Better Farms, PastureBase Ireland and Agricultural Sustainability Support and Advisory Programme.

The Efficient Use of Phosphorus in Agricultural Soils

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Introduction

Phosphorus (P) is an essential nutrient for plants to complete their growth cycle as it cannot be replaced by other nutrients. Phosphorus plays a key role in a number of cell biochemical functions such as energy transfer through ADP & ATP cycles; P is a component of DNA & RNA and vital for cell division. Phosphorus is also required in large amounts for germination and also in flower and seed production.
Phosphorus is a key nutrient to maximise the viability of our grassland and field crop production systems. There are many variables influencing soil P supply such as under lying parent material / bedrock, soil P sorption, desorption and mineralisation processes, soil test P levels and soil P loss through leaching or overland flow. Other soil characteristics such as soil drainage, soil structure, soil pH, soil organic matter and soil biological activity need to be considered when planning P applications during the growing season. To achieve high P fertiliser efficiency soils should be tested on a regular basis (3 to 5 years) to measure the soil P availability, to determine crop P advice and monitor changes in soil P levels over time. Soil P advice needs to be tailored to match farm soil type, location, climatic factors and production system.

Soil phosphorus trends overtime

Teagasc analyse farm soil samples annually which are submitted by clients through the soil testing service. Currently (2018) soil test results show that 85% of soil samples are sub-optimal for one or more of the major soil nutrients soil pH (Lime), P or K. Soil test results for grassland soils show that 60% of soils are at P Index 1 and 2, while 22% are optimal at P index 3 and 18% are index 4. Soils at index 4 have declined by ~ 50% since 2007 suggesting a drawing down of P reserves based on soil test results and reducing the risk of P loss to water. During the same period soils at index 1 and 2 have increased from 40% to 60%. In 2018 there are signs of improvements in soil P levels on grassland farms as soils tested at P index 1 and 2 have improved by 4%. On tillage farms there is a similar picture with 54% of soils at index 1 and 2, 25% of soils at index 3 and 22% of soils at index 4. Up until 2018 the soils data base would indicate that soils are been continually mined for both P and K. In 2018 there is sign of improvements with a reduction in the percentage of soils testing at soil P and K index 1. While noting the recent improvements these results indicate that over the last decade fertiliser programmes are not in balance to deliver sufficient P (inputs) to replace P removed in the form of either milk, meat, grass or grain (outputs).

National fertiliser phosphorus use

Phosphorus fertiliser use has declined rapidly between the early 1990's and 2008 /09 (see figure 1). There are many reasons for this steady decline in P fertiliser use firstly; fertiliser P recommendations were revised downwards in 1996 due to environmental concerns. Nitrates regulations where introduced in 2006 placing limits on whole farm P applications. Most recently in 2009 the price of fertilisers doubled which resulted in the lowest P use in Ireland on record at 20,231 tonnes of P fertiliser. Since 2009 there has been a good recovery in the use of P fertilisers with P use increasing to 46,387 tonnes in 2018. Changes to farm P limits as set out in Nitrates Directive have increased whole farm P allowances resulting in increased P use on farm over the last number of years. In 2016, there were in excess 200,000 soil samples taken which were mainly used for fertiliser planning purposes for an expanding dairy herd and significantly helped by an increase in the large number of farmers entering the GLAS scheme in which a farm fertiliser plan was mandatory. Phosphorus fertiliser use must increase if forage production is to keep a pace with expanding livestock numbers.

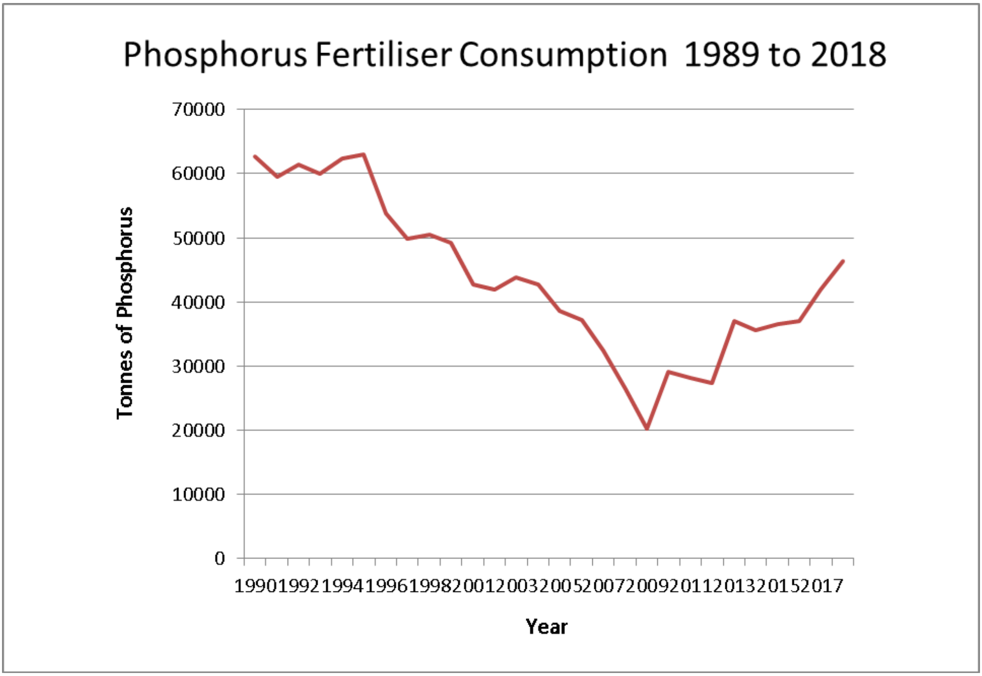
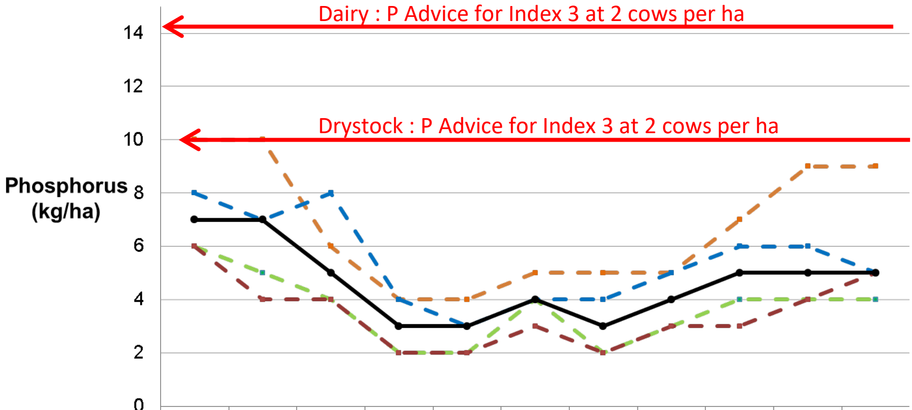


Figure 1. Fertiliser phosphorus sales between 1990 and 2018 (DAFM)

Fertiliser phosphorus use by farm system

Results from the fertiliser use survey (Dillion et al., 2018) shows the average use of P fertilisers by farming system between 2005 to 2015. Figure 2 shows the P required for at 2 LU/ha (red lines) on a dairy farm is 14kg P/ha (Index 3), however over the 10 year period P fertiliser applications ranged from 4 to 10 kg P/ha which is only 29 to 70 % of P fertiliser required for soil P maintenance on dairy farms. On drystock farms P fertiliser application rates ranged from 2 to 6kg P/ha which represents 20 to 40% of the P fertiliser required for soil P maintenance (10kg/ha). On tillage farms a 6.5t/ha crop of spring barley requires 25kg P/ha for grain yield and data from the survey indicates that between 2005 to 2015 only 3 to 8kg P/ha was applied which is only 12 to 32 % of crop P requirements. These figures clearly explain why soil P levels declined over the last decade on Irish farms as there is not enough P fertiliser been applied to replace the P removed (Index 3 P Advice) in crops produced from farms. Where this practice continues soil P fertility will be annually eroded reducing the yield potential of both grass and tillage crops. More worryingly production efficiency gains developed through advanced plant breeding will not be realised to their full potential on Irish farms.



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cattle	6	5	4	2	2	4	2	3	4	4	4
Dairy	10	10	6	4	4	5	5	5	7	9	9
Sheep	6	4	4	2	2	3	2	3	3	4	5
Tillage	8	7	8	4	3	4	4	5	6	6	5
All Systems	7	7	5	3	3	4	3	4	5	5	5

Figure 2. Phosphorus use by farm system between 2005 and 2015. Red lines show P index 3 (maintenance) advice for dairy and drystock systems stocked at 2 LU/ha (Teagasc, NFS).

Soil test phosphorus

The first step to managing soil P fertility is to determine the soil P levels with a soil test. The soil test measures a readily available soil P pool which indicates the soil P supply for crop production (figure 3). It is important to take good soil samples to ensure reliable soil P results for formulating the correct P fertiliser advice appropriate for the crop being grown. On grassland soils ensure that at least 20 representative soil cores are taken from within the area being sampled to the correct depth of 10cm. These 20 soil cores are amalgamated to make one composite soil sample representing the sampling area. More information of correct soil sampling procedure is available in FAI bulletin No 1 https://www.fertilizer-assoc.ie/wp-content/uploads/2015/10/Fert-Assoc-Tech-Bulletin-No.-1-Soil Sampling.pdf

The Morgan's P test measures the labile P pool (available & readiliy available P) in the soil that indicates plant available P supply. The Morgan's P test has been calibrated, and translated into critical soil test thresholds, for all the major crops produced in Ireland. The Morgan's test is currently the standard soil test used by the agricultural industry in Ireland and is approved by the Department of Agriculture, Food and the Marine (DAFM) for agri-environmental regulations and voluntary farm schemes. This soil P test is most suitable for use on acidic soils which are naturally most prevalent across Ireland.

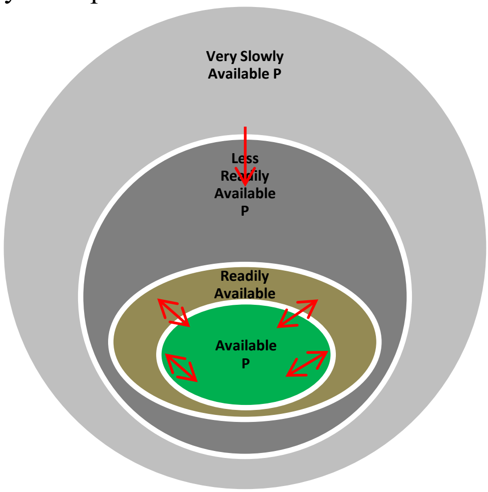


Figure 3. Different soil phosphorus pools and phosphorus movement between pools.

Effect of soil pH on phosphorus fixation and availability

Soil pH is a basic soil property which influences the soil chemistry and the availability of many nutrients, including P. Soil pH can influence P availability differently depending on the soil pH range (pH 4.5 to 8.0) typically found across the range of soils in Ireland. Soil P becomes less available for plant uptake under both alkaline and acidic soil conditions.

In acidic (low soil pH) soils free iron (Fe) and, or aluminium (Al) are more abundant and form strong bonds with P in the soil. Once P is bound to Fe and Al it will be less plant available. Rising soil pH towards more neutral levels (6.3-7.0) reduces the concentrations of free Al and Fe and the potential for further Fe-P and, or Al-P bonds to be formed with freshly applied P fertilisers. In addition, raising the soil pH will also help to release some of the Fe and Al bonded P previously "locked up". Figure 4 shows the forms of P that dominate in soils across the soil pH range typically found in soils. Note that P is most plant available between the pH range of 6.3 to 7.0.

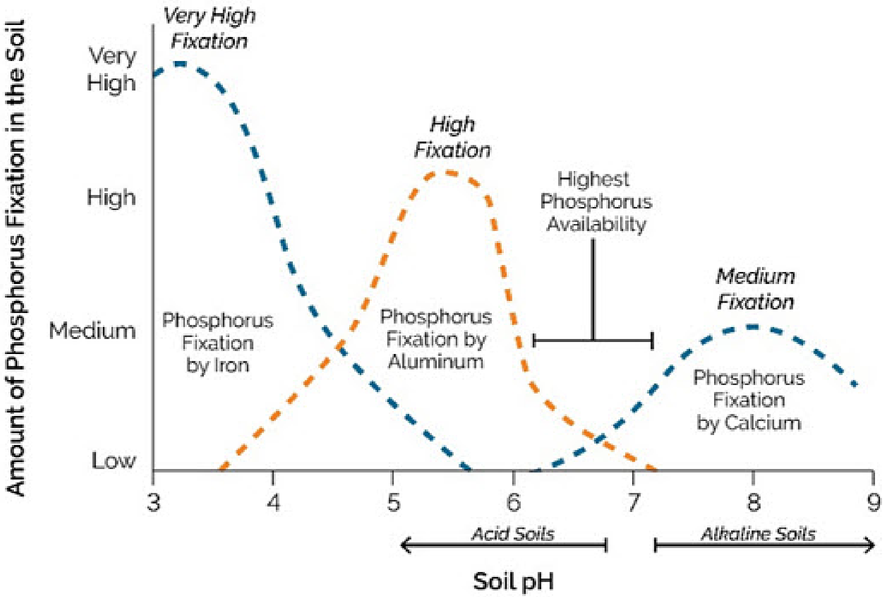


Figure 4. Strength and type of phosphorus bonds formed in soils across a range of soil pH levels typically found in soils.

In naturally alkaline (high pH) soils higher levels of free calcium (Ca) can react with soluble P forming Ca-P precipitates. As Ca bonds with P applied in fertilisers and manures it reduces the proportion available for plant uptake. The Morgan's P soil test method is less suitable on these naturally alkaline soils (pH >7.0) as this method is very efficient as breaking Ca-P bonds and may indicate higher soil P availability than quantities actually available for plant uptake i.e. giving a false-positive result.

Interaction of lime and phosphorus fertiliser

The management of lime and P fertilisers go hand in hand on acidic soils. Continuous application of P fertiliser on low pH (acidic) soils are a false economy due to the risk of the P applied been locked up and unavailable for plant uptake. On acidic soils the first step in soil fertility management should be to correct soil pH with lime applications. Once soil pH has been optimised (grassland soils pH ≥6.3 and arable soils pH ≥6.5) the efficiency of applied P in fertilisers and manures will also improve.

Research conducted at Teagasc, Johnstown Castle investigated the interaction of lime and P fertiliser across 16 acidic mineral soils from across Ireland (figure 5). The application of lime only increased soil test P by on average 5.7 mg/L P while the application fertiliser only (100 kg/ha P) raised soil test P by 40% more (8.1 mg/L P). However, where both lime and fertiliser P was applied the largest increase in soil test P was achieved (17.7mg/L), indicating higher availability of P from both soil reserves and fertiliser application.

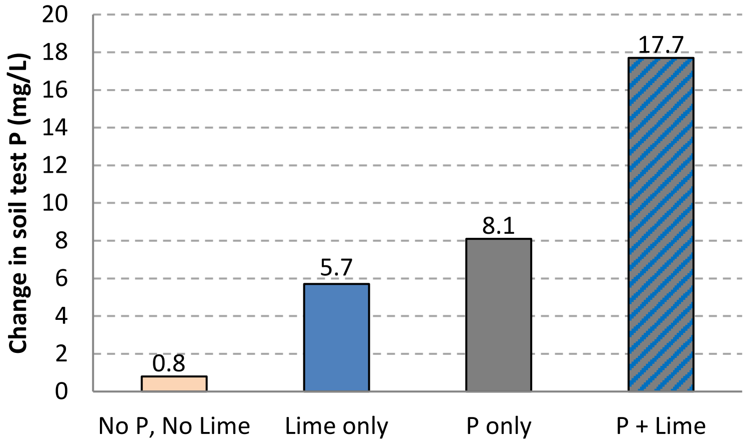


Figure 5. Average change in soil test phosphorus (Morgan's P) across 16 soils after 12 months incubation which were treated with lime only (5 t/ha of lime), fertiliser P only (100 kg/ha of P), and fertiliser P + lime.

Phosphorus and the environment

Where small amounts of phosphorus (<1 kg P /ha) enter a water body it may speed up a range of biological processes which cause eutrophication (growth of plants and algae which use up oxygen) of rivers and lakes. Phosphorus can be transported from agricultural land or from hard surfaces and roads to surface waters (rivers and lakes) during periods or higher rainfall either as soluble P or as particulate P (P bound to soil particles). Following storms or very heavy rainfall soil particles with P attached can move of land surfaces in run-off water and soil erosion during these intense weather events.

Under the Nitrates Directive, National Action Programme (NAP) a suite of agri-environmental measures and regulations has been implemented on farms in Ireland since 2006. The main aim of these regulations is to minimize the risk of P entering water bodies from agricultural land by constraining P use on farms and placing maximum limits of chemical or manure P inputs.

The first place to start to improve P use efficiency and to reduce P loss from agricultural soils is to take soil samples and use soil test results as a basis for fertiliser planning. Under NAP rules soils with high soil test P levels are considered more risky for P loss. Therefore, no further P fertiliser application is allowed on P index 4 soils (high soil test P). It is recommended to re-sample these soils after 2-3 years to check their soil test P status and adjust fertiliser plans accordingly. On fields where P fertiliser has been omitted for a number of years, soil sampling should be conducted to monitor changes in soil P over shorter time frames.

In order to minimize the risk of P loss to water fertiliser and manure management factors such as application timing and application rate must also be considered. It is best to apply P close to the period of rapid crop uptake and at rates that match crop uptake capacity or to meet soil build-up requirements. Phosphorus advice must also consider different soil types and the potential pathway for P loss from these soils. For example on heavy wet soils the main pathway for P loss will be over land flow while on light or drained peaty soil types P may move down through the soil profile.

Losses of P with soil erosion may often be lower compared to run-off P losses on grassland soils with a high soil test P status. Within a river catchment i.e. the area of land draining in to a river or stream, P tends to be lost from critical source areas (CSA's) which tend to occupy a smaller proportion of a whole catchment. CSA's are relatively small areas within a farm that have higher potential for P loss to water due to the heavy wet nature of the soil and close proximity to surface water bodies. A common rule of thumb is that 80% of the P loss comes from less than 20% of a catchment area (80:20 rule). Depending on the landscape and soil types present implementing the appropriate P management practices and targeting fertiliser and manure applications to lower risk areas will reduce excessive P loss that may impact on water quality.

Phosphorus index system for grassland & tillage crops

The aim of P nutrient advice is to maintain all fields at the optimum soil fertility level for the farming system practiced. On intensive farms where the aim is to maximise crop yields (grass / grain / root crops) aim for soil P index 3. The soil test indicates the plant available P in mg/L of soil (see table 1). The soil index system divides soils into one of four soil index levels based on the soil test P result. The soil index system for grassland and tillage crops and the corresponding soil test P ranges for each index are shown in Table 1. The soil index indicates the expected response to nutrients applied.

Table 1. Soil nutrient index, response to fertilisers and soil test range for phosphorus. (Source: Teagasc)

Soil Index	Response to Fertilisers	Soil test P (mg/L)	
		Grassland	Tillage
1	Definite	0 – 3.0	0 – 3.0
2	Likely	3.1 – 5.0	3.1 – 6.0
3	Unlikely / Tenuous	5.1 – 8.0	6.1 – 10.0
4	None	> 8.0	> 10.0

Soils within P index 1 and 2 are responsive to applied P. Intensively farmed soils at P index 1 or 2 have a higher P requirement as the soil P reserves are lower and additional P needs to be applied to meet crop demand and P removal in grain, straw, meat or milk, etc. and to build-up soil P reserves to the optimum soil index of 3. The aim is to build soil fertility levels at index 1 and 2 up to index 3 over a number of years. The rate of soil build-up will depend on a number of factors such as soil test P levels, soil type, nutrient application rate, and the amount of nutrient removed. Building soil fertility usually takes a number of years and applications of P for build-up should continue for a number of years until the soil is re-sampled.

Soils with a P index of 3 are at the optimum index for agronomic production, and have soil fertility levels sufficient to feed the crop. In order to maintain the soil P levels within this optimum range, the P applications should replace P removal over the growing season. It is therefore important that P off-take in grain, straw, meat or milk, animals etc. is accurately calculated.

Soils at index 4 are very fertile soils and soil reserves are more than sufficient to meet crop P requirements throughout the growing season. At these very high soil P levels there is increased risk of P loss from the soil. It is not recommended to apply further P fertilisers to soils at P index 4, with the exception of certain high value crops such as potatoes, beet, and some horticultural crops, where small qualities of P may be applied at planting to assist good crop establishment. Where grass and tillage crops are grown on index 4 soils it is recommended to omit P for a number of years (2 to 3 years) and then re-sample to monitor changes over time.

The speed of P decline on index 4 soils will depend on the soil type, the level of P in the soil, and the P removal on an annual basis. Regular soil testing is essential to monitor changes over time.

Phosphorus advice for grassland & tillage crops

Phosphorus advice is based primarily on the soil P index system which is supported by soil sampling and soil analysis using the Morgan's soil P test. Adjustments are made to the P fertiliser advice based on the farming system and intensity of production (i.e. expected crop yield or stocking rate).

Maintenance phosphorus rates (Index 3)

The first component of the P advice is maintenance (replaces P removed in milk / meat / grain) P applications are shown in table 2. Aim to maintain a soil P index 3 where there is a requirement for optimum grass dry matter production, early spring grass growth and to maintain sufficient P concentration in the herbage to meet animal health dietary requirements.

Table 2. Grazing maintenance rates of available soil phosphorus to replace offtakes (kg/ha)

Grassland Stocking Rate (kg/ha) Org N	Farming System	
	Dairy	Drystock
≤100	6	4
130	10	7
170	14	10
210	19	13
≥210	23	16

Soil phosphorus build-up rates (Index 1 & 2)

The second component of P advice is the requirement for soil build-up P based on the soil test result. Table 3 shows the P build-up rates as per the recommendations (Teagasc, 2016). Additional P is available under nutrient legislation (SI 605, 2017) for building soil P levels on intensively stocked grassland farms see table 4.

Table 3. Phosphorus rates (kg/ha) for Build-Up on mineral soils

Soil P Index	P Rates (kg/ha)
1	20
2	10
3	0
4	0

Table 4. Additional phosphorus rates (kg/ha) for Build-Up on mineral soils as per SI 605 of 2017

Soil P Index	P Rates (kg/ha)
1	50
2	30
3	0
4	0

Table 5 shows P advice for a dairy farm stocked at 2 LU / ha. These recommended rates need to be adjusted for specific farm details such as concentrate feed usage / recycling of animal manures. To determine the required rate of P a farm fertiliser plan must be completed annually.

Table 5. Phosphorus advice for a Dairy Farm stocked at 2.0LU/ha

Soil P Index	P Advice (kg/ha)
1	34
2	24
3	14
4	0

Adjusting for concentrate P

Farm P allowances need to be adjusted for concentrate feed P imported annually onto livestock farms. Each 1 tonne concentrate feed (ration) imported contributes **5kg P** import to the farm. . Feed ingredients such as pulp / distillers etc. contain lower P levels. Under Nitrates Directive rules 300kg concentrate feed (1.5 kg P) is deducted for every 85 kg Org. N/ha (=1 cow/ha) on the farm. This small deduction covers the P that cannot be managed / recovered within the farm due to grazing management. This concentrate P deduction is calculated based on the previous years feed usage and total farm organic N loading (stocking rate equivalent).

For example a farm with a total organic N loading of 8,500 kg can deduct 30 tonne of concentrate feed from annual feed use when calculating their whole farm P allowances. In effect this increases the whole farm P chemical allowance by 150 kg P (30 x 5kg P) per year.

Eq.1. 8,500 kg Org.N / 85 kg Org. N/ha = Average 100kg Org.N/ha for the farm

Eq.2.100 kg Org.N/ha x 300kg Conc. Feed = 30 tonnes of conc feed can be deducted.

Organic Fertilisers (Cattle slurry / Manures)

The P in farm produced organic fertiliser P (manures / cattle slurry) has been removed from the whole farm chemical P allowance calculations under the Nitrates Directive regulations. This P in manures / slurry which is generated on the farm needs to be recycled back to the areas of the farm where it was generated, for example the silage fields.

Where organic P as manure is applied to P index 1 or 2 soils the P is deemed to be 50% available in the year of application. To make up the remaining 50% of P chemical P fertiliser can be brought onto the farm to achieve total crop requirements for that year. This ensures that the grass crops receive sufficient P during the growing season. For example on a farm stocked at 2 LU/ha it can increase the farm P allowance by ~ 4kg/ha depending on specific farm details.

Cereal crop phosphorus advice

The P advice for tillage crops is based on maintaining the optimum index 3 for maximum grain production. Table 6 below shows the basis to the cereal P advice for example the rate of P required at index 3 for a 6.5t/ha grain crop (25 ÷ 3.8 = 6.5). Where higher yields are achieved (proof required) an extra 3.8 kg P for each 1 tonne of grain (wheat, barley or oats) yield may be applied. Table 7 shows the P rates for cereal crops as grain yield increases.

Table 6. Recommended rates of phosphorus for Cereals at 6.5t/ha

Soil P Index	P Rates (kg/ha)
1	45
2	35
3	25
4	0

Table 7. Phosphorus advice for cereals based on crop grain yield (kg/ha)

Soil P Index	6.5 t/ha	7.5 t/ha	8.5 t/ha	9.5 t/ha	10.5 t/ha	11.5 t/ha
1	45	49	52	56	60	64
2	35	39	42	46	50	54
3	25	29	32	36	40	44
4	0	0	0	0	0	0

Phosphorus programmes for grass and cereal crops

A fertiliser programme should encompass applying the right fertiliser products, in the right place (field), at the right rate, and the right time. Figure 6 shows a typical fertiliser timing schedule for grassland farms. The aim of the fertiliser plan is to match N-P-K-S nutrient requirements with grass demand over the growing season. Well drained versus poorly-drained soils may have a different grass growth profile and hence nutrient demand as indicated by the green and red grass growth curves. These differences on well- and poorly-drained soils need to be taken into account especially in early spring in relation to the timing and rates of the 1st and 2nd rounds of fertiliser. For example, on well-drained soils cattle slurry maybe used as a source of P in early February if soil temperatures and ground conditions are favorable. However, on poorly-drained soils, with very low grass growth during early season, it may be prudent to hold off the 1st round of fertiliser until conditions improve in late February/early March. Where no slurry was applied, an N-P-K compound should be applied in the 2nd or 3rd rounds (March/April) to help boost soil P availabliity before the onset of high grass growth rates.

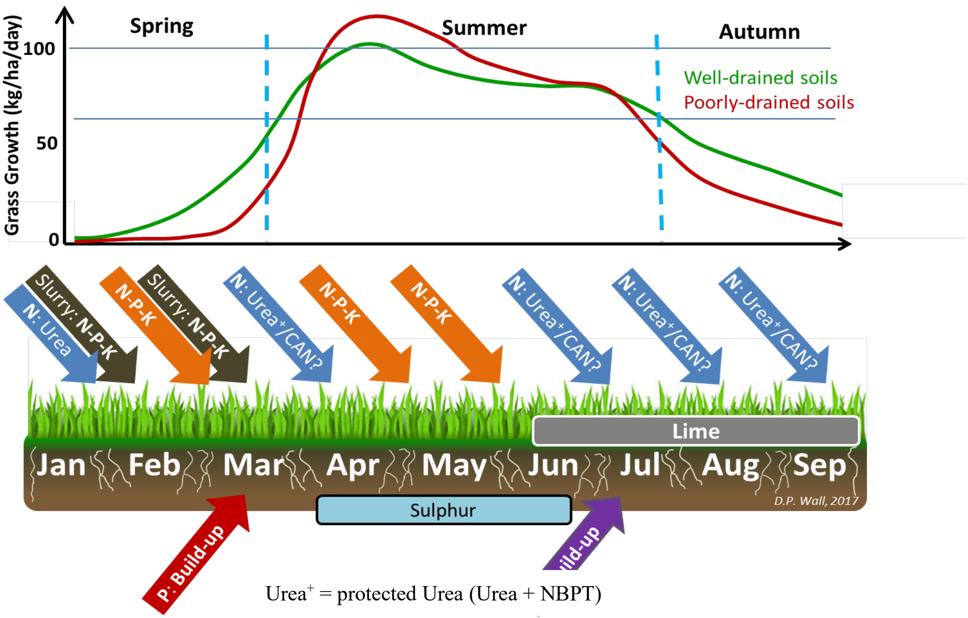


Figure 6. Typical grass growth profile for well drained (green line) and poorly drained (red line) soil types and suggested timings for N, P, K and S during the grazing season.

Winter cereals

Winter cereals have a higher P demand during the growing season compared to spring cereals due to their higher yield potential see table 7.

On very low to low P index soils a winter cereal crop should receive a P build-up application for index 1 and 2 soils of 20 to 10 kg P/ha at sowing time which should be incorporated or combined drilled to ensure it is in the correct zone for root access and reduce loss risk to water. In early spring the remaining crop P requirements can be broadcast in Late January / Early February. For winter crops sown on P index 3 soils crop P requirements should be broadcast in late January / early February typically with the crops 1st N and K requirements. This will replenish soil P serves and supply in season crop demands.

Spring cereals

Spring cereals have a shorter growing season compared to winter cereals and a lower yield potential. Apply all crop P requirements at sowing time and incorporate / combine drill into the seedbed at sowing time. This is critical especially for spring barley as the crops develops very rapidly and requires an easily access source of P in the first 3 to 6 weeks after sowing. On very low to low P index soils (Index 1 & 2) there is merit to combining drilling P especially for spring barley (see figure 7). This readily available source of P close to the rooting zone is critical to drive both root and tiller production.

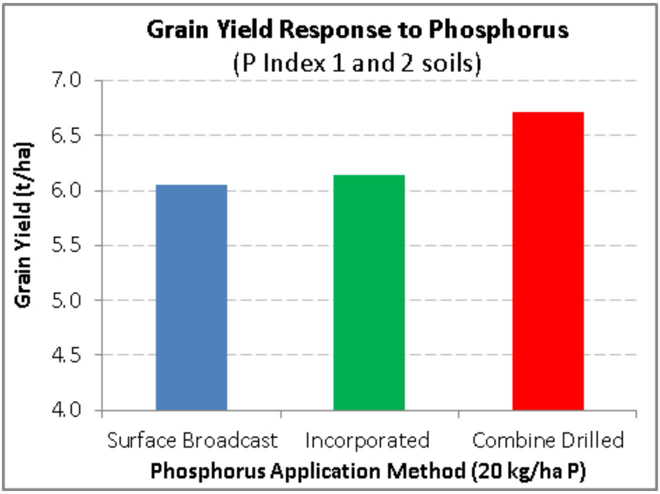


Figure 7. Average spring barley grain yield response to 20 kg/ha phosphorus applied using three application methods across 4 sites.

Fertiliser Selection & programmes

Grassland P fertilisers should be selected based on either grazing or grass silage requirements. In a grazing situation the majority of P and K is recycle back to the soil in the form of dung and urine. Phosphorus and potassium (K) that leave the farm in the form of either milk or meat needs to be returned in a fertiliser blend with a P : K ratio of 1 : 2 to replenish soil nutrient reserves. However, in a grass silage situation there are significant removals of both P and K as there is total crop removal at harvest time. P and K removed in cut grass needs to be return in a fertiliser blend with a P : K ratio of 1 : 6 / 7 to replenish soil nutrient reserves.

Grazing

Tables 8 & 9 show recommended rates of both P and K for dairy and drystock farms and suitable fertiliser products and rates to match P and K requirements as recommended for grazing ground. Where additional P and K is applied for soil fertility build-up the P : K ratios will change due to additional P and K required over index 3 rates. Additional nutrient (Build-Up) can be applied early / late in the growing season. Plan to apply P early (March / April) and K late (August / September).

Table 8. Recommended rates (kg/ha) of phosphorus (P) and potassium (K) for Dairy farms stocked at 2 LU/ha & suggest ed fertilisers

Soil Index	P[1]	K[2]	P:K Ratio	Typical P-K Products
1	34	90	1:2.6	566 kg/ha 18-6-12
2	24	60	1:2.5	400 kg/ha 18-6-12
3	14	30	1:2.1	230kg/ha 18-6-12
4	0	0	--	---

[1] Adjust P rates for concentrate P fed on farm each year

[2] Additional K is required at Index 1 & 2 as 65 to 130kg/ha of 50% K (MOP) once every 3 years (for soil K build-up)

Table 9. Recommended rates (kg/ha) of phosphorus (P) and potassium (K) for Drystock farms stocked at 2 LU/ha & suggested fertilisers

Soil Index	P[1]	K[2]	P:K Ratio	Typical P-K Products
1	30	75	1:2.5	300kg/ha 10-10-20
2	20	45	1:2.25	200 kg/ha 10-10-20
3	10	15	1:1.5	400 kg/ha 27-2.5-5
4	0	0	--	---

[1] Adjust P rates for concentrate P fed on farm each year

[2] Additional K is required at Index 1 & 2 as 30 to 90kg/ha of 50% K (MOP) once every 3 years (for soil K build-up)

Grass Silage

The grass silage crop removes significant amounts of both P and K as shown in table 10 and 11 below. Firstly recycle cattle slurry on the silage fields in order to return both P and K removed at harvest time in the grass silage crop. Table 10 shows fertiliser advice (P & K) and suggested fertiliser products where 33m³/ha cattle (3,000 gals/ac) is recycled on the silage fields. The 2nd application of fertilisers after the 1st cut is removed is required to replenish / build soil fertility reserves. Table 11 below shows suggested recommended fertiliser products in the absence of cattle slurry. A crop of grass silage will removes approximately 4kg P and 25kg K /tonne of grass DM. The 1st fertiliser applications are shown in table 11 will supply a proportion of the crops P and K requirements during the growing season which is driven by the rate of K and not to exceed 90kg K/ha in a single application. The remaining crop requirements are applied after the 1st cut is removed to balance / build soil fertility levels as shown in table 11.

Table 10. 1st Cut Grass silage phosphorus (P) & potassium (K) requirements (kg/ha) & suggested fertiliser programmes where 33m³ cattle slurry is applied

Soil Index	*P* [3]	*K* [4]	*P : K ratio*	*33m³/ha Cattle Slurry*		
				P - K Supplied (kg/ha)		Balance Application (after 1st Cut)[5]
1	40	185	1 : 4.6	13	106[2]	265 kg/ha 0-10-20
2	30	155	1 : 5.2	13	106[2]	170 kg/ha 0-10-20
3	20	125	1 : 6.3	26	116	90 kg/ha 50% K every 5 years
4	0	0	--	---		---

[1] Don't exceed 90kg K/ha in single application.

Index 1, 2 & 3 soils apply P & K balance after 1st cut as shown above.

[2] Additional K is required at Index 1 & 2 as 90 to 160kg/ha of 50% K (MOP) once every 3 years (for soil K build-up)

[3] P availability in slurry reduced to 50% availability on index 1 & 2.

[4] K in slurry reduced to 90% availability on index 1 & 2. [5]Rounded to the nearest 5kg/ha

Table 11. 1st Cut Grass Silage phosphorus (P) & potassium (K) requirements (5t/ha DM) & suggested fertiliser programmes where no slurry is applied.

Soil Index	P	K	P : K ratio	Fertiliser Options	
				1st Application[3]	Balance Application (after 1st Cut)[3]
1[1]	40	185	1 : 4.6	310kg/ha 0-7-30	250 kg/ha 0-7-30
2[1]	30	155	1 : 5.2	310kg/ha 0-7-30	185 kg/ha 0-7-30
3	20	125	1 : 6.3	310kg/ha 0-7-30	125 kg/ha 0-7-30
4[2]	0	0	--	---	---

[1] Don't exceed 90kg K/ha in single application. Index 1, 2 & 3 soils apply P & K balance after 1st cut as shown above.

[2] Additional K is required at Index 1 & 2 as 40 to 100kg/ha of 50% K (MOP) once every 3 years (for soil K build-up

[5]Rounded to the nearest 5kg/ha

Winter Wheat

When selecting a suitable fertiliser compound for winter crops it will depend on a number of factors such as soil test results, crop type and yield potential. Table 12 below shows the P and K requirements for a crop of winter wheat or barley yielding 10t/ha and recommended P & K rates based on grain yield and suggested fertiliser products.

Table 12. Phosphorus (P) and potassium (K) advice for 10 t/ha winter barley or winter wheat & suggested fertiliser programmes

Soil Index	P kg/ha	K kg/ha	P : K ratio	kg/ha[2]
1	58	130	1 : 2.2	555kg 10-10-20[2]
2	48	115	1 : 2.4	555 kg 12-8-20
3	38	100	1 : 2.6	525 kg 10-7-20
4	0	0		---

[1]Adjust P by 3.8kg/t, K by 10kg/t for lower or higher grain yields

[2] Additional K is required at Index 1 & 2 as 40 to 190kg/ha of 50% K (MOP) once every 5 years (for soil K build-up)

Spring Barley

When selecting a suitable compound fertiliser for spring barley it is important to select a fertiliser that will supply all the P and K in a single application at sowing time. It will be important to consider the N % in the fertiliser compound. Aim to deliver 30 to 60kgN/ha depending on sowing date. Regardless of soil P index it is recommended to apply all P and K at sowing time in close proximity to the seed. Examples of appropriate fertiliser blends / programmes based on P : K ratios and soil P and K indexes are shown in Table 13.

Table 13. Phosphorus (P) and potassium (K) advice for 7.5 t/ha spring barley or spring wheat & suggested fertiliser programmes

Soil Index	P kg/ha	K kg/ha	P : K ratio	kg/ha[2]
1	49	115	1 : 2.2	480 kg 10-10-20[2]
2	39	100	1 : 2.4	480 kg 12-8-20
3	29	85	1 : 2.6	480 kg 13-6-20
4	0	0	--	---

[1]Adjust P by 3.8kg/t, K by 11.4kg/t for lower or higher grain yields
[2] Additional K is required at Index 1 & 2 at 40 & 190 kg/ha as 50% K (MOP) once every 5 years (for soil K build-up)

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