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UPDATING GRASSLAND FERTILISER RECOMMENDATIONS: PRINCIPLES AND PRACTICE

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SUMMARY.

Providing fertiliser recommendations for grassland is challenging due to the variety and complexity of livestock production systems ranging from extended grazing to fully housed 'zero grazing' systems. Many farms use multiple grazings and cuttings and there is a wide range of field conditions and grass growth potential. Nutrients recycled at grazing and nitrogen (N) fixed by clover add another layer of complexity and the quantity of grass production is dependent on livestock stocking rates and concentrate use, and can be considerably lower than growth potential.

Nevertheless, many decades of research, principally since the 1940s, provide a sound basis for good nutrient management advice, covering the maintenance of soil fertility and the application of nutrients to maintain critical levels of soil nutrient reserves and stimulate the required response in grass growth in terms of grass energy, protein and dry matter (DM) yield. It is also important that nutrient management is integrated so that account is taken of the supply of major and micronutrients from soil, feed, clover, manure and manufactured fertiliser to ensure adequate grass growth and animal health.

There is some evidence from cultivar trials that nitrogen use efficiency and grass DM yields achieved from modern grass varieties have improved significantly in recent decades and there is only limited data on the ability of modern clover varieties in mixed swards to fix N. Recent field experiments conducted by ADAS and Rothamsted Research North Wyke indicate that the DM yield response of modern grass varieties to applied N may have increased since the 1980s and there are indications that modern grass/clover swards can fix at least 100-150 kg N/ha/yr during the growing season. There is also new data on the amount of potash (K_2O) taken off in cut grass and new developments in phosphorus (P) recommendations that take account of the P sorption capacity of different soils.

New grassland recommendation systems need to take account of and maximise the impact of recent research findings while also remaining relevant to modern livestock production systems. The challenge is to synthesise research into recommendations that are provided at an appropriate level of precision and are also easy to understand, accessible and recognisable so that farmers can relate them to their own systems. Only then will uptake and use of recommendations increase to further contribute towards improved nutrient use efficiency in grassland production.

CONTENTS

Keywords: Fertiliser recommendations, grassland, nutrient management, soil fertility, fertilisers, manures.

1. INTRODUCTION.

Providing fertiliser recommendations for grassland presents a number of technical and presentational challenges. Grass swards can be in place for several decades and in temperate regions growing seasons can last for more than 6 months. Grass is typically harvested through multiple grazings or cuttings through the year. There are a wide range of livestock and grassland management systems that integrate the cutting and grazing of grass in different ways. In some countries there has been a general focus on a single system, such as intensive and extended grazing systems in the Republic of Ireland and New Zealand. In other countries such as the UK and France there is a greater number of farms adopting a wider range of grassland systems, which often reflect differences in agro-climatic zones or a polarisation of approaches to increase output at one extreme or reduce costs at the other (Fisher and Jewkes, 2009).

When considering nutrient applications to grassland there are a number of factors to consider from field to field and from region to region, including:

- Rainfall, altitude, temperature.
- Past management / soil type / Soil Nitrogen Supply (SNS) / sulphur supply.
- Soil pH and soil nutrient reserves of phosphorus (P), potassium (K) and magnesium (Mg).
- Age of sward / clover content.

Furthermore, the rate of grass growth varies through the year; and nutrient applications, whether from livestock manures or manufactured fertiliser, need to be adjusted according to the stocking rate, the need for quality grass and the weather conditions during each phase in the growing season to ensure that grass and nutrients are utilised efficiently.

On grazing land it is important to account for nutrients recycled in dung and urine as well as limits to grass utilisation due to wastage and spoilage of grass (Richards, 1978; Richards *et al.,* 1976). Nutrients are often distributed unevenly at grazing resulting in a concentration of nutrients in some field areas and a deficit in others (Froment *et al.*, 1996; Richards and Wolton, 1976). It is also important to take account of improvements in the DM production potential of new grass varieties; the phosphate (P_2O_5) and potash (K_2O) offtake rates of modern grass and clover varieties; and the nutrition and energy provided by forage crops such as forage maize, brassicas, wholecrop cereals, root crops, and arable crops grazed *in situ* (Chaves *et al.*, 2009; Sampoux *et al.*, 2011; Wilkins and Lovatt, 2010).

Nutrient management guidance should also consider integration of feed advice in order to improve business profitability and farm nutrient balances, which is essential for sustainable production (AFRC, 1993; Scott, 2010). In many systems the optimum level of grass dry matter production is lower than the potential maximum production, and also lower than the level of production justified by the market value of forage and the price of manufactured fertiliser. Although a proportion of 'excess' grass may be needed as a 'buffer' or insurance policy against years of low productivity, there is no point in producing much more grass than the livestock on farm need.

There are therefore many factors to consider within a grassland fertiliser recommendation system; and yet the recommendations provided need to be not only scientifically robust, but also clear and easy to understand so that they can be readily used by farmers and advisers. A recommendation system should also be recognisable to practitioners and should acknowledge current industry trends in terms of changes to production systems and practices due to multiple economic and legislative drivers. A comprehensive recommendation system for grassland should provide guidance based on soil, environmental and economic factors whilst providing nutrient recommendations at an appropriate level of precision.

This paper outlines the principles of integrated nutrient management in grassland systems and focuses on the challenges, principles and practice of updating fertiliser recommendations to suit grassland farmers and advisers. Data is presented from recent N response experiments using modern grass and grass/clover seed mixes and options outlined for new grassland fertiliser recommendations.

2. INTEGRATED NUTRIENT MANAGEMENT.

For nutrient management in grassland to be effective it is important that all the principal factors and nutrient sources that determine nutrient use efficiency are considered. Scott (2010) argued that effective nutrient management planning (NMP) on livestock farms requires the integration of fertiliser, feed and manure (or organic materials in general). It is also important to consider soil physical structure and soil nutrient management, since soil structure and soil nutrient reserves can have a direct effect on the efficiency of nutrient uptake (Figure 1). The four factors and plans should be managed together as inter-related components of a single NMP.

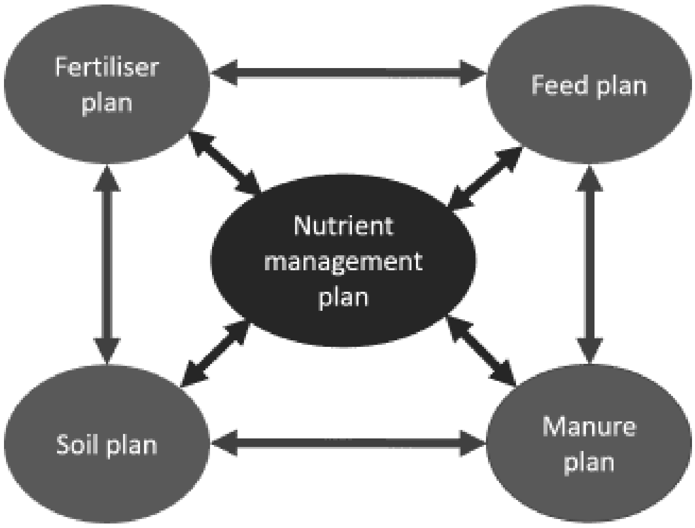

Figure 1: *Components of Integrated Nutrient Management Planning.*

Manufactured fertilisers and purchased feed provide an external input of nutrients to the system. Livestock manures produced on the farm recycle nutrients within the system, and it is important to account for other organic materials (e.g. biosolids, composts, paper sludge etc.), which bring nutrients on to the farm. Together these inputs provide the nutrients for grass growth and the energy that the livestock need for maintenance, liveweight gain and milk production.

The fertiliser plan is the subject of this paper and yet it cannot be effective without considering the influence of purchased feed and the use of organic materials. In a grass-based system the feed plan should complement the fertiliser plan by providing the protein, nutrients and energy that grazed grass, silage, hay or arable forage crops cannot provide at key points in the production cycle.

The manure management plan calculates the amount of manure produced and the amount available for spreading to land through the year while taking account of closed spreading periods and the availability of suitable land of moderate to low risk of surface runoff. The manure spreading plan should be integrated with runoff risk and soil nutrient reserve mapping and with crop requirements for nutrients. The soil plan is related to maintaining or enhancing soil fertility. It forms the foundation of an efficient production system and is alluded to in the following section.

2.1. Soil fertility.

The production potential of grassland is determined by growth factors such as soil temperature, energy from sunlight, water supply and nutrient supply. Soil temperature, sunlight and water supply are largely determined by climate and soil type, with water supply particularly determined by summer rainfall. Nutrient supply is largely determined by the inherent and manageable physical, chemical and biological properties of the soil. Inherent properties include soil texture (particle size distribution; influencing available water capacity) and clay mineralogy (influencing potash and Mg supply). Manageable properties include soil pH, soil organic matter content, soil structure and soil nutrient reserves. The soil's productive potential is also influenced by other inherent factors such as topography; which influences access, machinery use and hydrology.

Regular soil sampling and analysis to check soil pH and extractable P, K and Mg underpins nutrient management. Sampling of fields every 3-5 years is recommended. How the farmer uses and responds to the results largely determines the productivity and nutrient use efficiency of the farming system.

2.1.1. Liming.

To ensure optimum availability of a wide range of nutrients, non-calcareous mineral soils under continuous grass or grass/clover swards should be maintained at a pH of $6.0_{(water)}$; and if a barley crop is occasionally grown, at 6.2 (Defra, 2010). A neutral to slightly acidic soil pH of 6.0 to 7.0 also increases plant species diversity in grassland swards where nitrogen fertiliser is applied

(Crawley *et al.*, 2005); and yet the latest Professional Agricultural Analysis Group (PAAG) data indicates that in the UK 21% of grassland soils (that are tested) have a soil pH less than 5.5 and 2% less than 5.0 (PAAG, 2014; Figure 2). Some acid grasslands under low input grassland management within agri-environment schemes (e.g. *Glastir* in Wales) are maintained at lower pH to maintain particular ericaceous species of interest. Nevertheless, the PAAG data suggests that many grassland soils are managed well below optimum pH and a significant proportion of grassland soils in England and Wales are not tested at all. For example, in a recent survey of Welsh grassland farms, only 23% of grassland fields were tested for soil pH and only 7% were tested on a regular basis (every 3-5 years; Anthony *et al.*, 2012).

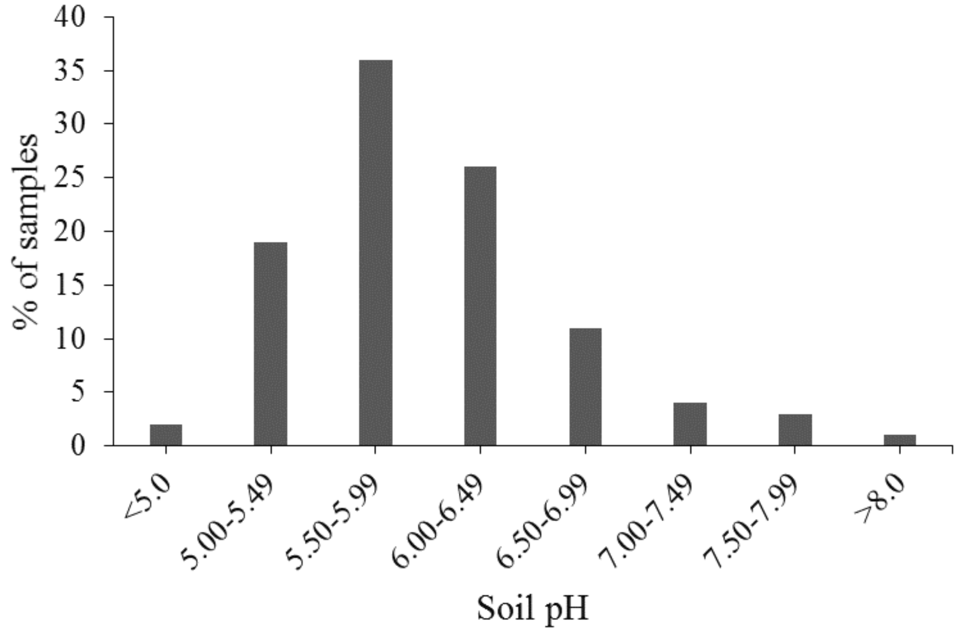

Figure 2. *Percentage of grassland soil samples in each soil pH$_{(water)}$ class (PAAG, 2014).*

2.1.2. Soil nutrient reserves.

Current concepts of the behaviour of P and K in soils represent the nutrients as existing in four different pools of decreasing plant availability. Movement between the three more 'available' pools is reversible such that when concentrations in the soil solution and the readily available pool are depleted these nutrients move from less available pools to compensate (Johnston *et al.*, 2001b). Equally when P and K are added to the soil, nutrients not taken up by the crop are distributed sequentially into the less readily available pool; known as 'fixed K' in the case of potassium. Critical levels of more 'readily available' soil P and K are required to achieve optimum yields and nutrient use efficiency.

A variety of extractants are used to characterise the soil solution and readily available pools of soil nutrients and estimate the readily available P and K status of soils; for example, Olsen, Bray and Modified Morgan methods for P and reagents using excess ammonium to exchange with K (MAFF, 1986;

Woodarda *et al.*, 1994). Different countries use different methods according to dominant soil types, soil pH and agroclimatic conditions. In England and Wales, the Olsen P method is used for P and ammonium nitrate extract for K. The relationship between extractable nutrients and yield or P and K offtake is often very good for single soil types (Figure 3; Johnston *et al.*, 2001a), but less good when different soil types are compared. There is also little information on the rates of reversible transfer between the readily available and less available pools of P and K, but some recommendation systems do attempt to account for differences between soils in the rate of transfer to the less readily available pool (e.g. P sorption index; Lumsdon, 2012) and the associated rate of decline in soil nutrient status; thought to be associated with clay mineralogy for K and soil pH, organic matter content, P speciation and the concentration of iron, aluminium or calcium for P fixing or 'reversion'. Rates of build-up and decline, however, can be checked by regular routine soil analysis every 3-5 years.

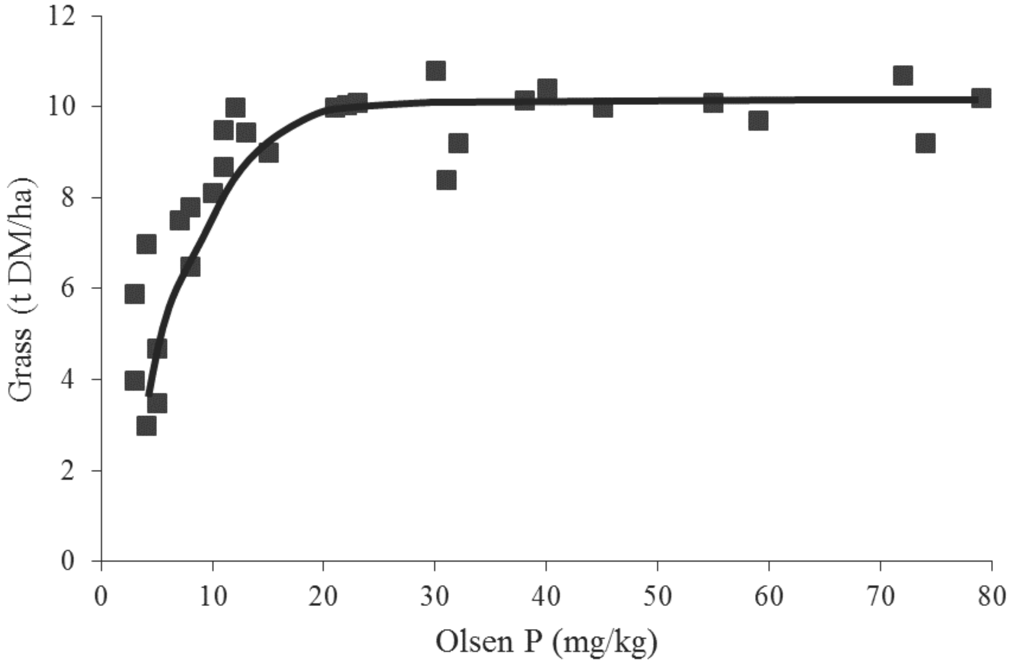

Figure 3. *Relationship between extractable (Olsen) P and grass dry matter (DM) yield in fields adequately supplied with major nutrients (source: Johnston et al., 2001a).*

In England and Wales, current recommendations advise that grassland soils should be maintained at soil P Index 2 (16-25 mg Olsen P/l) and K Index 2- (61-120 mg exK/l). The critical level for P and K and associated standard fertiliser recommendations are based on replicated, randomised-block design, quantitative experiments carried out in the UK during the 1940s to 1960s (Hemingway, 2007).

2.1.3. Soil structure.

Nutrient use efficiency and yield potential can also be influenced by soil structure; the arrangement of soil particles into soil aggregates (or 'peds'), the shape and size of these aggregates and the size, distribution and continuity of pores within and between aggregates to facilitate good drainage, aeration and water retention and supply. A well-structured soil consists of small, rounded aggregates and an even distribution of roots with *c.* 50% of the soil volume occupied by mineral and organic matter; *c.* 25% of the void space occupied by water; and *c.* 25% by air. In 'compacted' soils, void space and particularly macropore (or 'visible') pore space can be significantly reduced (Kurz *et al.*, 2006). There is good evidence to indicate that longer term grass leys of 10-15 years can improve soil structure and soil organic matter content to such an extent that root proliferation and access to nutrients is sufficiently improved (to provide a yield 'boost' particularly for spring sown arable crops (Johnston *et al.*, 2001a; Johnston *et al.*, 2009). However, while grassland soils generally have higher organic matter contents than arable soils and associated greater resistance and resilience to perturbation, they are also subject to soil degradation pressures from trampling by livestock, trafficking by machinery and cultivations at re-seeding or associated with previous arable rotations, particularly when soils are wet and in a 'plastic' state. Indeed, in a survey of 300 grassland soils in England and Wales, 60% were in 'moderate' condition, with productivity potentially compromised, and 10% were in 'poor' condition with clear signs that soil structure was limiting productivity and requiring intervention (Newell Price *et al.*, 2013).

Soil visual evaluation methods are available to help farmers assess their soils and maintain soil fertility and productivity. One such method links visual assessment findings to management interventions, such as aeration/slitting or sward lifting ("Healthy Grassland Soils"; Hargreaves *et al.*, 2015).

2.2. Nutrient applications.

While a critical level of soil fertility is required to optimise nutrient use efficiency and productivity, grass will often respond to additional nutrients applied in the form of manufactured fertilisers and organic manures. In higher output grassland systems, the principal nutrients that must be applied to meet grass dry matter (DM) yield requirements are nitrogen (N), sulphur and potassium. The DM yield response of grass to P additions is generally low and frequently not detectable (e.g. Penny *et al.*, 1980), although a yield response may occur when soil P reserves are low (soil Index 0-1), particularly when phosphate is applied in early spring.

Nitrogen application rates can be adjusted through the season according to rainfall (soil moisture) patterns and the amount of grass needed to match livestock energy requirements and grazing plans. However, sufficient sulphur and potassium must also be applied to facilitate the synthesis of amino acids and maintain cell turgor in leaves, thereby ensuring that N is used efficiently. For sulphur, in northern Europe, the amount provided from atmospheric deposition has decreased significantly in recent decades due to legislation restricting industrial emissions, such that the deficit now needs to be provided in the form of manufactured fertilisers or organic manures in the majority of lowland areas, particularly for second and later cuts of grass silage (Webb *et al.*, 2015).

For potassium, K_2O applications should be adjusted according to the N rate and associated expected yield to replace offtakes. However, the timing of potash applications should also be adjusted to avoid high applications in the spring to reduce the risk of tetany or hypomagnesaemia (grass 'staggers') in sheep and cattle. High levels of dietary K can have a detrimental effect on the metabolism of ruminants and while the general relationships between N and K applications in spring and tetany risk have been questioned (Hemingway, 2005), it is nevertheless clear that small reductions in available dietary Mg intake can have adverse effects on livestock health (Hemingway and Parkins, 2001).

Symbiotic *Rhizobia* bacteria associated with clover in grass/clover swards have the capacity to fix N from the atmosphere for use by grass and clover species, but for many clover varieties manufactured N fertiliser additions result in a reduction or elimination of clover and the N and grass DM that it provides. However, some modern clover varieties are more resistant to N fertiliser use and more research is needed to determine the extent to which they respond to N and S fertiliser. In England, *c.* 75% of grassland farmers had sown a proportion of their temporary grassland with a grass/clover mix in 2013-15; and c. 30% had sown all of their grass leys with a clover mix (Defra, 2015). These farmers therefore need guidance on the amount of grass DM and energy that can be produced from this source in terms of manufactured fertiliser N equivalent. Trials carried out in the 1970s and 1980s indicated that at peak content in a mixed sward of >20% of total DM, clover is capable of fixing 150-200 kg N/ha, representing a direct contribution to SNS (Morrison, 1987). Furthermore, without any N fertiliser input the DM yield of a grass/clover sward can represent 70-80% of that achieved at 'optimal' rates of N fertiliser application using a break-even ratio, 'price-based' approach (i.e. when the additional DM does not pay for the additional kg/ha of N applied).

Nutrients should therefore be applied to grassland to match the required and anticipated levels of grass growth. However, it is also essential that major and micro nutrients are supplied in sufficient quantities to ensure animal health. Deficiencies of micronutrients can result in major reductions in the health, fertility and productive performance of livestock. Fifteen micronutrient elements are believed to be essential for animal life: iron, iodine, zinc, copper, manganese, cobalt, molybdenum, selenium, chromium, tin, vanadium, fluorine, silicon, nickel and arsenic (Suttle, 2010). The availability of many of these elements, such as cobalt, copper and selenium, does not restrict grass growth, but too little in the overall diet can lead to deficiency in some animals. The aim should be to use micronutrient supplementation only where deficiency has been diagnosed. Furthermore, the supplement used should be cost effective and appropriate to the farming system in question (Fisher, 2004) and consideration should be given to the integration of feed and forage supply, since for some micronutrients the difference between deficiency and toxicity can cover a narrow range of concentrations in the diet.

2.2.1. Livestock manures.

A significant proportion of the nutrients required to maintain soil fertility and meet grass requirements can be provided by organic manures. A wide range of organic materials, including paper crumble, digestate (from anaerobic digestion plants) and biosolids (from wastewater treatment works) can be applied to grassland, and while the focus here is on livestock manures the integrated nutrient management principles applied to these are applicable to all organic materials.

Livestock manures are a valuable source of organic matter and nutrients. In the UK over 90 million tonnes of livestock manure supplying an estimated 410 kt of nitrogen (N), 270 kt of phosphate (P_2O_5) and 380 kt of potash (K_2O) are applied to agricultural land each year, which are worth in the region of £450 million (Williams *et al.*, 2000; Misselbrook *et al.*, 2014). The nutrients in livestock manures are typically not utilised effectively because of the high cost of handling, storing and applying to land. In general, the more productive the livestock system, the greater the quantity of manures produced in terms of nutrients, organic matter and volume (particularly on dairy farms in high rainfall areas); and the greater the management challenge in using nutrients effectively. However, whatever the level of output, a few basic principles apply to integrated manure and nutrient management on livestock farms.

Farmers and/or advisers should know the difference between 'readily available N' (the mineral N content of manures - ammonium-N, nitrate-N, and uric-N for poultry manures – that is potentially available for crop uptake) and 'crop available N' (the readily available N that remains for crop uptake after losses are taken into account). They should also know:

- Soil P, K and Mg reserves in each field and which fields/areas need 'building up' or 'running down'.
- How much livestock manure is produced on farm.
- Manure nutrient contents in terms of total and readily available nutrients.
- How much manure is applied to each field.
- How much crop available N is provided by each manure application depending on when and how the manure was applied.
- On soils with low P and K reserves, how much readily available phosphate and potash is applied as organic manure.

Straw-based farmyard manure (FYM) can be stacked in field heaps at relatively little cost and in Scotland, Wales and England can be spread when field conditions allow (i.e. closed periods do not apply). By contrast, slurry storage represents a significant cost and in Nitrate Vulnerable Zones slurry applications are subject to closed spreading periods to reduce the risk of nitrate leaching losses to ground and surface waters. Ease of handling can be improved through slurry separation with the volume of slurry reduced by 10-20% depending on the technology used. The liquid portion (like the unseparated slurry) is a high readily available N manure (typically 50-70%

readily available N) while the solid fraction contains a greater proportion of phosphate and organic matter.

Manure N efficiency (i.e. the percentage of total N applied that is taken up by the crop and is therefore equivalent to manufactured N fertiliser) of slurries is improved by using storage (to enable spring applications) and the use of precision application equipment such as trailing shoe and shallow injection machinery. Precision application equipment improves nutrient use efficiency by reducing ammonia volatilisation and allowing more uniform application (than surface broadcasting) across bout widths and reduced sward contamination, which allows slurry to be applied closer to grazing or cutting dates, thereby increasing opportunities for spreading. However, on most farms the costs of increased slurry storage capacities and precision application equipment is significantly greater than the value of increased nutrient use efficiency.

Decision-support tools such as PLANET, MANNER-*NPK* (Nicholson *et al.* 2013) and the "Fertiliser Manual (RB209)" can be used to determine how crop-available N is likely to change with manure application rate, timing and method in different agro-climatic regions. On fields receiving organic manures the grass N requirement that is not provided by crop-available manure N can be supplied by manufactured N fertiliser. It is the livestock production and grassland management system that should determine the amount and timing of manufactured N fertiliser (and associated nutrient) applications.

2.3. Integration with livestock and grassland management.

Grass growth potential varies according to a number of soil and site factors (see section 2.1), but also with the pattern of grazing and cutting through the season that influences the amount of leaf area within the sward that can intercept sunlight (green area index – GAI). For example, highest grass DM yield (but not necessarily quality) is achieved from cutting four times at four to five week intervals, starting in late May (Binnie and Chestnutt, 1991; Morrison *et al.*, 1980).

Cutting and grazing sequences and associated nitrogen applications should be adapted so that grass of sufficient quantity and quality is produced at key stages in the production cycle. For example, a spring calving dairy herd needs a good supply of grass throughout the grazing season with emphasis placed on the grazing areas to optimise production and quality from spring grass. Set stocking or grazing frequently in a paddock system ensures that a higher proportion of grass leaves are eaten before they die and increases the quantity of herbage consumed per hectare. Grazing the sward tightly in early season also results in lower stem development and a higher proportion of leaf in the sward in mid to late season thereby maintaining grass quality and milk yields per hectare in later season. For an autumn calving herd the emphasis should be placed on making sufficient high quality silage to achieve good performance during the winter, while farms with an all year round calving policy must balance the grazing/cutting system to provide high quality forage throughout the year (Milk from Grass, 1991).

Whichever grassland management and calving system is used, planned nutrient applications may also aim to provide a buffer of forage for times when grass growing conditions are poor. There are two main approaches advocated by researchers and advisers to present fertiliser recommendations; a 'price-based' approach and a 'systems' approach.

The 'price-based' approach uses a measure of the economic optimum level of grass production based on the principle that nitrogen application rates should be set at the point on the DM yield response curve at which any additional N (in terms of kg N/ha) would not pay for the additional forage produced, i.e. the point at which it would be cheaper to purchase the forage than use additional manufactured fertiliser N to grow it in the field. This approach aims to optimise outputs relative to the price of nitrogen fertiliser and the price of forage and in so doing will limit (to some extent) the proportion of N applied that is lost to the environment. It assumes that stocking rates should be matched to grass growth potential and that concentrate use should complement forage production rather than be the principal means of providing energy for meat and milk production.

The 'systems' approach attempts to account for differences in the requirements of a wide range of grassland production systems and seeks to grow sufficient grass to meet the energy needs of livestock, depending on the stocking rate, concentrate feed use and milk yields or rate of liveweight gain. It provides greater flexibility in fertiliser use and is responsive to different production systems, but requires the calculation of a number of different factors. In England and Wales, the current N recommendations for grassland ("Fertiliser Manual (RB209)"; Defra, 2010) was the first attempt to establish a 'systems approach' in the UK and was considered by some authors to be a step in the right direction although it was acknowledged that the system did have some limitations (Scott, 2010; Jewkes and Fisher, 2011). For example, the proportions of land that were cut and grazed was fixed and the approach was reactive to the production system in place rather than challenging the producer to achieve greater efficiency or profitability.

Within a genuinely flexible 'systems' approach, the area put down to first cut silage should be influenced by the stocking rate needed on the remaining grazing platform to optimise grazing productivity through the season (Milk from Grass, 1991). The amount of fertiliser nitrogen to apply on the cutting land would then depend on the site or grass growth class (GGC) and the amount of grass silage needed to 'fill' the silage clamp; in other words to provide sufficient energy to feed the housed livestock over winter plus any required 'buffer'. The "Fertiliser Manual" does not allow this degree of flexibility and it would be challenging to provide clear and simple advice using this type of energy model approach.

When prescribing nitrogen application rates it is also important to encourage a realistic level of precision in nutrient planning as the amount to apply depends on many factors; too much interpolation and fine adjustment can imply an undue level of certainty. For example, in temperate grassland regions, growing conditions in spring are rarely moisture limited and N requirements can be predicted with a degree of certainty, whereas in the latter part of the season production levels are far less certain. Over the summer months, when evapotranspiration rates are higher, water supply and associated grass growth are largely dependent on rainfall. Nitrogen fertiliser application rates and timings should therefore be matched to soil moisture and rainfall patterns, particularly on lighter soils in drier regions. A nutrient plan can be produced to match the cutting/grazing pattern and energy requirements of the system, but summer grass productivity and the N rates that should be applied will depend on rainfall patterns and the frequency of grazing/cutting (which influences green area index and associated grass growth rates). Phosphate, potash and magnesium application rates can be adjusted to match offtakes. It may be better to provide N recommendations to the nearest 30-50 kg N/ha or even ranges that should provide the amount of grass DM yield required and then allow farmers to adjust application rates according to grass growth rates, grazing regime and rainfall patterns.

3. UPDATING FERTILISER RECOMMENDATIONS.

Fertiliser recommendations may be updated due to a number of possible developments. These may include better understanding of the science that underpins the recommendations; new developments in terms of grass/clover varieties or livestock breeding; changes in the environment such as lower sulphur deposition; changes in the industry due to a wider adoption of certain grassland production systems; and improved understanding in terms of how recommendations are best presented.

It is essential that fertiliser recommendations are underpinned by robust scientific evidence and, where this is not available in any significant volume, by sound agronomic principles. Current fertiliser recommendations in the UK are largely based on many years of robust, quantitative data from well-designed experiments conducted in the 1940s to 1980s. For example, the N response models that underpin current N recommendations are based on experiments carried out in the mid-1980s (e.g. Morrison *et al.*, 1980; Morrison, 1987), and supported by experiments conducted since the 1940s on all grass growth classes (GGCs) under cutting regimes at sites all over the UK and Europe. However, it is unlikely that such extensive experimentation will be repeated in the near future, which leaves a number of research gaps.

3.1. Impact of grazing livestock.

We still have a limited understanding of fertiliser requirements at grazing. Grazing influences the production and response of grass to N application due to changes in GAI, recycling of nitrogen (and other nutrients) via dung and urine deposited during grazing, and because of spoilage due to trampling and the adverse physical effects of dung and soil (on contamination and covering of the sward), and urine (on grass scorch). There is a need to measure the response of grass to different annual rates of N using grazing stock *in situ* (Dale *et al.*, 2013), since the growth pattern of grazed land is very different from land that is cut three to four times in a growing season. The net effects of urine and dung returns, treading and spoilage and multiple grazing defoliations should be measured and compared with the production of cut grass at the same rates of N application.

3.2. Up to date nitrogen response data.

Since the 1980s many new grass and clover varieties have emerged and there is good evidence to indicate that breeders have enhanced characteristics such as sugar content and N use efficiency and therefore DM yield. For example, Camlin (1997) compared yield of cultivars bred in 1980 and 1995 and estimated that grass DM yield improved by about 0.5% per annum as a result of greater growth potential of the newer varieties. More recent estimates have ranged from 0.3% (Chaves *et al.*, 2009; Sampoux *et al.*, 2011) to over 1% per annum (Wilkins and Lovatt, 2010). There is therefore good evidence to suggest that the N response models need updating. Nevertheless, comprehensive response data at different N application rates covering the range of GGCs is lacking, which makes it difficult to estimate the yields of DM, energy and protein that can be achieved with modern varieties of perennial ryegrass (*Lolium perenne*) at different fertiliser rates.

3.3. New clover varieties.

Some new clover varieties are more resistant to N fertiliser and their ability to contribute fixed N in mixed swards with modern grass varieties is relatively unknown. Grass/clover swards are increasingly popular (Defra, 2015), so it is important that farmers are provided with robust information to help them estimate how much N can be supplied by modern clover varieties and how management and weather conditions can affect their growth.

3.4. Forage crops.

When the price of purchased feed increases, many farmers seek to use home-grown forage crops to provide additional energy and protein. Robust guidance is therefore needed on the dry matter production potential and forage quality of these crops when harvested as wholecrop and when grazed *in situ*. Depending on the area of forage crops grown on farm, such considerations could have a significant impact on the amount of grass needed from cutting land and at grazing.

3.5. Updating the recommendations.

Despite the evidence gaps, fertiliser recommendations can still be updated to reflect modern practices and trends. Nevertheless, as part of the updating process, decisions need to be made on which parts of the recommendation system can be updated and how.

In some circumstances there may be a strong case for updating the recommendations even without direct experimental evidence, if there is a significant amount of practitioner experience supported by agronomic and scientific principles and knowledge. For example, changes that have occurred in production systems, grass/clover varieties, atmospheric deposition and overall production potential, may require recommendations to be updated; and if changes in farm practice are further supported by recent data (even if it is of limited quantity) the case for change will be even more convincing.

Fertiliser recommendation and wider nutrient management guidance should take account of modern grassland production systems in terms of the range of economically viable systems, use of concentrates, growing of forage crops, production levels (milk yield and liveweight gain) and the sward characteristics of permanent and temporary grassland. They could also take account of emerging trends in terms of the systems and approaches to livestock production that are likely to dominate in the near future due to market pressures, regulation, industry aspirations and environmental concerns.

3.6. Relevance and clarity.

For fertiliser recommendations to be adopted and applied they need to be relevant, clear and logical in terms of the underpinning science and presentation to the user. Farmers and advisers need to be able to relate the recommendations to their own production systems and as such the system and language used should be recognisable and as simple as possible. The soil-plant system is complex, and is made even more so when livestock are introduced; the challenge is in generating a recommendation system that provides clear messages.

UK Department for Environment Food and Rural Affairs (Defra) project IF01121 assessed the views of farmers and advisers in England and Wales on the "Fertiliser Manual (RB209)" grassland recommendations, including awareness of the information, how it compared with current farm practices, how easy it was to understand and how it was used on farms. Survey outputs indicated that the grassland section was used by around 70% of grassland advisers, largely via hard copy. Users had a high level of confidence in the grassland recommendations and some thought the manual was a useful reference document and easy to use. However, only 13% of farmers personally used the recommendations and many farmers and advisers found the process of generating recommendations difficult to understand and overly complex.

There was a common view that changes were required to the content and presentation of the manual. Specifically there was a need to streamline and simplify the content and generally make the manual more 'farmer-friendly' (i.e. greater use of non-technical language). Suggestions for improving the format included the use of simple flow charts rather than detailed tables to describe the process of generating recommendations. In addition, many farmers could not fit their system to the total N requirement classes and had more than one option when interpolating between classes, resulting in more than one possible recommendation.

Another recommendation from IF01121 was that revisions should be made through a process of co-design involving farmers, advisers and agricultural scientists. Failure to extensively involve all groups risks a low uptake of future recommendations. A communications plan to raise awareness and increase use was also a key requirement. It is also important to be clear about the target audience and to recognise that farmers and advisers may have different requirements.

4. NEW DATA AND NEW DEVELOPMENTS.

Defra project IF01121 provided data on the N response of new perennial ryegrass varieties, the contribution of fixed N from clover in mixed swards and phosphate and potash offtake values for cut grass. The influence of P-fixing in different soils is also worth considering and has been adopted in some grassland recommendation systems around the world including in Scotland (Lumsdon, 2012; SRUC Technical Note TN668).

4.1. Nitrogen response of modern grass varieties.

As part of the Defra IF01121 validation project, ADAS and Rothamsted Research North Wyke conducted field-based N response experiments at twelve sites in England and Wales; two fields with contrasting sward age and fertiliser/manure history at each of six core sites (Figure 4). Each experiment used a randomised block design and a standard protocol with six rates of fertiliser N from 0 to 450 kg N/ha and four replicates of each treatment. Grass dry matter (DM) yield and herbage quality was measured on each plot at each of four cuts using a Haldrup plot harvester. The data from each experiment was summarised and statistically analysed using standard GENSTAT analysis of variance and nitrogen curve-fitting procedures.

Figure 4. *Six core locations for the 12 IF01121 N response field experiments.*

At any given level of manufactured N fertiliser, the grass DM yields measured in IF01121 were significantly higher than the indicative yields from cut grassland (derived from the N response trial work in the 1970s and 1980s) in the "Fertiliser Manual", using the same curve-fitting procedure. This indicates that recommendations in the Manual were consistently under-estimating the amount of grass that can be produced from cut grassland. Indeed, the indicative yields in the manual for Good/V good GGC land were similar to the yields measured in 2013 at a Poor GGC site in the Peak District at 345-375 m above sea level.

From 0 to 300 kg N/ha, grass DM yield response ranged from c.11 to 34 kg DM/kg of N applied and was greater at low SNS and low clover sites. The observed DM yields for each rate of fertiliser N were generally greater for the modern grass varieties used in the IF01121 experiments than the DM yields observed in the original 1970s/1980s trials, particularly at higher rates of fertiliser N (Figure 5). It is important to take account of possible differences in experimental protocols and management histories between the older and more recent sites. Nevertheless, the results indicate that modern grass varieties may be capable of producing more grass dry matter per kilogramme of fertiliser N applied than the older varieties used in the trials that underpin current grassland recommendations.

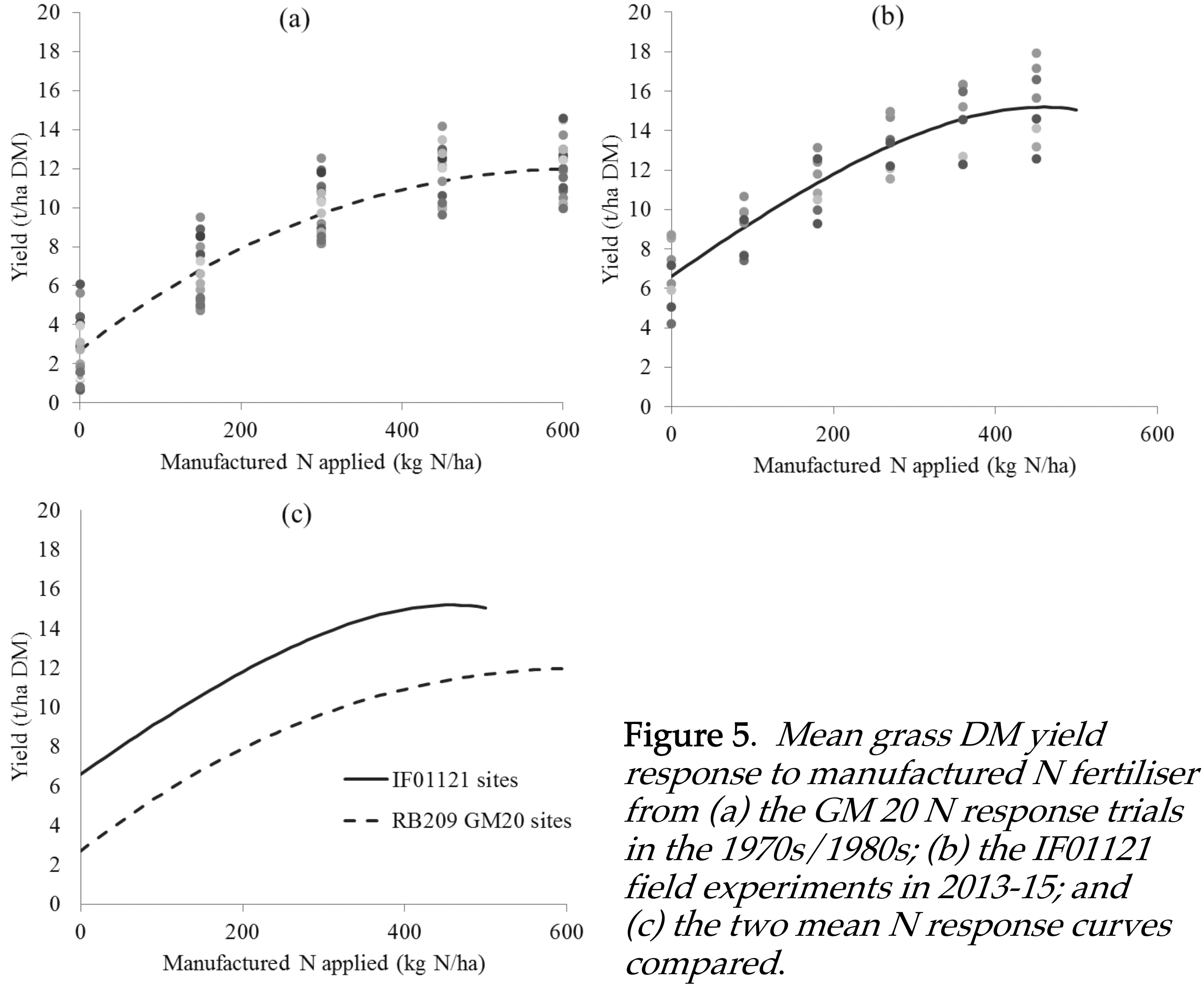

Figure 5. *Mean grass DM yield response to manufactured N fertiliser from (a) the GM 20 N response trials in the 1970s/1980s; (b) the IF01121 field experiments in 2013-15; and (c) the two mean N response curves compared.*

The field-based N experiments indicated good responses to fertiliser N up to and beyond 450 kg N/ha. For lowland swards between 1 and 10 years of age, 'optimum' DM yields (12.6 – 17.0 t DM/ha) were typically 15% to 36% greater than the maximum DM yield predicted by the model used in the "Fertiliser Manual" (12.5 t DM/ha). This supports estimates from other researchers that grass DM yield from modern perennial ryegrass cultivars has improved by 0.3-1% per annum as a result of greater growth potential in newer varieties (Wilkins and Lovatt, 2010; Sampoux *et al.*, 2011)

4.2. Fixed nitrogen from clover.

In 2013, two sites with second year leys in Ceredigion (west Wales) and Devon (south west England) were included with 7% clover in the seed mix (w/w) and the standard rates of manufactured N fertiliser were applied (0 to 450 kg N/ha over four cuts). SNS at these sites would have been low without clover addition; making it possible to compare the productivity of these sites with other low SNS sites without clover in Ceredigion and Shropshire (Figure 6).

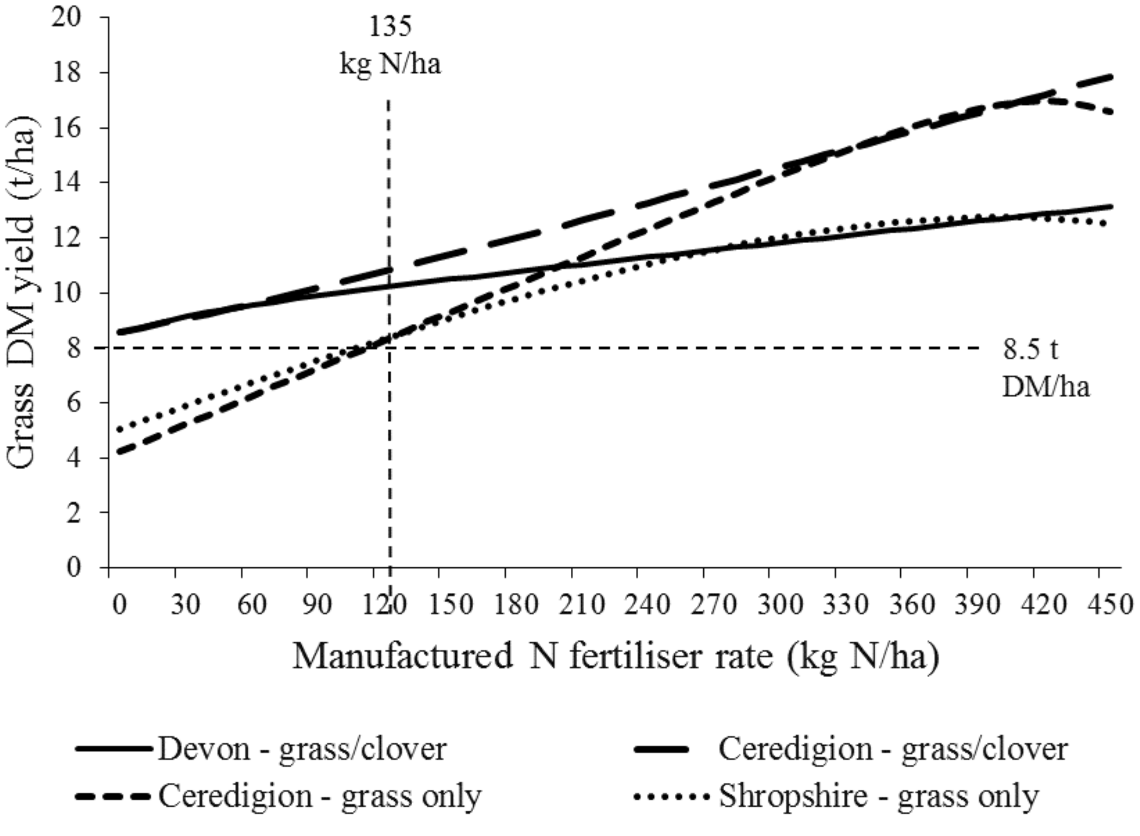

Figure 6. *Grass DM yield response to manufactured N fertiliser in two grass/clover swards and two grass only swards in 2013. The curves were fitted to the data using a linear + exponential equation.*

Clover contents at both grass/clover sites were high by mid-season (>40%) and were effective in increasing yield at lower manufactured N fertiliser rates, typically increasing grass DM yield by 2-3 t/ha compared to swards without clover. The data indicates that these modern clover varieties can fix around 100-150 kg N/ha over the growing season and that modern clover varieties can tolerate up to 240 kg N/ha in the form of manufactured N fertiliser over three cuts. Overall, the results demonstrate the importance of clover in low to moderate output systems.

4.3. Potash offtake.

The potash concentration in herbage was measured at each of four cuts at the twelve IF01121 N response sites and adjusted to 15-20% DM (Figure 7). Mean potash offtakes at second, third and fourth cuts were 42-63% higher than the offtake values in the "Fertiliser Manual". This has implications for potash fertiliser recommendations (although more evidence is needed) and emphasises the importance of regular soil sampling and analysis to check soil pH and nutrient reserves.

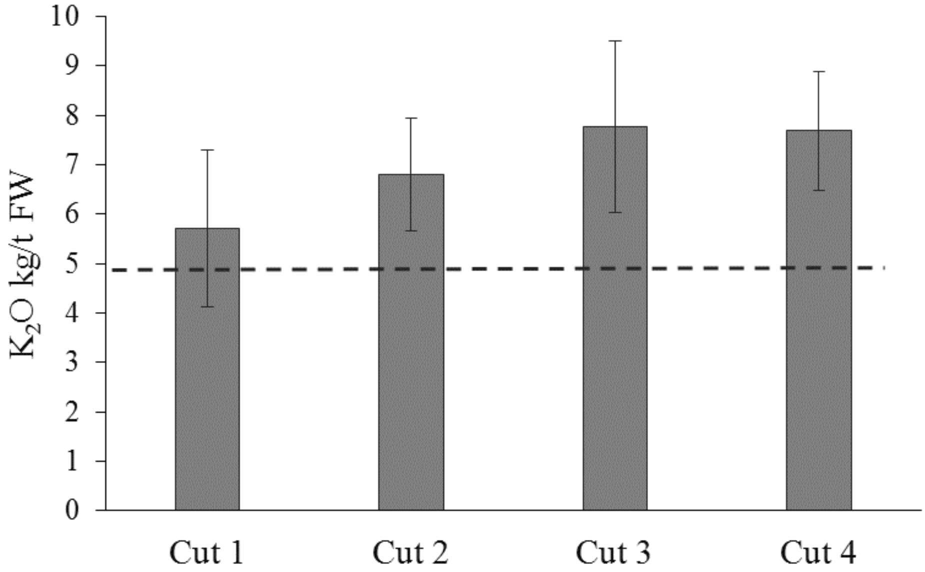

Figure 7. *Mean potash (K_2O) offtake values at each of four cuts at the twelve IF01121 N response sites. Error bars represent one standard deviation from the mean. The hatched line indicates the potash offtake value for fresh grass (15-20% DM) in the "Fertiliser Manual" of 4.8 kg K_2O/t fresh material.*

4.4. Soil phosphorus-fixing properties.

Soils vary in their capacity to fix P and this influences the amount and frequency of phosphate that needs to be applied to maintain soils at target P index. Soil testing every 3-5 years allows soil P reserves to be verified, but nevertheless in high P-fixing soils this could result in the amount of P in the readily available pool declining to below the level that is critical for optimal production between sampling dates. Consequently, in some countries, adjustments have been made to P recommendations to account for the level of P-fixing in different soil types. For example, in Scotland non-calcareous mineral soils have been mapped at soil association level as index 1, 2 and 3 to reflect inherent soil phosphorus sorption capacity (PSC). For established grass/clover swards the target soil P status on PSC 1 and 2 soils has been lowered to the lower band of moderate (M-; 4.5-9.4 mg P/l using the Modified

Morgan method), but remains at M+ (9.5-13.4 mg P/l) on PSC3 soils (Table 1). For grass only swards the target soil P status remains at M- for all soils.

Table 1. *Effect of P sorption capacity (PSC) on adjustments (kg P_2O_5/ha/year) to build-up or run-down soil P status for cereal-based arable rotations and established grass/clover swards (source: SRUC Technical Note TN668).*

P sorption capacity	**Soil P status** **Very low (VL)**	**Low (L)**	**Mod (M-)**	**Mod (M+)**	**High (H)**
PSC1	+40	+20	0	-10	-20
PSC2	+60	+30	0	-20	-30
PSC3	+80	+40	+20	0	-40

The decision on whether fertiliser recommendation systems should take into account the differing capacity of soils to bind with applied P will depend on the proportion of soils with contrasting P sorption capacity in any particular region or country and the extent to which the benefits in nutrient use efficiency and business profitability, justify the additional complexity in the recommendations. This is a decision that has to be made on a regional or national basis.

5. FERTILISER RECOMMENDATIONS – OPTIONS.

New data on the response of modern grass varieties to fertilisers and on the ability of new clover varieties to fix N could potentially allow the models that underpin fertiliser recommendations to be updated. However, presentation, structure, ease of use and the ability of farmers and advisers to relate their systems to the recommendations is key to determining uptake and use. The following sections discuss three different approaches to grassland fertiliser recommendations; namely, 'price-based', 'responsive' and 'land potential-based'; and the use of case studies to illustrate fertiliser use at different levels of production intensity.

5.1. Price-based.

Fertiliser recommendations based on the so called 'economic optimum', used the price of fertiliser and the value of forage to determine when the economic optimum fertiliser application had been reached. Historic data suggested that the response of grass to N fertiliser was almost linear up to applications of 200-300 kg N/ha/yr and declined thereafter until a maximum yield was reached at about 500-600 kg N/ha/year. For beef and sheep grazing systems, the economic optimum was considered to be the point at which less than 10 kg DM of grass per ha was produced for an additional kg of N applied. For dairy grazing systems and cut grass 7.5 kg of grass DM yield was needed to pay for each additional kg of N fertiliser. Data from Defra project IF01121 indicate that, in general, modern grass varieties have similar N response characteristics (in terms of the shape of the response curve), but that N use efficiency and DM yields may be 10-35% higher than in older varieties depending on the level of N supply. While some grass swards continue to give a linear response to fertiliser N beyond 400-500 kg N/ha, for most swards the same 'price-based' approach could be used for modern grass varieties while taking account of the higher DM yields achieved.

Where response to N continues to increase linearly above 200-300 kg N/ha, there would be justification in sustaining higher N fertiliser rates in economic terms, but the main limitation would then be based on the level of stocking that is sustainable without increasing soil and sward degradation and the amount of N loading on the environment that is acceptable. While the N use efficiency in percentage terms does not reduce at higher rates of N fertiliser below the economic optimum, the overall loading on the environment will increase the potential for elevated losses to the air and water environments. It is therefore likely that recommended N fertiliser rates for grassland in livestock production systems will not increase above those provided in recent decades. However, the amount of grass DM produced per kg of N applied could be greater and this would need to be reflected in any revised set of recommendations.

A recommendation system using the price-based approach could be used, and similar principles to those used in Milk from Grass (1991) developed for present day grassland farming systems, in which subtle changes to N fertiliser application rates (±50-70 kg N/ha) are made at each GGC according to SNS and sward management; stocking rate on grazing land is adjusted through the season to optimise production levels (liveweight gain or milk yield) per hectare (Table 2). However, such a system assumes that all farmers would apply fertiliser at an application rate determined by the GGC in each field and the price of fertiliser, rather than their individual approach to grass utilisation and their target level of intensity in terms of grazing and production. Livestock farms can be profitable at different levels of intensity and so advising livestock farmers to apply higher amounts of N fertiliser may not make sense economically or environmentally. It is the lack of flexibility in the 'price-based' method that gave rise to a more systems-based approach.

Table 2. *Target grazing stocking rates (cows/ha) through the grazing season for autumn calving cows (assuming 'economic optimum' rates of N fertiliser applied; source: Milk from Grass, 1991).*

Time	Grass growth class				
	Very good	**Good**	**Average**	**Poor**	**Very poor**
Apr-May	8	7	7	7	7
Jun – mid July	7	7	5	5	4
Mid July – early September	7	6	3	3	2
September - housing	3	3	2	2	2

5.2. Responsive.

A second approach to grassland fertiliser recommendations is the systems approach used in the "Fertiliser Manual" (Defra, 2010). This uses the same N response data used in previous editions to underpin the recommendations, but bases the N recommendation on the actual amount of grass DM that should be grown to fulfil the energy requirements of the livestock on farm. In this way it reflects what the farmer is already doing in terms of stocking rate, concentrate use and, in the case of dairy farmers, milk yield per cow. The energy model underpinning the recommendations was robust, but the assumptions used in terms of the proportion of land that is cut and grazed and therefore the level of intensity that could be adopted on cutting land did not allow much flexibility in terms of how cutting and grazing land is managed .

Information from Defra project IF01221 suggests that other challenges associated with the paper-based version were the level of complexity, the difficulty in generating a recommendation for any single cut or grazing, the difficulty of matching some farmers' system to the recommendation tables and the fact that the recommendations merely responded to what the farmer was doing rather than indicating areas where improvements could be made in terms of productivity or efficiency. Nevertheless, many farmers and advisers who used the manual were able to derive a recommendation for their farm and, once they had become familiar with the new approach, were able to apply it to numerous farms. Some advisers, having invested the time to understand and implement the new systems approach, were keen to retain it. Nevertheless, it should be possible to improve the clarity, simplicity and flexibility of the approach.

5.3. Land potential approach.

To develop the systems approach further, there is a case for developing a recommendation system that provides farmers and advisers with information aimed at improving productivity and efficiency rather than the recommendation system merely responding to the current situation on farm. One possible approach would be to start with GGC (i.e. land potential), the chosen proportion of grass/clover and grass only swards and the level of N fertiliser use anticipated by the farmer. These parameters would then determine the appropriate long term target stocking rate. The proportion of cutting and grazing land could then be allocated, depending on the silage making policy (one, two or multi-cut system), and monitoring of grazing sward heights through the year used to adjust the size of the grazing area. This allows farmers to integrate cutting and grazing at an appropriate level of production in terms of land potential and farming system.

5.4. Case studies.

To complement the recommendation system, case studies could provide guidance for grazing at different levels of intensity and for cutting at different levels of N use (high, medium and low). For grazing, the case studies could provide the amount of energy and grass DM likely to be produced at three levels of N use, based on field history (SNS) and GGC (e.g. Very Good/Good, Average and Poor/Very poor), and the appropriate target stocking rate for effective grass utilisation. Case studies at different levels of N use could also be provided for cutting land since data obtained from on-farm surveys has shown that farmers generally do reduce N fertiliser rates for silage production at lower levels of overall production intensity (Chadwick and Scholefield, 2010 – unpublished).

The silage production case studies could start with the livestock housing period, the number of livestock and their energy requirements and therefore the amount of conserved grass DM required to feed the livestock over winter. Then, taking account of waste and spoilage in the field and clamp, and the area allocated to cutting, the appropriate N fertiliser rate could be selected based on the typical N response curve for the GGC. For both grazing and cutting land, high, medium and low intensity situations could be illustrated to provide examples for those operating at different levels of intensity. The farmer or adviser would then be better able to answer the question "how much N do I need to apply for my system, and for other systems?"; and information would be provided at the level of intensity at which each farmer wishes to engage.

6. CONCLUSIONS.

Grazing livestock farms are varied and complex systems, which makes nutrient management and the provision of fertiliser recommendations for grassland challenging, both in terms of approach and presentation. Nutrient management should be integrated to take account of major and micro-nutrients supplied from the soil, feed, manures, clover and manufactured fertilisers. Fertiliser recommendations should be set within the context of the energy needs of livestock and should reflect the current range of production systems and emerging trends. They should also take account of the response to applied nutrients of modern grass and clover varieties and of changes in the supply of nutrients from other sources (e.g. sulphur from atmospheric deposition). Finally, despite the complexity of the production systems themselves, fertiliser recommendations need to be made as easy to understand as possible; provided at an appropriate and realistic level of precision; and also be clear, accessible and recognisable so that farmers and advisers can relate them to their own systems.

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