June 2016

Research Review No. 3110149017

Review of evidence on the principles of crop nutrient management and nutrition for grass and forage crops

Paul Newell Price[1], Kate Smith[2] and John Williams[2]

[1]ADAS Gleadthorpe, Meden Vale, Mansfield, Nottinghamshire, UK, NG20 9PD

[2]ADAS Boxworth, Battlegate Road, Boxworth, Cambridgeshire, UK, CB23 4NN

This review was produced as part of the final report of an 8.5 month project (3110149017) which started in September 2015. The work was funded by AHDB under a contract for £98,669. There were six work packages. This report reviews findings from WP3 – Grass and forage crops.

While the Agriculture and Horticulture Development Board seeks to ensure that the information contained within this document is accurate at the time of printing, no warranty is given in respect thereof and, to the maximum extent permitted by law, the Agriculture and Horticulture Development Board accepts no liability for loss, damage or injury howsoever caused (including that caused by negligence) or suffered directly or indirectly in relation to information and opinions contained in or omitted from this document.

Reference herein to trade names and proprietary products without stating that they are protected does not imply that they may be regarded as unprotected and thus free for general use. No endorsement of named products is intended, nor is any criticism implied of other alternative, but unnamed, products.

CONTENTS

1. Abstract

The Crop Nutrient Management Partnership was set up by AHDB to review and revise the “Fertiliser Manual (RB209)” and produce a new “Nutrient Management Guide (RB209)” for release in May 2017. The main aim of this work package was to review research carried out on nutrient management in grass and forage crops to inform revisions of RB209. Literature searches were carried out to identify research from the UK and northern continental Europe since 2009 to inform revisions of the grassland and forage crop sections. Data was also gathered from a number of relevant stakeholder groups and research projects.

Compared with trials carried out primarily in the 1980s and 90s, there is a relative paucity of data on grass/clover and forage crop response to applied nutrients in England and Wales. Nevertheless, recent evidence indicates that modern grass swards can produce more grass dry matter (DM) yield than older swards at any given rate of applied nitrogen (N). This has important implications for grass N recommendations, although further research is needed to confirm the findings and to provide evidence for the response of grass to N when grazed. Declines in sulphur deposition have increased the reliance of grass swards on sulphur mineralised from the soil and applied as manufactured fertiliser or organic manure. There is increasing evidence to indicate that sulphur should be applied to grass and forage crops in high risk situations (i.e. infrequent applications of organic manure, on lighter soils and in higher rainfall areas).

Phosphate and potash recommendations are sound, but further work is needed on the response of grass herbage to P fertiliser applications where soil P reserves are low or moderate; on identifying and mapping high P-fixing soils in England and Wales; and on grass potash offtake values. The importance of micronutrients for plant and animal health and options for supplying micronutrients to crops and livestock also need to be covered in the new recommendations.

There was very little research or data made available on the response of forage crops to applied nutrients, although there is some useful new data on forage maize. The evidence indicates that only minor amendments are needed to forage crop recommendations.

Options have been provided for N recommendations that draw from the best aspects of the 7th and 8th editions. The existing sulphur, phosphate and potash recommendations from grazed and cut grass have been reviewed. Recommendations for forage maize, Brassicas, whole-crop silage and swede and kale grazed *in situ* have also been reviewed. Sections and appendices will be revised and combined for a single entry on grass and forage crops for livestock farmers.

2. Introduction

Defra's Fertiliser Manual (RB209), 8th edition provided industry standard recommendations for nutrient use for most agricultural crops including grassland. In the 8th edition, the structure of the nitrogen (N) recommendations for grassland was completely changed from that in the 7th edition, at the request of Defra to make the recommendations more applicable/relevant to the range of livestock production systems. The new recommendations used a 'systems' approach with N recommendations adjusted for the amount of grass production needed on a farm based on the intensity of production and use of concentrates in the livestock system. Although this new conceptual approach was widely regarded as a major improvement, the technical detail of the new recommendations and the way they were presented in the 8th edition, was subject to much discussion and there was no opportunity to test the new system on farmers and advisers before publication.

The different livestock types, wide range of livestock and grassland management systems and agro-climatic regions in England and Wales make the provision of grassland recommendations challenging. The number and timing of cuttings and grazings varies within and between farms; factors to consider which will vary from field to field and from region to region include:

- Rainfall, altitude, temperature
- Past management / soil type / Soil Nitrogen Supply (SNS)
- Age of sward / clover content

It is important to account for nutrients recycled at grazing and limits to utilisation due to wastage and spoilage of grass (Richards and Wolton, 1976; Richards *et al*. 1976 and Richards, 1978). Improvements in the dry matter (DM) production potential of newer grass varieties (Chaves *et al*., 2009; Sampoux *et al*., 2011; Wilkins and Lovatt, 2010) and the phosphate and potash offtake rates of modern grass and clover varieties are another important consideration. New information on the nutrient requirements of forage crops such as forage maize, Brassicas, whole-crop cereals and root crops was needed for integration into livestock production systems. Nutrient management guidance should also consider integration of feed advice in order to improve business profitability and farm nutrient balances, which may be a vital component for sustainable production in the future (AFRC, 1993; Scott, 2010).

Surveys carried out in 2012 and 2013 as part of Defra project IF01121 indicated that the 8th edition grassland section was used by around 70% of grassland advisers, largely via hard copy, but only 13% of grassland farmers, with many finding it difficult to use. Field experiments carried out between 2012 and 2014 indicated a greater DM yield response to N fertiliser from modern grass varieties compared with trials carried out in the 1970s/80s that were used to underpin the 8th edition recommendations. These findings identified a clear need for a technical update of the current fertiliser recommendations for grassland and a thorough simplification of how the recommendations are presented. Changes in forage crop practices with greater use of whole-crop cereals and crops grazed *in situ* has also stimulated the need for an update of the fertiliser recommendations.

This work package reviewed the current recommendations and additional relevant research with a view to revising RB209 and producing the AHDB Nutrient Management Guide to be released in 2017. The new guide will provide practical, robust and clear information on nutrient management to optimise economic production and minimise environmental impact by reduced nutrient loss.

2.1. Aims and objectives

The main aim of the work package was to review research since 2009 on crop nutrition for the main grassland and forage crops of England, Wales and Northern Ireland (N.I.) and based on the findings, and where appropriate, to revise and amalgamate the grassland and forage crop sections in the "Fertiliser Manual (RB209)" to produce new, clear, coherent, up to date, standalone and scientifically robust recommendations. The main objectives were to:

- Evaluate and review Defra and AHDB (and where applicable other UK) research undertaken. since 2009 on the principles of crop nutrient management and nutrition for grassland and forage crops.
- Identify where changes to recommendations could be made.
- Present changes in a format suitable for a future RB209 revision.

The specific detailed objectives were to:

i. Use the review of evidence to develop new N recommendations for grassland.
ii. Provide options for presenting nitrogen recommendations.
iii. Review phosphate (P_2O_5) and potash (K_2O) recommendations for grazed and cut grass and update recommendations where necessary.
iv. Update forage crop recommendations, including forage maize, cereals grown for whole-crop silage (with and without legumes), Brassicas, crops grazed *in situ* (swede and kale).
v. Amalgamate grassland and forage crop sections and related appendices into a single complete section.
vi. Identify gaps in knowledge & future research required.

3. Methodology

Relevant data and information from industry contacts (Appendix III) and from Defra and AHDB projects was collated and reviewed for evidence produced since 2009. In addition, ‘Web of Science’ searches were carried out using keyword combinations to find relevant UK-affiliated research on crop nutrient management carried out since 2009.

3.1. Online searches

‘Web of Science’ is a web-based scholarly research database and search facility that provides access to bibliographic information such as the Science Citation Index (http://apps.webofknowledge.com). Combinations of keywords, search strings and boolian operators were used to reduce bias and provide more focused and productive results. The geographical range was limited to United Kingdom and Western European affiliated research papers, however this occasionally included research carried out elsewhere (e.g. New Zealand), and if relevant this evidence was included in the review. Where searches returned a large volume of papers, the geographical range was limited to the United Kingdom.

The database and search terms used, along with the number of hits (Appendix I) and a full list of the evidence produced was recorded. Two screenings were then carried out to refine the search results and identify relevant research papers.

3.1.1. Screening the results

The first screening used the title of the evidence to check its relevance to addressing the aims and objectives. The second filter used the full abstract to check for relevance and to select research papers that would be used in the review. This resulted in a final list of 35 research papers.

The quality of the collated data was assessed for scientific rigour and relevance; field trials lacking robust scientific protocols that did not include the use of replicated treatments in a randomised block design or some other adequate replication methodology to take account of spatial variation in soil properties (and other crop growth determining factors), standard error and variance were not included in the review. All data sourced as part of the review were evaluated to assess the quality of the data.

Where the evidence indicated a need to change fertiliser recommendations this is specified in the following sections. Revisions will be made in an associated Appendix, which will be produced once the selected option for grassland N recommendations (from those provided in this report) is clear. The review clearly states where updates cannot be made due to a lack of robust or up to date evidence.

3.2. Projects and data

Evidence and data was collated from AHDB Dairy and AHDB Beef & Lamb research partnership outputs and other grass and forage crop nutrient management projects, including:

- AHDB Cereals & Oilseeds project 3699 – 'Modern triticale crops for increased yields, reduced inputs, increased profitability and reduced greenhouse gas emissions from UK cereal production'.
- AHDB Dairy project 74316 'Assessment of varietal characteristics important to low and zero inorganic nitrogen input herbage production'.
- Dale, A., Aubry, A., Ferris, C., Laidlaw, S., Bailey, J., Higgins, S. and Watson, C. (2013). Critique of RB209 8th Edition Grassland nitrogen recommendations for dairy systems. AFBI Report. 171pp.
- Defra project IF01121 'Validation of Fertiliser Manual (RB209) recommendations for grassland'
- Defra project KT018 'Nutrient management decision support systems process improvement'.
- Defra project LS3650 'Utilise genetic variation within and between improved grass populations to improve the sustainability of UK grassland'.
- Wilkins, P.W. and Lovatt, J.A. (2010). Gains in dry matter yield and herbage quality from breeding perennial ryegrass. In: Grasses for the Future. M. O'Donovan and D. Hennessy (eds.) Proceedings of an International Conference, Cork, 14-15 October. Teagasc. 43-50.

3.3. Deliverables

These included:

- A comprehensive simplification of the recommendations (in terms of approach and presentation), incorporating an appropriate level of precision while retaining scientific rigour to take account of important factors such as livestock production intensity and system potential.
- Options for presenting N recommendations, including grass silage crop recommendations and consideration of the influence of Grass Growth Class (GGC) and Soil Nitrogen Supply (SNS).
- Production of typical ranges of grass DM yield produced from different levels of N fertiliser use.

Grass DM response to applied N

Assessment of grass N response incorporated findings from Northern Ireland (N.I.), Defra project IF01121 'Validation of fertiliser manual (RB209) recommendations for grassland' and from other fertiliser N response plots used in projects such as DC-*Agri* (Defra/ WRAP, WRAP Cymru and Zero Waste Scotland funded project OMK001-001) and Defra project AC0116 and the Innovate UK ‘Grass sense’ project.

New grassland N response data was compared statistically with IF01121 outputs (and the N response curves generated for the 8th edition) and the overall response to differential rates of N fertiliser assessed using ‘linear + exponential’ curve fitting and analysis of variance.

In addition to updating the N recommendations, we have reviewed the evidence to support maintaining the current sulphur recommendations, including evidence from N.I. supporting the possible need for additional sulphur applications ahead of first cut silage crops.

Options for presenting N recommendations

Outputs and experience from Defra project IF01121 surveys, case studies and focus groups have been used to produce options for presenting N recommendations in a clear and simplified format while retaining scientific rigour and an appropriate degree of precision. Options for presenting N recommendations include:

- Methods to account for different levels of livestock production intensity and system potential.
- Options for assessing the amount of fertiliser N to apply at grazing.
- Options for treating silage as a crop, taking account of growth stage at cutting, quality targets and sward clover content.

The following section reviews recent research on the response of grass to nitrogen, sulphur, phosphate, potash and lime; the effect of grazing on DM yield; and the effect of nutrient applications on grass and silage quality. Section 5 reviews grassland recommendation systems in the UK and Republic of Ireland (ROI). Recent research on the response of forage crops to applied nutrients is reviewed in section 6. Sections 7 and 8 outline gaps in knowledge, future research requirements and the main conclusions of the review. Options for presenting new grassland N recommendations are provided in Appendix II.

4. Response of grass to applied nutrients

4.1. Response of grass to nitrogen

The energy model that underpins the nitrogen recommendations in the “Fertiliser Manual (RB209)” used a nitrogen response curve that was based on the GM20, GM23 and GM24 trials carried out in the 1970s through to the early 1990s. There is some evidence to indicate that modern grass varieties have a greater DM yield response to N fertiliser applications compared with the GM20-24 trials (e.g. Chaves *et al*., 2009; Sampoux *et al.*, 2011 and Wilkins and Lovatt, 2010). Camlin (1997) compared yields 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). Field experiments carried out between 2012 and 2014 (Defra project IF01121) also indicated a greater DM yield response to N fertiliser applications of newer grass varieties compared to trials carried out in the 1970s/80s. The IF01121 experiments included 10 sites assessed over three years (2012-14) with sward ages mostly ranging between one and ten years; one higher altitude (> 300 m above sea level) sward was around twenty years old. This compares with the 48 trials in the GM20-24 datasets that were repeated in successive years. Furthermore, all the IF01121 experiments were carried out at sites that had been in grass for a number of years, while the GM20-24 trial sites had previously been in an arable rotation. This is likely to have resulted in contrasting levels of Soil Nitrogen Supply (SNS) with the IF01121 sites supplying greater levels of mineralised N. Nevertheless, it was worth comparing the older and newer datasets to determine whether differences in the DM yield response were statistically significant.

The N response curves from the two datasets were compared using regression analysis and parallel curve analysis. Linear + exponential curves (Y= A + B*(R**X) + C*X; where Y is the DM yield and X is the N fertiliser rate) were fitted to both sets of data for N fertiliser rates ranging from 0 to 450 kg N/ha. The parallel curve analysis involved 4 stages:

i. A single curve was fitted to all the data.
ii. Parallel curves were fitted to the two sets of data with different intercepts for the 2 curves; A was allowed to vary with parameters B, C and R kept constant for the two curves.
iii. A, B and C were allowed to vary with R kept constant for both curves.
iv. All parameters were allowed to vary, i.e. the curves fitted were the best for each individual dataset.

At each stage the sums of squares (s.s.) explained by the fit was calculated and the improvement in fit determined (*Table* 1). The percentage variance accounted for was 64% at stage 1 and 84% at

Stage 2, providing a significant improvement in fit using the parallel curves compared with the single curve. Stages 3 and 4 did not provide a significant improvement on stage 2, indicating that the data can be fitted best by two parallel lines (Table 1 and Figure 1) with the DM yield response from the IF01121 data around 3.9 t DM/ha above that for the GM20-24 data.

Table 1. Accumulated analysis of variance from parallel curve fitting to compare IF01121 and GM20-24 N response data.

Change	Degrees of freedom	Sum of squares	Mean square	Variance ratio	*P* value
+ N (Stage 1)	3	1378.940	459.647	168.39	<0.001
+ Group (Stage 2)	1	433.208	433.208	158.71	<0.001
+ N.Group (Stage 3)	2	0.173	0.086	0.03	0.969
+ Separate non-linear (Stage 4)	1	0.025	0.025	0.01	0.924
Residual	120	327.557	2.73		
Total	127	2139.903	16.85		

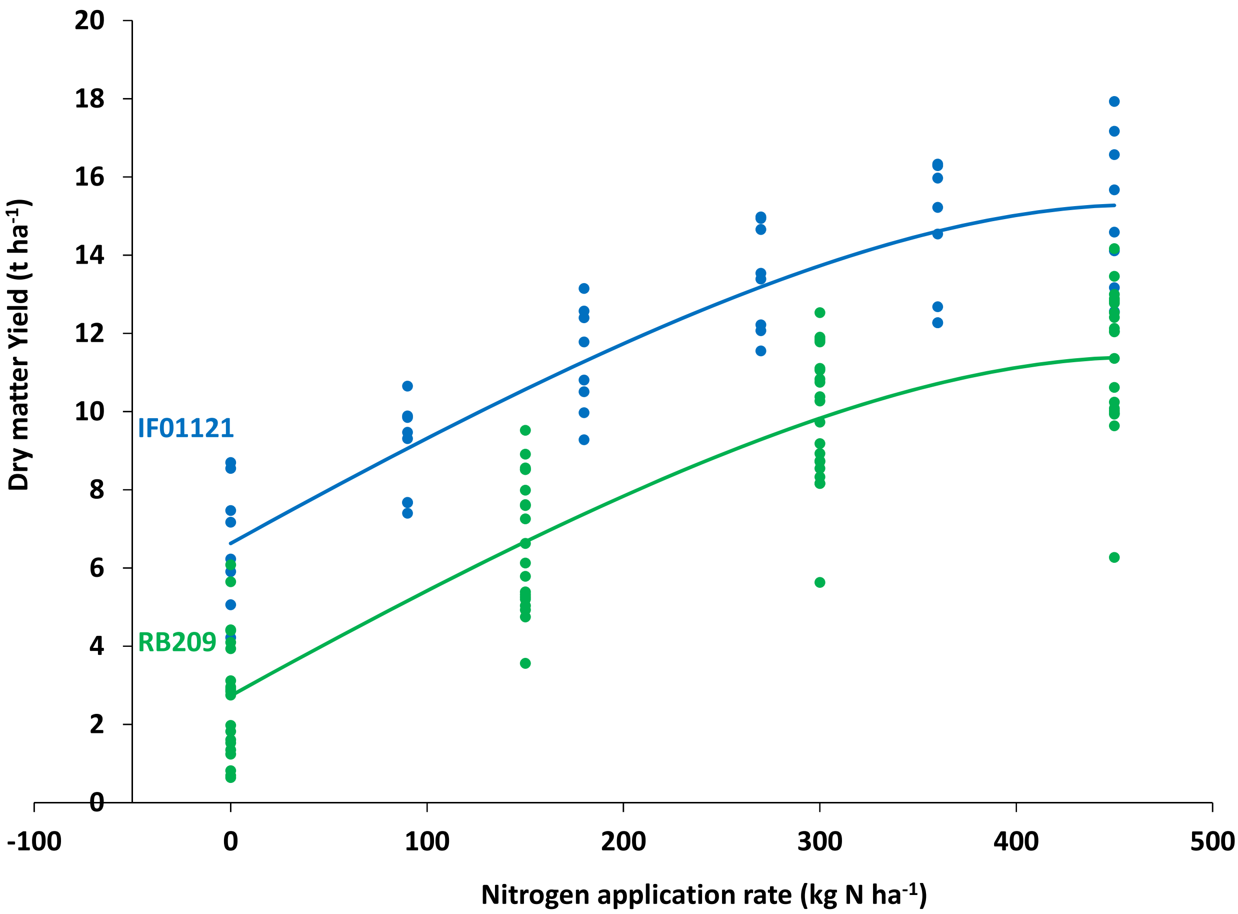

Figure 1. Parallel curves fitted to the IF01121 and GM20-24 DM yield response data.

Wilkins and Lovatt (2011) found that modern perennial ryegrass varieties yielded 12-38% more than older varieties (cv. Talbot and cv. S23) at the N fertiliser application rate tested of 385 kg

N/ha. By comparison, the IF01121 swards on average yielded 36% more than the older GM20-24 varieties at the same level of N use (Figure 1). This is at the upper end of the range measured by Wilkins and Lovatt (2011). However, if modern grass varieties are more efficient in their ability to convert N into dry matter one would expect the DM yield differential to be greater at higher N fertiliser rates than at lower rates, i.e. the two N response curves should be divergent, with the modern variety response curve having a steeper slope compared with the older variety response curve. The fact that the difference in yield between old (GM20-24) and modern (IF01121) varieties was similar at 0 kg N/ha and 400 kg N/ha indicates that the difference between the two datasets was more to do with SNS (or the comparative ability of the swards to exploit the nitrogen supplied from the soil) than the relative fertiliser N use efficiency of modern and older perennial ryegrass varieties. More work is needed comparing the N response curves of older and modern ryegrass varieties in replicated field experiments at a number of sites using differential N rates. Therefore, there is insufficient evidence from replicated UK grassland field experiments to justify a change to the N response curves used to underpin the grassland N recommendations in the "Fertiliser Manual (RB209)".

N response by defoliation

When providing N recommendations for grassland it is important to consider the amount of N to apply for each cut (of silage or hay) and grazing. The effects of grazing on herbage production is covered in section 4.5. To investigate DM yield response by cut, data was collated from a number of replicated, randomised block, field experiments using differential fertiliser N rates carried out in England, Wales and N.I.:

- Defra IF01121 – 4 cuts taken at 10 separate sites; first cut in late May/early June with subsequent cuts at approximately six week intervals
- AFBI Hillsborough Estate, County Down – 3 cuts taken at 4 separate sites; first cut in mid-May/early June with subsequent cuts at six to eight week intervals
- Defra AC0116 – 3 cuts taken at two separate sites; first cut in mid-May/early June with subsequent cuts at six to eight week intervals
- Innovate UK, Grass Sense project – 2 cuts taken at three separate sites; first cut in May/June and second cut in July/August

Linear + exponential curves were fitted to the data and the optimum N rate calculated using a break-even ratio of 10:1 (Chadwick and Scholefield, 2010). Meta-data on GGC, SNS and sward age was also collated to investigate the effect of these factors on DM yield response. The experimental protocols for first cut silage were the most consistent in terms of the defoliation timing and yet there was a remarkable degree of variation in DM yield response (Figures 2 to 4). $Nopt_{10}$ (The fertiliser N rate at economic optimum yield, based on a break-even ratio of 10:1) ranged from

62 to >170 kg N/ha, while the DM yield ranged from 2.3 to 7.7 t DM/ha (Table 2). The variation in DM yield at each N fertiliser rate was mainly a function of SNS (Figures 2 to 4).

Table 2. Ranges of nitrogen (N) optimum fertiliser rate at a break even ratio of 10:1 by cut and for the whole season and number of observations for which N-optimum was reached. Note: for the remaining observations N-opt was either not reached or exceeded the highest N-rate.

	1st Cut	2nd Cut	3rd Cut	4th Cut	Whole season
N-opt (kg N/ha)	62 to 170	47 to 147	30 to 91	15 to 38	110 to 406
Dry matter yield at N-opt (t/ha)	2.3 to 7.7	2.4 to 5.9	1.2 to 5.7	0.3 to 2.9	7.0 to 16.9
Number of observations N-opt reached	16	19	8	3	19
Total number of observations	22	22	16	10	22

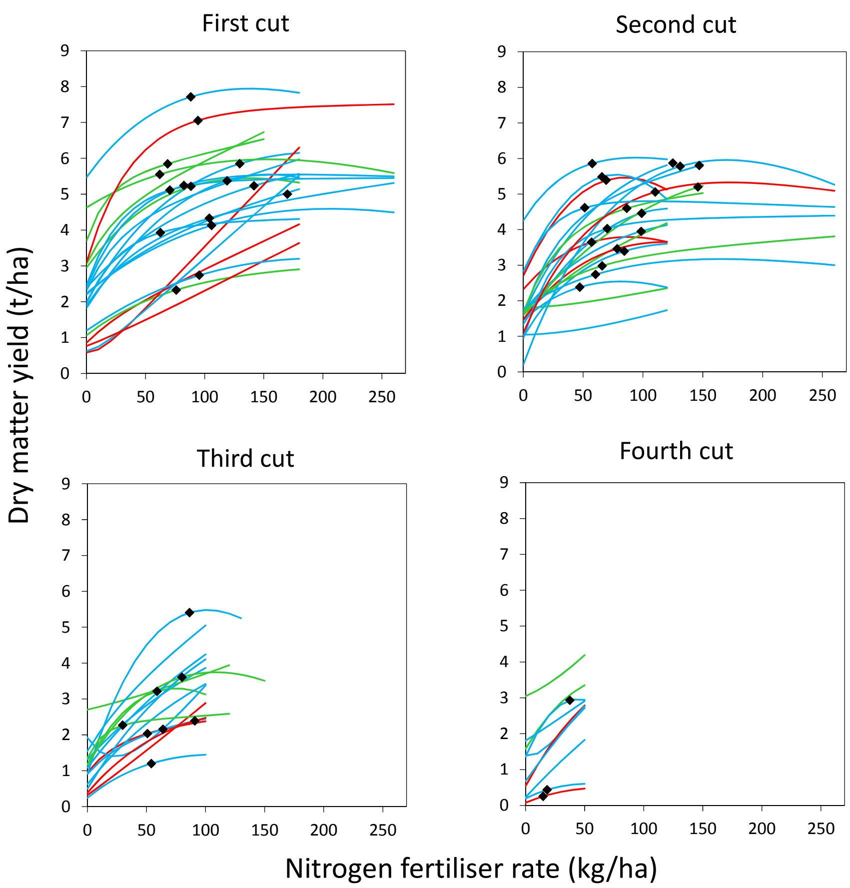

Figure 2. Fitted (linear + exponential) yield response curves by cut; colour coded by Soil Nitrogen Supply (SNS) Index: Low, Moderate and High. Diamonds represent grass yields at nitrogen optimum at a break even ratio of 10:1.

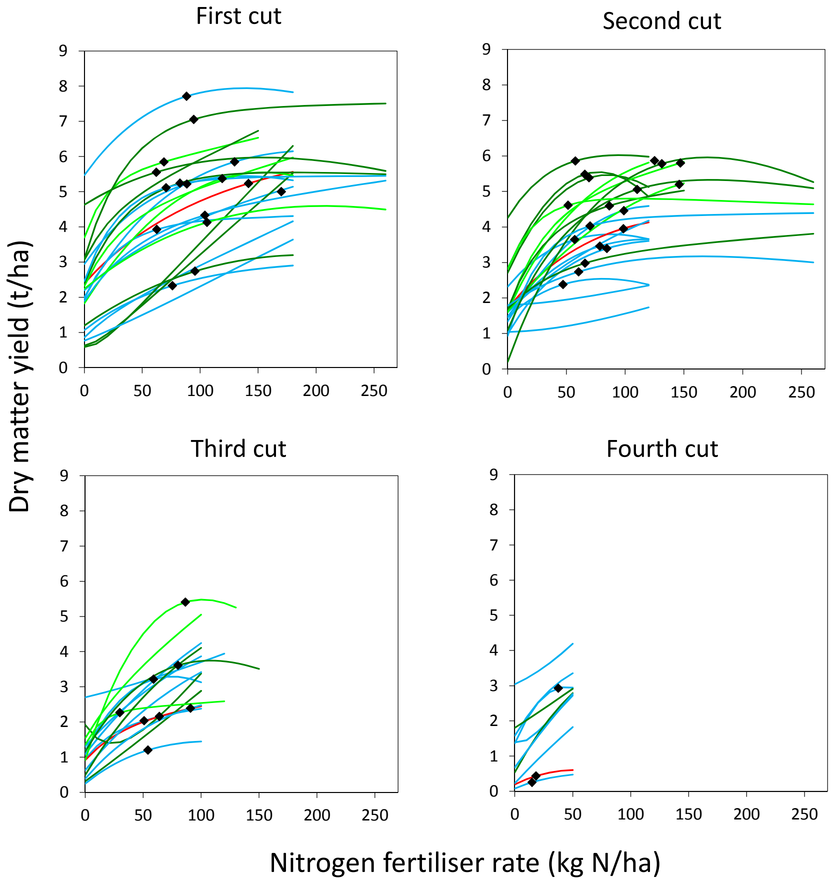

Figure 3. Fitted (linear + exponential) yield response curves by cut; colour coded by Grass Growth Class: Poor/Very poor, Average, Good and Very good. Diamonds represent grass yields at nitrogen optimum at a break even ratio of 10:1.

The $Nopt_{10}$ for second cut grass varied from 47 to 147 kg N/ha, while the DM yield ranged from 2.4 to 5.9 t DM/ha. For third cut grass, $Nopt_{10}$ ranged from 30 to 91 kg N/ha and the DM yield at 75 kg N/ha ranged from 1.2 to 5.7 t DM/ha. For fourth cut, $Nopt_{10}$ ranged from 15 to 38 kg N/ha and the DM yield ranged from 0.3 to 2.9 t DM/ha. Given the large degree of variability in DM yield response to applied N and in $Nopt_{10}$, and to optimise yield and N fertiliser use efficiency, the N recommendations at each cut should take into account both the potential productivity of grass swards at higher rates of applied N and the N level at which some swards approach a plateau in terms of their DM yield response. In any particular field and year, it is impossible to predict the shape of the N response curve without applying differential N rates to plots set up for this purpose, so N recommendations should reflect the risk of applying N beyond maximum yield (based on recent data) and therefore the risk of low N fertiliser use efficiency at higher N rates.

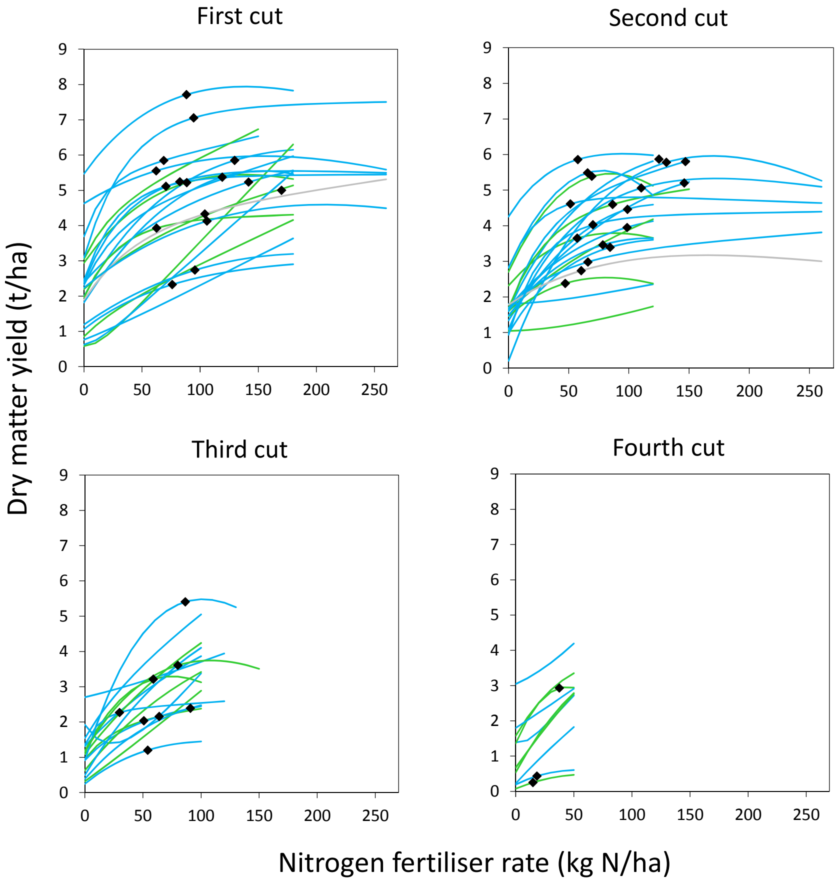

Figure 4. Fitted (linear + exponential) yield response curves by cut; colour coded by sward age: less than 5 years old and greater than 5 years old. Diamonds represent grass yields at nitrogen optimum at a break even ratio of 10:1.

Higgins *et al.* (2012) in a field study in N.I., assessed the effect of annual applications of N fertiliser applications (at 0, 75, 150, 225 and 300 kg N/ha) as calcium ammonium nitrate on grass (the sward was predominantly meadow grass and ryegrass) productivity and soil chemical properties. Overall, the study found that there was a highly significant (P <0.001) effect of N rate on grass dry matter yields (Table 3), with mean annual (all 3-years) yields reaching 11.5 t/ha at a N application rate of 300 kg N/ha/yr.

Table 3. Mean annual total (three cuts) grass dry matter (DM) yield (t/ha) in response to nitrogen (N) fertiliser rate (highly significant (P <0.001) effect), for pelleted and ground lime combined (no significant difference between different liming materials). Taken from Higgins et al. (2012).

	Mean annual DM yield (t/ha)		
N-rate (kg N/ha/yr)	2007	2008	2009
0	9.01	4.94	4.71
75	10.04	6.87	7.35
150	11.29	8.91	9.91
225	12.09	10.61	11.26
300	11.72	11.15	11.76
LSD	0.62	0.54	0.48

4.1.1. Response of different grass species or grass-legume mixes

A number of studies have investigated the response of different grass species or mixes to N fertiliser inputs. For example, Dale *et al.* (2015), in a field experiment located in N.I., assessed the response of seven forage types, to cattle slurry applied at 4 different rates (supplying 0, *c.*100, *c.*200 and *c.*300 kg total N/ha/yr) in 3 split applications by trailing shoe. Average DM yield response to slurry was 15.6 kg DM kg^{-1} N. The results suggest that slurry applied to swards containing legumes on soils with a high P-content will have a lower DM response to slurry N, resulting in a lower slurry-N recovery than on swards of perennial ryegrass or cocksfoot-dominated low-input mixtures. To maximise slurry N-recovery, it was recommended that applications after first-cut where growth rate is likely to be slow or where there is a high legume content should be avoided.

AFBI carried out a series of grass mixture trials from 2003 to 2005 in Loughgall, Co Armagh, N.I. Ten mixtures were included in the trial comprising various proportions of tall fescue, timothy, perennial ryegrass, cocksfoot and meadow fescue. The trials were maintained for three years using a replicated (three times) design of the following treatments:

i. Organic management: no manufactured N fertiliser applied, with white clover included in the mixture and an application of phosphate and potash to simulate a slurry application
ii. Low Input: 170 kg N/ha, 99 kg P_2O_5/ha and 145 kg K_2O/ha per annum
iii. High Input: 360 kg N/ha, 294 kg P_2O_5/ha and 240 kg K_2O/ha per annum

In 2004, the mean DM yield under organic management was 36% of the High Input management. White clover progressively dominated the swards and only 3 cuts were achieved. The highest DM yield under organic management of 6.6 t/ha was from a grass mixture comprising 50% Bareno Brome, 30% cocksfoot and 20% late tetraploid perennial ryegrass.

The highest yield under the Low Input treatment was 14.1 t DM/ha from a mixture comprising 20% late tetraploid perennial ryegrass, 20% timothy, 20% meadow fescue, 20% tall fescue and 20% cocksfoot. The highest yield under the High Input treatment was 17.2 t DM/ha from a mixture comprising 50% brome, 20% late perennial ryegrass and 30% tall fescue. The most persistent and productive mixtures over a 3 year period were 'Barmix' type mixtures, with a component of deep-rooted species, tall fescue and cocksfoot. It was also found that cocksfoot tended to dominate when its component in the sward was increased. The highest yields compare favourably with yields achieved using perennial ryegrass dominated swards (Figure 1).

The main advantages of grass-legume swards is that they reduce reliance on N fertiliser inputs, tend to produce higher yields compared to growing component species alone at low N fertiliser rates, produce more balanced feeding values and increase nutrient-use efficiency. Disadvantages of forage legumes include lower persistence than grass under grazing, unpredictable nature of N-fixation, lower productivity than systems reliant on manufactured N fertiliser (Humphreys *et al*., 2009), risk of livestock bloat, difficulties with preservation when ensiling and with maintaining optimum legume proportions (Phelan *et al.* 2014).

Høgh-Jensen and Schjoerring (2010) in a field experiment located in Denmark, assessed the impact of NPK fertiliser applications (see Table 6for rates) made during the first week of April on yield and N-offtake of ryegrass and white clover grown separately or as a mixture, when the swards were 1 and 2 years-old. It was found that without the addition of manufactured N fertiliser, ryegrass-clover mixtures (sown to achieve a target composition of 1/3 clover to 2/3 ryegrass) consistently out yielded pure stands of either clover or ryegrass in terms of DM production. Furthermore, ryegrass grown with clover, accumulated substantially higher amounts of N, P, and K than ryegrass in a pure stand. The growth of white clover was significantly depressed by N application, particularly when P and K were also applied. In contrast, ryegrass yield responded to increasing availability of N, P and/or K. The study demonstrated there is a complex interaction of growth and nutrient acquisition when ryegrass and clover are grown as a mixture.

Suter *et al*. (2015), in a 3-year field study carried out across the EU, compared total N-uptake of grass monoculture and grass mixtures containing varying amounts of legumes. At each site, manufactured N fertiliser was applied at a standard rate across all plots, but differed (0 to 150 kg N/ha) between sites reflecting differences in background productivity. Overall, it was found that in all years N-uptake was significantly (P <0.05) greater in grass-legume mixtures (195 to 286 kg N/ha/yr) than in grass monocultures (119 to 178 kg N/ha/yr). Nitrogen-uptake increased with increasing proportion of legumes up to one third of sward composition. Grass mixtures containing one third legumes attained similar to 95% of the maximum N-total acquired by any stand and had

57% higher N-total than grass monocultures. Furthermore, relative N gain by mixtures was not related to site productivity, indicating that grass-legume mixes can provide increases in N-uptake over grass monocultures in both low and high productivity sites, although legume covers and the increased uptake associated with grass-legume swards was limited by temperature. This adaption to site productivity can be explained by N_2 fixation being largely regulated by the N-sink strength of the whole system. The study also reported that N-losses from grass-legume swards can be lower compared to fertiliser grassland systems due to three mechanisms: i) nitrogen fixed symbiotically is stored within legume nodules and is therefore not freely available, ii) symbiotic N_2 fixation is downregulated if demand is low and iii) in grass-legume systems, grass species take up N-fixed by legumes and from mineralised organic matter. The authors concluded that the use of grass-legume mixtures can contribute to improving resource use efficiency in grassland systems over a wide range of productivity levels, implying important savings in manufactured N fertiliser and significant potential for climate change mitigation.

Nyfeler *et al.* (2011) reported that the acquisition of fixed-N was maximised in grass-legume mixed swards compared to pure legume stands. The highest yields were achieved in mixed grass-legume swards receiving low to moderate N-fertiliser inputs (50 to 150 kg N/ha) containing *c.*40-60 % legumes. It was concluded that, increasing the proportion of grasses, increased both the proportion of N-fixed contained in the legume species and the transfer of fixed-N to grasses; legumes are able to regulate N_2-fixation according to N-demand (or sink). Therefore, in order to maximise N-fixation and N-acquisition by grass-legume swards, it is important to achieve the correct balance between N-fertiliser inputs and the proportion of grass and legumes species in a sward.

Other authors have investigated the productivity and profitability potential of grass and grass-clover swards. Within dairy systems, stocking rate and milk output tend to be higher on grass-based systems receiving manufactured N fertiliser compared to grass-clover based systems. However, grass-clover can support an annual stocking density of 2.15/ha and a milk output of 14 t/ha (Humphreys *et al*., 2009). In a later study, Humphreys *et al.* (2012) assessed the profitability of dairy production systems based on N fertilised grass and grass-white clover grassland, by comparing data collected from system-scale studies carried out in Ireland between 2001 and 2009. Ten fertilised grass systems stocked between 2.0 and 2.5 livestock units (LU) ha^{-1} with N rates between *c.*170 and *c.*350 kg N/ha were compared with 8 grass-white clover systems stocked between 1.75 and 2.2 LU/ha with N fertiliser inputs between *c.*80 and *c.*100 kg N/ha. The study compared the profitability of systems with changes in manufactured N fertiliser and milk prices. It was found that, in scenarios of high manufactured N fertiliser prices combined with intermediate or low milk prices grass-white clover systems were more profitable than fertilised grass systems. Given manufactured N fertiliser and milk prices at the time of the study (1990 – 2005), fertilised grass systems were more profitable than grass-clover systems. However, with increasing manufactured fertiliser costs relative to milk prices differences between the two systems became less pronounced. The study concluded that, in the future, it is likely that grass-clover systems will become a profitable alternative to grass systems relying on manufactured N fertiliser.

Gierus *et al.* (2012) in a field experiment located in Germany, assessed the DM yield production of 6 different forage legume species grown with perennial ryegrass compared to monoculture of ryegrass (with or without slurry applied at 200 kg N/ha; supplying approximately 70 kg crop available N/ha) in a 1 year-old sward. Overall, it was found that all legume-ryegrass mixes yielded more than ryegrass (both with and without slurry application) grown as a monoculture. Among the legume-grass mixes the lowest yields were achieved with ryegrass grown either with Birdsfoot trefoil (mean *c.*6.3 DM/ha) or Caucasian clover (mean *c.*5.8 kg DM/ha), due to deficient establishment of the legumes. The highest ryegrass yields were achieved when grown as part of a white clover-ryegrass mix (*c.*4.4 kg DM/ha). However, maintaining the optimum legume content (of 40-60% of herbage dry matter) to achieve these benefits remains a major challenge. Consistent with Humphreys *et al.* (2012), the findings support that grass-legume mixes yield well and can be used to reduce costs and improve profitability when fertiliser prices are high and milk commodity prices low.

King *et al.* (2012) compared the effect of N-fertiliser (0 and 125 kg N/ha) and harvest date on the yield and chemical composition of five common grasses and red clover at Grange, Co. Meath, Ireland. Data were analysed using regression analysis, allowing comparisons between species at common growth stages whilst removing the confounding effect of differences in maturity between species harvested on the same date. The main findings from the study were that Timothy grass was the most productive in terms of dry matter yield, but the poorest in terms of digestibility, with potential impacts on both animal and bioenergy production potential. Nevertheless, timothy has the potential to provide cheaper feed per unit of DM than other grass species. However, Italian ryegrass was the most suitable for ensiling due to its higher water soluble carbohydrate concentration. While red clover had a higher mean DM digestibility and crude protein concentration, but lower water soluble carbohydrate (WSC) concentration and higher buffering capacity, which could compromise preservation during ensiling.

Høgh-Jensen and Schjoerring (1994), reported that N accumulation more than doubled in ryegrass clover mixtures compared to ryegrass grown alone (Table 4). The study also reported increases in dry matter and N accumulation when P fertiliser was applied, however K had no effect. The symbiotic N_2-fixation was determined in this experiment using ^{15}N isotope dilution as described in detail by Høgh-Jensen and Schjoerring (1994), using grass in pure stand as the reference (Fried and Middelboe, 1977). The quantity of fixed N_2 (BNF) in the harvested clover when grown alone, was increased when P or K was applied. When clover was grown with ryegrass, harvested BNF increased following P or K application, but only when no N fertiliser was applied (Table 4).

Table 4. Nitrogen (N) accumulation and amount of N fixed by clover in brackets in two production years. Taken from Høgh-Jensen and Schjoerring (2010).

Year	Treatment N, P, K (kg/ha)	Pure Clover (kg/ha)		Clover mix (kg/ha)		Grass mix (kg/ha)	Pure Grass (kg/ha)
1	0, 0, 0	232^{b}	$(201)^{ab}$	178^{ab}	$(161)^{ab}$	49^{c}	18^{c}
	0, 0, 120	251^{ab}	$(201)^{ab}$	148^{bc}	$(141)^{bc}$	36^{c}	24^{c}
	0, 20, 0	280^{a}	$(225)^{a}$	189^{a}	$(179)^{a}$	46^{c}	20^{c}
	0, 20, 120	271^{ab}	$(223)^{a}$	191^{a}	$(181)^{a}$	58^{c}	23^{c}
	120, 0, 0	238^{ab}	$(174)^{c}$	139^{c}	$(120)^{cd}$	110^{b}	81^{b}
	120, 0, 120	259^{ab}	$(177)^{bc}$	94^{d}	$(86)^{e}$	126^{ab}	96^{ab}
	120, 20, 0	277^{ab}	$(178)^{c}$	112^{cd}	$(103)^{de}$	136^{ab}	90^{ab}
	120, 20, 120	271^{ab}	$(191)^{bc}$	83^{d}	$(77)^{e}$	142^{a}	102^{a}
2	0, 0, 0	163^{c}	$(142)^{cd}$	65^{d}	$(60)^{d}$	52^{e}	11^{b}
	0, 0, 120	200^{b}	$(170)^{bc}$	131^{b}	$(124)^{b}$	62^{de}	14^{b}
	0, 20, 0	213^{b}	$(179)^{ab}$	139^{b}	$(131)^{b}$	79^{c}	16^{b}
	0, 20, 120	233^{a}	$(203)^{a}$	167^{a}	$(158)^{a}$	73^{cd}	13^{b}
	120, 0, 0	169^{c}	$(115)^{d}$	69^{d}	$(56)^{d}$	119^{ab}	74^{a}
	120, 0, 120	211^{b}	$(167)^{bc}$	108^{c}	$(95)^{c}$	114^{b}	80^{a}
	120, 20, 0	217^{ab}	$(172)^{b}$	102^{c}	$(88)^{c}$	124^{ab}	82^{a}
	120, 20, 120	232^{a}	$(190)^{ab}$	98^{c}	$(89)^{c}$	135^{a}	82^{a}

In a review of the potential of legumes to increase sustainability of ruminant production systems, Peyraud *et al*. (2009) concluded that the yield value of grass-clover mixes (consisting of 30-80% clover) can be equivalent to fertiliser N-inputs of 150 to 350 kg N/ha and productive grass-clover mixes can fix 150 to 350 kg N/ha (Peyraud et al., 2009). This agrees with the potential nitrogen supply values given in the “Fertiliser Manual (RB209)”.

The N response experiments set up as part of Defra project IF01121 included two sites in Ceredigion (west Wales) and Devon (south west England) with 7% clover in the seed mix (w/w). 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 5). Standard rates of manufactured N fertiliser were applied; 0 to 450 kg N/ha over four cuts. 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 (which is at the lower end of the range suggested by Peyraud *et al*., 2009) 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.

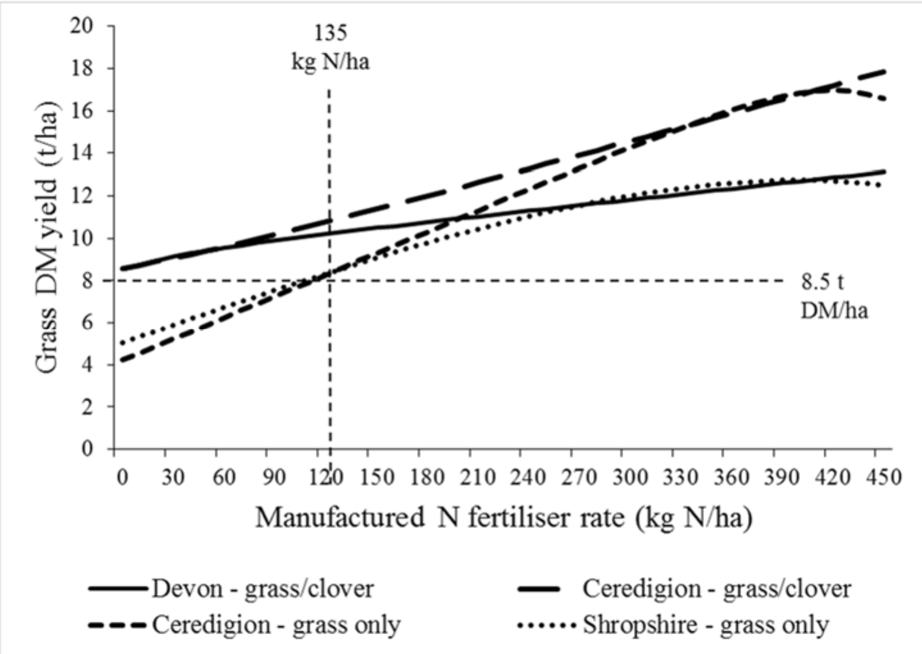

Figure 5. Grass dry matter (DM) yield response to manufactured nitrogen (N) fertiliser in two grass/clover swards and two grass only swards in 2013. The curves were fitted to the data using a linear + exponential equation. Data taken from Defra project IF01121.

The results, while interesting, are from a limited number of sites and do not negate the need for further N response experiments on a selection of grass and grass-clover swards at the same site or sites. Old and modern perennial ryegrass varieties could be included to assess contrasting DM yield responses at differential N rates.

4.1.2. Sward age

Sward age is often cited as an important factor determining grassland productivity (e.g. Frame and Laidlaw, 2014; Cashman *et al*., 2016). However, there is limited evidence assessing the productivity and quality of permanent grassland swards (i.e. swards greater than five years old), and in particular how botanical composition of older swards affects grass yield and nutrient value, and how this varies with environmental conditions (Michaud *et al*., 2015). In a two year study (2009-2010) Michaud *et al.* (2015) assessed how production and forage quality varied with species composition in 190 permanent grasslands located in France, spanning a range of soil, climatic and management conditions. Michaud *et al.* (2015) found that over a wide range of environmental and different management practices, vegetation characteristics (i.e. functional types e.g. legumes) explained approximately half of the variance of forage quality and 20-40% of the variance of biomass production. This view is supported by Baumont *et al.* (2012) who explained that the forage value of permanent grasslands can in some cases be equal to that of sown grasslands.

In a study of ten perennial cultivars conducted over three years at Teagasc Moorepark, Fermoy, Co Cork, Ireland, Cashman *et al*. (2016) found that DM yields under conservation management (six mechanical defoliations from late March to mid-October) were *c*.18% higher on average in the first year after sowing compared with the second year; and *c*.43% higher on average compared with the third year. They concluded that the results from the first harvest year may not represent the long-term performance of a grass sward; and also found that DM yield and sward density decline faster when swards are under conservation management as opposed to grazing management (Cashman *et al*., 2016).

Comparison of N response data from Defra project IF01121 and from the GM20, GM20, GM24 (cutting data only) and GF01 (permanent pasture treatments only) trials carried out from 1970 to 1993 indicate that modern grass varieties produce higher DM yields than older varieties at any given level of N supply (section 4.1). Indeed, the data indicates that one to ten year old grass swards with minimal invasion by less productive species can yield 15% to 36% more DM than older varieties used in the trials that underpin the 8th edition grassland recommendations. This is supported by the experiments carried out by Wilkins and Lovatt (2011). However, there was no relationship between sward age and DM yield response within the IF01121 dataset (12 sites all with one to ten year old swards), other than for a first year ley that out-yielded all other swards (cf. Cashman *et al*., 2016), indicating that lower productivity relates to swards older than ~10 years, swards with a significant production of less productive species, such as broadleaved weeds (e.g. *Rumex* spp.) and meadow grass, and swards at higher altitudes (the altitude ‘cut off’ for downgrading the Grass Growth Class by one in RB209 is 300 m). It is the combination of sward age (older/newer varieties) and sward composition (less/more productive species and the influence of clover) that determine the DM yield response. Grassland N recommendations should therefore provide an indication of the typical range of DM yields that can be achieved at any given level of N supply for well-managed younger and older swards.

4.1.3. Conclusions for grassland N recommendations

Grassland N recommendations should aim to take account of the contrasting DM yield response of older and newer perennial ryegrass varieties to applied nitrogen and the wide range of sward composition in terms of the proportion of modern perennial ryegrass varieties that they contain. However, there is limited evidence of how modern perennial ryegrass varieties respond to differential rates of applied N and limited data on the age of swards or the proportion of modern grass varieties in swards. For example, the IF01121 N response data was derived from a limited number of sites and agro-climatic conditions, and it is difficult to assess how typical the swards were of current grassland in England and Wales. Nevertheless, the IF01121 data provide some indication of the growth potential of modern grassland swards, and could be used to guide recommendations based on indicative DM yield ranges; to reflect the N response of older and younger grass varieties and the varying composition of grass swards.

The review by Peyraud *et al*. (2009) of the contribution of legumes to N supply are in agreement with the potential nitrogen supply figures for clover in the “Fertiliser Manual” (RB209). The values in RB209 should therefore be retained. Nevertheless, there is a need for field experiments to determine the N supply of modern clover varieties, comparing grass-clover swards with older and more modern perennial ryegrass varieties at the same site or sites.

4.2. Response of grass to sulphur

Sulphur (S) is an essential nutrient for grass growth and nutritional quality (Bailey, 2016). Grass and particularly legumes have one of the highest requirements for S. Indeed, as sulphur deposition reduced in the UK in the 1970s and 80s grass and oilseed rape were the first crops to show S deficiency symptoms with associated impacts on yield.

Declining S deposition during the last 30-years and the decreasing use of S containing fertilisers has led to an increase in S-deficient crops including grass and legumes. Indeed, S deposition no longer supplies a significant proportion of crop S requirements (Webb *et al*., 2015). Tallec *et al*. (2008) reported that the greater S requirement of legumes compared with grasses leads to inter-specific competition between *Trifolium repens* (white clover) and *Lolium perenne* (perennial ryegrass) under cutting, resulting in the replacement of clover by grass. Reduced N fixation by clover therefore leads to decreased sward productivity in low input systems and the need for greater inputs of manufactured N fertiliser. Reductions in S deposition could therefore result in a reduction in the abundance of leguminous species in grassland swards.

Defra project SCF0308 (Webb *et al*., 2015) concluded that within grassland systems, the need for S fertiliser appears to be greatest for grass swards cut more than once; and that the amount of S currently being applied is insufficient to provide optimum yield. Brown *et al*. (2000) reported yield increases of 35% on sandy soils and 11% on clay soils for swards cut 3 times per year and fertilised with 400 kg N/ha. Largest yield responses have previously been detected from 2nd and later cuts (Scott *et al*., 1983; Stevens and Watson, 1986; Brown *et al*., 2000).

The “Fertiliser Manual (RB209)” advises the application of 40 kg SO_3/ha as a sulphate containing fertiliser applied at the start of growth before each cut. However, only 10% of grassland soils receive S fertilisers (Anon., 2014); and the average SO_3 application to grassland (33 kg SO_3/ha) is less than the average application applied to arable crops (58 kg SO_3/ha). Livestock manures are applied to around 50% of grassland soils (Anon., 2014), providing useful quantities of S, but this leaves half of the grassland area relying on S deposition and mineralisation of organic matter to supply S to the growing crop. On lighter soils and in higher rainfall areas (prone to S leaching) this could lead to S deficiency in grass and grass-clover swards.

Given the difficulty in predicting where crops may respond to S fertiliser and the declining role of S deposition in meeting crop demand, Webb *et al*. (2015) conclude that the guidance proposed by Cussans *et al*. (2007) should be incorporated into RB209, i.e. that S is applied, either as mineral fertiliser or livestock manures, to all crops and grass grown on:

- Sandy soils
- Loamy and coarse silty soils in areas with > 175 mm overwinter rainfall
- Clay, fine silty or peat soils in areas with >375 mm overwinter rainfall

Data from N.I. indicates that S deficiency can be prevalent at first cut even on heavy textured soils, but is often corrected by cuts 2 and 3 (Bailey, 2016). Herbage analysis and interpretation using the Diagnosis and Recommendation Integrated System (DRIS) provides an accurate indication of the S sufficiency status of grass and hence the degree to which S supply is influencing grass DM yield. The addition of organic manure had a small effect on grass S sufficiency status, but cannot be relied on to supply the S needs of silage crops. Further work is therefore needed using S fertiliser to produce a response curve. This has been identified as a research gap for the application of S fertiliser before first cut (Bailey, 2016; Eriksen, 2009). Bailey (2016) recommended that S should be applied routinely to all grass silage swards in early spring, at a rate of 35-40 kg SO_3/ha, "since this rate of application should eliminate all risk of S deficiency, with little risk of S over-supply even on moderate texture soils, and in many cases obviate the need for further S applications later in the season".

Some nutrient management systems recommend using the N:S ratio of grass herbage samples to determine S deficiency. For example, SRUC Technical Note 652 indicates that a response to S fertiliser is highly likely when the total N:total S ratio in herbage is greater than 16:1 (Sinclair *et al*., 2013). This is supported by Mathot *et al*. (2009) who discuss the development of indicators for S deficiency in grass using data collected from field and pot experiments carried out from 1986 to 2008, and propose a diagnostic tool based upon linear relationships linking the S and N content of grasses. The dataset excludes swards containing more than 20% of legumes. Using the tool, grass S nutrient status can be placed into one of four categories: *certainly sufficient*, *probably sufficient*, *probably deficient* and *certainly deficient*. The authors recommend validating the tool with a large independent dataset.

Sirius minerals provided data from an experiment carried out on a permanent grass sward on sandy loam soil in Central England, assessing the yield response of second cut grass silage to sulphur fertiliser application. Sulphur fertiliser applications increased grass dry matter yields by *c.*0.8 t/ha compared to the untreated control (P< 0.01), with grass responding to application rates of up to 20 kg/ha SO_3.

4.2.1. Conclusions for grassland S recommendations

The current recommendations appear sound, but the advice to apply S fertiliser in the situations suggested by Cussans *et al*. (2007) could be included. Given the findings of Bailey (2016), it may also be sensible to remove the sentence “Deficiency at first cut is less common but can occur on light sand and shallow soils”, while being wary that over supply of S can be detrimental to animal health.

4.3. Response of grass to phosphate and potash

Potash supply should be proportional to the amount of nitrogen applied to grassland although applications in spring prior to first cut silage (or hay) should be limited to 80-90 kg K_2O/ha to reduce the risk of ‘staggers’ (hypomagnesaemia). The aim should be to apply ‘maintenance applications of potash fertiliser to balance the offtake in cut or grazed grass over the year (Sinclair *et al*., 2013).

The yield response of grass to phosphorus (P) is more variable and soil analysis does not always predict such variation (Valkama *et al*., 2016). For phosphate, grass DM yield responses are generally significant when soil P reserves are low, although this is not always the case (Mahli *et al*., 2009); while at target (Olsen P Index 2) and higher levels, responses are usually negligible (Paynter and Dampney, 1991; Power *et al*., 2005). Soil type has an important influence on the yield response to P fertiliser and the amount of phosphate fertiliser needed to build soil reserves from one Index to another (Bolland *et al*., 2003). Phosphorus uptake and yield at any given P Index can also be increased by improving soil structure, and thereby affect root growth and distribution, soil aeration and access to water and nutrients (Ball *et al*., 2005).

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 extractable soil P 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; Sinclair *et al*., 2015a). 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 5). For grass only swards the target soil P status remains at M- for all soils.

Research carried out in N.I. (Daly *et al*., 2015) supports the use of P sorption capacity to adjust P recommendations in soils with different parent materials and chemical properties (e.g. calcareous soils, extractable aluminium and soil pH).

Table 5. Effect of phosphorus (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: Sinclair et al., 2015a - 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

Researchers in the Republic of Ireland (ROI) and N.I. have investigated the benefit of adjusting P fertiliser recommendations according to relatively small changes in soil P status. Bailey *et al*. (2014) summarised the evidence used to justify splitting the Olsen-P Index 2 range into a 2- P-building range and a new 2+ target range for grassland in Northern Ireland. Using data from 12 farms in N.I., they found that at 2nd cut, Diagnosis and Recommendation Integrated System (DRIS) P Indices, which provide a reliable measure of herbage P sufficiency status (Bailey *et al*., 1997), were significantly and positively correlated with Olsen P, and declined to negative (deficient) values when Olsen P fell below 20 mg P l^{-1} (i.e. the mid-point of the RB209 P Index 2 range). Furthermore, at Olsen P Index 2-, swards had ‘Low’ herbage P status when RB209 P recommendations were closely followed, but herbage P status was ‘Adequate’ when 15 kg P/ha more than the RB209 recommendation was applied ($P<0.05$). Bailey *et al*. (2014) suggested that the full P Index 2 range (16-25 mg P/l) should be split into equal sub-ranges, 2- and 2+, and that proportionately higher P recommendations should be assigned to the 2-sub-range.

The NI soil and grass analysis results align with research carried out in the Republic of Ireland. For example, Schulte (2007) outlines why ROI has opted for a higher target Morgan soil P test Index for grassland; the new P-building range, i.e. Morgan Index 2 for Irish grassland, is equivalent to 16-20 mg Olsen P/l, i.e. the new Index 2- ‘P-building’ range for NI grassland; and the new ‘Target’ P range, Morgan Index 3 for Irish grassland is equivalent to the new ‘Target’ Index 2+ range for NI grassland (although the Morgan Index 3 range extends to the equivalent of 30 mg Olsen P/l).

The amount of phosphate and potash to apply as ‘maintenance’ dressings is a function of the P and K content of the grass sward. It is important therefore that the offtake estimates in recommendations reflect the P and K contents in grass and clover at each cut or grazing through the season. A number of research projects have investigated the P and K content of grassland swards and how this varies with species composition, nutrient addition and time of year.

Høgh-Jensen and Schjoerring (2010) investigated variations in above-ground accumulation of N, P and K in white clover and ryegrass grown separately or in mixture under field conditions in Denmark (18 km west of Denmark) over three cuts (2 June, 7 July, 28 August, and 29 October) in 1998 and four cuts (31 May, 8 July and 12 October) in 1999. They reported that the interaction between grass and clover grown together is complex and involves competition, facilitation and complementarity. For instance, ryegrass grown with clover accumulated significantly more N, P and K than when grown alone, conversely the growth of white clover was significantly reduced by N application particularly when P and K were also applied. The proportions of P and K in ryegrass shoots grown in monoculture were only half that in mixture with clover (Table 6). Conversely, clover grown with ryegrass had a lower shoot P concentration compared to growing alone. Crush *et al.* (2015) demonstrated that modern white-clover cultivars use soil-P more effectively compared to older cultivars. Increased P-efficiency by white-clover, was due to repeated selection of shoot traits, as there were no differences in root morphology or architecture between cultivars.

In Defra project IF01121, at twelve N response sites in England and Wales, phosphate and potash concentrations in herbage were measured at each of four cuts from plots given the RB209 recommended rate of N, phosphate and potash and adjusted to 15-20% DM (Figure 6 and 7). Mean phosphate offtakes were very similar to the offtakes values in the “Fertiliser Manual”. However, potash offtakes at second, third and fourth cuts were 42-63% higher than the offtake values in the 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.

Table 6. Phosphorus (P) and potassium (K) offtakes (kg ha^{-1}) of mixtures and pure stands of white-clover and perennial ryegrass (1 year and 2 years after establishment) following the application of nitrogen (N), P, K fertiliser at different rates, applied during the first week of April in each year. Taken from Høgh-Jensen and Schjoerring (2010).

Year	N, P, K rate (kg/ha/yr)	Phosphorus offtake (kg/ha)				Potassium offtake (kg/ha)			
		Pure clover	Clover mix	Grass mix	Pure grass	Pure clover	Clover mix	Grass mix	Pure grass
1	0, 0, 0	19.6^{ab}	13.3^{a}	7.7^{cd}	4.3^{b}	104^{d}	69^{c}	62de	23^{c}
	0, 0, 120	18.0^{b}	8.9^{bc}	7.1^{d}	4.4^{b}	173^{abc}	106^{b}	58^{e}	29^{c}
	0, 20, 0	23.5a	12.7^{a}	9.2^{cd}	3.9^{b}	148^{c}	109^{b}	70de	26^{c}
	0, 20, 120	22.0^{ab}	13.4^{a}	10.9^{c}	4.5^{b}	183^{ab}	136^{a}	96^{cd}	30^{c}
	120, 0, 0	18.7^{ab}	9.7^{b}	15.0^{b}	13.7^{a}	101^{d}	58^{c}	128^{c}	115^{b}
	120, 0, 120	19.0^{ab}	6.4^{cd}	17.0^{b}	13.6^{a}	176^{ab}	67^{c}	175^{b}	141^{a}
	120, 20, 0	24.0^{ab}	7.6b^{cd}	22.5^{a}	12.9^{a}	168^{bc}	64^{c}	181^{ab}	117^{b}
	120, 20, 120	22.4^{ab}	6.0^{d}	21.8^{a}	14.6^{a}	199^{a}	59^{c}	216^{a}	146^{a}
2	0, 0, 0	13.9^{d}	5.4^{c}	7.8^{c}	2.5^{c}	79^{f}	31^{d}	57^{e}	14^{c}
	0, 0, 120	16.4^{c}	9.5^{b}	9.9^{c}	3.3^{c}	144^{bc}	99^{b}	82^{d}	20^{c}
	0, 20, 0	19.5^{b}	12.2^{a}	14.6^{b}	3.7^{c}	126de	66^{c}	101^{cd}	22^{c}
	0, 20, 120	21.9^{a}	13.9^{a}	13.6^{b}	2.9^{c}	141^{cd}	124^{a}	98^{d}	18c
	120, 0, 0	14.9^{cd}	5.6^{c}	12.9^{b}	11.3^{b}	74^{f}	29^{d}	100^{cd}	88^{b}
	120, 0, 120	16.4^{c}	8.3^{b}	14.0^{b}	13.2^{ab}	157^{b}	74^{c}	146^{b}	132^{a}
	120, 20, 0	21.0^{ab}	8.9^{b}	18.3^{a}	14.5^{a}	123^{b}	42^{d}	120^{c}	124^{a}
	120, 20, 120	19.7^{ab}	8.9^{b}	18.8^{a}	14.6^{a}	173^{a}	70^{c}	176^{a}	129^{a}

Values followed by different letters are significantly different (P <0.05)

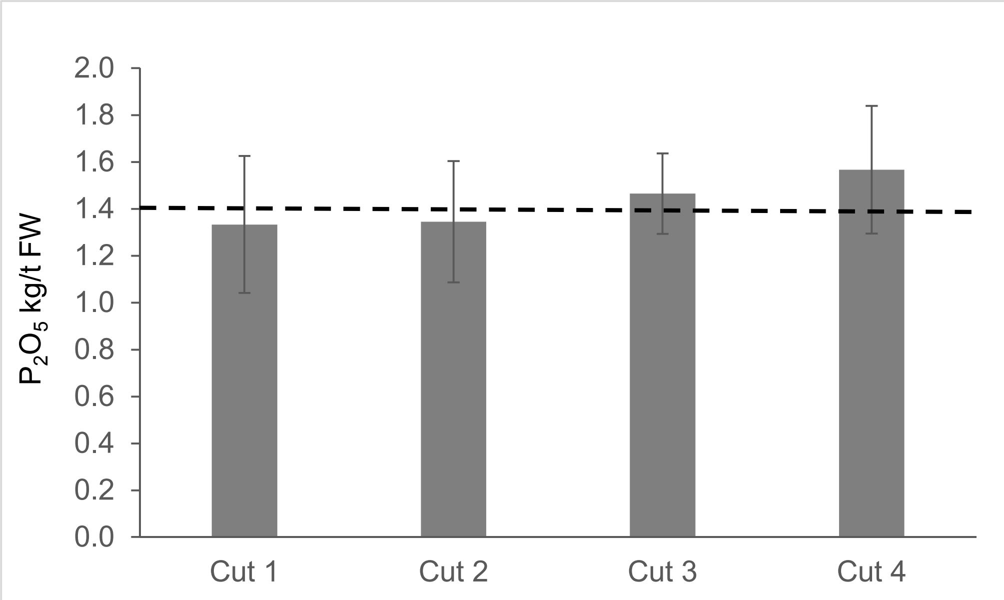

Figure 6. Mean phosphate (P_2O_5) offtake values at each of four cuts at the twelve IF01121 N response sites. Error bars represent one standard deviation from the mean. The hatched line indicates the phosphate offtake value for fresh grass (15-20% dry matter) in the "Fertiliser Manual" of 1.4 kg P_2O_5/t fresh material.

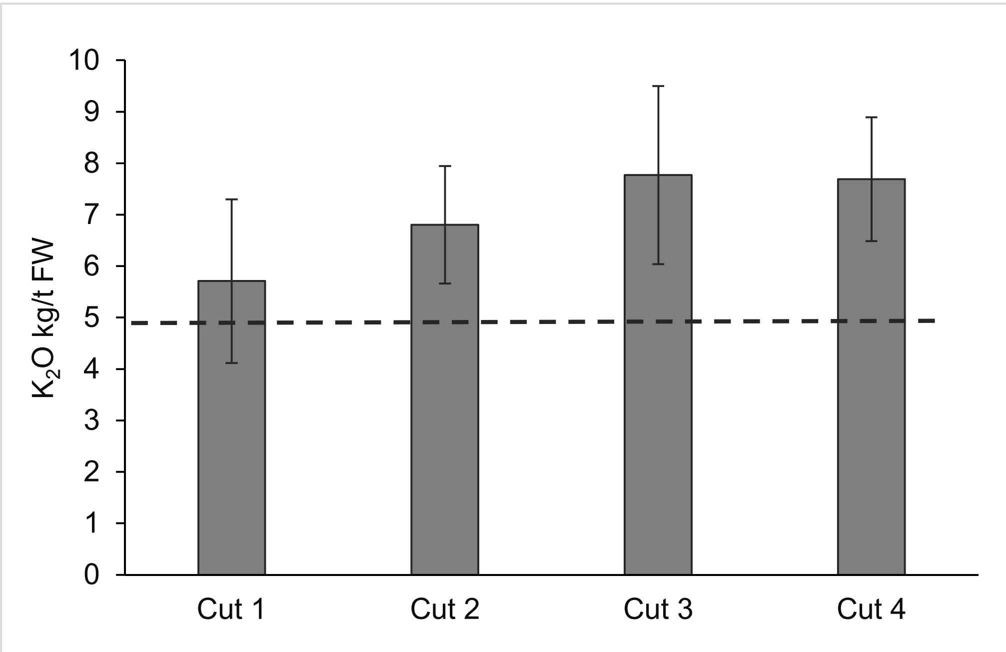

Figure 7. Mean potash (K_2O) offtake values at each of four cuts at the twelve IF01121 N response sites. Error bars represent one standard deviation from the mean. The hatched line indicates the potash offtake value for fresh grass (15-20% dry matter) in the "Fertiliser Manual" of 4.8 kg K_2O/t fresh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

Higgins *et al.* (2012) (Section 4.1) reported that lime applied annually (studied over 3 years) to a permanent grassland has a cumulative effect and by the third year of application, significantly increased the P-removal of the herbage (30.7 kg P_2O_5/ha) compared to treatments receiving no lime (28.6 kg P_2O_5/ha). The authors suggest that the lime may have increased the mineralisation of soil P or stimulated root growth.

The effects of different potash fertiliser rates on forage grass yields, K herbage content and soil fertility were assessed in demonstration plots, on a sandy loam soil in Warwickshire (Potash Development Association (PDA) leaflet 5b, 2007a). At the start of the trial soil was at K_2O Index 1 and K_2O was applied to plots for 4 consecutive years at three different rates: 0, 160 and 320 kg K_2O/ha. In year one, the site responded to potash with yield increases of 12-15 %, and by years 3 and 4, yields on the 320 kg K_2O/ha were double that relative to the control. Overall, large quantities of potash were removed in the silage and it was found that the application of 160 kg K_2O/ha did not maintain the initial soil K_2O levels despite yields and K offtakes being lower compared to the higher K_2O rate. Applications of 320 kg K_2O/ha helped to maximise silage yields, K offtakes and also maintained or slightly improved soil potash levels. Silage analysis demonstrated that at maximum yields, N and K are removed at similar amounts, indicated by N:K ratios of 1:1 therefore, both N and K should be replaced by similar amounts to maximise yields and nutrient efficiency.

The K_2O requirements of perennial ryegrass/white clover were assessed in a 3-year field trial undertaken by Kingshay Farming Trust (PDA leaflet 26, 2007). In this study, the mean potash content of perennial ryegrass/white clover silage at 25% DM was 6.8 kg K_2O/t of fresh material (averaging 6.7 kg K_2O/t at first cut; 7.0 kg K_2O/t at second cut; and 6.4 kg K_2O/t at third cut), which was consistently higher than the RB209 8th edition standard value of 6.0 kg K_2O/t.

Finally, there is some evidence that changes in nutrient management practices may have increased P use efficiency in some European countries. For example, Milhailescu *et al.* (2015) compared P use efficiency (PUE) and farm-gate P balances on intensive grass-based dairy farms in Ireland before and after the implementation of good agricultural practice regulations (GAP). Comparisons indicate that post GAP introduction there was a reduction in P surpluses by 74% per hectare and 81% per kg of milk solids. The improvements in P balance were due to both a reduction in P fertiliser application rates and improvements in P management, including a shift to spring application of organic manures.

4.3.1. Conclusions for grassland phosphate and potash recommendations

Recommendations have been developed in Scotland to take account of the P-fixing capacity of different soils, based on a map of soil parent material types (as defined by soil associations) and the contrasting P response of different crops. A similar approach could be developed for England and Wales by assessing the P-fixing capacity of different soil associations.

Research in ROI and NI indicates that Olsen P Index 2 could be split into a lower and upper sub-band with grass P recommendations increased for the lower sub-band. Similar research is required in England and Wales to determine the herbage P sufficiency status at different levels of Olsen P and P fertiliser use.

Data from Defra project IF01121 and the PDA (2007) indicates that the fresh grass potash offtake values in the "Fertiliser Manual (RB209)" may underestimate the amount of potash removed within cut grass systems. However, the IF01121 and PDA data is limited in amount (14 sites). More data is needed for which the grassland management (primarily cutting date, K Index and nutrient applications) is known.

4.4. Response of grass to lime

Higgins *et al*. (2012) in a field study in N.I., assessed the effect of annual applications of pelletized dolomitic lime compared to ground lime on grass (sward predominantly meadow grass and ryegrass) productivity and soil chemical properties when receiving N-fertiliser applications (at 0, 75, 150, 225 and 300 kg N/ha) as calcium ammonium nitrate. Overall, the study found that there was no difference in any of the parameters measured (including dry matter yield; Table 3) when applying pelletized lime compared to ground lime.

4.4.1. Conclusions for liming recommendations

It is clear from Higgins *et al*. (2012) that the ability of different liming products to raise pH by a certain amount on any given soil is determined by application rate and neutralising value (NV). The speed of change in pH is determined by the fineness and hardness of the liming product and associated solubility. There is therefore no need to change the recommendations. However, the RB209 Technical Working Group felt that inclusion of the liming factor in the RB209 lime recommendations table would aid the clarity and precision of the recommendations. Consideration should also be given to the inclusion of advice on the use of seashell sand and its impact on soil pH.

Sinclair *et al*. (2014) provide advice on GPS sampling for soil pH and the variable rate application of lime. These recommendations will be incorporated into the "Nutrient Management Guide (RB209)".

4.5. Impact of grazing upon herbage production

The DM yield response of grassland to applied nutrients varies according to grassland management in terms of the frequency of defoliation, whether the sward is cut or grazed and the level of N fertiliser use. It is acknowledged that the DM yield ranking of grass cultivars can vary according to whether they are tested under long-cycle (infrequent cutting), short-cycle (simulated grazing) or livestock grazing conditions (Jafari *et al*., 2003). Indeed, cultivars that perform better under a cutting regime may be inferior under animal grazing. This is supported by observed differences in sward structure between cut and grazed swards (Smith *et al*., 1971). Grazed swards tend to produce lower dry matter yields than less frequently defoliated cut swards (Binnie and Chestnutt, 1991; Boswell, 1977; Wilkins, 1989; Cashman *et al*., 2016). This is due to a number of factors including higher overall Green Area Index (GAI) and higher DM yield per tiller under the less frequent defoliation within a silage cutting regime (Matthew *et al*., 1996), as well as the effects of treading, plant pulling and selective grazing, particularly at higher N fertiliser rates (Evans *et al*., 1998; Richards, 1978).

It is unclear if the difference in sward heights resulting from selective grazing can affect annual DM yields when comparing cut and grazed swards managed at the same average height and defoliation frequency. DM yields of perennial ryegrass under a non-uniform defoliation regime (simulating grazing) were similar to those obtained under a uniform defoliation regime (simulating cutting), although the frequency of defoliation and the amount of fertiliser applied may influence the outcome; Smith *et al*. (1975) and Remison and Snaydon (1980) in Dale *et al*., (2013). Dry matter yield and digestibility under simulated grazing has been shown to correlate well with yields under rotational livestock grazing, particularly in established swards (Cashman *et al*., 2016).

Reduced dry matter offtakes at higher defoliation frequencies is supported by data collated from Reaseheath College, Rothamsted Research North Wyke and the AHDB ‘Low N Grass’ project (74316). Since the replicate yields were not available, the mean DM yields were plotted rather than fitting a specific growth curve (Figure 8 and Figure 9). All the sites had high SNS status with mean y0 (i.e. yield at 0 N kg/ha) at Reaseheath in 2010-12 (7 or 8 cuts) measured at 6 to 7 t DM/ha and mean y400 at 8.8 to 11.5 t DM/ha. The sites where 5 to 6 cuts were taken yielded similar quantities of grass DM as the moderately yielding IF01121 sites (Figure 1) with y0 (DM yield at 0 kg N/ha) at 4.5 to 6.3 t DM/ha and y400 at 11.6 to 12.8 t/ha.

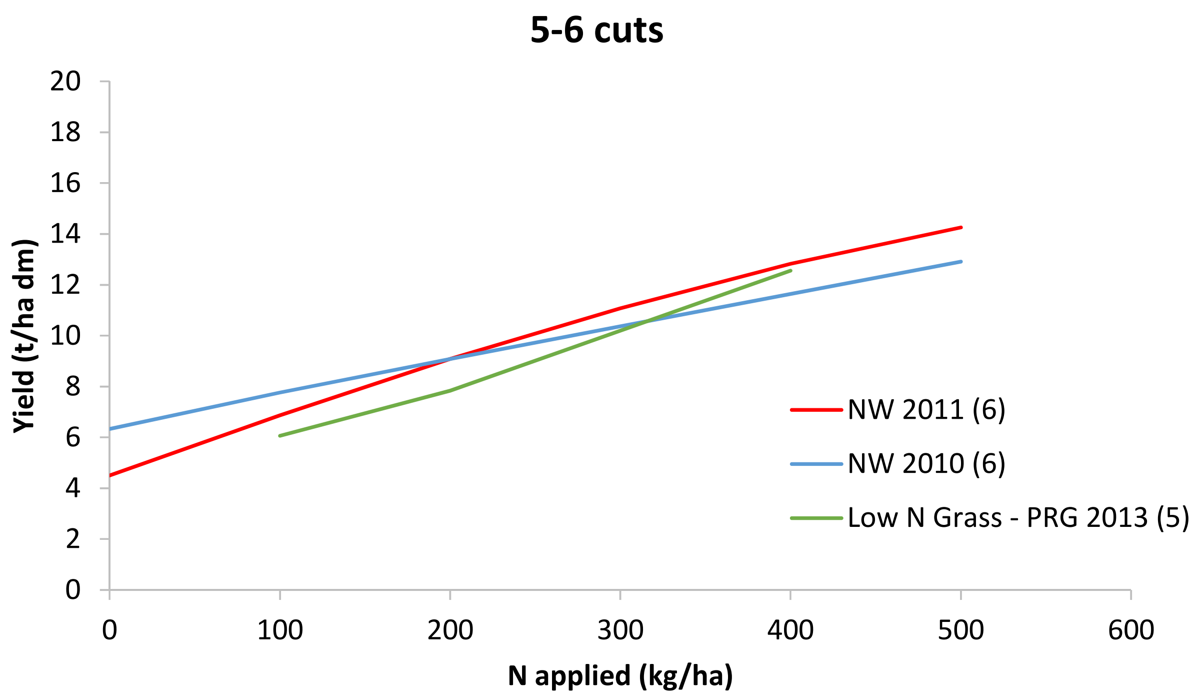

Figure 8. Grass dry matter (DM) yield response to manufactured nitrogen (N) fertiliser from field experiments carried out in the UK where 5-6 cuts of grass were taken and 3 to 6 levels of fertiliser N were used up to at least 400 kg N/ha. The legend indicates the site reference (and the number of cuts taken).

At the 'Low N Grass' sites in 2013-14, where 9 cuts were taken, mean y100 was 3.8 to 4.5 t DM/ha and mean y400 was 9.5 to 10.9 t DM/ha. This contrasts with y400 values at the IF01121 sites that typically ranged from 12.5 to 16.9 t DM/ha (Figure 1). The differences in yield between the 2010-14 experiments using 8-9 cuts of grass and the IF01121 field experiments (2012-14 using 4 cuts) confirm that data from a three or four cut system should not be used to predict typical yields from multiple cut or livestock grazing systems; and vice versa (Cashman *et al*., 2016). This may partly explain the difference in DM yields between the IF01121 experiments and the N response trials from the 1970s and 80s (such as GM 20, GM 23 and GM24) used to produce indicative yields for the 8th edition of RB209. For example, the GM23 series of 22 trials (1978-79) used 6 cuts of grass (Morrison, 1980; 1987).

The DM yield N response curves used in the "Fertiliser Manual (RB209)" were derived from a selection of datasets from the GM20, GM24 (cutting data only) and GF01 (permanent pasture treatments only) trials carried out from 1970 to 1993, amounting to 148 site years. The number of datasets in Good/Very good, Average and Poor/Very poor Grass Growth Classes (GGC) were 44, 88 and 16 site years, respectively. The derived N response curves were used to predict the amount of N fertiliser to apply for both cutting and grazing land. Given what is known about the contrasting production potential of cut and grazed swards and the apparent improved N use efficiency and productivity of modern perennial ryegrass varieties, it is likely that the N response curves used within the 8th edition model approximately reflect the production potential of modern grazed swards, but underestimate the production potential of cut swards. This has implications for the grassland N recommendations themselves, with the effect from this consideration alone being a reduction in the N fertiliser required to meet a given level of energy requirement. However, it is also important to take account of the assumptions used to calculate the effect of other key factors within the energy model, such as livestock energy requirements themselves, grass utilisation efficiency (spoilage) and concentrate substitution effects (the suppression of grass/silage DM intake per kg of concentrate DM fed), since these factors also have important and sometimes opposing effects on the N fertiliser recommendation (Dale *et al*., 2013).

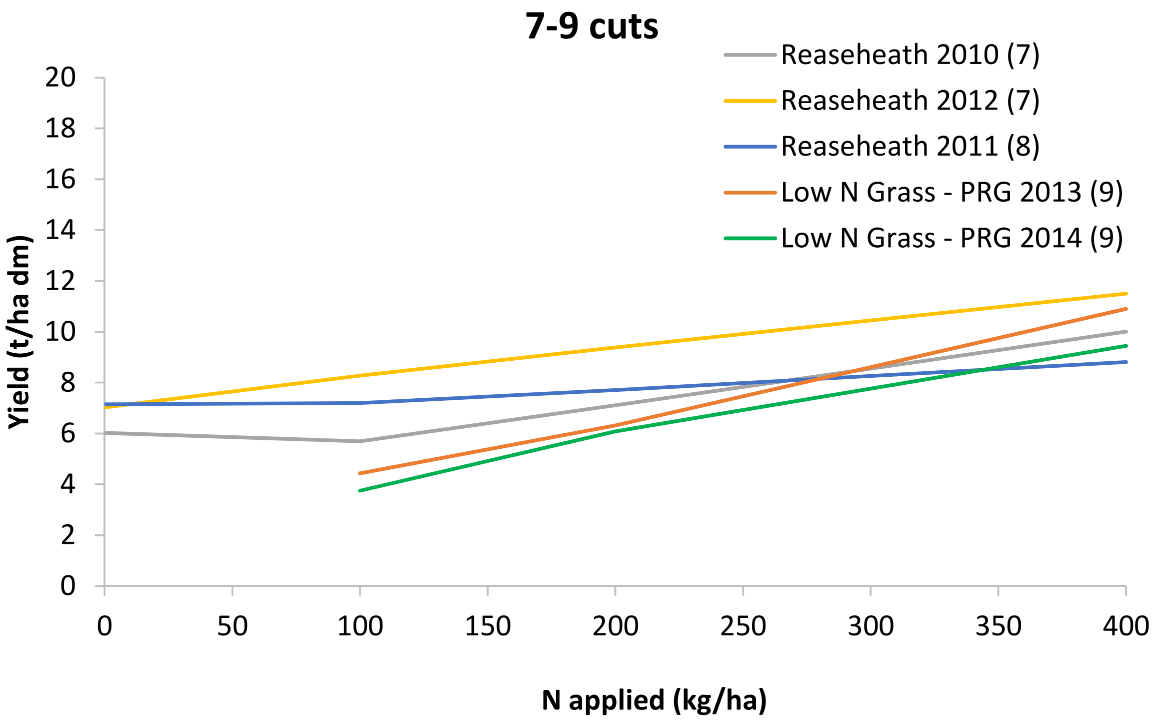

Figure 9. Grass dry matter (DM) yield response to manufactured nitrogen (N) fertiliser from field experiments carried out in the UK where 7-9 cuts of grass were taken and 3 to 5 rates of fertiliser N were used up to 400 kg N/ha. The legend indicates the site reference (and the number of cuts taken).

4.5.1. Grazing height

Pre-grazing herbage mass can have a significant impact on grass dry matter intake (GDMI), pasture quality and milk production; current guidance recommends that grass covers are kept low in the spring. For instance, studies have shown that lower pre-grazing herbage mass (from 7950 to 2180 kg DM/ha) increased GDMI due to, higher leaf proportions and lower stem and dead material proportions (Hodgson and Wilkinson, 1968, in Wims *et al*., 2014). Furthermore, lowering spring herbage mass can increase overall milk production (e.g. Curren *et al.* 2010).

Wims *et al*. (2014) in a field experiment located in Ireland, compared the effect of 3 different pre-grazing herbage mass treatments (Low: 1,150; medium 1,400 and high: 2,000 kg DM/ha) on perennial ryegrass pasture and dairy cow productivity. In contrast to current guidance, it was found that grass production was significantly (P<0.01) reduced on the *low*-treatment (10,142 kg DM/ha) compared to the *high*-pre-grazing herbage treatment (12,112 kg DM/ha). Notably, cows required more grass silage supplementation (+73 kg DM/ha) during the grazing season, demonstrating that there can be an increased requirement for purchasing feed when maintaining very low herbage mass.

Phelan *et al.* (2013a) recommended that for grass-clover mixes and optimal herbage production, swards should be grazed to 4 cm height; while there was no evidence that post-grazing height (4, 5 or 6 cm) had an effect on the white-clover content. In contrast, a further study, on a grass-clover sward in Ireland, Phelan *et al.* (2014) found that reducing the grazing height from 6 to 2.7 cm (in the summer to winter period) increased both clover content and clover yield in the sward. Furthermore, a defoliation interval of 42 days achieved the highest total yield at 11 t DM/ha. Overall, Phelan *et al.* (2014) recommended a defoliation interval of 42 days combined with a grazing height of 2.7-3.5 cm for grass-clover swards.

4.5.2. Treading by livestock

Treading by cattle is another factor associated with grazing that can impact on herbage yields. Glasshouse experiments have indicated that white-clover on 'wet' soils can be more susceptible to damage by treading compared to perennial ryegrass (e.g. Grant *et al.* 1991). In a field experiment, Phelan *et al.* (2013b) assessed the effect of treading on clover content, herbage production and soil properties within three clover based grazing systems on a 'wet' soil in Ireland. The study found that treading reduced (P <0.001) annual yields of white clover and perennial ryegrass by similar amounts, with yield reductions of 0.45 and 0.59 t/ha, respectively. In contrast to earlier studies, it was concluded that there was no difference in the susceptibility of white-clover or ryegrass to damage by treading.

Frame and Laidlaw (2014) reported that soils with a high organic matter content and associated higher water retention capacity are particularly susceptible to poaching. They found that the risk of damage was also highest on re-seeded swards that have not yet developed sufficient root mass to strengthen the soil surface.

4.5.3. Grazing returns

On grazed systems it is important to account for the nutrients recycled from dung and urine, although the uneven nature of livestock excreta deposition creates problems for predicting its influence on DM yield response at the field scale. It is estimated that >70% of the consumed N is recycled through the direct decomposition of animal excreta and that inorganic soil N under urine patches can be up to 10 times greater than under dung patches and more than 30 times greater compared to areas free from animal excreta (Afzal and Adams, 1992, in Eriksen *et al.* (2015)). However, only a proportion of a grazed field will receive nutrients from livestock excreta in any given season. Overlapping of excreta patches tend to occur in parts of the pasture where animals gather. For example, Betteridge *et al.* (2010) monitored grazing steers on a steep 11 ha hill paddock and found that cows camped on flatter areas, with only 10% of the paddock containing 61% of all urine patches excreted during the grazing period (12 days).

The proportion of pasture covered by urine and dung patches depends on estimates of the mean size of urine or dung patches. For example, the proportion of pasture covered by urine patches over an annual grazing season, at a stocking rate of 3.2 cows/ha, increases from 23%, when considering a urine patch of 0.33 m^2, to 33% for a larger urine patch of 0.5 m^2 (Dennis *et al*., 2011, in Dale *et al*., 2013). On a New Zealand dairy farm with a stocking rate of 3 cows/ha/yr, Haynes and Williams (1993) calculated that 23% of the pasture would be covered in excreta (urine and faeces) after one year.

Dale *et al*. (2013) estimated that, even at relatively high stocking rates of 3 cows/ha, up to 30-50% of the pasture area is affected by urine and dung patches every year (Richards and Wolton, 1976 etc.), and will benefit from enhanced herbage growth following nutrient returns from animal excreta. Excretal N recovery by herbage is low, being on average 27% for urinary N and 11% for faecal N (averages from numerous studies summarised in Dale *et al*., 2013). However, several studies indicate that a lower recovery of urinary N occurs when the sward receives inorganic fertiliser N in addition to urine and faeces applications (e.g. Deenen and Middelkoop, 1992; Di *et al*., 2002).

Measurements of N leaching losses under different management systems can provide an indication of the amount of N recycled at grazing. Eriksen *et al*. (2015) investigated the effect of management practices (i.e. combinations of cutting, grazing and spring slurry application) on nitrate leaching from a grass-clover ley site in Denmark. It was found that a combination of spring slurry application (100 or 200 kg total N/ha) and grazing resulted in the highest N leaching losses of *c*. 60 kg N/ha. However, when either grazing or spring slurry application was carried out alone nitrate leaching losses were reduced to *c*. 20 kg N/ha.

A dairy cow urinates on average 9 times per day (Aland *et al*., 2002; White *et al*., 2001) and defecates 12 times per day on average (Aland *et al*., 2002; Haynes and Williams, 1993; Orr *et al*., 2012; White *et al*., 2001). If we assume from this that 40% of excreted N is derived from urine and 60% from dung, and that 27% of excretal N is recovered from urinary N and 11% from faecal N, the average N recovery is approximately 17%. Assuming lower N recovery when swards receive inorganic fertiliser N in addition to urine and faeces applications (Deenen and Middelkoop, 1992; Di *et al*., 2002), this can be rounded down to 15%. We therefore conclude that at low to moderate N rates (often corresponding to low or moderate stocking rates), grazing has a positive effect due to approximately 15% recovery of applied N. This positive grazing effect results in higher grass yields under livestock grazing than under simulated grazing (i.e. short-cycle cutting). This effect is likely to occur at N rates up to 300 kg N/ha (Richards, 1978; Richards and Wolton, 1976), but it is difficult to predict as it depends on local environmental conditions and seasonal effects.

In the 8th edition of RB209 no account was taken of nutrient returns at grazing. By contrast, in the 7th edition the N recommendations for grazing dairy cattle on Average, Poor or Very Poor GGC land were reduced by 40 kg N/ha relative to the cutting recommendations to take account of grazing returns (Dampney, 1992). However, for grazing on Good and Very good GGC land, N rates were increased by 40 kg N/ha and 80 kg N/ha respectively, compared with rates under a cutting regime.

4.5.4. Conclusions for grazing and grassland management recommendations

- Nutrient cycling at grazing is complex. Nutrient returns from excreta is uneven, particularly for N in urine patches. Nevertheless, the research indicates that around 15% of excretal N is typically recovered by a grass sward and this figure has been used to adjust N recommendations at grazing. The uneven deposition of phosphate and potash by grazing livestock suggests that there could be clear advantages from GPS sampling for soil pH and soil nutrient reserves in grassland fields. This advice will be incorporated into the section on the “Principles of grassland nutrient management”.
- DM yields tend to be lower over shorter grazing cycles compared with longer cutting cycles. Research in ROI indicates that cutting regimes can produce DM yields that are *c.*20% higher on average than under a grazing regime (Cashman *et al*., 2016). This has implications for the amount of fertiliser N (and other nutrients) to apply to cutting and grazing land to achieve target grass DM yield and quality. However, there is currently not sufficient data on grass DM yields under grazing management in England and Wales. The approach in the 8th edition of RB209 that used the same N response curves for cutting and grazing has therefore been retained. Indeed, on 26th April 2016 the Livestock Technical Working Group (TWG) agreed that the GM20/23/24 data should continue to be used to underpin the recommendations with indicative DM yield ranges used to illustrate the potential of modern grass varieties. However, adjustments are made for nutrient returns at grazing (see above).
- Grazing height can influence sward recovery, DM yield and overall productivity of grazing livestock systems. However, there are a number of approaches within the industry and

advice on herbage mass at the start and end of each grazing cycle should not form part of nutrient management recommendations.

- Treading and trampling by livestock can have a negative impact on sward productivity. Nutrient management guidelines should therefore signpost users to industry advice on grassland and soil management related to the risks of causing compaction or poaching.

4.6. Grass and silage quality

4.6.1. Effect of nitrogen rate

Factors which can influence silage quality include: grass species, rate of N application and stage of maturity at harvest. Bednarek *et al*. (2015) assessed the effect of mineral NPK fertiliser applications on N-fractions (i.e. total, protein, mineral, ammonium and nitrate nitrogen) within Timothy grass in a three year replicated field experiment in Poland. Nitrogen fertiliser was applied as ammonium nitrate (AN) at 3 rates: 120, 240 and 360 kg N/ha. It was found that the content of total, protein, ammonium and nitrate nitrogen was positively correlated with the rate of mineral fertiliser application, mainly N and phosphate and to a lesser extent potash application rate. However, even at the higher N fertiliser rate, the Timothy grass did not contain excessive amounts of ammonia or nitrates and was a valuable bulk feed, indicating that whole season N fertiliser rates up to 360 kg N/ha did not have a detrimental effect on grass silage quality.

King *et al.* (2013) investigated the impacts of N fertiliser rate (0 or 125 kg N/ha) and harvest date on silage quality (fermentation characteristics and aerobic stability) and dry matter yield of silage produced from 5 different grass species; perennial ryegrass (*Lolium perenne* cv. Gandalf), italian ryegrass (*Lolium multiflorum* cv. Prospect), tall fescue (*Festuca arundinacea* cv. Fuego), cocksfoot (orchardgrass, *Dactylis glomerata* cv. Pizza) and timothy (*Phleum pratense* cv. Erecta). Five harvest dates were distributed fortnightly from 12 May to 7 July. Overall, it was found that there was little effect of N fertiliser on the extent or direction of fermentation with the ryegrass and tall fescue silages, which exhibited a lactic acid dominant fermentation. However, during fermentation, timothy and cocksfoot had higher pH (>4.2), butyric acid (> 10 g/kg dry matter) and ammonia-N (>100 g/kg total N) levels, indicative of secondary clostridial activity during storage; and the italian ryegrass herbage incurred the greatest dry matter losses during ensiling, particularly following the early harvest dates, suggesting yeast fermentation of sugars.

Durant & Kerneis (2015) assessed the effect of manufactured fertiliser and organic manure applications on forage yield and feed value (crude protein content and digestibility) in a 7-year experiment located on a permanent grassland in Western France. The results demonstrated that N applied at rates of 60 and 100 kg N/ha/yr did not improve feed value (crude protein content and digestability), however, after the first year of the experiment it did improve DM yield.

As part of the Defra IF01121 validation project, herbage quality was measured on each plot at each of four cuts at twelve sites in England and Wales. There was a relationship ($P<0.05$) between fertiliser N rate at first cut and herbage quality at four out of the ten IF01121 sites. There was a significant correlation for crude protein (CP) and metabolisable energy (ME) at 3 out of 10 sites, and for neutral detergent fibre (NDF) at 2 out of 10 sites. However, at only two sites (both in Cheshire) was there a relationship between fertiliser N rate and all three key measures of herbage quality.

Crude protein (CP) is a measure of the nitrogen content of the cut grass and indicates the maturity of grass at the time of cutting, and the time interval between N fertiliser application and cutting. A CP content of 120-150 g/kg (12-15%) indicates that grass was cut at an optimal stage of growth (Corrall *et al.*, 1982). At a long term grass site in Devon, CP ranged from 11.3 to 19.0% with 'target' concentrations measured at 40-80 kg N/ha (Figure 10).

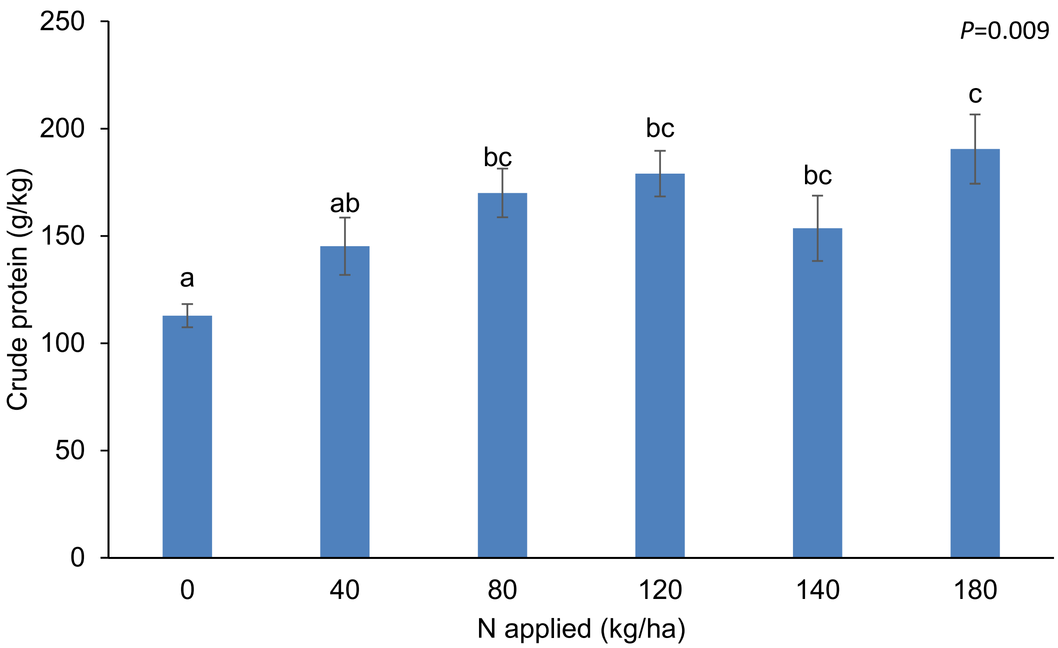

Figure 10. The relationship between fertiliser nitrogen (N) rate and crude protein for first cut silage at a long term grass site in Devon. Values with the same letter are not significantly different (P >0.05). Error bars represent the standard error of the mean.

High protein concentrations can indicate high ammonia levels, which can result in poor fermentation and waste in the silage clamp. High ammonia levels can be caused by high protein levels in grass at cutting or by cutting young, low sugar content grasses when wet. It is an important consideration when planning fertiliser N application rates (Thomas *et al.*, 1991).

Metabolisable energy (ME) is a measure of the energy value of silage expressed as the amount of energy contained in every kg of grass/silage dry matter. The younger and drier the grass, the more energy the grass/silage will supply for milk and liveweight gain (Yan *et al*., 1997). There was no relationship between ME and N fertiliser rate at seven out of ten sites. However, at three sites, ME decreased with increasing fertiliser N rate (e.g. Figure 11), with energy value reducing from 'top quality' (11.4-11.7 ME) at 0-40 kg N/ha to 'average/good' (10.1-10.8 ME) at 180 kg N/ha.

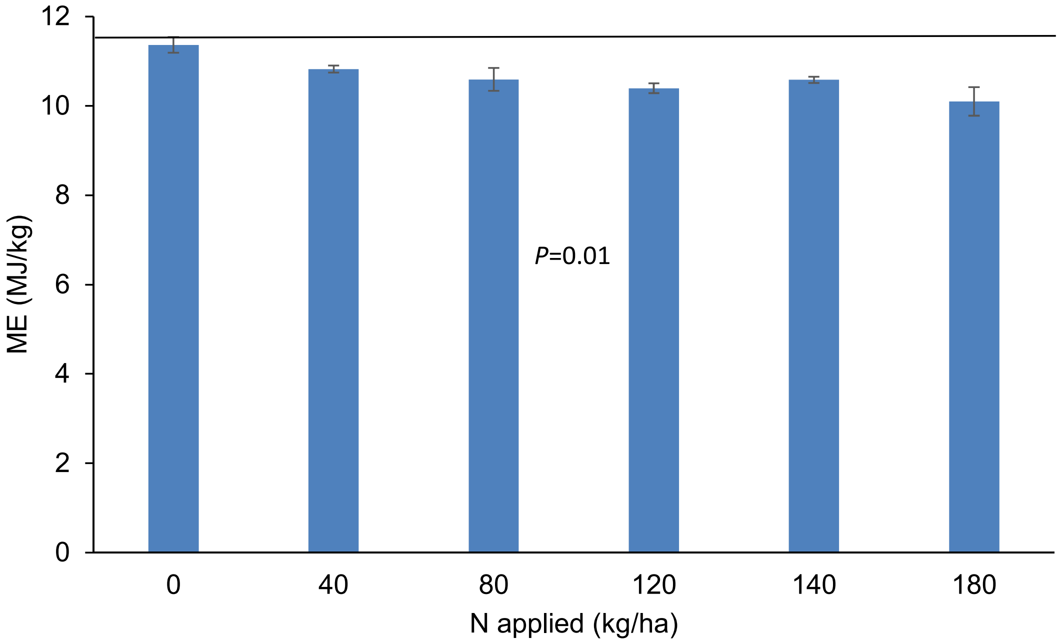

Figure 11. The relationship between fertiliser nitrogen (N) rate and Metabolisable energy (ME) for first cut silage at a long term grass site in Cheshire. Error bars represent the standard error of the mean. The straight line indicates the ME value (11.5 MJ/kg DM) used in the energy model underpinning the 8th edition grassland recommendations.

ME values were generally 'good' (10.6 to 11.6 ME) at N fertiliser rates between 40 and 140 kg N/ha. There was therefore some indication that ME values can reduce below the levels assumed in the 8th edition energy model at higher rates of fertiliser N. A reduction in ME of 1 MJ/kg DM (i.e. an ME value of 10.5 MJ/kg compared with 11.5 MJ/kg used in the energy model) would have the effect of increasing the total N fertiliser requirement by *c*. 20 kg N/ha to achieve the same level of ME per hectare (i.e. an additional 20 kg N/ha would be needed to achieve the same amount of ME/ha, particularly for first cut fertiliser N rates above 100 kg N/ha at which ME can be suppressed). However, this effect was only measured at three out of ten sites and it was not possible to predict when it occurs.

Neutral detergent fibre (NDF) is a measure of the total fibre in grass/silage and also indicates the bulkiness of the feed and the likely level of intake (Corral *et al*., 1982; Minson, 1990). Young grass silage tends to have an NDF of 45–50%, and mature grass silage 60-65%. Late cut, 'stemmy' silages have the highest NDF values (Corral *et al*., 1982). High NDF values tend to indicate lower digestibility, energy and protein values, but NDF can improve intake and rumen health (Minson, 1990). The ideal NDF range in grass/silage is 50-55% (500 – 550 g/kg DM; Corral *et al*., 1982). There was a positive relationship between fertiliser N rate and NDF at two out of ten sites (e.g. Figure 12). This was supported by findings from the AHDB 'Low N Grass' project (74316).

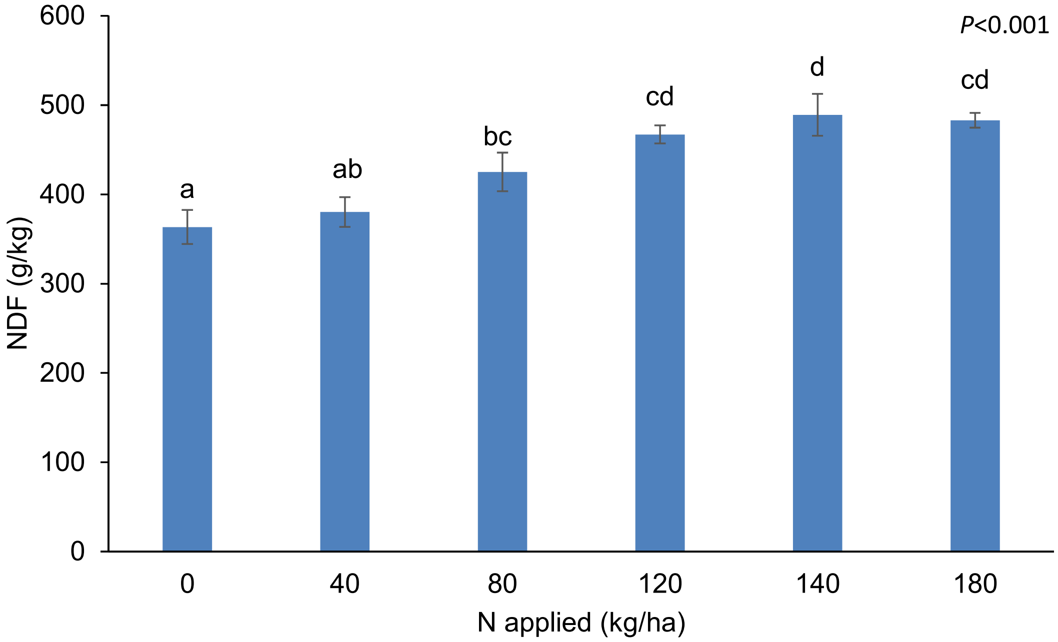

Figure 12. The relationship between fertiliser nitrogen (N) rate and neutral detergent fibre (NDF) for first cut silage from a third year ley in Cheshire. Values with the same letter are not significantly different (P >0.05). Error bars represent the standard error of the mean.

Overall, fertiliser N rate did not have an important effect on herbage quality, with no relationship between N rate and key measures of herbage quality at most sites. Assuming moderate to high output systems, at the few sites where there was a reduction in ME values with increasing N rate it could still be in the farmer's interest to use higher N rates to produce more ME overall, although lower ME in terms of MJ/kg DM could reduce milk yield per cow if not compensated for by increased concentrate use. However, higher ammonia-N levels at the highest N rates (140-180 kg N/ha) may result in poor fermentation in the clamp.

4.6.2. Micronutrients

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; and cobalt deficiency reduces Vitamin B12 production in rhizobium, thereby lowering N fixation and associated productivity (Sinclair *et al*., 2015b). The aim should be to only use micronutrient supplementation where deficiency has been diagnosed.

Selenium (Se) is an essential trace element for animal health. Borowska *et al.* (2011) investigated the effect of applying farmyard manure (FYM) manure at different rates (0, 20, 40, 60 and 80 t/ha) on Se contents in the soil and in red clover. Applying manure at 80 t/ha resulted in a 1.7 fold increase in the Se concentration in the soil (mean background Se content = 0.101 mg/kg). Furthermore, the highest selenium concentrations in red clover were measured from plots receiving 40 and 60 t FYM/ha; about 25% higher than the control.

Sinclair *et al*. (2015b) provide advice on the management of cobalt (Co) in grassland soils. Soils in Scotland have been mapped as “high”, “moderate” or “low” risk for Co deficiency, according to parent material, soil drainage characteristics and soil texture. High risk soils include organic soils; drifts derived from acid schists, granulites, granitic rocks, greywackes and shales; and fluvioglacial sands and gravels. Interpretative scales for soil extractable Co concentrations (mg/kg) are also provided and soil testing is advised in areas mapped as “high” predicted risk; and on peaty soils herbage analysis is also advised. Co deficiency can be corrected for approximately 4 years through the application of hydrated cobalt sulphate to pasture in early spring. However, there are concerns over the use of Co salts as suspected carcinogens, and suppliers of trace elements for livestock in the UK prefer to provide intraruminal boluses or drenches containing cobalt to supplement grass. Selenium (Se) can also be supplied as a grassland fertiliser in deficiency situations (Scott, 2010). However, feed and forage supply needs to be carefully integrated, since for some micronutrients, such as Se, the difference between deficiency and toxicity can cover a narrow range of concentrations in the diet.

4.6.3. Effect of Biostimulants

At the Experimental Unit of the University of Natural Sciences and Humanities in Siedlce (Poland), Godlewska and Ciepiela (2015) investigated the effect of the biostimulant Kelpak® (a seaweed extract containing plant growth regulators cytokinins and auxins and amino acids) on the content of micronutrients in two grass species grown in monoculture: *Dactylis glomerata* L. (cv. Amila) and *Festulolium braunii* (K.Richt.) A. Camus (cv. Felopa) grown in a monoculture.

Kelpak SL was applied at 0 (control) and 2 dm^3/ha, and nitrogen was applied at 0, 50, 100 and 150 kg/ha, with grass cut three times in each year (2010-2012). The application of Kelpak consistently and significantly increased Zn, Cu, Fe and Mn concentrations in the grass species tested, regardless of other factors, although differences were numerically small (e.g. mean Zn content at 100 kg N/ha was 25.9 mg/kg DM with Kelpak SL and 23.8 mg/kg DM without; mean Cu content at

100 kg N/ha was 6.7 mg/kg DM with Kelpak SL and 6.0 mg/kg DM without). The concentrations of Zn, Cu and Fe decreased with increasing N rate, while the Mn concentration increased. The application of Kelpak increased the Fe:Mn ratio in the dry matter of both grasses, which implies an increased risk of manganese deficiency (Malhi *et al*., 1998).

In two similar studies, Ciepiela *et al*. (2013) and Ciepiela and Godlewska (2015) found that Kelpak in combination with N fertiliser (applied at 0, 50, 100 and 150 kg/ha) significantly increased the yields and chlorophyll content of two perennial ryegrass cultivars and four grass-red clover mixtures. The highest DM yields, protein and chlorophyll contents were measured when Kelpak was sprayed and N fertiliser applied at a rate of 150 kg/ha. Kelpak had a small, but statistically significant (P<0.05) additional effect to the N fertiliser.

4.6.4. Conclusions for grass and silage quality recommendations

- At some sites, application rates of fertiliser N above 120-140 kg N/ha for first cut silage reduced the quality of cut grass in terms of ammonia-N content and ME. Although the stage of maturity at harvest can have an influence, it is difficult to predict the agro-climatic or growing conditions in which this deterioration in grass/silage will occur and therefore manufactured N fertiliser rates above 120 kg N/ha should be avoided.
- The importance of micronutrients for grass/clover productivity and animal health needs to be made clear in the recommendations and options for correcting potential deficiencies provided, including the use of micronutrients in fertilisers (e.g. selenium). The possible use restriction of cobalt under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations should be borne in mind for the 2017 AHDB "Nutrient Management Guide (RB209)".
- Studies in Poland indicate that biostimulants containing seaweed extract (from the kelp species *Ecklonia maxima*) when applied with or without N fertiliser can improve grass DM yield and quality in terms of protein and micronutrient content, although there were some concerns over the biostimulant increasing the risk of manganese deficiency due to increases in the Fe:Mg ratio. Research should be carried out to determine whether biostimulants can increase yield and quality of grass/clover swards in England and Wales, which have contrasting soils and agro-climatic conditions compared with eastern Poland.

5. Grassland N recommendation systems

This section outlines the grassland N recommendation systems currently used within Scotland, the Republic of Ireland and England and Wales, and compares the different approaches in relation to the factors that are taken into account within each system.

5.1. Fertiliser N recommendations in Scotland – SRUC Technical Note 652

The N recommendations for established grassland in Scotland (SRUC, 2013) involve the following two stages:

i. Select the 'site class' (equivalent to Grass Growth Classes in RB209); defined on a 1 to 5 scale based on rainfall and soil type (*Table* 7), with site class 5 having about half the grass growth potential of site class 1.
ii. Identify the 'appropriate' nitrogen rates and sequences (kg N/ha) for each grass field based on site class and grass management strategies, expressed as a set of 'defoliation' sequences (
iii. *Table* 8).

The technical note states that "in practice, levels of N use may be less than the figures shown… (see Table 8)…to reflect the level of intensity and production that is required on that particular farm unit".

The nitrogen rates and sequences are derived from whole season "standard or maximum" recommendations, which are reduced by 10kg N/ha with each site class, such that recommendations for site class 5 are 40 kg N/ha less than for site class 1. When these differences are distributed between multiple 'defoliations' the resultant differences between site classes are relatively small

Table 7. Definition of site classes within the nitrogen recommendations in Scotland.

Soil texture	Average Apr-Sep rainfall (mm)*			
	More than 500	425-500	350-425	Less than 350
	Site class **			
Sands and shallow soils	2	3	4	5
All other soils	1	2	2	3

*Approx. 50% annual rainfall

**Add 1 for farms above 300 m

Table 8. A sub-section of the nitrogen (N) recommendations for established grassland showing appropriate application rates and sequences for site classes 1 to 3 (SRUC, 2013).

Grass management	Defoliation sequence	Nitrogen application rate (kg/ha)		
		Site Class 1	Site Class 2	Site Class 3
2 or 3 cuts silage + grazing	S S	120-90	120-90	120-90
	S S G	120-90-60	120-90-60	120-90-60
	S S S	120-90-70	120-90-70	120-90-70
	S S S G	120-90-70-30	120-90-60-30	120-90-60-20
1 cut silage + grazing	S	120	120	120
	S G	120-70	120-70	120-70
	S G G	120-60-50	120-60-50	120-60-50
	S G G G	120-60-50-40	120-60-50-40	110-60-50-40
Grazing with low clover	G	90	90	90
	G G	80-60	80-60	80-60
	G G G	80-60-50	80-60-50	80-60-50
	G G G G	80-60-50-40	80-60-50-40	80-60-50-40

G = grazing; S = Silage

The Scotland N recommendations do not take account of Soil Nitrogen Supply.

5.2. Fertiliser N recommendations in the Republic of Ireland (ROI)

The N recommendations for established grassland in Ireland (Coulter and Lalor, 2008) are split between grazed and cut grass. The N fertiliser recommendations for grazed grass are essentially based on stocking rate and involve the following four stages:

i. Select the advised N application rate according to your stocking rate (*Table* 9). The advised rates are “for swards ≥ 3 years old with no clover and of average soil–N fertility when grazed by bovines”.
ii. For good ryegrass swards less than 3 years old, an additional 25% N may be applied where necessary, provided that the rates do not exceed those prescribed in the ROI Statutory Instrument (SI) 610 of 2010.
iii. Make adjustments for soils of lower than or greater than average fertility: “At stocking rates below 200 kg/ha N, rates of N greater than those shown in this table can be applied on poorer soils. Lower N rates may be appropriate on soils with above average natural fertility”.
iv. Select the optimum timing of N applications and the appropriate annual start and end of N fertiliser application according to the length of the grazing season (Table 10; Collins and

Cummins, 1996). “While these dates are recommended, decisions in each individual year will need to be adjusted depending on the prevailing weather conditions”.

The recommendations include the note that “management should promote clover growth as a good clover sward will reduce N requirements or make N fertiliser application unnecessary”.

Table 9. Available nitrogen (N) rates for swards that are greater than 3 years old, with no clover and of average soil-N fertility when grazed by bovines (Coulter and Lalor, 2008).

Grassland stocking rate		N advice
(kg/ha N)	(LU/ha)*	(kg/ha)
≤ 90	<1.1	40
110	1.3	75
130	1.5	111
140	1.6	122
150	1.8	141
160	1.9	168
170	2.0	201
180	2.1	216
190	2.2	237
200	2.4	275
210	2.5	306
≥210	>2.5	279

*Based on annual nutrient excretion rates for livestock, as specified in SI 610 of 2010, e.g. a dairy cow producing 85 kg N/year.

The N recommendations for cut grass are influenced by two main factors, the number of cuts taken each year and the grazing history. They involve the following four stages:

i. N application rates are advised for first and subsequent cuts of silage and for hay (*Table* 11).
ii. An adjustment is made for N that is applied at early grazing; “assume that 20% of this remains available for first cut silage”
iii. An adjustment is made for swards less than 4 years old; “an extra 25 kg/ha may be used where necessary for establishment of a good ryegrass sward if pasture is less than 4 years old”
iv. An adjustments is made for SNS from grazing in the previous year; “where silage fields were grazed rather than cut in the previous year, apply 100 kg/ha for first cut, and 85 kg/ha for second and subsequent cuts”.

Table 10. Suggested timing of available nitrogen (N) applications for swards grazed by bovines at various stocking rates (Coulter and Lalor, 2008).

Stocking rate (kg N/ha)	N rates (kg/ha) for approximate application dates								Total N rate (kg/ha)
	Jan/ Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
≤ 90			25						40
110		15	30	15		15			75
130		28	35	25		25			111
140		28	35	25		25	17		122
150		29	44	26		26	17		141
160		29	44	35		35	26		168
170		34	53	42		42	31		201
180	32	32	48	38		38	28		216
190	31	41	54	37		37	37		237
200	30	53	53	37	37		37	27	275
210	31	54	54	56	37		37	37	306
≥210	32	55	55	38	38		38	28	279

At stocking rates above 210 kg/ha N, N advice is constrained by SI 610 of 2010.

Table 11. 'Available nitrogen (N)' rates for cut swards within the ROI grassland fertiliser recommendations (Coulter and Lalor, 2008).

Crop	N application rate (kg/ha)
Silage: first cut	125
Silage: second or subsequent cut	100
Hay	65-80

For both cut and grazed grass recommendations, the contribution of crop available N from organic manures is deducted from the advised total N rates to determine the amount of manufactured fertiliser N to apply. A final check is then conducted to ensure that total N recommendations (organic and manufactured N fertiliser) are compliant with maximum levels permitted within SI 610 of 2010.

5.3. Fertiliser N recommendations in England and Wales – the "Fertiliser Manual (RB209)"

The "Fertiliser Manual (RB209)" adopted a markedly different approach to grassland N fertiliser recommendations compared with previous editions. Previous editions had used the economic optimum to set N application rates based on the price of N fertiliser relative to the value of grass dry matter with the break-even ratio (the amount of grass DM needed to pay for a kg of fertiliser N applied) arbitrarily set at 7.5 or 10, depending on the livestock and grassland management system; within the 7th edition $N_{7.5}$ (the economic optimum N rate at a break-even ratio of 7.5) was adopted for dairy grazing systems and cut grass, while N_{10} was adopted for beef and sheep grazing systems. The new 'systems' approach adopted in the 8th edition ("Fertiliser Manual (RB209)") was based on the need to supply sufficient home-grown forage to meet the needs of a wide range of livestock production systems at different levels of management intensity, defined in terms of stocking rate, concentrate use and, for dairy systems, level of milk production. However, the economic optimum concept was retained with N_{opt} set at N_{10} under cutting and grazing for all livestock types and N_{10} values determined for Very good/Good, Average and Poor/Very poor GGC, based on a selection of N response trials carried out in the period 1970 to 1993.

The N recommendations for established dairy grassland in England and Wales (Defra, 2010) involved the following steps:

i. Determine the GGC based on soil type (categorised by water holding capacity) and Average Annual Summer Rainfall; to provide an indication of summer water supply.
ii. Use the GGC to select the relevant whole season total N requirement table.
iii. Select the target milk yield per cow per year.
iv. Calculate and select the dry matter tonnage of concentrated fed per cow per year.
v. Calculate and select the stocking rate in terms of livestock units (LU)/ha; the number of livestock as LU (lactating cows plus followers on average on farm for the year) divided by the total area of grass and forage crops, including forage maize.
vi. If the livestock system does not match any of the milk yield – concentrate use – stocking rate categories within the Table, interpolate between stocking rate and concentrate values by assuming a proportional difference in N requirement between values.
vii. Determine the SNS for the field; taking into account clover content and previous cropping, grassland management (cut or grazed), N fertiliser use and organic manure applications.
viii. Adjust the whole season total N requirement according to the SNS (increase total fertiliser N inputs by 30 kg N/ha in low SNS situations and decrease by 30 kg N/ha in high SNS situations) and the clover content of the sward (estimated to supply 180-300 kg N/ha, depending on clover content; 20-60%).
ix. Split the total N requirement for cut and grazed swards into 3-6 applications over the growing season according to the recommended splits provided (e.g. for grass silage; 40% for first cut (could be split further, Feb-Mar 15%, April 25%), 35% for second cut (could be split further, May 20%, June 15%); 25% for subsequent cuts (could be split further, July 15%, August 10%).

x. An adjustment made for cutting after early spring grazing; reduce the 1st cut recommendation by 25 kg N/ha.

The N recommendations for established grassland under beef production in England and Wales (Defra, 2010) involved the following steps:

i. Determine the GGC based on soil type (categorised by water holding capacity) and Average Annual Summer Rainfall.
ii. Use the GGC to select the relevant whole season total N requirement table.
iii. Select the intensity of the system based on the housing period and amount of concentrate fed through the winter housing season (e.g. the intensively and moderately grazed beef systems are based on a typical housing period of 170 days, with concentrate use of 0.2 to 0.4 t/animal/yr).
iv. Calculate and select the dry matter tonnage of concentrated fed per cow per year.
v. Calculate and select the stocking rate in terms of livestock units (LU)/ha; the number of livestock as LU (beef cattle plus young stock on average on farm for the year) divided by the total area of grass and forage crops, including forage maize.
vi. If the livestock system does not match any of the intensity – concentrate use – stocking rate categories within the Table, interpolate between stocking rate values by assuming a proportional difference in N requirement between two values.
vii. Determine the SNS for the field; taking into account clover content and previous cropping, grassland management (cut or grazed), N fertiliser use and organic manure applications.
viii. Adjust the whole season total nitrogen requirement according to the SNS and the clover content of the sward.
ix. Split the total N requirement into 3-6 applications over the growing season according to the recommended splits provided.
x. An adjustment made for cutting after early spring grazing; reduce the 1st cut recommendation by 25 kg N/ha.

The N recommendations for established grassland under sheep production in England and Wales (Defra, 2010) involved the following steps:

i. Determine the GGC based on soil type (categorised by water holding capacity) and Average Annual Summer Rainfall.
ii. Use the GGC to select the relevant whole season total N requirement table.
iii. Select the intensity of the system based on whether ewes are fed concentrates and conserved forage during lambing (ewes fed 1.0 kg concentrate/ewe/d are in an intensively grazed system and those fed 0.5 kg/ewe/d are moderately grazed).

iv. Calculate and select the stocking rate in terms of livestock units (LU)/ha; the number of livestock as LU (ewes and lambs on average on farm for the year) divided by the total area of grass and forage crops.
v. If the livestock system does not match any of the intensity – stocking rate categories within the Table, interpolate between stocking rate values by assuming a proportional difference in N requirement between two values.
vi. Determine the SNS for the field.
vii. Adjust the whole season total nitrogen requirement according to the SNS and the clover content of the sward.
viii. Split the total N requirement into 3-6 applications over the growing season according to the recommended splits provided.
ix. An adjustment made for cutting after early spring grazing; reduce the 1st cut recommendation by 25 kg N/ha.

5.4. Comparison of N recommendation systems

Dale *et al*. (2013) provided a useful summary of comparisons between the grassland N recommendation systems in ROI, Scotland and England and Wales (
Table 12). They noted that, while there are clear differences in complexity between the systems, there are also similarities in terms of the components used:

- All three systems contain separate recommendations for grazed and cut swards, and recommendations are adjusted to reflect different levels of production ‘intensity’. However, only the SRUC Technical Note uses grassland management (defoliation sequences) as a measure of production intensity and only the manual (RB209) takes account of milk yield (in dairy systems) and concentrate inputs (in dairy and beef systems).
- Both the “Fertiliser Manual (RB209)” and SRUC TN652 use Grass Growth Classes to adjust N recommendations, with the manual using three GGC’s and TN652 adjusting N rates on a five point scale. However, the manual and TN652 make opposite adjustments in N rate to take account of GGC; the manual increases N rates for the poor growth class to take account of lower N use efficiency in drier/cooler areas (e.g. to provide 7 t DM/ha in intensively cut grass systems, N rates are increased by 140 kg N/ha for a Poor/Very poor GGC site compared to a Good/Very good GGC site), while TN652 reduces N rates by 10 kg N/ha per site class resulting in N recommendations for site class 5 that are 40 kg N/ha lower than site class 1. The ROI recommendations provide recommendations for soils with an “average soil-N fertility”, stating that lower N rates may be used on high soil-N fertility sites, and higher rates on low soil-N fertility sites where stocking rate is below 200 kg N/ha (2.4 LU/ha); they therefore use a similar logic to the manual. It could be argued that Grass Growth Classes are only justified where there are clear differences in N response between

classes and there are also regions of contrasting water supply (based on soil type and summer rainfall) within a territory. Average annual rainfall (1981-2010) in ROI ranges from 1,000-1,400 mm in the west (with rainfall exceeding 2,000 mm in some mountainous areas) to 750-1,000 mm in the east (Irish Meteorological Office). In Scotland the range within productive grassland areas (i.e. lower altitudes) is from 2,000-3,000 mm in the west to 700-1,000 mm in the east; and in England and Wales from 1,000-2,000 mm in the west to 600-800 mm in the east (Met Office). The need for Grass Growth Classes to represent regions with contrasting grass growth potential may therefore be greatest in England and Wales.

- TN652 does not take account of SNS, while the manual specifies three Soil Nitrogen Supply categories based on current clover content and cropping, grassland management (cut or grazed), N fertiliser use and organic manure applications in previous years. The ROI recommendations highlight that where cut swards were grazed in the previous year, the N recommendations for cutting should be reduced by 25 kg N/ha for first cut and 15 kg N/ha for second and subsequent cuts.
- Only the manual takes into account substitution rate, forage utilisation (spoilage) and grass and silage energy content. The manual also includes a wide range of systems, with stocking rates ranging from 1.5 to 4.0 LU/ha, compared with <1.1 to >2.5 LU/ha for the grazing recommendations in the ROI. However, the manual (RB209) provides recommendations for high levels of purchased feeds (e.g. 4.4 t concentrate/cow/year at a stocking rates of 3.0-4.0 LU/ha), which exposes dairy producers to market volatility in terms of feed and milk prices (e.g. Mihailescu *et al*., 2015b).

Validation of N response curves covered in section 4.1

There are a number of other factors that influence grass growth and its response to fertiliser N that need to be considered as part of an integrated approach to soil and nutrient management. These include the influence of defoliation processes, treading and compaction, as well as the effects of faecal and urine returns. However, while some of these factors, such as nutrient cycling could be incorporated into the energy or nutrient model that underpin the recommendations, most of them are not key input factors to be included in a N recommendation system for grassland advisers and farmers.

Table 12. A comparison of the components included in the nitrogen (N) fertiliser recommendations currently adopted in Scotland the Republic of Ireland and within England and Wales (Dale et al., 2013).

	Scotland	Republic of Ireland	England and Wales (RB209 8th Edition)
Grass Growth/Site class	✓	×	✓
Soil Nitrogen Supply	×	✓[1]	✓
Intensity of production system –			
Grass management	✓	×	×
Stocking rate	×	✓	✓
Milk yield	×	×	✓
Concentrate input	×	×	✓
Separate recommendations for cut and grazed swards	✓	✓	✓
Expected grass requirements calculated and expected herbage yields indicated	×	×	✓
Substitution rate, forage utilisation, grass and silage energy content included in calculation of forage requirements	×	×	✓

[1] for cut swards only, although “lower N rates” are advised for grazed swards with “above average natural fertility”.

Use of the ‘energy model’ – influence of principal factors on N recommendations

There have been a number of criticisms of the N recommendations in the “Fertiliser Manual (RB209)” both in terms of the complexity and number of adjustments required to generate a N recommendation for each cut or grazing, and in the energy model or ‘back calculation’ method that underpins the recommendations (Dale *et al*, 2013; Defra project IF01121). Within the energy model, the fundamental DM yield response of grass to N fertiliser is based on field trials carried out from 1970 and 1993 and the same response curves are used for cut and grazed grass (see Section 4.1). The amount of N fertiliser needed to meet livestock energy requirements, therefore, does not take account of the improved production performance of modern perennial ryegrass varieties or the contrasting potential for DM offtake of infrequently cut and frequently grazed swards. The following assumptions used within the “Fertiliser Manual (RB209)” are highlighted by Dale *et al*. (2013); each factor has implications for N fertiliser requirements, although some factors in combination would cancel each other out:

- Improved production performance of modern perennial ryegrass varieties – would reduce N fertiliser recommendations
- Lower DM yield potential of grazed swards compared with cut swards – would increase N fertiliser recommendations for grazed swards
- Underestimation of ME required for maintenance - would increase N fertiliser recommendations
- Overestimation of the average liveweight of dairy cows - would reduce N fertiliser recommendations
- Underestimation of the energy required to produce a litre of milk - would increase N fertiliser recommendations
- No account of energy associated with live weight change during lactation, growth, or pregnancy - would increase N fertiliser recommendations
- Underestimation of the ME content of grass silage – would increase N fertiliser recommendations
- Overestimation of the utilisation of forage at grazing (80%, cf. 50-70%; e.g. Mayne *et al*., 2002; Ganche *et al*., 2012) - would increase N fertiliser recommendations

While each of the above factors in isolation can have a significant effect on the N fertiliser levels recommended, when combined they have the effect of cancelling each other out and the overall balance would depend on the specific values selected for each factor. So, while the energy model could be criticised as being overly simplistic it could also be argued that a more complex approach that includes a greater number of fine adjustments could make revision of the model more demanding with a relatively small improvement in the accuracy of the recommendations provided.

Dale *et al*. (2013) also used CAFRE Benchmarking data (from 2009-2012) and data from 12 dairy farms (monitored in the Vision II and DAIRYMAN projects) to compare the RB209 8th edition N recommendations with actual milk yield – concentrate input – stocking rate scenarios and current N usage on silage fields in N.I. They found that the “Fertiliser Manual (RB209)”:

- Overestimates cut grass N requirements (by 95 kg N/ha on average) for lower intensity milk production systems; and both cut and grazed N recommendations in scenarios where stocking rates are high and concentrate feed levels are low
- Underestimates cut grass N requirements (by 80 kg N/ha on average) for higher intensity production systems; and both cut and grazed N recommendations when stocking rates are <2.0 cows/ha and concentrate levels are at the upper end of the range

These findings have important implications for the validity of the 8th edition recommendation system under certain scenarios. However, to revise the systems approach, incorporating a more ‘accurate’ energy model would require a significant amount of research including sensitivity analysis to assess the consequences in terms of the resulting N recommendations. It may be more pragmatic to adopt a simplified recommendation system that avoids the potential pitfalls of a detailed systems approach.

Overview of different recommendation systems and discussion of ‘systems’ approach to nutrient management.

A ‘systems’ approach encourages farmers and advisers to consider the amount of purchased feed and manufactured fertiliser that is used to achieve a desired level of liveweight gain or milk yield. Clearly, the amount of concentrate and manufactured fertiliser purchased has implications for the nutrient use efficiency and net profitability of the system, as well as the resilience to market pressures such as relative changes in the price of meat, milk, feed and fertiliser. For example, Mihailescu *et al*. (2015b) carried out a 3-year study in Ireland, assessing the impact of N and P use efficiency on 19 intensive grass-based dairy farms. The study found that mean net profit increased with mean milk receipts and decreased with mean expenditure on manufactured fertilisers, implying that increasing milk receipts while optimising the use of manufactured fertiliser can be an effective strategy to increase net profit. The study also concluded that higher input systems were more vulnerable in periods of low milk prices and emphasised the importance of optimising inputs to improve economic sustainability. Eight farms exceeding the limit of 2 livestock units (LU)/ha, imposed through the Nitrates Directive, had 1.6 times higher net profit compared with the remainder. Nevertheless, the results indicated that Irish dairy farms, as low-input production systems, have the potential to improve both economic production (as indicated by net profit per hectare) and environmental sustainability (as indicated by N and P balances per hectare, N and P use efficiencies and litres of milk produced per kilogram of imported N). The importance of the balance between grass forage production and concentrate use is also supported by Ryan *et al*. (2011) who evaluated nitrogen efficiency as a key indicator of economically sustainable production on grass-based and high-concentrate dairy production systems in Ireland. They reported that as N concentrate increased, N surplus per hectare increased and N use efficiency per hectare decreased.

Mihailescu *et al*. (2014) reported improvements in nutrient management within grassland systems in the Republic of Ireland. Case studies of intensive grass-based dairy farms, before and after the implementation of good agricultural practice (GAP) regulations in 2006, indicated that N surplus both per ha and per kg of milk solids had decreased by 40% and 32%, respectively (Mihailescu *et al*. 2014). The reductions in N-surplus were achieved through a reduction in manufactured N fertiliser inputs and increased spring application of organic manures. Following the implementation of GAP regulation, mean N-surplus was 175 kg N/ha, which was lower than the mean for dairy farms in northern and continental Europe of 224 kg N/ha. The mean NUE of 0.23 was similar to the European mean, reflecting the low input/ low output systems typically adopted in ROI, involving seasonal milk production, low use of concentrates, imported feed and forages, high use of grazed grass and lower milk yields per hectare (Mihailescu *et al*. 2014).

Thus, these studies highlight the importance for N fertiliser recommendations to provide clear guidance on the amount of DM yield that can be produced at different levels of N input. Ideally, recommendations should direct users towards profitable systems that are resilient within a variety of market conditions.

5.5. Options for presenting nitrogen recommendations for grassland

Current and previous recommendation systems in the UK and ROI provide a number of approaches to presenting N recommendations for grassland. The options for presenting grassland N recommendations in England and Wales include:

- Retain the systems approach, including the current energy model that underpins the current recommendations, and incorporate a table that provides indicative DM yields according to N fertiliser rate for each GGC to introduce the concept of growing enough grass to meet the energy needs of any given system (Appendix II). The recommendations could also include a flow chart to take users through the process of generating a N recommendation; and worked examples and case studies to illustrate how the process works for low, medium and high output systems. This approach provides recommendations for a wide range of intensities and systems, and includes factors such as forage utilisation and forage energy content to calculate grass forage and therefore N requirement. The systems approach provides flexibility in matching recommendations to the production system on each farm. However, the resultant recommendations are much more complicated than other systems. Given that many producers are not able to fit their system into the wide range of milk yield, concentrate use and stocking rate combinations provided in the 8th edition (Defra project IF01121), a narrower range of viable systems could be presented to illustrate a narrower range of possible combinations with fewer rows per Table. This would avoid the implication that the range of systems presented are exhaustive.
- A Table that presents indicative DM yield to represent the range of productivity in swards with differing proportions of modern perennial ryegrass varieties under a cutting regime at various levels of N fertiliser use and for three Grass Growth Classes.
- N recommendations under a grazing system by stocking rate or indicative DM yield, assuming low concentrate use; similar to the grazing recommendations used in ROI

(Coulter and Lalor, 2008). N rates can be adjusted from mid-season onwards according to grass growth, summer rainfall and livestock requirements. Such an approach is simple and easy to interpret, and is appropriate for production systems based on spring calving and grazed grass.

- N recommendations for a number of selected defoliation or management sequences (i.e. similar to the approach for Scotland) for specific levels of production, based on indicative target DM yields. This approach allows users to select a level of N use to achieve the DM yields required for their system, is easy to interpret, clearly sets out how much N to apply for each cut or grazing cycle, and offers sufficient detail to allow recommendations to be tailored to different intensities of production.
- Specific grass silage crop recommendations presented by cut for a given GGC and SNS with adjustments made according to rainfall from mid-season onwards. Different recommendations could be provided for different levels of production (Appendix II).

Recommendation tables should be complemented by text that outlines the principles of nutrient management for grassland and clearly specifies the key factors and general issues to consider. A number of options for presenting grassland N recommendations are provided in Appendix II.

6. Response of forage crops to applied nutrients

6.1. Response to nitrogen

Maize

The “Fertiliser Manual (RB209)” recommends 150 kg N/ha of fertiliser N at a SNS of zero, i.e. around 170-210 kg N/ha in terms of N supply. An inadequate supply of N results in less starch for storage in the grain, and reduced yield and protein (PDA, 2008). However, if the nitrogen supply is too high, leaf growth is excessive, increasing the proportion of leaf and stem to grain, reducing the starch content of silage, delaying maturity and potentially resulting in lodged crops (PDA, 2008; Coulter and Lalor, 2008). Applying too much N can therefore be more damaging than applying too little (Coulter and Lalor, 2008).

At 100 sites over five years (2010-2014), Jewkes *et al*. (2013) measured soil mineral N (SMN) and mineralisable N in the spring prior to manure applications; and dry matter yield and N offtake (stems and cobs) at harvest to determine the range of SNS, N offtake, DM yield and overall N balance (SMN and mineralisable N plus added N fertiliser, minus total plant N) values in forage maize crops. The relationship between N balance and total plant N was linear, with the amount of N in the crop at harvest increasing with increasing negative N balance. At a zero N balance, the crop offtake was 189 kg N/ha (+/- 40 kg/ha), which corresponded to a DM yield of 15.7 t DM/ha (+/-

1.8 t DM/ha). This was below the level at which cob production (in which starch/energy production is concentrated) is compromised by stover/leaf growth. Plotting a simplified N balance (i.e. SMN plus mineralisable N minus plant N) against DM yield indicated a mean N requirement of 95 kg N/ha (as manufactured N fertiliser and/or manure crop available N) for a DM yield of 16 t/ha at zero balance.

Corcoran *et al*. (2016) investigated the effects of degradable plastic mulch (green and yellow with degradation scores of 3 and 5 respectively), N fertiliser rate (0, 50, 100 and 150 kg N/ha) and N application timing (100% at sowing or 50% at sowing and 50% at growth stage V6-V8) on forage maize yield and composition. The green plastic mulch treatment resulted in greater whole-crop yield (P<0.05) (13.5 cf. 12.7 t DM/ha), and crop nitrogen uptake (P<0.05) compared to the yellow mulch, although the yellow mulch had a higher starch content (P<0.05; 372 cf. 327 g/kg DM). The split application of N 50% at sowing and 50% at V6-V8 increased starch concentration (P<0.001), but decreased nitrogen use efficiency and whole-crop yield (P<0.05). The split application of N conferred no overall benefit compared to 100% application of N at sowing. The highest grain yields were achieved at 100 kg N/ha under yellow mulch (7.0 t DM/ha) and at 150 kg N/ha under green mulch (7.7 t DM/ha). The highest whole-crop yields were achieved at 150 kg N/ha for both yellow (13.4 t DM/ha) and green (15.1 t DM/ha) plastic mulch.

Kayser *et al.* (2011) reported findings from a 4-year experiment on the response of forage maize to N application at N-rates (0, 80, 160 and 240 kg N/ha/yr), applied either as manufactured fertiliser, cattle slurry or pig slurry. Over the 4-years, yields and N-offtakes at 0N were high (mean of *c.*13.5 t/ha and *c.*150 kg N/ha, respectively), indicating high SNS. Responses to N-input were small with apparent N recoveries of 14-22% for manures and mineral fertilisers. The study concluded, that care should be taken when growing maize on soils with high potential N mineralisation.

Lynch *et al.* (2013) assessed the effect of N application rate (*c.*30 and *c.*170 kg N/ha, supplied as 30 kg N/ha as crop available N from cattle slurry and the remainder as calcium ammonium nitrate), harvest date and cultivar on maize yield and the quality of whole-crop, cob and stover silages. Overall, the study found no effect of N application rate on DM yield, nutritive value or ensiling characteristics of maize whole-crop or cob silage. However, the higher N-rate (*c.*170 kg N/ha) significantly increased stover DM yield (P<0.05) compared to the lower N-rate (*c.*30 kg N/ha). Whole-crop and stover harvested later had a lower digestible content and underwent a more restricted fermentation compared to silages produced from maize harvested earlier.

As part of Defra project WQ0140 (*Competitive maize cultivation project with reduced environmental impact*) the response of maize to N application rate (0, 40, 80, 120, 160 and 200 kg N/ha) was measured at two sites one in Nottinghamshire the other in Norfolk in 2014, on sandy loam textured soils. At Nottinghamshire, yield response to N application rate was low, giving an N-opt of *c.*20 kg N/ha and DM yield of 17.5 t/ha, at a BER of 6.5. While at the Norfolk site, maize yields increased linearly with N application rate and N-opt was not reached; the highest N rate (200 kg N/ha) resulted in a mean DM yield of 18.8 t/ha. The high yields achieved at both experimental sites were typical of the year, due to the ideal maize growing conditions in 2014.

The above results indicate that no change is needed to the N recommendations for forage maize in the 8th edition of RB209.

Forage rape

Keogh *et al.* (2012) assessed the impact of N application on forage rape yield in a field study at three sites at Moorepark in Ireland. Overall, it was found that forage rape yield increased up to the maximum N rate applied (120 kg N/ha), when sown in early August, giving a mean yield (across the 3 experiments) of 4.9 t/ha. The study concluded that the optimal sowing time for forage rape in Ireland was early August. The results for forage rape indicate that there may be a case for a small increase in N recommendations in zero SNS Index situations, but there is insufficient data from England and Wales to justify this.

Stubble turnips

Keogh *et al.* (2012) also assessed the impact of N application on stubble turnip yields at two sites of contrasting fertility (SNS). Stubble turnips sown in early to mid-August, showed less of a response beyond 40 kg N/ha giving a mean yield (of the two sowing dates) of 4.1 t/ha at the fertile site. However at the less fertile site, yield increased up to the maximum N-rate applied (120 kg N/ha), giving a mean yield (at the two earlier sowing dates) of 4.7 t/ha. The results for stubble turnips indicate that there may be a case for a small increase in N recommendations in zero SNS Index situations, but there is insufficient data from England and Wales to justify this.

Forage triticale

Knapowski *et al.* (2012) assessed the effect of N application rate (80 or 120 kg N/ha) and foliar application of zinc (Zn) (applied at 0, 0.1 and 0.3 kg Zn/ha) on grain Zn and copper (Cu) content of triticale. Overall, it was found that an N application of 120 kg N/ha resulted in a significant increase in the Zn content and a decrease in the Cu concentration in grain compared to applications of 80 kg N/ha. Furthermore, applying foliar Zn at all rates resulted in significant increases in Zn content and a decrease in the copper concentration in triticale grain. Wojtkowiak *et al.* (2014) found that higher (120 kg N/ha) N applications to triticale, as urea in 2 splits, (at tilling and a foliar application at stem extension) resulted in higher concentrations of P, calcium (Ca) and magnesium (Mg). The accumulation of glutenins typically increased in response to higher (120 kg N/ha) doses of N.

Innovate UK project 101093, which was reported as part of AHDB Cereals & Oilseeds project 3699, investigated the N response of modern triticale crops. Clarke *et al*. (2016) found no significant difference in the N requirements of winter wheat and triticale (see WP4 report). However, it was recognised that triticale has a greater lodging risk than wheat, so less N may be required in situations of high lodging risk. Nevertheless, the results indicate that RB209 (8th edition) N recommendations for triticale (which are about 100 kg/ha lower for triticale than for wheat) were insufficient to meet crop demand. It is therefore proposed that winter triticale grown for grain should use the same N recommendation table as winter wheat. However, forage triticale is harvested earlier than grain triticale. Based on harvest at early milky development (GS71; mid/end June) and the fact that total N uptake by GS61 was not significantly different between the triticale and wheat varieties (Clarke *et al*., 2016), it is proposed that the new triticale N recommendations (i.e. winter wheat recommendations) should be reduce by 50 kg N/ha (assuming 30 kg N/ha less uptake and 60% fertiliser efficiency). On medium soils at SNS Index 1, this would equate to a N recommendation of 170 kg N/ha.

Whole-crop wheat

No new data was available to review the N requirements of whole-crop wheat. However, it was agreed at the Livestock TWG on 26th April 2016 that N recommendations for whole-crop wheat should be the same as wheat grown for grain with no adjustments made to account for harvest date, as whole-crop wheat is generally cut later than forage triticale. For example, fermented whole-crop is cut at soft dough stage (GS85), while high dry matter whole-crop is cut closer to fully ripe (GS87-89).

Kale

Understanding how nitrate and nitrite accumulate in forage crops is critical, in order to prevent feeding livestock forage containing high nitrate levels which can negatively impact on animal health, i.e. through nitrite poisoning. The timing of harvest can have a significant effect on the N-content of kale; Korus and Lisiewska (2009) reported that later cuts of kale contained between 17% more total-N and 8% more protein-N than earlier cuts, with mean total-N and protein-N (over 2 experimental years) of 0.58 and 0.52 g /100g, respectively. Furthermore, nitrate and nitrite concentration were reduced by 83% (294 mg /kg) and 46% (0.22 mg/kg) in later cuts. While no yield data was available from this study, the findings can be used to provide advice on the time interval between N fertiliser applications and harvesting or grazing of kale for forage.

Swede and kale grazed in situ

No new data was available on nutrient requirements for crops grazed *in situ*, so it was proposed that the N recommendations for grazed crops should be the same as the recommendations for harvested crops. However, using grazing return principles, the SNS following swede and kale grazed *in situ* should be increased by one level relative to harvested crops, as is the case in The Green Book (Coulter and Lalor, 2008). This was supported by the Livestock TWG on 26th April 2016.

6.2. Response to sulphur

Maize

Trials data indicate that some forage maize crops respond to sulphur applications. In a replicated field plot trial conducted at Henfaes Research Centre, near Bangor, a sulphur application of 18 kg SO_3/ha yielded 1.9 t DM/ha more than where sulphur was not applied (13.8 t/ha cf. 11.9 t/ha; $P<0.05$). However, the higher rates of S application (36 and 54 kg SO_3/ha) had no effect. Nitrogen was applied at 109 kg N/ha, and phosphate and potash according to RB209 recommendations.

At a Maize Growers association (MGA) site in Oxfordshire (sandy silt loam; pH 6.2, P Index 4, K Index 2; previous crop: tomatoes) a trial was carried out to investigate the yield and quality response of forage maize to sulphur at three levels of N (17.5, 35 and 50 kg N/ha) and three corresponding levels of S (50, 100 and 150 kg SO_3/ha); using ammonium nitrate to provide the N treatments and ammonium sulphate to provide the N + S treatments. The addition of S increased DM yields at each rate of N (17.5 kg N/ha, with/without 50 kg SO_3/ha; 35 kg N/ha with/without 100 kg SO_3/ha; and 53 kg N/ha with/without 150 kg SO_3/ha). DM yield increases of 33% were measured at 18 kg N/ha from 50 kg SO_3/ha; 15% at 35 kg N/ha from 100 kg SO_3/ha; and 15% at 53 kg N/ha from 150 kg SO_3/ha (P <0.05). The highest N and S rates also increased starch and protein content (P <0.05). However, at a similar trial in Cheshire there was no DM yield response to applied N or S fertiliser.

Wortmann *et al*. (2009) estimated the forage maize physiological requirement for S was 60 kg SO_3/ha for a crop of 15 t/ha. This is the amount that needs to be supplied from all sources; air, soil and applied fertiliser. The authors reported no DM yield response to applied S fertiliser and attributed this to adequate SOM concentrations and associated mineralisation of S at the sites investigated. Webb *et al*. (2015) reported that sulphur deposition in England and Wales, net of leaching was 8.5-12 kg SO_3/ha in 2009-11 and was estimated to be 4.0-7.5 kg SO_3/ha by 2020.

The “Fertiliser Manual (RB209)” and The Green Book (Coulter and Lalor, 2008) do not recommend any sulphur on forage maize as a low protein crop grown primarily for starch production. Indeed, many forage maize crops receive livestock manures or other organic materials (e.g. digestate) that contain both sulphur and nitrogen and it could be considered that the modest requirement of forage maize for S could be met by this source. Nevertheless, a number of trials have measured a forage maize DM yield response to the application of S fertiliser. Therefore, on land that does not receive regular applications of organic manure, and with declining rates of S deposition, it would be prudent to follow the guidelines proposed by Cussans *et al*. (2007) for wheat, and apply 20-50 kg SO_3/ha to forage maize crops (applied in seedbed or at least before two leaf stage) grown on sandy soils; loamy and coarse silty soils in areas with > 175 mm overwinter rainfall; and on clay, fine silty or peat soils in areas with >375 mm overwinter rainfall.

Forage rye and triticale

No new data was available on the response of forage rye and triticale to sulphur applications. In the absence of any research to quantify the S response from oats, rye and triticale, it is recommended that the 25-50 kg/ha SO_3 recommendation for winter wheat is applied to all winter and spring sown cereals crops. However, not all cereal crops will respond to S. The risk matrix developed by Cussans *et al*. (2007) and published in AHDB Cereals & Oilseeds Information Sheet 28 should therefore be included in a revised RB209.

Forage rape

No new data was available on the response of forage rape to sulphur applications. However, the recommendations for oilseed rape (OSR) can be used as a comparison. Recent work on winter OSR supports the current RB209 recommended rate of 50-75 kg/ha SO_3 (see WP4 report). Given the unavailability of data on forage rape it is recommend that the 50-75 kg/ha SO_3 recommendation for winter OSR is applied to forage rape.

Other forage crops

In view of the unavailability of data on the response of other forage crops to sulphur it is recommended that the risk matrix developed by Cussans *et al*. (2007) is adopted with a recommended application of 25-50 kg/ha SO_3 in higher S deficiency risk situations and where organic manures are not applied prior to the growing season; or organic manures have not been regularly applied in previous years.

6.3. Response to phosphate and potash

The K_2O and P_2O_5 requirements of different forage crops (whole-crop wheat, Italian ryegrass, perennial ryegrass/white clover, fodder beet, kale and maize) were assessed in a 3-year field trial (PDA leaflet 26, 2007) with nutrients supplied by applying a combination of manure and manufactured fertiliser. Overall, the results demonstrated that more K_2O was removed than N, while K_2O removal was 3-6 times greater than P_2O_5 removal (Table 13). Overall, P_2O_5 offtakes were slightly lower and K_2O offtakes higher than standard values (Table 13). For fodder beet, there was a large difference between measured K_2O offtake (4.0 kg/t FW) and standard figures (1.7 kg/t FW for sugar beet; roots only), indicating that further evidence is required to refine standard values for K_2O removal by fodder beet.

Table 13. Amount of phosphate and potash removed by forage crops (taken from PDA leaflet 26, 2007b).

	Measured values		Standard values	
	Phosphate	Potash	Phosphate	Potash
Whole-crop wheat	1.8	5.4	n/d	n/d
Italian ryegrass	1.4	6.3	1.7	6.0
Perennial ryegrass/white clover	1.3	6.8	1.7	6.0
Fodder beet	0.7	4.0	0.8	1.7
Kale	0.9	5.0	1.2	5.0
Maize (silage)	1.7	6.5	1.4	4.4

Overall, due to the limited availability of new data to review the phosphate and potash requirements of forage crops, it is proposed that no changes be made to the recommendations apart from introducing fodder beet (roots only) offtake values.

Swede and kale grazed in situ

Using grazing return principles, it was proposed that the P_2O_5 and K_2O requirement on grazed crops should be reduced by 30-60 kg/ha relative to harvested crops, due to less nutrient offtake. This was supported by the Livestock TWG on 26th April 2016.

6.4. Conclusions for forage crop fertiliser recommendations

Nitrogen

- No change is needed to the N recommendations for forage maize in the 8th edition of RB209.
- There may be a case for a small increase in N recommendations for forage rape and stubble turnips in zero SNS Index situations, but there was insufficient data from England and Wales to justify this.
- It is proposed that the N recommendations for forage triticale should be 50 kg N/ha lower than the new winter wheat recommendations to account for the earlier harvest date for forage triticale, and assuming 30 kg N/ha less uptake and 60% fertiliser efficiency.
- The N recommendations for whole-crop wheat should be the same as for wheat grown for grain.
- The SNS following swede and kale grazed *in situ* should be increased by one level relative to harvested crops.

Sulphur

- For non-Brassica forage crops it is recommended that on land not receiving regular applications of organic manure or where sulphur-containing organic materials have not been applied prior to the growing season, it would be prudent to follow the guidelines proposed by Cussans *et al*. (2007) for wheat and apply 20-50 kg SO_3/ha in higher risk situations according to the soil type/overwinter rainfall guidelines.
- For forage rape and kale grown on mineral soils, where organic manures have not been applied regularly in previous years, it is recommended that 50-75 kg/ha SO_3 be applied as a sulphate containing fertiliser in late February to early March.

Other nutrients

- Given the lack of available data on the response of forage crops to other nutrients, it is proposed that no changes be made to the recommendations.
- The one exception is that on swede and kale grazed *in situ*, phosphate and potash recommendations should be reduced by 30-60 kg/ha relative to harvested crops, to reflect lower nutrient offtake (i.e. grazing returns).

7. Gaps in knowledge and future research required

Knowledge gaps are greatest for the fertiliser requirements of grazed grass due to limited information on recycling of nutrients, spoilage and wastage at grazing with modern grass varieties; the contribution of modern clover varieties to grass dry matter yields and SNS and how this varies with weather conditions from year to year; contrasting grass DM yield response to N fertiliser of older and more modern grass varieties and at lower and higher altitude sites; and the response of forage crops to nutrients in a range of conditions (Table 14). A number of research papers and projects support the knowledge gaps identified in Table 14. For example:

Grazed systems

There is limited evidence on the impact of grazing on nutrient recycling. Eriksen *et al.* (2015) demonstrated that nitrate leaching losses can be high from grass-clover swards that are both grazed and receiving N-inputs from manufactured fertiliser. Further work is required to link stocking rate, grazing behaviour to nutrient recycling and herbage yields and quality.

Grass-clover swards

Peyraud *et al.* (2009) and Phelan *et al*. (2014) outlined a number of limitations surrounding the use of legumes which require further research. It is difficult to predict DM production in grass-clover swards and maintaining optimum clover contents in swards is challenging. In addition, legumes can be difficult to conserve as silage or hay, and can increase the risk of bloat in livestock.

Phelan *et al.* (2015) outlined that further research into forage legumes, should take a “back to basics” approach and focus on the effects of management practices including sowing dates, regrowth/rest periods and post-grazing heights.

Impacts on SNS with a rotation

The importance of accounting for high mineralisation potential in crop rotations has been highlighted in studies which have shown low N-fertiliser responses and high NO_3-N leaching losses from maize following grass (e.g. Eriksen *et al*., 2015 and Kayser *et al*., 2011). Further research is required to understand the yield response of maize at varying SNS Indices and climatic conditions in order to maximise nutrient-use efficiencies. Nevertheless, over-sowing maize with ryegrass can be effective at reducing surplus soil mineral nitrogen content before the onset of over-winter drainage, thereby reducing NO_3-N leaching losses (e.g. Eriksen *et al*., 2015 and Defra project WQ0140). Further research into over-sown maize is required, in order to provide clear guidance on establishment methods, cover crop species and destruction techniques that do not have a negative impact on maize yields and quality.

Forage crops

Korus and Lisiewska (2009) highlighted that further research is required to improve our understanding of the accumulation of nitrate and nitrite in kale. Nitrate is as a source of nitrite, which is formed in the rumen after ingestion. Nitrite poisoning is uncommon in store lambs, but when the problem occurs, lamb losses can be high.

Nutrient-use efficiency

Mihailescu *et al.* (2014 & 2015a) reported that N and P use efficiency has increased on Irish grass-based dairy farms since the introduction of GAP regulations. Improvements have mainly arisen due to a reduction in N and P fertiliser inputs and a shift towards spring application of organic manures, thus indicating an increased awareness of the fertiliser value of organic manures and the importance of accounting for nutrient inputs from manure when planning fertiliser applications. The dominance of N-fertiliser inputs on Irish low input/ low output dairy farms means that improvement to the NUE of fertiliser N and organic manures will be of central importance for reducing N-surpluses and increasing NUE and productivity. Mihailescu *et al.* (2014) suggest improvements to N-balances and NUE can be achieved through optimising management practices such as: nutrient management planning, grazing management and grass utilisation and use of grass-clover swards. Whilst, for P further improvements in PUE can be achieved by optimising P fertiliser application and feed imports and improved on-farm P recycling.

Table 14. Summary of knowledge gaps relating to grass and forage crops, and suggestions for work to address these gaps.

Area	Knowledge gaps	Relevant work underway	Future work	Level of priority
Grazed grass N	Limited information on recycling of nutrients, spoilage and wastage at grazing		Grazing experiments on response to N	High
Cut grass N	Information on N response across a range of conditions.		N response of old and new grass swards tested in a range of GGC and agro-climatic conditions	High
Soil compaction	Limited information on the effect of soil structural degradation on grass and grass/clover response to nutrients		N response experiments in field situations on soils in moderate and poor condition	High
Cut grass S	Information on S response, particularly at first cut.		S response of old and new grass swards tested in a range of GGC and agro-climatic conditions	High
Cut grass K	Information on potash offtake values in cut grass		Collation of data from various sources including future N response experiments	High
Grass P	Information on grass response at P Index 2 and case for splitting into two sub-bands		Analysis of grass herbage in relation to soil Olsen P and P fertiliser applications	Medium
Clover DM yield and N fixing	Contribution of modern clover varieties to grass dry matter yields and SNS		Response of modern grass and clover varieties to differential rates of N	High
Clover DM yield and older/younger perennial ryegrass swards	Production potential of grass-clover swards		Comparison between clover swards with older and modern grass varieties	High
Clover persistence in grass-clover swards	Techniques to increase the persistence of clover in grass-clover swards		Trials investigating contrasting management regimes	Medium
Forage crop nutrients	Response of forage crops to nutrients; and P and K offtake values of modern varieties		N and S response experiments including measurement of nutrient offtakes	High

Area	Knowledge gaps	Relevant work underway	Future work	Level of priority
Accumulation of nutrients in forage rape and kale	Level of beneficial and toxic substances in forage crops		N and S response experiments to integrate herbage analysis	Medium
Yield response of maize in varying SNS and climatic conditions	Effect of site history on forage maize N and S requirements and nutrient-use efficiencies		N and S response experiments at a variety of sites	High
P-fixing capacity	The range of P-fixing capacity within grassland soils in England and Wales		Literature search to determine key P-fixing properties and soil mapping	High
Biostimulants	Effect on grass yield and quality in UK conditions		Yield and quality response experiments	Medium

8. Conclusions

Nitrogen response of grass and clover

A limited number of N response experiments indicate that modern grass swards (1 to 10 years old) are capable of producing higher grass DM yields than older grass swards. This has implications for N grassland recommendations in terms of the amount of N to apply to produce a given level of grass DM. Indicative DM yields provided in the N recommendations should reflect the N response of older and younger grass varieties and the varying composition of grass swards. However, more data is needed on the response of modern grass and grass-clover swards to nitrogen.

Sulphur recommendations for grass

The current grass sulphur recommendations appear sound, but it is recommended that the advice to apply S fertiliser in the situations suggested by Cussans *et al*. (2007) is included. Given the findings of Bailey (2016), it may also be sensible to remove the sentence “Deficiency at first cut is less common but can occur on light sand and shallow soils”, while being wary that over supply of S can be detrimental to animal health.

Phosphate and potash recommendations for grass

Work is needed in England and Wales to assess the P-fixing capacity of different soils to produce a map of soil parent material types (as defined by soil associations) and the contrasting P response of different crops. Research in ROI and NI indicates that Olsen P Index 2 could be split into a lower and upper sub-band with grass P recommendations increased for the lower sub-band. Similar research is required in England and Wales to determine the herbage P sufficiency status at different levels of Olsen P and P fertiliser use. More data is needed on potash offtake in grass for which the grassland management (primarily cutting date, K Index and nutrient applications) is known.

Lime and soil sampling and analysis recommendations

There is no need to change the fundamental principles currently provided. However, the lime factor will be incorporated into lime recommendation tables; and advice on GPS sampling for soil pH and nutrient reserves, and the variable rate application of lime will be incorporated into the “Nutrient Management Guide (RB209)”. Consideration should also be given to the inclusion of advice on the use of seashell sand and its impact on soil pH.

Grazing and grassland management recommendations

There is currently not sufficient data on grass DM yields under grazing management in England and Wales. The current approach that uses the same N response curves for cutting and grazing should therefore be retained, but account will be taken of nutrient returns at grazing.

Grazing height can influence sward recovery, DM yield and overall productivity of grazing livestock systems. However, there are a number of approaches within the industry and advice on herbage mass at the start and end of each grazing cycle should not form part of nutrient management recommendations.

Nutrient management guidelines should include advice on grassland and soil management related to the risks of causing compaction or poaching. Readers will be signposted to industry advice on soil structure in the “Principles of nutrient management” section.

Grass and silage quality recommendations

For first cut silage, manufactured N fertiliser application rates above 120 kg N/ha should be avoided, where possible.

The importance of micronutrients for grass/clover productivity and animal health needs to be made clear in the recommendations and options for correcting potential deficiencies provided, including the use of micronutrients in fertilisers (e.g. selenium).

Research should be carried out to determine whether biostimulants can increase yield and quality of grass/clover swards in England and Wales.

Forage crop N fertiliser recommendations

No change is needed to the N recommendations for forage maize in the 8th edition of RB209. There may be a case for a small increase in N recommendations for forage rape and stubble turnips in zero SNS Index situations, but there was insufficient data from England and Wales to justify this.

It is proposed that the N recommendations for forage triticale should be 50 kg N/ha lower than the new winter wheat recommendations to account for the earlier harvest date for forage triticale, and assuming 30 kg N/ha less uptake and 60% fertiliser efficiency. Whole-crop wheat recommendations will be the same as wheat grown for grain.

Forage crop S recommendations

For non-Brassica forage crops it is recommended that on land not receiving regular applications of organic manure or where sulphur-containing organic materials have not been applied prior to the growing season, it would be prudent to follow the guidelines proposed by Cussans *et al*. (2007) for wheat and apply 20-50 kg SO_3/ha in higher risk situations according to the soil type/overwinter rainfall guidelines.

For forage rape and kale grown on mineral soils, where organic manures have not been applied regularly in previous years, it is recommended that 50-75 kg/ha SO_3 be applied as a sulphate containing fertiliser in late February to early March.

Forage crop recommendations for other nutrients

Given the lack of available data on the response of forage crops to other nutrients, it is proposed that no changes be made to the recommendations; apart from introducing fodder beet (roots only) offtake values, and reducing phosphate and potash recommendations for forage crops grazed *in situ* to account for grazing returns.

Options for presenting nitrogen recommendations for grassland

A number of options for presenting grassland N recommendations are presented in Appendix II. Three options for presenting the N recommendations were considered at the Livestock TWG Meeting on 26th April 2016 and further guidance will be gathered by AHDB staff at other events before a final decision is made on the presentation to be used in the "Nutrient Management Guide (RB209)" in late summer 2016.

9. References

Afzal, M. & Adams, W.A. (1992). Heterogeneity of soil mineral nitrogen in pasture grazed by cattle. Soil Science Society of America Journal, 56, 1160-1166.

Agricultural and Food Research Council (AFRC) (1993). Energy and protein requirements of ruminants. An advisory manual prepared by the AFRC Technical Committee on Responses to Nutrients. CAB International, Wallingford UK.

Aland, A., Lidfors, L. and Ekesbo, I. (2002). Diurnal distribution of dairy cow defecation and urination. *Applied Animal Behaviour Science*, **78**, 43-54.

Anon. 2014. The British Survey of Fertiliser Practice Fertiliser Use On Farm Crops For Crop Year 2013. https://www.gov.uk/government/collections/fertiliser-usage.

Bailey, J.S. (2016). Managing Sulphur to Optimise Grass Production. Fertiliser Association of Ireland. Proceedings of Spring Scientific Meeting 2016, 2nd February 2016. Horse and Jockey, Thurles, Co. Tipperary; pp. 13-16.

Bailey, J.S., Cushnahan A. and Beattie, J.A.M. (1997). Plant and Soil, 197: 137-147

Bailey, J.S., Mellon, J. and K. Hamill, K. (2014). Managing phosphorus to optimise grass production. Proceedings of Agricultural Research Forum, 2014, p.3 ISBN: 978-1-84170-605-4.

Ball, B.C., Bingham, I., Rees, R.M., Watson, C.A. and Litterick, A. (2005). The role of crop rotations in determining soil structure and crop growth conditions. Canadian Journal of Soil Science, 85, 557-577.

Baumont, R., Michaud, A. & Delaby, L. (2012). Forage services provided by permanent grassland: grass production and feeding value for ruminants. *Fourrages*, 219-228.

Bednarek, W., Dresler, S. & Tkaczyk, P. (2015). Nitrogen fractions in timothy grass (phleum pratense l.) Fertilized with different doses of mineral fertilizers. *Journal of Elementology*, **20**, 49-58.

Betteridge, K., Hoogendoorn, C., Costall, D., Carter, M. and Griffiths, W. (2010). Sensors for detecting and logging spatial distribution of urine patches of grazing female sheep and cattle. *Computers and Electronics in Agriculture* **73**, 66-73.

Binnie, R.C. and Chestnutt, D.M.B. (1991). Effect of regrowth interval on the productivity of swards defoliated by cutting and grazing. *Grass and Forage Science*, **46**, 343-350.

Bolland, M.D.A., Allen, D.G. and Barrow, N.J. (2003). Sorption of phosphorus by soils. How it is measured in Western Australia. Bulletin 4591. Western Australia: Department of Agriculture and Food.

Borowska, K. & Koper, J. (2011). Dynamics of Changes of Selenium Content in Soil and Red Clover (Trifolium pratense L.) Affected by Long-Term Organic Fertilization on the Background of Selected Soil Oxidoreductases. Polish Journal of Environmental Studies, 20, 1403-1410.

Boswell, C.C. (1977). Effects of cutting regime on pasture production. *New Zealand Journal of Experimental Agriculture*, **5**, 403-408.

Brown, L., Scholefield, D., Jewkes, E.C., Preedy, N., Wadge, K., Butler, M. (2000). The effect of sulphur application on the efficiency of nitrogen use in two contrasting grassland soils. J. Agric. Sci. 135, 131–138.

Cashman, P.A., McEvoy, M., Gilliland, T.J. and O'Donovan, M. (2016). A comparison between cutting and animal grazing for dry-matter yield, quality and tiller density of perennial ryegrass cultivars. *Grass and Forage Science*, **71**, 112-122.

Chadwick, D and Scholefield, D. (2010). Support paper for revision of the RB209 grassland section - unpublished. North Wyke Research, Devon.

Chaves, B., De Vliegher, A., van Waes, L., Carlier, L. and Marynissen, B. (2009). Change in agronomic performance of Lolium perenne and Lolium multiflorum varieties in the past 40 years based on data from Belgium VCU trials. Plant Breeding, 128, 680-690.

Ciepiela, G. A., Godlewska, A. & Jankowska, J. (2013). The effect of biostimulant on yields of mixed grass/red clover stands and chlorophyll content in crop plant leaves under different nitrogen fertilisation regimes. Fresenius Environmental Bulletin, 22, 3700-3708.

Ciepiela, G.A. and Godlewska, A. (2015). The effect of the biostimulant Kelpak SL on Lolium perenne L. yield, protein and chlorophyll contents at different nitrogen levels. *Agrochimica* **59**(2), 124-136.

Ciepiela, G.A., Godlewska, A. and Jankowska, J. (2013). The effect of biostimulant on yields of mixed grassland/red clover stands and chlorophyll content in crop plant leaves under different nitrogen fertilisation regimes. *Fresenius Environmental Bulletin* **22**(12A), 3700-3708.

Clarke, S., Roques, S., Weightman, R. & Kindred, D. (2016). Modern triticale crops for increased yields, reduced inputs, increased profitability and reduced greenhouse gas emissions from UK cereal production. AHDB Cereals & Oilseeds Project Report No. 556.

Collins, J. F. and Cummins, T. (1996). Agroclimatic Atlas of Ireland, Agnet, Dublin, ISBN 0 951155148.

Corcoran, E.M., O'Kiely, P.O., Gilland, T.J., Burke, J.I. and Lynch, M.B. (2016, submitted). Nitrogen fertiliser rate and timing, and mulch type: effects on forage maize yield and composition. Submitted to the European Grassland Federation Conference, 2016.

Corrall, J., Morrison, J and Young, J. W. O. (1982). Grass production. In: C. Thomas and J. W. O. Young (eds.) Milk from Grass, Grassland Research Institute and ICI Agricultural Division, pp. 1-19.

Cougnon, M., Baert, J., Van Waes, C., Poinsard, L. & Reheul, D. (2014). Production of mixed crops of tall fescue and Italian ryegrass with and without red clover in Belgium. Fourrages, 185-190.

Crush, J. R., Ouyang, L. & Nichols, S. N. (2015). Root morphology and architecture, and internal phosphate use efficiency, in related white clover cultivars of different ages. New Zealand Journal of Agricultural Research, 58, 302-310.

Curran J., Delaby L., Kennedy E., Murphy J.P., Boland T.M. and O'Donovan M. (2010). Sward characteristics, grass dry matter intake and milk production performance are affected by pre-grazing herbage mass and pasture allowance. Livestock Science 127, 144-154.

Cussans, J.W., Zhao, F.J., McGrath, S.P. & Stobart, R. 2007. Decision support for sulphur applications to cereals. AHDB Cereals & Oilseeds Project Report No. 419, August 2007, 32pp.

Dale, A. J., Laidlaw, A. S., Bailey, J. S. & Mayne, C. S. (2015). Effect of dairy slurry application rate and forage type on production, soil nutrient status and nitrogen-use efficiency. Grass and Forage Science, 70, 44-58.

Dale, A., Aubry, A., Ferris, C., Laidlaw, S., Bailey, J., Higgins, S. and Watson, C. (2013). Critique of RB209 8th Edition Grassland nitrogen recommendations for dairy systems. AFBI Report. 171pp.

Daly, K.; Styles, D.; Lalor, S.; *et al*. (2015). Phosphorus sorption, supply potential and availability in soils with contrasting parent material and soil chemical properties. European journal of soil science, 66(4), pp.792-801.

Dampney, P.M.R. (1992). The response of whole year grass silage production to nitrogen. Unpublished report on the analysis of data used to prepare RB209 6th and 7th editions. 28 pp.

Deenen, P. and Middelkoop, N. (1992). Effects of cattle dung and urine on nitrogen uptake and yield of perennial ryegrass. *Netherlands Journal of Agricultural Science*, **40**, 469-482.

Di, H.J., Cameron, K.C., Silva, R.G., Russell, J.M. and Barnett, J.W. (2002). A lysimeter study of the fate of N^{15} labelled nitrogen in cow urine with or without farm dairy effluent in a grazed dairy pasture soil under flood irrigation. *New Zealand Journal of Agricultural Research*, **45**, 235-244.

Dennis, S.J., Moir, J.L., Cameron, K.C., Di, H.J., Hennessy, D. and Richards, K.G. (2011). Urine patch distribution under dairy grazing at three stocking rates in Ireland. Irish Journal of Agricultural and Food Research 50, 149-160.

Durant, D. & Kerneis, E. (2015). Effects of fertilisation on forage yield, feed value, and plant diversity in a permanent grassland located in the marshes of Western France. Fourrages, 157-165.

Eriksen, J. 2009. Soil sulphur cycling in temperate agricultural systems. *Advances in Agronomy*, **102**, 55-89.

Eriksen, J., Askegaard, M., Rasmussen, J. & Soegaard, K. (2015). Nitrate leaching and residual effect in dairy crop rotations with grass-clover leys as influenced by sward age, grazing, cutting and fertilizer regimes. *Agriculture Ecosystems & Environment*, **212**, 75-84.

Evans, D.R., Williams, T.A., Jones, S. and Evans, S.A. (1998). The effect of cutting and intensive grazing managements on sward components of contrasting ryegrass and white clover types when grown in mixtures. *The Journal of Agricultural Science*, **130**, 317-322.

Frame, J. and Laidlaw, A.S. (2014). "Improved grassland management," The Crowood Press Ltd, Malborough, UK.

Fried M. and Middelboe V. (1977). Measurement of amount of nitrogen fixed by a legume crop. *Plant Soil* **47**, 713–715

Ganche, E., O'Donovan, M., Delaby, L., Boland, T. and Kennedy, E. (2012). Effects of grazing severity on early lactation dairy cow performance. In: Grassland – A European Resource. Proceedings of the 24th General meeting of the European Grassland Federation, Lublin, Poland, 3-7 June 2012. Pp 204-206.

Gierus, M., Kleen, J., Loges, R. & Taube, F. (2012). Forage legume species determine the nutritional quality of binary mixtures with perennial ryegrass in the first production year. *Animal Feed Science and Technology*, **172**, 150-161.

Godlewska A., Ciepiela G.A. 2016. The effect of the biostimulant Kelpak SL on the content of some microelements in two grass species. *J. Elem*., **21**(2): 373-381. DOI: 10.5601/jelem.2015.20.2.858.

Grant S.A., Torvell L., Sim E.M. and Small J. (1991). The effect of stolon burial and defoliation early in the growing season on white clover performance. *Grass and Forage Science*, **46** 173-182.

Haynes, R.J. and Williams, P.H. (1993). Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* **49**, pp. 119-199.

Higgins, S., Morrison, S. & Watson, C. J. (2012). Effect of annual applications of pelletized dolomitic lime on soil chemical properties and grass productivity. *Soil Use and Management*, **28**, 62-69.

Hodgson J. and Wilkinson J.M. (1968). The influence of the quantity of herbage offered and its digestibility on the amount eaten by grazing cattle. Journal of the British Grassland Society 23, 75–80.

Høgh-Jensen H., Schjoerring J.K. (1994). Measurement of biological dinitrogen fixation in grassland: comparison of the enriched 15N dilution and the 15N natural abundance method at different nitrogen application rates and defoliation frequencies. *Plant Soil* **166**,153–163.

Hogh-Jensen, H. & Schjoerring, J. K. (2010). Interactions between nitrogen, phosphorus and potassium determine growth and N-2-fixation in white clover and ryegrass leys. *Nutrient Cycling in Agroecosystems*, **87**, 327-338.

Humphreys, J., Casey, I. A. & Laidlaw, A. S. (2009). Comparison of milk production from clover-based and fertilizer-N-based grassland on a clay-loam soil under moist temperate climatic conditions. *Irish Journal of Agricultural and Food Research*, **48**, 189-207.

Humphreys, J., Mihailescu, E. & Casey, I. A. (2012). An economic comparison of systems of dairy production based on N-fertilized grass and grass-white clover grassland in a moist maritime environment*.* *Grass and Forage Science*, **67**, 519-525.

Jafari, A., Connolly, V. and Walsh, E.J. (2003). Genetic analysis of yield and quality in full-sib families of perennial ryegrass (*Lolium perenne* L.) under two cutting managements. *Irish Journal of Agricultural and Food Research*, **42**, 275-292.

Jewkes, E., Blake-Kalff, M. and Blake, L. (2013). Evaluation of the GrowHow N-Min service for use in maize cropping. Poster presentation at the International Fertiliser Society Annual Conference, December, 2013.

Kayser, M., Benke, M. & Isselstein, J. (2011). Little fertilizer response but high N loss risk of maize on a productive organic-sandy soil. *Agronomy for Sustainable Development*, **31**, 709-718.

Keogh, B., McGrath, T. & Grant, J. (2012). The effect of sowing date and nitrogen on the dry-matter yield and nitrogen content of forage rape (*Brassica napus* L.) and stubble turnips (*Brassica rapa* L.) in Ireland. *Grass and Forage Science*, **67**, 2-12.

King, C., McEniry, J., Richardson, M. & O'Kiely, P. (2012). Yield and chemical composition of five common grassland species in response to nitrogen fertiliser application and phenological growth stage. *Acta Agriculturae Scandinavica* Section B-Soil and Plant Science, **62**, 644-658.

King, C., McEniry, J., Richardson, M. & O'Kiely, P. (2013). Silage fermentation characteristics of grass species grown under two nitrogen fertilizer inputs and harvested at advancing maturity in the spring growth. *Grassland Science*, **59**, 30-43.

Knapowski, T., Ralcewicz, M., Spychaj-Fabisiak, E. & Murawska, B. (2012). Effect of the rate of nitrogen and zinc on the zinc and copper accumulation in grain of spring triticale cultivar kargo. *Journal of Elementology*, **17**, 421-429.

Korus, A. & Lisiewska, Z. (2009). Effect of Cultivar and Harvest Date of Kale (Brassica Oleracea L. Var. Acephala) on Content of Nitrogen Compounds. *Polish Journal of Environmental Studies*, **18**, 235-241.

Lynch, J. P., O'Kiely, P. & Doyle, E. M. (2013). Yield, nutritive value and ensilage characteristics of whole-crop maize, and of the separated cob and stover components - nitrogen, harvest date and cultivar effects. *Journal of Agricultural Science*, **151**, 347-367.

Malhi S.S., Nyborg M., Harapiak J.T. (1998). Effect of long-term N fertilizer-induced acidification and liming on micronutrients in soil and in bromegrass hay. *Soil and Tillage Research*, **48**(1-2): 91-101.

Malhi, S.S., Coulman, B. and Schoenau, J.J. (2009). Maximising timothy forage yield and quality by balanced nitrogen, phosphorus and sulfur fertilization. *Agronomy Journal*, **101**, 1182-1189.

Mathot, M., Thelier-Huche, L. & Lambert, R. (2009). Sulphur and nitrogen content as sulphur deficiency indicator for grasses. *European Journal of Agronomy*, **30**, 172-176.

Matthew, C., Hernandez-Garay, A. and Hodgson, J. (1996). Making sense of the link between tiller density and pasture production. *Proceedings of the New Zealand Grassland Association*, **57**, 83-87.

Mayne, C.S., Patterson, D. and Rankin, W.S.A. (2002). On farm monitoring of grass growth, grass quality and herbage intake of dairy cows in Northern Ireland. End of Project Technical Report presented to Agrisearch, July 2002

Michaud, A., Plantureux, S., Pottier, E. & Baumont, R. (2015). Links between functional composition, biomass production and forage quality in permanent grasslands over a broad gradient of conditions. *Journal of Agricultural Science*, **153**, 891-906.

Mihailescu, E., Murphy, P. N. C., Ryan, W., Casey, I. A. & Humphreys, J. (2014). Nitrogen balance and use efficiency on twenty-one intensive grass-based dairy farms in the South of Ireland. *Journal of Agricultural Science*, **152**, 843-859.

Mihailescu, E., Murphy, P. N. C., Ryan, W., Casey, I. A. & Humphreys, J. (2015a). Phosphorus balance and use efficiency on 21 intensive grass-based dairy farms in the South of Ireland. *Journal of Agricultural Science*, **153**, 520-537.

Mihailescu, E., Ryan, W., Murphy, P. N. C., Casey, I. A. & Humphreys, J. (2015b). Economic impacts of nitrogen and phosphorus use efficiency on nineteen intensive grass-based dairy farms in the South of Ireland. *Agricultural Systems*, **132**, 121-132.

Minson, D.J. (1990). Forage in Ruminant Nutrition. Academic Press, London.

Morrison, J. (1987). Grassland production: fertilizer-N, water and white clover. In: Nitrogen and water use by grassland. AFRC Colloquium held at North Wyke Research Station, March 1987. (Ed. R. J. Wilkins). Pp 6-24.Richards, F. J. (1959). A flexible growth function for empirical use. *Journal of Experimental Botany* **10**, 290-300.

Morrison, J., Jackson, M. V. and Sparrow, P. E. (1980). The response of perennial ryegrass to fertilizer nitrogen in relation to climate and soil. Report of the joint ADAS/GRI Grassland Manuring Trial- GM20. GRI Technical Report No 27, 1980.

O'Dovnovan M. and Delaby L. (2008). Sward characteristics, grass dry matter intake and milk production performance is affected by timing of spring grazing and subsequent stocking rte. *Livestock Science* **115**, 158-168.

Orr, R.J., Griffith, B.A., Champion, R.A. and Cook, J.E. (2012). Defaecation and urination behaviour in beef cattle grazing semi-natural grassland. *Applied Animal Behaviour Science*, **139**, 18-25.

Paynter, R.M. and Dampney, P.M.R. (1991). The effect of rate and timing of phosphate fertiliser on the yield and phosphate offtake of grass grown for silage at moderate to high levels of soil phosphorus. *Grass and Forage Science,* **46**, 131-137.

PDA (2007a). Results from grass demonstration plots. Potash Development Association leaflet 5b.

PDA (2007b). Nutrient requirements of forage crops. Potash Development Association leaflet 26.

PDA (2008). Forage maize fertiliser requirements. Potash Development Association leaflet 17.

Peyraud, J. L., Le Gall, A. & Luescher, A. (2009). Potential food production from forage legume-based-systems in Europe: an overview. *Irish Journal of Agricultural and Food Research*, **48**, 115-135.

Phelan, P., Casey, I. A. & Humphreys, J. (2013a). The effect of target postgrazing height on sward clover content, herbage yield, and dairy production from grass-white clover pasture. *Journal of Dairy Science*, **96**, 1598-1611.

Phelan, P., Casey, I. A. & Humphreys, J. (2014). The effects of simulated summer-to-winter grazing management on herbage production in a grass-clover sward. *Grass and Forage Science*, **69**, 251-265.

Phelan, P., Keogh, B., Casey, I. A., Necpalova, M. & Humphreys, J. (2013b). The effects of treading by dairy cows on soil properties and herbage production for three white clover-based grazing systems on a clay loam soil. *Grass and Forage Science*, **68**, 548-563.

Power, V., Tunney, H. and Jeffrey, D.W. (2005). The phosphorus requirements for silage production on high fertility soils. *Irish Journal of Agricultural and Food Research*, **44**, 281-296.

Remison, S. U., and Snaydon, R. W. (1980). Effects of defoliation and fertilizers on root competition between *Dactylis glomerata* and *Lolium perenne*. *Grass and Forage Science*, **35**, 81-93.

Richards, I.R. (1978). Influence of soil and sward characteristics on the response to nitrogen. In "Proceedings, International meeting on animal production from temperate grassland, Dublin, June 1977" (B. Gilsenan, ed.), pp. 45-49, Dublin.

Richards, I.R. and Wolton, K.M. (1976). Spatial distribution of excreta under intensive cattle grazing. *Journal of the British Grassland Society* **31**, 89-92.

Richards, I.R., Wolton, K.M. and Ivins, J.D. (1976). Note on effect of sheep grazing on yield of grass swards. *Journal of Agricultural Science* **87**, 337-340.

Ryan, W., Hennessy, D., Murphy, J. J., Boland, T. M. & Shalloo, L. (2011). A model of nitrogen efficiency in contrasting grass-based dairy systems. Journal of Dairy Science, 94, 1032-1044.

S.I. No. 610 of 2010. Statutory Instruments. European Communities (Good Agricultural Practice for protection of waters) Regulations 2010. pp 41-42.

Sampoux, J.P., Baudouin, P., Bayle, B., Béguir, B., Bourdon, P., Chosson, J-F., Deneufbourg, F., Galbrun, C., Ghisquière, M., Noël, D., Pietraszek, W., Tharel, B. and Viguié, A. (2011). *Field Crops Research*, **123**, 117-129.

Schulte, R.P.O., 2007. Modelling phosphorus from grassland: agronomically and environmentally sustainable advice. End-of-project-report 5188. Teagasc, Johnstown Castle.

Schulte, R.P.O., Melland, A.R., Fenton, O., Herlihy, M., Richards, K. and Jordan, P. (2010). Modelling Soil Phosphorus Decline: Expectations of Water Framework Directive Policies. Environmental Science & Policy 13, 472–484. (PDF Download Available). Available from:

https://www.researchgate.net/publication/223042325_Modelling_Soil_Phosphorus_Decline_Expectations_of_Water_Frame_Work_Directive_Policies [accessed Mar 24, 2016].

Scott, N.M., Watson, M.E., Caldwell, K.S. and Inkson, R.H.E. (1983). Response of grassland to the application of sulphur at two sites in North-east Scotland. J. Sci. Fd. Agric. 34: 357-361.

Scott, P.R. (2010). Nutrient planning in dairy farming on temperate grassland – the need for an integrated approach. Proceedings of the International Fertiliser Society, 684, 32 pp.

Sinclair, A., Crooks, W. and Coull, M. (2014). Soils information, texture and liming recommendations. SRUC Technical Note TN656. April 2013, 6pp.

Sinclair, A., Crooks, W., Edwards, T. and Coull, M. (2015a). Management of cobalt in grassland. SRUC Technical Note TN664. September 2015, 6pp.

Sinclair, A., Edwards, T. and Coull, M. (2015b). Managing soil phosphorus. SRUC Technical Note TN662. April 2015, 8pp.

Sinclair, A., Shipway, P. and Crooks, W. (2013). Fertiliser recommendations for grassland. SRUC Technical Note TN652. April 2013, 8pp.

Smith, A., Arnott, R.A. and Peacock, J.M. (1971). A comparison of the growth of a cut sward with that of grazed swards, using a technique to eliminate fouling and treading. *Journal of the British Grassland Society*, **26**, 157.

Smith, A., Arnott, R.A. and Macauley, J.R. (1975). Sward productivity under alternate or repeated cutting of adjacent small areas. *Journal of the British Grassland Society*, **30**, 201-208.

Stevens, R.J. and Watson, C.J. (1986). The response of grass for silage to sulphur application at 20 sites in Northern Ireland. Journal of Agricultural Science (Cambridge), 107: 565-571.

Suter, M., Connolly, J., Finn, J. A., Loges, R., Kirwan, L., SEBASTIA, M.-T. & Luescher, A. (2015). Nitrogen yield advantage from grass-legume mixtures is robust over a wide range of legume proportions and environmental conditions. Global Change Biology, 21, 2424-2438.

Suttle, N. F. (2010). Mineral nutrition of livestock. 4th ed. CABI Publishing. ISBN 978-1-84593-472-9.

Tallec, T., Diquélou, S., Lemauviel, S., Cliquet, J.B., Lesuffleur, F. & Ourry, A. 2008. Nitrogen:sulphur ratio alters competition between Trifolium repens and Lolium perenne under cutting: Production and competitive abilities. European Journal of Agronomy 29, 94–101.

Thomas, C., Reeve, A. and Fisher, G.E.J. (1991). Milk from Grass, 2nd edn. Scottish Agricultural Colleges, Perth.

Valkama, E., Virkajärvi, P., Uusitalo, R., Ylivainio, K. and Turtola, E. (2016). Meta-analysis of grass ley response to phosphorus fertilization in Finland. *Grass and Forage Science* **71**(1), 36-53.

Webb, J., Fraser, A., Wiltshire, J., Jephcote, C., Rose, R. and Vincent, K. (2015). Review of crop requirements for sulphur and the adequacy of current sulphur fertilizer recommendations. Final report for Defra project SCF0308. 51pp.

White, S.L., Sheffield, R.E., Washburn, S.P., King, L.D. and Green, J.T. (2001). Spatial and time distribution of dairy cattle excreta in an intensive pasture system. *Journal of Environmental Quality*, **30**, 2180-2187.

Wilkins, P.W. (1989). Genotype/harvesting frequency and genotype/nitrogen level interactions for annual dry matter yield in *Lolium perenne* in relation to breeding. *Euphytica*, **41**, 207-214.

Wilkins, P.W. and Lovatt, J.A. (2010). Gains in dry matter yield and herbage quality from breeding perennial ryegrass. In: Grasses for the Future. M. O'Donovan and D. Hennessy (eds.) Proceedings of an International Conference, Cork, 14-15 October, 2010. Teagasc. 43-50.

Wims, C. M., Delaby, L., Boland, T. M. & O'Donovan, M. (2014). Effect of pre-grazing herbage mass on dairy cow performance, grass dry matter production and output from perennial ryegrass (Lolium perenne L.) pastures. *Animal*, **8**, 141-151.

Wojtkowiak, K., Stepien, A., Warechowska, M., Konopka, I. & Klasa, A. (2014). Effect of fertilisation technique on some Indices of nutritional value of spring triticale grain. *Journal of Elementology*, **19**, 229-242.

Wortmann, C.S., Dobermann, A.R., Ferguson, R.B., Hergert, G.W., Shapiro, C., Tarkalson, D.D & Walters, D.T. 2009. High-Yielding Corn Response to Applied Phosphorus, Potassium, and Sulfur in Nebraska. Agronomy & Horticulture -- Faculty Publications. Paper 327.

Yan, T., Gordon, F.J., Agnew, R.E., Porter, M.G. and Patterson, D.C. (1997). The metabolisable energy requirement for maintenance and the efficiency of utilisation of metabolisable energy for lactation by dairy cows offered grass silage-based diets. *Livestock Production Science* **51**, 141-150.

Other reports

- AHDB Cereals & Oilseeds project 3699 – 'Modern triticale crops for increased yields, reduced inputs, increased profitability and reduced greenhouse gas emissions from UK cereal production'.
- AHDB project 74316 'Assessment of varietal characteristics important to low and zero inorganic nitrogen input herbage production'.
- Dale, A., Aubry, A., Ferris, C., Laidlaw, S., Bailey, J., Higgins, S. and Watson, C. (2013). Critique of RB209 8th Edition Grassland nitrogen recommendations for dairy systems. AFBI Report. 171pp.
- Defra project IF01121 'Validation of Fertiliser Manual (RB209) recommendations for grassland'
- Defra project KT018 'Nutrient management decision support systems process improvement'.
- Defra project LS3650 'Utilise genetic variation within and between improved grass populations to improve the sustainability of UK grassland'.

- Wilkins, P.W. and Lovatt, J.A. (2010). Gains in dry matter yield and herbage quality from breeding perennial ryegrass. In: Grasses for the Future. M. O'Donovan and D. Hennessy (eds.) Proceedings of an International Conference, Cork, 14-15 October. Teagasc. 43-50.

Acknowledgments

- AFBI
- BSPB
- British Grassland Society
- BSPB (British Society of Plants Breeders)
- CF Fertilisers UK Ltd
- DLF
- Ecopt Consultancy
- FACTS
- Institute of Biological, Environmental and Rural Sciences (IBERS), Aberystwyth University
- K+S UK & Eire Ltd
- Maize Growers Association (MGA)
- NIAB
- Potash Development Association (PDA)
- Rothamsted Research
- Scotland's Rural College (SRUC)
- Sirius minerals (data on sulphur supply to grass)
- Yara

Appendix I – Search terms and number of results

Titles searched, from 2009 onwards, inverted commas used around search terms. Number of papers returned refers to pre-screening of titles or abstracts.

- Grass and Fertiliser refined by Netherlands or Wales or Germany or England or France or Denmark or Poland or Ireland = **14 papers**
- Grass and Fertili* refined by Ireland or Scotland or England or Netherlands or Denmark or Germany or wales or France = **18 papers**
- Grass and dry matter yield = **14 papers**
- Grass and nitrogen refined by Northern Ireland or Wales or Scotland or Ireland or England = **19 papers**
- Grass and Potassium = **14 papers**
- Grass and phosphorus refined by France or Ireland or Scotland or Germany or Netherlands or Northern Ireland = **14 papers**
- Grass and sulphur refined by France or England or Belgium = **3 papers**
- Grass and sulfur refined by France or England or Belgium = **3 papers**
- Grass and potash = **No results**
- Grass and sward age = **1 paper**
- Grass and spoilage = **No results**
- Grass and nutrient management = **No results**
- Grass and phosphate = 14 papers refined by Northern Ireland or Scotland or Wales or England or Ireland
- Grass and yield response = **No results**
- Grass and nutrient management = **No results**
- Grass and production refined by Ireland or Wales or Northern Ireland or England = **41 papers**
- Grass and productivity refined by England or Scotland or Northern Ireland or Ireland or Wales = **12 papers**
- Grass and yield response = **9 papers**
- Grass and livestock refined by Ireland or France or Germany or Belgium = **7 papers**
- Maize and fertiliser refined by England or Germany or Scotland or Northern Ireland or France or Denmark or Netherlands or Belgium = **27 papers**
- Maize and dry matter yield refined by Germany or France or Denmark = **5 papers**
- Maize and nitrogen refined by Ireland or Wales or Northern Ireland or Scotland or England = **23 papers**
- Maize and potassium refined by Scotland or Northern Ireland or Germany = **5 papers**

- Maize and phosphorus refined by Belgium or France or Scotland or Northern Ireland or Ireland or Germany or Netherlands or England or Denmark = **26 papers**
- Maize and sulphur = **11 papers**
- Maize and fertili* refined by Northern Ireland or England or Scotland = **13 papers**
- Maize and potash = **No results**
- Maize and nutrient management = **No results**
- Maize and phosphate = **8 papers**
- Maize and nutrient management = **No results**
- Maize and production Ireland or Scotland or England = **15 papers**
- Maize and yield response = **No results**
- Maize and productivity Germany or Poland or Northern Ireland or England or France or Denmark or Belgium = **17 papers**
- Maize and livestock refined by Netherlands = **4 papers**
- Forage and fertiliser refined by Germany or Switzerland or Denmark = **4 papers**
- Forage and dry matter yield = **23 papers**
- Forage and nitrogen refined by Northern Ireland or England or Scotland or Ireland or Wales = **9 papers**
- Forage and potassium refined by Switzerland = **1 paper**
- Forage and phosphorus refined by Netherlands or Switzerland or Germany or Denmark = **4 papers**
- Forage and sulphur = **No results**
- Forage and sulfur = **No results**
- Forage and fertili* = **9 papers**
- Forage and potash = **No results**
- Forage and nutrient management = **No results**
- Forage and phosphate = **No results**
- Forage and nutrient management = **No results**
- Forage and production refined by England or France or Northern Ireland or Ireland or Belgium or Germany or Denmark or Scotland or Wales = **52 papers**
- Forage and yield response = **No results**
- Forage and livestock refined by Scotland or Germany or Netherlands or England = **8 papers**
- Triticale and fertiliser refined by Poland = **1 paper**
- Triticale and fertili* refined by Poland = **6 papers**
- Triticale and dry matter yields = **No results**
- Triticale and nitrogen = Poland or Denmark = **6 papers**
- Triticale and potassium = **No results**

- Triticale and phosphorus refined by Denmark = **1 paper**
- Triticale and sulphur = **No results**
- Triticale and sulfur = **No results**
- Triticale and potash = **No results**
- Triticale and nutrient management = **No results**
- Triticale and phosphate = **No results**
- Triticale and nutrient management = **No results**
- Triticale and production = **No results**
- Triticale and productivity = **No results**
- Triticale and yield response = **No results**
- Triticale and livestock = **No results**
- Swede and fertiliser = **No results**
- Swede and fertili* = **No results**
- Swede and dry matter yield = **No results**
- Swede and nitrogen = **No results**
- Swede and potassium = **No results**
- Swede and phosphorus = **No results**
- Swede and sulphur = **No results**
- Swede and sulfur = **No results**
- Swede and potash = **No results**
- Swede and nutrient management = **No results**
- Swede and phosphate = **No results**
- Swede and nutrient management = **No results**
- Swede and production = **No results**
- Swede and productivity = **No results**
- Swede and yield response = **No results**
- Swede and livestock = **No results**
- Kale and fertiliser = **1 paper**
- Kale and fertiliser = **1 paper**
- Kale and dry matter yield = **No results**
- Kale and potassium = **No results**
- Kale and phosphorus = **No results**
- Kale and sulphur = **No results**
- Kale and potash = **No results**
- Kale and nutrient management = **No results**
- Kale and phosphate = **No results**
- Kale and nutrient management = **No results**

- Kale and productivity = **No results**
- Kale and production = **No results**
- Kale and yield response = **No results**
- Kale and livestock = **No results**
- Clover and fertiliser refined by Scotland or Denmark or Ireland or Northern Ireland Scotland or Denmark = **3 papers**
- Clover and fertili* refined by Scotland or Poland or Northern Ireland or Ireland or France or Denmark or Wales or Belgium = **16 papers**
- Clover and dry matter refined by Wales = **1 paper**
- Clover and nitrogen refined by Wales or Denmark or France or Poland or England or Scotland or Netherlands or Ireland or Germany = **21 papers**
- Clover and potassium refined by Netherlands or Denmark = **2 papers**
- Clover and phosphorus = **1 paper**
- Clover and sulphur refined by France = **3 papers**
- Clover and potash = **No results**
- Clover and sward age = **1 paper**.
- Clover and spoilage = **No results**
- Clover and nutrient management = **No results**
- Clover and phosphate = **5 papers**
- Clover and nutrient management = **No results**
- Clover and production refined by Ireland or North Ireland or England or Belgium or Denmark or Wales = **14 Papers**
- Clover and productivity refined by Denmark or France or England = **3 papers**
- Clover and yield response = **No results**
- Clover and sward age = **1 paper**
- Clover and livestock = **3 papers**
- Grassland fertiliser recommendations and farmer attitudes = **No results**
- Nutrient management and grassland farmer = **No results**
- Grassland fertiliser and production = **No results**
- Grassland fertiliser and yield response = **1 paper**
- Grassland fertiliser and farmer attitudes = **No results**
- Grassland fertiliser and farmer = **No results**

Appendix II – Options for grassland N recommendations

N response Table

A first recommendation table could provide an indication of the dry matter yield produced at different levels of N fertiliser use for the three Grass Growth Classes at Moderate SNS (Table A1). The ranges reflect the contrasting amount of grass DM produced by older swards with a low proportion of modern perennial ryegrass (PRG) cultivars (low productivity) and younger swards with a high proportion of modern PRG varieties (higher productivity). Indicative DM yield ranges are based on the three N response curves used in the 8th edition of RB209 (Chadwick and Scholefield, 2010) and allowing for a DM yield increase of up to 30% due to modern perennial ryegrass cultivars (Wilkins and Lovatt, 2010). The DM yields assume that swards are cut 4 to 5 times (May-September) and minimal clover content of less than 10-15% cover in mid-season. No account is taken of in-field losses or spoilage in the clamp. The table provides an indication of the amount of N fertiliser needed (as crop available N from organic manure or manufactured N fertiliser) to achieve a given level of grass DM yield. It also indicates that the grass DM yield on Poor/Very poor GGC sites is likely to be lower than on Good/Very good or Average GGC sites at any given level of N use; and that at higher N rates the N use efficiency is significantly reduced on Poor/Very poor GGC sites.

Table A1. Typical ranges for grass dry matter (DM) yield response at different levels of nitrogen (N) fertiliser use.

	Grass DM yield response[1] by Grass Growth Class		
N rate kg/ha	Good/Very Good	Average	Poor/Very poor
0	4-5	3-4	2-3
50	5-7	4-6	3-5
100	6-8	5-7	4-6
150	7-9	6-8	5-7
200	8-10	7-9	6-8
250	9-13	8-12	7-10
300	10-15	9-14	7-11
350	11-16	10-15	8-12

[1] typical whole season DM yield ranges from cut grass swards with minimal clover content over 4-5 cuts. To account for field losses and spoilage in the clamp, these values can be reduced by 20%.

At the Livestock TWG Meeting on 26th April 2016, Table A1 was thought to be useful in providing an indication of dry matter yields that can be achieved at different levels of N fertiliser use. However, it was suggested that the table could be presented in a different colour format from the actual N recommendations, to make it clear that it is a representation of how N response works and not a recommendation. It was also felt that there was no need to specify that the data is derived from experiments using 4-5 cuts (see footnote to Table A1).

The N response Table could also be presented as a graph, which more clearly illustrates the flattening of the N response at higher rates of N, particularly for Poor/Very Poor GGC sites (Figure A1).

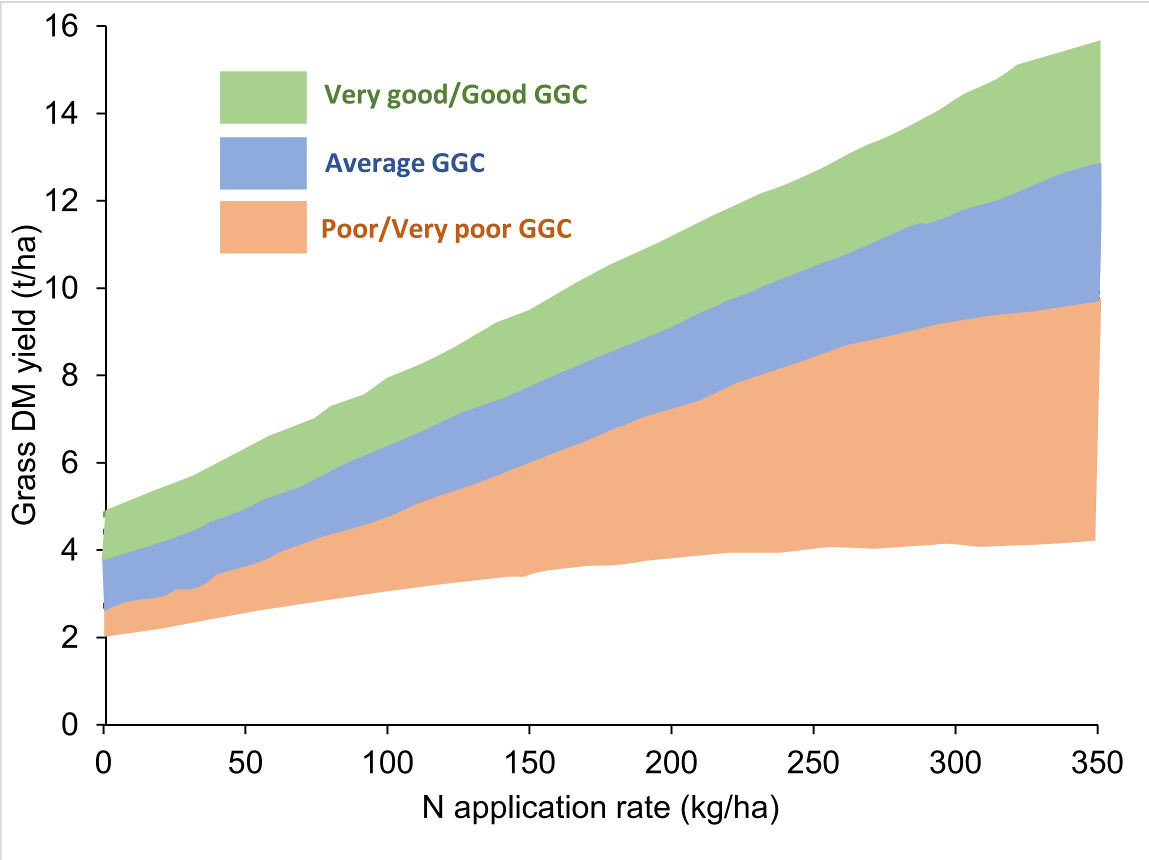

Figure A1. Grass dry matter (DM) yield nitrogen (N) response curve ranges by grass growth class (GGC) for grass swards > 3 years old with minimal clover and Low soil nitrogen supply (SNS) to Moderate SNS.

At the Livestock TWG Meeting on 26th April 2016, Figure A1 was appreciated as a schematic or illustration of the way the world works in terms of N response. The graph can be used to illustrate the principles of N response on grassland. Figure A1 could be used to illustrate the principles of yield response to nitrogen, and the impact of grass growth class (GGC). However, some considerations needs to be given to the Poor/Very poor GGC especially at high nitrogen rates. Some land has very limited N response potential due to physical limitations, such as wetness, low temperature (higher altitude/latitude sites) and north-facing aspect (Figure A1). It was also stated that it may not be necessary to include both Table A1 and Figure A1 in the recommendations.

Grazing N recommendations

An alternative to the current systems approach is to provide recommendations for a narrower range of circumstances. For example, N recommendations could be provided that assume a low level of concentrate use and vary the N rate according to stocking rate or indicative DM yield (Table A2). Such an approach could be used for all livestock types and adjustments can be made according to the amount of rainfall through the season. The grazing recommendations are indicative only and provide a base from which to develop a nutrient plan. At the Livestock TWG Meeting on 26th April 2016, it was stressed that they need to work as a planning tool. It was also proposed that the N recommendations should be linked to indicative DM yield ranges as the indictor of intensity, rather than stocking rate (Table A2). The importance of providing supporting guidance for upland grazing systems and of taking account of the nutrients in applied organic manures was also highlighted. N should be applied as crop available N from manure applications (see organic materials section) and/or as manufactured fertiliser, with N rates adjusted through the season according to summer rainfall and livestock requirements.

Indicative DM yield ranges are based on the N response curve used in the 8th edition of RB209 (Chadwick and Scholefield, 2010) for Very Good/Good Grass Growth Class land and allowing for a DM yield increase of up to 30% due to modern perennial ryegrass cultivars (Wilkins and Lovatt, 2010). The N rates are selected to avoid high N concentrations in herbage over a 21-30 day grazing rotation. Grazing rotation length will vary through the season, but in some higher output systems the average is around 25 days. The recommendations take account of highest growth rates in late spring and early summer (April to June); the potential for limited rainfall (and soil water supply) in mid-summer; and high grass growth potential in the autumn (around one third of grass DM yield can be produced in August to October).

Table A2. Nitrogen (N) recommendations for grazing land by stocking rate.

	N application rate (kg/ha)[1] per grazing rotation and approximate application date							
Indicative DM yield[1] (t/ha)	**Jan/ Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Total N applied (kg N/ha)**
4-5		30						**30**
5-7		30		20				**50**
6-8		30		30		20		**80**
7-9		40		30	30	30		**130**
9-12		30	30	30	30	30	30	**180**
10-13	30[2]	40	40	30	30	30	30	**230**
11-14+	30[2]	40	50	50	40	30	30	**270**

[1] The recommendations take account of N recycled at grazing

[2] Only applicable to areas with a long grass growing season; the first N application could be applied as early as mid to late January, with the second application in early March. No N should be applied after mid-August.

Rates shown apply to:

- Very Good/Good Grass Growth Class and Moderate SNS land. Rates should be adjusted through the season according to grass growth, summer rainfall and livestock requirements.
- Grazed swards with low clover only (i.e. less than 10-15% cover in mid-season; for grass/clover swards see ‘Grazing of Grass/Clover Swards – Nitrogen’).

Don’t forget to deduct nutrients applied as organic manures (see organic materials section)

N recommendations by ‘management sequence’ and GGC

Recommendations could be provided that indicate the amount of N to apply at each defoliation and the amount of grass DM yield that should be expected from low clover swards according to GGC (Table A3). Indicative DM yield ranges are based on the three N response curves used in the 8th edition of RB209 (Chadwick and Scholefield, 2010) for Very Good/Good, Average and Poor/Very poor Grass Growth Class land and allowing for a DM yield increase of up to 30% due to modern perennial ryegrass cultivars (Wilkins and Lovatt, 2010). The recommendations take account of the fact that Poor/Very poor GGC sites, on average, need more N to produce a given amount of grass DM than Average or Good/Very good GGC sites. ‘G’ means a grazing rotation to which N should be applied, i.e. N is applied prior to the grazing rotation. A single ‘G’ therefore means that N should only be applied to the first grazing rotation. ‘S’ means a grass silage cut for which a N fertiliser application should be made, e.g. for a second cut of silage, N is applied immediately after first cut. A two ‘S’ sequence (S S) means that N fertiliser should be applied in early spring ahead of first cut and immediately after first cut for a second cut of silage. ‘H’ means a N application associated with a cut of hay or haylage.

The N recommendations included the following considerations:

- Grazing recommendations take account of 15% of N recycled at grazing (rounded up or down to the nearest 10 kg N/ha).
- Grazing - the maximum amount of N per application was set at 80 kg N/ha. This is in line with previous N recommendations for grazing.
- The maximum whole season N rate was set at 330 kg N/ha to reduce risk of exceeding maximum/optimum N rate and to improve N use efficiency, as indicated by Defra IF01121 N response curves.
- To reduce the risk of N fertiliser being applied at rates that exceed the maximum yield achievable at sites/seasons with limited growth potential:
    - First cut recommended rates were set at a maximum of 120 kg N/ha.
    - Second cut recommended rates were set at a maximum of 90 kg N/ha.

    - Third cut recommended rates were set at a maximum of 75 kg N/ha.
    - Fourth cut recommended rates were set at a maximum of 50 kg N/ha.
- For grazing and cutting combinations, the N rate for the final grazing was reduced by 15% to take account of N cycling at the first grazing unless no N was applied to the final grazing in which case the N rate for the first grazing was reduced.
- For hay production, overall N rates were reduced by 5% relative to silage cut yields to take account of later cutting and bulking out of the hay crop.

Good/Very good GGC sites with 2-10 year old swards are likely to achieve target DM intake values at the higher end of the range. First year grass leys can achieve yields that are 10-20% above the upper end of the range. Poor/ very poor GGC sites are likely to achieve DM intake levels towards the lower end of the range in most years.

At the Livestock TWG Meeting on 26th April 2016, it was stated that the presentation was understandable and user friendly; and a convenient starting point for discussion of grazing and cutting intensities. It was agreed that DM yield rather than DM intake should be used (Table A3); hay recommendations should be integrated into the table; and grass/clover recommendations should be retained as a separate section. Guidance on optimal timings of N applications in cutting and grazing situations should also be included.

The recommendations were also trialled at agricultural events such as Scotgrass on 18th May 2016 and Beef expo on 20th May 2016 with a number of respondents stating that total N rates should be included in the management sequence table; and that the hay recommendations should include an option for a grazing-hay-grazing sequence (Table A3).

Table A3. Grassland nitrogen (N) recommendations by ‘management sequence’, indicative dry matter yields (t DM/ha) and GGC. All rates apply to Moderate SNS sites with minimal clover content (i.e. less than 10-15% cover in mid-season).

Management sequence	Indicative DM yield (t/ha)[1]	N rates (kg N/ha) by Grass Growth Class					
		Good/ Very good		Average		Poor/ Very poor	
		N rates (kg N/ha)	Total (kg N/ha)	N rates (kg N/ha)	Total (kg N/ha)	N rates (kg N/ha)	Total (kg N/ha)
G	3-4	0	0	30	30	50	50
GGG	6-8	30-30-20	80	50-30-30	130	70-70-30	170
GGGGGG	9-12+	30-30-30-30-30-30	180	40-40-40-40-30-30	220	N/A[3]	N/A[3]
SG	5-7	50-0	50	70-0	70	100-50	150
SG	6-8	60-30	90	70-40	110	N/A[2]	N/A[2]
SSG	7-9	70-30-30	130	80-40-40	160	100-75-75	250
SSG	8-11	80-50-40	170	80-70-50	200	N/A[3]	N/A[3]
SSSG	10-13	90-60-60-40	250	110-75-75-50	310	N/A[3]	N/A[3]
SSSSG	11-14+	100-75-75-30-30	310	100-75-75-50-30	330	N/A[3]	N/A[3]
GSG	5-7	40-0-0	40	30-40-0	70	40-70-30	140
GSG	7-9	30-70-30	130	40-80-30	150	80-110-50	240
GSSG	9-12	40-90-40-30	200	50-100-60-30	240	N/A[3]	N/A[3]
GSSSG	11-14+	50-100-60-60-30	300	50-100-70-70-30	320	N/A[3]	N/A[3]
H	4-5	30	30	50	50	80	80
HG	6-8	60-30	90	80-30	110	100-80	180
GHG	7-9	30-60-30	120	40-80-40	160	50-100-80	230

[1] For grass swards in their second year or older
[2] Rates required over two or more ‘defoliations’ may impair grass quality
[3] DM yield yields unlikely to be achieved

Don’t forget to deduct nutrients applied as organic manures (see organic materials section)

Grass silage recommendations

Nitrogen recommendations should relate to modern grassland systems; provide some indication of the level of production; and be clear. A significant proportion of farmers and advisers consulted as part of telephone surveys, email surveys and focus groups in Defra project IF01121 called for a simplification of the N recommendations. Many farmers and advisers requested explicit guidance on how much nitrogen to apply prior to each cut of silage to achieve a given level of production. Table A4 provides N recommendations and associated indicative in-field DM yields for grass silage production on swards with low clover content over 1 to 4 cuts. Indicative DM yield ranges are based on the N response curve used in the 8th edition of RB209 (Chadwick and Scholefield, 2010) for Very Good/Good Grass Growth Class land and allowing for a DM yield increase of up to 30% due to modern perennial ryegrass cultivars (Wilkins and Lovatt, 2010).

The recommendations are applicable to any livestock system in a Very good/Good GGC and Moderate SNS situation. Adjustments can be made according to summer rainfall and livestock requirements. The user has to assess how the recommendations relate to their particular production system and their overall requirement for grass DM. However, advice on energy requirements can be provided as part of forage and feed planning recommendations. Nitrogen rates per silage cut are also provided in Table A3 as part of a 'management sequence' approach, but there may be advantages to providing silage crop recommendations for clarity and ease of use, as is the case for hay N recommendations in the "Fertiliser Manual (RB209)".

Table A4. N recommendations (kg N/ha) for grass silage by cut.

Indicative DM yield[1] (t/ha)	N application rate (kg N/ha)				Total N applied[2] (kg N/ha)
	1st cut	2nd cut	3rd cut	4th cut	
5-7	70	-	-	-	**70**
7-9	80	50	-	-	**130**
10-13	100	75	75[3]	-	**250**
11-14+	120	90	70[3]	30[3]	**310**

[1] DM yield as harvested in the field for all cuts combined. Does not include spoilage in the clamp.

[2] As manufactured fertiliser and crop available N from organic materials.

3 If previous growth has been severely restricted by drought, reduce or omit this application.

- N rates are for Very good/Good GGC sites (i.e. sites that receive adequate rainfall throughout the summer to support grass growth - see GGC Table) with Moderate SNS. For High SNS sites, apply 10 kg N/ha less for first cut, and 20 kg N/ha less for second cut. For Low SNS sites, apply 10 kg N/ha more for first cut, and 20 kg N/ha more for second cut.

- For 1st cut rates over 90 kg N/ha, apply 40 kg N/ha in mid-February to early March with the remainder in late March to early April and at least 6 weeks before cutting.
- Applications for second and subsequent cuts should be made as soon as possible after the previous cut.

Don't forget to deduct nutrients applied as organic manures (see organic materials section)

At the Livestock TWG Meeting on 26th April 2016, it was stated that grass silage production is a fixed cost activity so it is important to maximise the return on the investment. However, it was also noted that some livestock farmers (e.g. beef producers) take a later single cut of silage for bulk feed using moderate N rates and the recommendations should reflect this. The Livestock TWG thought the recommendations were clear and usable.

Systems approach

The "Fertiliser Manual (RB209)" provided grassland N recommendations for a wide range of livestock systems. A large number of users were able to match their farm to the recommendation tables. However, providing a large number of stocking rate – concentrate – milk yield combinations gave the impression that all situations were covered, when in fact they were not. There was also an undue level of precision associated with the current recommendations, which were accepting of production systems that are not profitable under current market conditions (e.g. the use of high levels of purchased feeds).

It was therefore proposed by the project team that a reduced number of cells could be provided within the recommendation tables to cover a range of situations (Table A5). A simplified and revised systems approach could still have provided a useful level of flexibility for multiple approaches to feeding livestock within dairy, beef and sheep production systems. A flow chart taking users through the process of generating a recommendation could also have aided clarity and comprehension. Indicative yield ranges were also included to reflect the difference in productivity between older and younger swards (Table A5).

The recommendations in Table A5 used the same energy model that underpinned the "Fertiliser Manual (RB209)" grassland N recommendations due to the uncertainties in changing numerous factors within the model, including DM yield response to applied N and livestock energy requirements. The project team proposed that if a detailed systems approach (as used in the 8th edition) was to be retained, recommendation tables would be provided for dairy, beef and sheep systems across all three GGC's.

Table A5. Whole season total N requirement for Good / Very good GGC dairy grassland.

Dairy Grass Growth Class *Very Good / Good*					
			Total N requirement		
Milk yield	Concentrate use	Stocking Rate	Cut		Grazed
l/cow/yr	t/cow/yr	LU/ha	kg/ha	Indicative yield (t DM/ha)	kg/ha
8,000 to 10,000	4.4	3.5	310	10-13	210
		3.0	260	9-12	150
8,000 to 10,000	3.7	2.6	310	10-13	210
		2.2	240	9-12	150
6,000 to 8,000	1.5	2.2	360	11-14	340
		1.6	210	8-11	170
6,000 to 8,000	0.9	1.9	330	10-13	320
		1.5	230	9-12	190
4,000 to 6,000	0.9	2.4	350	11-14	330
		1.8	210	9-13	180
4,000 to 6,000	0.5	2.1	320	11-14	290
		1.7	220	9-13	190
< 5,000 extended grazing	0.5	2.2	310	11-14	240
		2.0	270	10-13	200

At the Livestock TWG Meeting on 26th April 2016, it was agreed that the 8th edition systems approach provided a useful basis for the development of future recommendations, and that it should be built on to provide recommendations in a different format using the same yield response model. It was also noted that the principles underpinning the 8th edition recommendations were well formulated and formed the basis of a useful approach that takes account of a wide variety of contrasting production systems.

‘Road testing’ of grassland N recommendations

Three options for presenting the N recommendations were considered at the Livestock TWG Meeting on 26th April 2016

- A ‘two tables’ option – one for silage and one for grazing (Tables A2 and A4)
- A ‘management sequence’ option (Table A3)
- Both options (Tables A2, A3 and A4)

A consensus was not reached and it was decided that all three options (along with the N response schematic) should be ‘road tested’ at agricultural events such as Scotgrass on 18th May 2016 and Beef expo on 20th May 2016. The overall feedback from farmers and advisers consulted at these events was positive with suggestions incorporated into Tables A2, A3 and A4. Stakeholders appreciated the N response schematic and indicated a need for guidance on how to measure/monitor grass DM yields. The general consensus was that using both options (i.e. all three tables) was not necessary with approximately 60% favouring the ‘management sequence’ option and 40% favouring the ‘two tables’ option. Further guidance will be gathered by AHDB staff at other events before a final decision is made in late summer 2016.

Appendix III - companies invited to submit data and/or opinions

ADAS

Agrii

AHDB (RB209 Livestock Technical Working Group)

Association of Independent Crop Consultants (AICC; various individual contacts)

Bangor University

British Grassland Society

BSPB (British Society of Plants Breeders)

CF Fertilisers UK Ltd

DLF

Ecopt Consultancy

Frontier Agriculture Ltd

Germinal

Harper Adams University

Hutchinsons

Institute of Biological, Environmental and Rural Sciences (IBERS), Aberystwyth University

International Fertilizer Society

James Hutton Institute

K+S UK & Eire Ltd

Maize Growers Association (MGA)

NIAB

NRM Laboratories

OMEX

Origin Fertilisers

Potash Development Association (PDA)

Rothamsted Research

Scotland’s Rural College (SRUC)

Sirius Minerals

SOYL

Teagasc

Wageningen UR (Netherlands)

Yara