Hay meadow just prior to cutting, Gowk Bank SSSI, Cumbria © Peter Wakely/Natural England

Upland Hay Meadows: what management regimes maintain the diversity of meadow flora and populations of breeding birds? (NEER005)

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Upland Hay Meadows: what management regimes maintain the diversity of meadow flora and populations of breeding birds?

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Cover photograph

Hay meadow just prior to cutting, Gowk Bank SSSI, Cumbria © Peter Wakely/Natural England.

Executive summary

Management of the English uplands is complex and achieving good environmental outcomes, while taking into account the needs of owners, stakeholders and other interests is a balancing act. An uplands evidence review has been undertaken in which a number of candidate topics have been considered. These topics were identified through stakeholder input, reflection on areas of advice subject to challenge and looking at what could make a difference on the ground. The five priority topics identified have formed the review programme and will help further the understanding of available evidence to support uplands management.

This topic review focused on a series of questions which were evaluated against scientific evidence. The topic review has also helped identify areas for future research; in the next phase, beyond the review programme, additional relevant information will be considered, for example social and economic factors, current working practices and geographic scale. The evidential conclusions drawn from these additional areas will help inform our future advice and practical management of the uplands on the ground.

Context

Species rich upland hay meadows (UHM) are a rare and diminishing grassland type in England. These meadows support a high diversity of plants and provide valuable habitat for breeding waders and passerines. Despite considerable conservation efforts to protect and maintain them, principally through agri-environment scheme agreements, available evidence indicates that many meadows have continued to decline in quality. This has resulted in concern amongst farmers and ecologists that certain elements of meadow management, promoted under Higher Level Stewardship, may be incompatible with both maintenance of their biodiversity interest and provision of a viable hay crop for winter forage. There is particular concern and disagreement about the following aspects of meadow management:

- the amount, timing and frequency of nutrient and lime applications;
- the intensity of spring-grazing and date at which meadows are 'shut-up' for hay; and
- control measures for rushes, which are reported to have increased in frequency within hay meadows.

Purpose

The purpose of the topic review is to report available evidence on these aspects of meadow management and their impact on floristic diversity and populations of breeding birds, which represent the main conservation interests of this grassland type.

Scope

This topic review considers aspects of the management of upland hay meadows and the maintenance of their floristic and breeding bird interest within the context of UK farm regimes. These meadows are important mostly for their variety of plants and providing breeding habitat for a number of species of waders and passerines hence the review's focus on these interests.

This topic review focuses only on the direct effects of grassland management on breeding birds, namely nest destruction by either trampling, hay cutting or other field operations, for example spreading of farmyard manure.

This topic review does not consider evidence on the impact of meadow management on invertebrates, mammals, or species of birds which use the meadows for feeding alone. It does not consider the indirect impacts of grassland management interventions on birds as these have been comprehensively reviewed elsewhere.

This topic review does not consider the effect of the state of our knowledge on Natural England's policy and advice.

The search for evidence was confined to upland hay meadows and closely related neutral grassland from the UK and from analogous meadows across sub-montane and montane areas of western and central Europe.

Wider considerations

The influences of other in-field management interventions, of stocking restrictions and management on open moorland, and wider landscape scale processes on upland hay meadows biodiversity are considered in the introduction in paragraph 1.21 and Section 6 but did not fall within the formal scope of this review so evidence on these was not formally evaluated. However, it will be important that the impact of these factors is accounted for when revised management guidance is drawn up following this review.

Questions addressed by the topic review

The over-arching question for the topic review is:

What management regimes maintain the floristic diversity and populations of breeding birds within upland hay meadows?

Three sub-questions provide further focus, namely:

a) What types, rates of application and timing/periodicity of nutrient and lime applications maintain the floristic diversity and breeding bird populations of upland hay meadows?
b) What management methods or approaches control rushes (*Juncus* spp.) in upland hay meadows and maintain the floristic diversity of the meadows?
c) What spring-grazing levels, timing of shut-up/closure for hay and cutting dates maintain the floristic diversity and breeding bird populations of upland hay meadows?

Due to the multiple factors being considered under sub-questions (a) and (c) evidence relating to discrete elements within these sub-questions was assessed separately.

Process

An initial literature search and a call for evidence from stakeholders produced a list of 1667 relevant papers. Filtering reduced this list to 130 papers that were likely to be relevant and these were assessed against inclusion-exclusion criteria. As a result of this process 49 papers were accepted for quality assessment and data extraction (Appendix 1) with 53 additional references being considered to be of relevance to the review although not providing quantifiable evidence.

Summary of conclusions

We assessed the nature and strength of the evidence for each sub-question and from this developed evidence statements and drew conclusions. See Appendix 3 for the full list of evidence statements.

What management regimes maintain the floristic diversity and populations of breeding birds within upland hay meadows?

Overall the evidence evaluated provides support for a recognisable traditional hay meadow management regime, but with:

- more meadow-specific tailoring of nutrient input regimes according to soil-nutrient status, past history and management objectives;
- less uniformity of hay cutting dates at the landscape scale than has been the case in the last 20 years, to mimic the longer window for hay cutting that existed in the past when botanical diversity was higher;
- ideally, more flexibility to respond to spring weather conditions in any one year, for example by early shut-up of meadows in warm springs, though further work is required to inform this.

a) What types, rates of application and timing/periodicity of nutrient and lime applications maintain the floristic diversity and breeding bird populations of upland hay meadows?

There is strong evidence showing that nutrient applications of c. 18 kg N ha^{-1} yr^{-1} or greater led to significant reductions in floristic diversity in upland hay meadows and meadows on related neutral grassland types. The limited available evidence specific to Farm Yard Manure (FYM) inputs indicates that rates of 12 tonnes ha^{-1} $year^{-1}$ (equivalent to 9 kg N ha^{-1}, 10 kg P ha^{-1} and 69 kg K ha^{-1} annually) may maintain current diversity on *Anthroxanthum oderatum* – *Geranium sylvaticum* (hereafter referred to as MG3 following the National Vegetation Classification) meadows which have a history of inputs at this rate, but that botanical enhancements (increases in the cover of positive indicator species) occurred at the lower rate of 6 tonnes FYM ha^{-1} $year^{-1}$.

However, there is strong evidence to suggest that botanical responses to nutrient applications are driven by which ever macro-nutrient is growth-limiting in the grassland and potentially by historic nutrient inputs. As a consequence the additional application of nutrient for any given meadow should be informed by its soil nutrient status, grass utilisation, past fertility management and conservation objectives.

The evidence suggests that the amount of nutrients applied (rate) is the single most important factor influencing botanical response, with the evidence for any additional differential impacts of form (FYM versus inorganic fertilizers) being very limited and equivocal. Similarly the little evidence which does exist for MG3 and related grassland types suggests there is no significant effect of either different timings and or frequencies of nutrient inputs on floristic diversity. Occasional liming to maintain a pH of around 6 appears consistent with maintaining vegetation quality on MG3 hay meadow with a past history of lime application.

In contrast evidence for breeding birds suggests that there are benefits associated with FYM application through increasing prey abundance and availability, and with avoidance of any agricultural operations (including nutrient inputs) in spring when lapwing are breeding. Whilst no studies examined the impact of application frequency on breeding waders, as a general principle less frequent applications might be predicted to be beneficial in reducing overall disturbance to nests and fledglings.

b) What management methods or approaches control rushes (*Juncus* spp.) in upland hay meadows and maintain the floristic diversity of the meadows?

There was little available evidence on rush control on species-rich grasslands and no evidence relating to their control within upland hay meadows.

Available evidence suggests that mowing rushes flush with the ground at least twice during the summer can reduce their vigour, and where only one cut is possible a late summer cut is most effective. Herbicide by weed wiping application can also be effective, although not without damage to other vegetation. Care should be taken to avoid poaching and creation of bare ground, which abundant rush seed will quickly exploit.

c) What spring-grazing levels, timing of shut-up/closure for hay and cutting dates maintain the floristic diversity and breeding bird populations of upland hay meadows?

Quantitative evidence on the impact of different spring grazing intensities and durations is limited to one study, which suggests that grazing to an average sward height of 5-6 cm rather than 3-4 cm and that shutting up meadows before the 15th May will maintain floristic diversity. This study also points to an important interaction between spring temperature (T-sum) and sward development in any given year and date at which meadows are shut-up, with significant effects on botanical composition particularly likely in warm wet years. The scope to use T-sum to inform the date at which meadows are best “shut-up” should be further explored.

Whilst there is good evidence proving a relationship between trampling by livestock and losses of nests in ground-nesting birds, which increase with grazing intensity and duration, most of the studies evaluated are correlative. None specify a sustainable stocking rate for breeding birds, although one study presents a “standardised trampling value” per type of livestock and per bird species from their data (survival rate per animal per hectare per day) which can be used to determine likely losses over a given grazing period.

There is a clear dichotomy in the preferred grazing intensities of the breeding birds of upland hay meadows between lapwing which prefer a moderate level of grazing to retain a short sward into late spring and the lighter grazed, and more heterogeneous vegetation preferred by other breeding birds (snipe, redshank, curlew, whinchat and skylark).

Studies comparing hay cutting dates indicate that consistently cutting on the 21st July maintains MG3 grassland in the short term (over 4 years). However, the window of time in which hay cutting takes place is significantly shorter than in the period before mechanisation, with most meadows cut by early August instead of cutting extending into September. Periodic late cutting may be helpful in mimicking this past management and allowing return of later seeding species. However, no direct or quantifiable evidence exists to support this assertion.

Evidence from a large number of studies shows that cutting of meadows prior to the peak fledging date of the bird studies reduced nest success. For yellow wagtails, which nest later than the breeding waders which use meadows, evidence suggests that delaying cutting until after 8th July enhances breeding success in the short term. Accumulated spring temperature (T-sum) has been shown to influence nesting and fledging in any one year and subject to further research could be used to inform the timing of hay cut under variable spring temperatures to enable better protection for breeding birds.

Research recommendations

Assessment of the available evidence indicates that the following areas would benefit from further research:

- Examination of the impacts of N application ≤20 kg N ha^{-1} yr^{-1} on floristic diversity (with directly equivalent FYM treatments) across a range of MG3 meadows with different nutrient management histories.
- Exploration of the role of P in influencing floristic diversity on MG3 meadows.
- Investigation of the impact of different seasonality and periodicity of nutrient input on MG3 meadows and its impact on both botanical composition and breeding birds.
- Identification of the reasons for increases in rush species within upland hay meadows.
- Trialling of sustainable, non-damaging rush control measures (including the use of lime) on MG3 meadows.
- The feasibility of determining and applying a threshold T-sum, to inform the time at which meadows are shut-up for any given year. This should be investigated across a range of MG3 sites and impacts on botanical composition and breeding birds assessed.
- Determination of the importance of regeneration by seed in maintenance of populations of long-lived perennials within MG3 meadows.

- Investigation of the historical management of hay meadows and their changing climatic and environmental context.

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1 Introduction

Background

1.1 In March 2011, Defra published the Government's review of uplands policy, which sets out a range of actions the Government, led by Defra, will take in partnership with others in the public, private and voluntary sectors to help secure a sustainable future for the English uplands. The actions in the Uplands Policy Review sit under four main themes:

- Supporting England's hill farmers.
- Delivering public goods from upland environments (including biodiversity).
- Supporting sustainable upland communities.
- Driving and monitoring change.

1.2 Natural England has a specific role in helping deliver the Uplands Policy Review; in particular through our research and evidence-based advice, our delivery of agri-environment schemes, and our partnership work with the hill farming and moorland management sector and rural communities to deliver a wide range of public goods and environmental benefits. Our role in the uplands is also shaped by our broader remit in the delivery of the government's Natural Environment White Paper and Biodiversity 2020 commitments that focus on the enhancement and protection of ecosystem services and the natural environment, including improving the condition of England's SSSIs. Biodiversity 2020 objectives for SSSIs are to achieve 50% in favourable condition and 95% in favourable recovering condition by 2020.

1.3 For these reasons, it is important that our advice and decisions are based on sound evidence and that our evidence processes are transparent and robust.

The need for the review programme

1.4 The English Uplands are extensive and include a diverse range of biotopes, species, and land management practices. It is widely recognised that they provide provisioning, regulatory, and cultural ecosystem services and that deriving all the benefits that society seeks from the uplands presents a number of environmental conservation and land management challenges. There is also considerable disagreement about the effects of various land management operations on upland biodiversity. This review programme seeks to improve the evidence base to support better advice and decisions on future management of the uplands by carefully assessing the best available information on the effects of land management activities on upland biodiversity and ecosystems.

The nature of the evidence

1.5 Over several decades, a body of evidence has accumulated exploring the effects of different types of land management interventions on a range of upland ecosystem services, habitats and species. There is a wide variety of study types, for example randomised control trials, before-and-after, correlation, and case-control studies, which may have taken advantage of opportunities for natural experiments. Although there are many methodological differences within this literature, notably the lack of consistency between measurement methods and different outcome measures, overall the results provide a basis from which conclusions about intervention effects and research needs can be developed.

1.6 It is worth noting a number of significant challenges associated with undertaking a review of the evidence on upland management interventions. Firstly, the search strategy needs to be broad enough to capture studies from non-traditional sources including those not indexed in environmental databases, and work that may be in the 'grey' literature (such as reports or case studies). Furthermore, studies may report novel measures that may be difficult to relate to effects on biodiversity or ecosystem services. Finally the wide range of study types can make it difficult to compare results across studies.

Overall scope of the Upland Evidence Review Programme

1.7 The uplands encompass a variety of habitats and species, delivering a wide range of ecosystem services, and are subject to a variety of land management interventions. This topic report presents the findings from the review of hay-meadow management. This topic review forms part of a wider review programme of upland biodiversity and ecosystem evidence which focuses on five topics where there is significant challenge:

- The impact of tracks on the integrity and hydrological function of blanket peat.
- Restoration of degraded blanket bog.
- The effects of managed burning on upland peatland biodiversity, carbon and water.
- Upland Hay Meadows: what management regimes maintain the diversity of meadow flora and populations of breeding birds?
- Impact of moorland grazing and stocking rates.

1.8 Consideration of other relevant information, such as social and economic factors, is an important part of the process of developing our advice, but is not part of the Upland Evidence Review Programme. Whilst consideration of the likely effect of future climate scenarios is specifically excluded from the topic reviews, evidence on the interaction between meadow management practices and weather variables and their impact on meadow biodiversity has been considered.

Review topic: Hay meadow management

The issue

1.9 Upland Hay Meadows (UHM) are a rare and diminishing resource in Great Britain. Recent estimates suggest that total extent of these meadows is 870 ha in England with a further 26 ha in Scotland (Bullock *et al.* 2011). In England meadows are largely confined to the North Pennines, Lake District and County Durham with some outliers further north. Meadows are restricted to the floors and lower slopes of valley heads between 200 and 400 m in elevation, where extensive hay meadow treatment has been applied in a sub-montane climate (Jefferson, 2005) with a short growing season, sometimes significantly less than five months, and often high annual rainfall (Betton, 2012).

1.10 Agricultural intensification over the last 60 years has resulted in the loss of many semi-natural or unimproved upland meadows through conversion to species-poor grassland (Jefferson, 2005; Hewins *et al.* 2005) as well as continued deterioration of floristic diversity within remaining MG3 hay meadows (Critchley *et al.* 2004; Pacha & Petit 2008; O'Reilly 2010). Application of fertilisers and herbicides, drainage, ploughing and reseeding, and a shift from hay to silage production with more frequent and earlier cutting have all been identified as causes of reduced meadow biodiversity and loss.

1.11 The extent of floristic change and breeding bird impact is dependent on the intensity, duration and combination of management changes. Intensive management for silage production or "ensiling" typically leads to such rapid and substantial reductions in floristic diversity that the meadow is lost via conversion to species-poor grassland, dominated by a few nutrient demanding species and providing unsuitable nesting habitat for ground nesting birds. Ensiling removes the need to leave grass to wilt and dry by anaerobically fermenting the damp cut grass in big bales or in a silage clamp. It is generally accompanied by an increased use of inorganic fertilisers to encourage growth of multiple silage crops for cutting, with re-seeding with perennial ryegrass *Lolium perenne* and with more intensive grazing. In contrast at the other end of the improvement spectrum floristic diversity may be far less affected by repeated early cutting on its own.

1.12 Due to their scarcity the nature conservation value of these meadows is recognised both nationally and internationally. They are recognised as a 'priority habitat' in England (ie they are listed as a habitat of principal importance under section 41 of the Natural Environment and Rural Communities Act 2006) and as an Annex 1 habitat under the EC Habitats Directive 6520 (Northern Hay Meadows - British types with *Geranium sylvaticum*).

1.13 Despite considerable conservation initiatives, notably the widespread promotion and take up of agri-environmental scheme agreements and designation of a significant proportion of meadow as SSSIs, there has been a continued decline in floristic richness and deterioration in botanical quality in the highest quality meadows over the last twenty years (Critchley *et al.* 2004; Hewins *et al.* 2005; Pacha & Petit 2008; O'Reilly 2010). Associated declines are also reported in a number of characteristic and rare plants of these meadows, including five species of lady's-mantle *Alchemilla* spp. (Bradshaw, 2009) and in the populations of a number of breeding bird species (Wilson, Vickery & Browne, 2001; Fuller *et al.* 2002; Court 2001) for which hay meadows provide important nesting and/or feeding habitat, in association with other components of the upland landscape.

1.14 There is concern amongst some farmers and ecologists that the meadow management, promoted through relevant Higher Level Stewardship options, may be contributing to the observed deterioration in vegetation quality (both declines in floristic diversity and increase in frequency of occurrence of rushes), and decline in breeding bird populations. Specific concerns have been raised about discrete aspects of meadow management.

1.15 In particular there is a divergence of opinion between farmers and ecologists around what constitutes a sustainable nutrient regime for species-rich meadows (both farmyard manure and inorganic fertiliser) with some landowners asserting that higher nutrient input and use of inorganic fertiliser instead or alongside farmyard manure would halt declines in floristic diversity and encourage recovery, whilst some ecologists assert that reducing nutrient inputs further would better deliver this objective. There is also discussion around what levels of spring-grazing and what "shut-up" date best maintains floristic diversity. Finally there is a great deal of concern in some upland areas that frequency of rushes has increased markedly within hay meadows, to the detriment of rarer hay meadow species and forage quality, and that appropriate control measures are urgently required. The review evaluates available evidence on these issues.

What is included in this topic review?

1.16 This topic review covers aspects of the management of upland hay meadows and the maintenance of their floristic and breeding bird interest within the context of UK farm regimes. These meadows are important mostly for their variety of plants and providing breeding habitat for a number of species of waders and passerines, hence the reviews focus on these interests.

1.17 This topic review focuses only on the direct effects of grassland management on breeding birds, namely nest destruction by trampling, hay cutting or other field operations, for example spreading of farmyard manure.

What is excluded from this topic review?

Other fauna

1.18 The intimate mix of herbs and grasses in species-rich hay meadows provide valuable habitat for invertebrates and insect life within these meadows is abundant (Gamble & St Pierre, 2010). Few nationally scarce invertebrate species have been recorded from these meadows

(Colenutt *et al.* 2003), although for many invertebrate groups there is very little information for upland hay meadows (Buglife, 2013). As a consequence this review does not consider evidence on impacts of management interventions on invertebrates or on mammals, for which little monitoring work has been done in upland habitats (Defra 2010).

1.19 A wide range of birds utilise the meadows for feeding but nest elsewhere. Evidence on the impact of hay meadow management on these species is not considered within this review.

Indirect impacts on breeding birds

1.20 The many indirect mechanisms by which changes in lowland (enclosed) grassland management affect birds and their food resources, both seed and invertebrate have not been considered here. These mechanisms are comprehensively reviewed by Vickery *et al*. (2001) and summarised by McCracken & Tallowin (2004) and are simply described in the schematic below (see Figure 1).

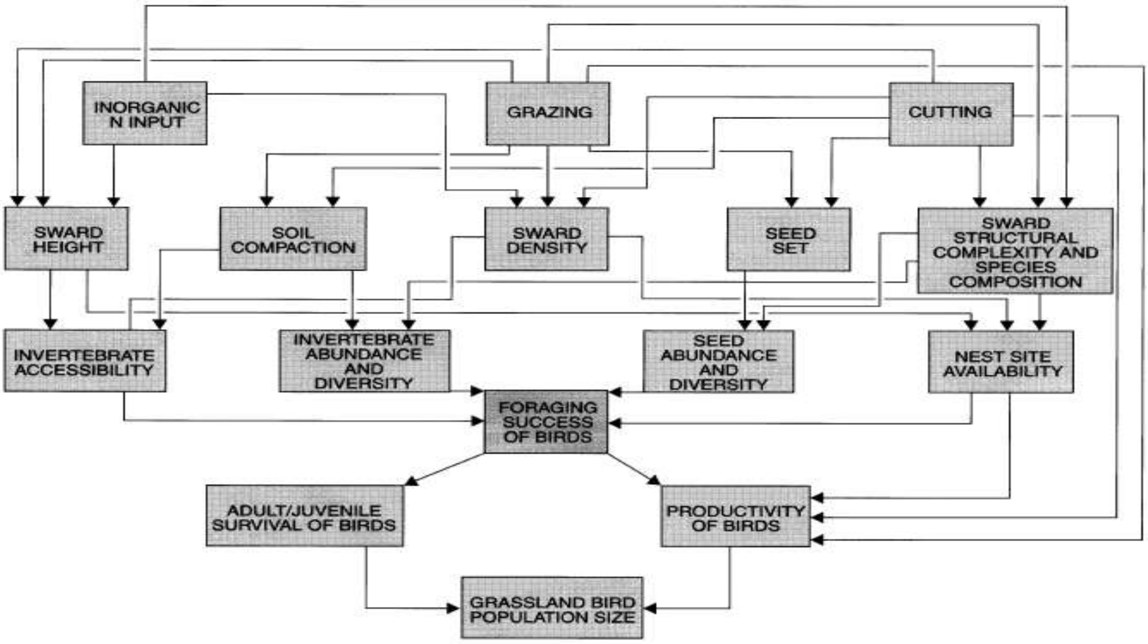


Figure 1 Schematic diagram of the indirect effects of grassland management on birds (from Vickery *et al.* 2001)

Other in-field management interventions

1.21 The focus of this review is restricted to evaluating available evidence of impacts on upland hay meadows of a small number of in-field management interventions. A number of additional in-field management interventions have been identified as having a significant influence on hay meadow biodiversity. These are summarised below and should be considered in the determination of any resultant management guidance.

1.22 **Aftermath grazing** - The importance of aftermath grazing, ideally by cattle, is identified in a number of evidence sources as being important for maintaining maximum diversity of MG3 grassland and related grassland types by provision of regeneration niches in the sward (Bradshaw, 2009; Smith & Ruston, 1994; Kirkham, Mountford & Wilkins 1996). Aftermath grazing is also important for getting the meadows in a condition suitable for breeding waders in the following spring. Cattle are preferable to sheep, as cattle provide a more heterogeneous sward.

1.23 **Changes in livestock breed** - Evidence from a recent review of stocking changes across the UK (Cumulus, 2012) reports that a change from traditional breeds to continental or improved breeds of cattle and sheep has changed the grazing pressure on different parts of farms. The higher nutritional requirements of continental/improved breeds has led to an intensification of use and management of in-bye and marginal land, leading to a loss of semi-natural grassland habitats due to agricultural improvement. This change has also contributed to under-grazing on open moorland where forage is poorer. Changes from hard-mouthed native type cattle to softer-mouthed, heavier continental types have also been suggested as a reason for the increase in Upper Teesdale of jointed and soft rushes, *Juncus* sp. (Bradshaw, 2010).

1.24 **Soil compaction** - Bradshaw (2009) suggests that decline in botanical quality of the meadows is in part related to the stocking of heavier continental-cross suckler cows which have replaced dairy cows and the over-wintering of sheep in the meadows. The resulting soil compaction may have deleterious impacts on botanical quality (a Defra funded research project BD 5001 is currently investigating this relationship and means of alleviating compaction in grasslands). Compaction may also reduce food availability/suitability for probing wader species like snipe.

1.25 **Drainage** - Many studies have stressed the importance of moist grassland soils for breeding waders (Beintema *et al.* 1990; Breewer *et al.* 2000; O'Brien 2002; Wilson *et al.* 2004). Lapwings in the Pennine Dales showed a preference for damp meadows with *Caltha*, whilst occurrence of five breeding wader species was strongly aligned to fields with wet areas irrespective of their species richness (Small, 2002). Conversely, deterioration in the condition of existing field drains within meadows is thought to have resulted in increased water-logging, with associated deterioration in vegetation quality, in particular an increase in rushes (Betton, 2012; Bradshaw, pers comm.).

The over-arching topic review question

1.26 **What management regime/s maintain the floristic diversity and breeding bird populations in upland hay meadows?**

The following sub-questions will be the focus of the topic review:

a) What types, rates of application and timing/periodicity of nutrient and lime applications maintain the floristic diversity and breeding bird populations of upland hay meadows?
b) What management methods or approaches control rushes (*Juncus* spp.) in upland hay meadows, maintain the floristic diversity of the meadows and ensure suitability of the hay crop as a winter feedstuff?
c) What spring-grazing levels, timing of shut-up/closure for hay and cutting dates maintain the floristic diversity and breeding bird populations of upland hay meadows?

1.27 Due to the multiple variables considered in sub-questions (a) and (c) these questions have been further broken down into the following subsidiary questions to enable easier consideration of evidence.

1.28 For sub-question (a) What types, rates of application and timing/periodicity of nutrient and lime applications maintain the floristic diversity and breeding bird populations of upland hay meadows?:

1) What quantity/rate of nutrients maintains the sward composition of upland hay meadows?
2) Does the type/form in which nutrients are supplied result in different impacts on either botanical composition or breeding bird populations of upland hay meadows?
3) Does the timing of application (for example, spring/autumn/winter) effect either botanical composition or breeding bird populations?
4) Does the frequency of application (for example, annual/biennial/triennial etc) effect botanical composition or breeding bird populations?
5) Is application of lime consistent with maintaining upland hay meadow sward composition and if so what regime?

1.29 For sub question (c) What spring-grazing levels, timing of shut-up/closure for hay and cutting dates maintain the floristic diversity and breeding bird populations of upland hay meadows?:

1) Which spring grazing levels and shut-up dates maintain floristic diversity and breeding bird populations of upland hay meadows?
2) What cutting date maintains floristic diversity and breeding bird populations of upland hay meadows?

1.30 Chapter 2 briefly describes the methods and process for this topic review. Chapters 3 to 5 consider the three sub-questions in turn. These chapters provide a short summary of the evidence, underpinned by a more detailed analysis of the evidence used to derive evidence statements, which encapsulate the nature and strength of the evidence. Conclusions are reached about what constitutes sustainable meadow management based upon the evidence reviewed. Recommendations for further research are suggested where gaps in the evidence are identified.

Definitions and descriptions

1.31 The following is the definition of terms considered within the hay meadow management review.

1.32 Upland hay meadows are species-rich plant communities principally allied to the National Vegetation Classification (NVC) types MG3 *Anthoxanthum odoratum-Geranium sylvaticum* (sweet vernal-grass and wood crane's-bill) grassland and MG8 *Cynosurus cristatus-Caltha palustris* (crested dog's-tail – marsh marigold) grassland, which typically overlie freely draining mineral soils (Rodwell, 1992).

1.33 These meadows are characterised by a dense growth of grasses and broadleaved herbs up to 60 to 80 cms high. No single grass species is consistently dominant and a striking feature of the vegetation is the abundance and variety of broadleaved herbs. The grasses, sweet vernal-grass *Anthoxanthum odoratum*, cock's-foot *Dactylis glomerata*, rough meadow-grass *Poa trivialis*, red fescue *Festuca rubra*, Yorkshire fog *Holcus lanatus* and common bent *Agrostis capillaris* are all constant components of the community. Sub-montane species such as wood crane's-bill *Geranium sylvaticum*, melancholy thistle *Cirsium helenioides* and globeflower *Trollius europeaus* can be locally prominent, alongside a diverse range of other broadleaved herbs including lady's-mantles, commonly *Alchemilla glabra* and *A.xanthochlora*, great burnet *Sanguisorba officinalis*, pignut *Conopodium majus*, common sorrel *Rumex acetosa*, red and white clovers *Trifolium pratense* and *T.repens*, bulbous buttercup *Ranunculus bulbosus*, meadow vetchling *Lathyrus pratensis*, rough hawkbit *Leontodon hispidis* and yellow rattle *Rhinanthus minor*).

1.34 A **generalised traditional annual management cycle** for upland hay meadows as described in Gamble & St Pierre (2010) is as follows:

In early spring, sheep which may have been grazing on higher ground or moorland for much of the year are brought down to the meadows for lambing. Lambs are born in April and stay in the fields with the ewes, feeding on hay and new grass. Cattle begin calving and are let onto the fields to graze once the fields have dried out sufficiently. The meadows are "shut-up" (ie all stock removed in May) to allow the hay crop to grow and the sheep and lambs are led back to the fell. Depending on the weather and altitude, haymaking starts in July or early August.

When the hay has been made and stored, livestock are let back into the meadows to graze uncut edges/slopes and then removed to allow the grass to grow again. They are later let back on to graze the aftermath, through into Autumn and a tup ram runs with the ewes to conceive the following year's lambs. In winter hay is fed to the livestock with sheep grazing sometimes continuing on the meadows whilst cattle are housed in doors. During the winter months light dressings of well rotted farmyard manure are spread on the meadows. Periodic application of lime forms part of the traditional management. Rates, frequency and timing of nutrient application vary considerably.

1.35 **Floristic or botanical diversity** is used within this topic review to describe both species evenness and richness (number of species/unit area).

1.36 **Breeding birds** describe those species which nest and raise fledglings in the meadows. These are curlew, lapwing, redshank, snipe, skylark and yellow wagtail.

1.37 A full glossary of terms is provided in Section 6.

2 Methods

2.1 This chapter briefly sets out how this topic review was undertaken following the approach described *Natural England Evidence Reviews: guidance on the development process and methods* (Stone, 2013).

General principles

2.2 The review process systematically identifies all available studies providing evidence for the specific questions posed. Those that fail to meet the inclusion criteria are then sifted out.

2.3 The PICO framework provides a structured approach to formulating review questions and framing the over-arching search strategy (Stone, 2013) so inclusion criteria can be objectively set.

2.4 **PICO** comprises the following four elements:

- **Population** - the population/species/habitat of interest, in this instance, species-rich upland hay meadow communities conforming to NVC types MG3 and MG8.
- **Intervention** - the activity or approach to be used, in this instance, nutrient and lime additions, rush control measures, spring-grazing and hay cutting.
- **Comparison** - the main alternative to the intervention, in this instance, no nutrient and/or lime applications, no rush control, no grazing; and/or a Comparator, which in this instance is improved or semi-improved meadow grasslands often dominated by rye-grass (NVC types MG6 *Lolium perenne-Cynosurus cristatus* grassland and MG7 *Lolium perenne* leys and related grasslands) which are less species-rich and diverse than upland hay meadows as defined here.
- **Outcome** - the outcomes that are being considered, in this instance, whether floristic diversity and breeding bird populations of upland hay meadows are maintained.

2.5 The quality of evidence provided by each included study is then objectively evaluated against a quality assessment checklist, with a narrative summary captured in an evidence table (Stone, 2013).

2.6 This topic review provides a narrative overview of the evidence from included studies, with the evidence statements providing a synthesis for each sub-question using:

- The best available evidence of the effect of an intervention.
- The strength (quality and quantity) of supporting evidence and its applicability to the populations and settings in question.
- The consistency and direction of the evidence base.

2.7 There was no meta-analysis of outcome data.

Evidence search

2.8 Literature searches were conducted using the terms listed below. The evidence search was restricted to the UK and those parts of Europe known to support the Annex 1 Mountain hay meadows (see Assessing applicability page 13). References were downloaded, or manually added if necessary, into a reference manager database (EndNote Web) and duplicates removed. In addition, there was an open call to interested stakeholders to submit evidence material for consideration as part of the review.

Search terms

2.9 The following search terms were used (an asterisk denotes a wild card search term allowing for several permutations of the term).

2.10 For population (ie habitat or species):

Upland hay meadows, Upland meadow grasslands, MG3 *Anthoxanthum odoratum – Geranium sylvaticum* grassland, Mountain hay meadows, Northern hay meadows, *Mesotrophic* meadow, *Mesotrophic* grassland, Meadow grassland, Hay meadows, Upland valleys, Grassland. Breeding waders, Breeding birds, Ground nesting birds, Curlew, Lapwing, Redshank, Snipe, Grey partridge, Skylark, Twite, Yellow wagtail, Invertebrates.

2.11 For intervention:

Fertiliser application, Lime application, Inorganic fertiliser, Farmyard manure, Slurry, Basic slag, Organic fertiliser, Manure, Dung, Dunging, Nutrients, Atmospheric nitrogen, Nitrogen deposition, Nitrogen, Phosphorus, Hay making, Rush (*Juncus* spp) control, Rush management, Rush reduction, Drainage, Spring grazing, Cutting dates, Shut-up date, Grazing management, Clos*date, Clos*, Date*, Cutting, Mowing dates, Hay making.

2.12 Comparison/control:

No fertiliser application, No lime application, No rush control, No grazing.

2.13 Outcomes (or effect):

Plant species composition, Plant species richness, Plant species diversity, Species rich, Botanic composition, Semi-natural grassland, NVC type, Agricultural improvement, Vegetation change, Biodiversity, Habitat quality, Population change, Density, Abundance, Hay quality, Hay yield, Hay.

Search strategy

2.14 The following databases were searched:

Web of Knowledge (WoK) including Web of Science (WoS), Zoological Record (ZR), Centre for Agricultural Bioscience International (CABI) abstracts, British Library Electronic Theses Online (BL Ethos), Google scholar, Google.

2.15 Publication searches were undertaken on:

Natural England Olib, Scottish Natural Heritage website, Refdoc, Worldcat, COPAC, Agricola, British Library inside web and Countryside Council for Wales Olib.

2.16 The open call for evidence attracted seven submissions from stakeholders.

Selection of studies for inclusion

2.17 The search strategy resulted in1667 titles. These were screened first by title and abstract. 130 references were determined to be relevant and the full papers retrieved and checked against the inclusion-exclusion criteria. 49 papers were accepted for quality assessment and data extraction.

Table 1 Study numbers

Review stage	Number of studies
Studies captured using search terms in all sources (including duplicates)	1667
Studies remaining after title filter	193
Studies remaining after abstract filter	130
Studies remaining after full text filter	95
Studies used in review	49

Study type and quality appraisal

2.18 Each study was categorised by study type (type 1-4) and graded for quality using a code '++', '+' or '-', based on the extent to which the potential sources of bias had been minimised. The studies were categorised into the following study types:

Table 2 Study types

Rating	Definition
1	Meta-analyses, systematic reviews of Randomised Control Trials (RCTs), or RCTs (including cluster RCTs).
2	Systematic reviews of, or individual, non-randomised controlled trials, case-control trials, cohort studies, controlled before-and-after (CBA) studies, interrupted time series (ITS) studies, correlation studies.
3	Non-analytical studies, for example, case reports, case series studies.
4	Expert opinion, formal consensus.

Table 3 Study quality categories

Rating	Definition
++	All or most of the methodological criteria have been fulfilled. Where they have not been fulfilled the conclusions are thought very unlikely to alter (low risk of bias).
+	Some of the criteria have been fulfilled. Those criteria that have not been fulfilled or not adequately described are thought unlikely to alter the conclusions (intermediate risk of bias).
-	Few or no criteria have been fulfilled. The conclusions of the study are thought likely or very likely to alter (high risk of bias).

2.19 A considerable number of studies evaluated were multi-factorial experiments, examining the impact of multiple management interventions on sward composition. The design of these studies sometimes meant that different elements of a study differed in their statistical power. Where this is the case, different quality scores were assigned to the relevant sub-questions.

2.20 Table 4 presents a breakdown of studies by sub-question and as categorised by their evidence type and quality. Details of each study can be found in Appendix 1. The main reasons for studies being assessed as (-) quality were (i) failure to describe methods adequately, (ii) a low quality measure of ecosystem and biodiversity outcomes, and (iii) failure to take potential confounding factors into account.

2.21 The strength of evidence is described in terms of strong, moderate, or weak. This is partly a subjective judgment, taking account of not only the number of supporting studies and their quality scores, based on the criteria in Table 3, but also a consideration of the aims and focus of a study. A study may for example have a very high quality score based on the design and analysis, and the findings in relation to hay meadows may be important, but the aims of the study may be wider and cover a range of management treatments. The strength of evidence is defined as follows:

- **Strong** - evidence from a number of studies, or one or two very high quality studies.
- **Moderate** - evidence from two or three studies, of which at least one must be a minimum of '2+'.
- **Weak** - one or a small number of low quality studies, usually includes ' – ' scores.

Table 4 Studies by sub-question and as categorised by their evidence type and quality

Study type & quality	Review sub-question		
	(a) Nutrient additions	**(b) Rush control**	**(c) Spring grazing and hay cutting**
1++	Edwards & Younger (2006); Kirkham *et al*. (2012)[a]; Kirkham, Mountford & Wilkins (1996); Mountford, Lakhani & Kirkham (1993); Smith *et al.* (1996)[c]; Tallowin *et al.* (1994); Tallowin (1996)	Merchant (1995)	Smith & Rushton (1994); Smith *et al*. (2012)
1+	Honsova *et al.* (2007); Kirkham *et al.* (2008); Kirkham *et al*. (2012)[b]; Smith, Pullan & Shiel (1996)	Mercer, Reavey & Morgan (2008)	Smith *et al.* (1996)[d]; Smith, Pullan & Shiel (1996)
1-		Wolton (2000)	
2++	Baines (1990); Small (2002)	Cherrill (1995)	ADAS (1996); Kruk, Noordervliet & ter Keurs (1996); Pacha & Petit (2008); Shrubb (1990); Small (2002);
2+	Aerts, de Caluwe & Beltman (2003); Askew (1993) Crawley *et al.* (2005); Lawes, Gilbert & Masters (1882)	Smolders *et al.* (2008)	Breeuwer (2009); Broyer (2009); Devereux *et al.* (2004); Green *et al.* (1997); Greubler *et al.* (2012); Smith & Jones (1991); Critchley, Fowbert & Wright (2007); O'Brien (2002)
2-	Critchley *et al.* (2002); Critchley, Fowbert & Wright (2007); Hochberg & Zopf (2011); Jeangros, Sahli & Jacot (2003); Starr-Keddle (2011); Starr-Keddle (2012)		
3++	Simpson & Jefferson (1996); Tallowin (1998); Vickery *et al.* (2001)		
3+			Court *et al*. (2001); Fuller (1996); Wilson (1991)
3-			Humbert *et al.* (2012)
4-	ADAS (1993)	RSPB (2007)	

[a] assessed as 1++ for lime component of study;
[b] assessed as 1+ for FYM and inorganic equivalent components of study;
[c] assessed as 1++ for fertiliser component of study; and
[d] assessed as 1+ for the grazing component of the study.

Study categorisation

Description of studies

2.22 The 49 evaluated studies are described fully in Appendix 2. They include:

- 15 randomised controlled or non-randomised controlled trials;
- 25 correlation studies;
- 7 non analytical studies/reviews; and
- 2 references providing expert opinion/formal consensus.

2.23 These studies tested a range of different environmental interventions related to the effects of aspects of hay meadow management on botanical and faunal diversity, specifically maintaining populations of breeding birds. They fell into five different categories:

- nutrient and/or lime addition - type, rate and periodicity;
- rush control;
- grazing regime/intensity;
- meadow shut-up and hay cutting dates; and
- direct and indirect impacts of meadow management on birds.

NB Studies sometimes fell into more than one category, as they covered a wide range of management interventions.

Country of studies

2.24 Thirty five studies were conducted in the UK and Ireland, whilst the remaining 12 were from Continental Europe. Appendix 1 shows the country in which the research took place for each study evaluated.

Length of outcome measures

2.25 Eight studies measured short-term outcomes (up to 12 months follow up) only. Fourteen studies measured longer term outcomes (between one and eight year follow ups) whilst six studies measured outcomes over ten years or more. Appendix 1 shows the length of outcomes measured for each evaluated study. Fifteen studies either investigated correlative relationships or were reviews with no length of outcome measure determined. Such studies are ascribed to “not applicable (NA)” in Appendix 1.

2.26 Judgements were made on whether studies were of sufficient duration to enable reliable measurement of a biological response. Where this was not the case, for example, when fertiliser was applied in one year and the vegetation response was measured in the next year alone, the study is marked as a (-) in the quality assessment process as potentially significant lag effects would not have been detected.

Assessing applicability

2.27 Each study was assessed on its external validity: that is, whether or not it was directly applicable to the target population and setting in the scope. This assessment took into account where each study was undertaken and any reasons why the evidence provided may reduce or limit its relevance to this review. These factors are briefly summarised in Section 3, for the suite of studies contributing evidence on each of the three sub-questions.

2.28 Only studies that provided evidence on the specific management interventions under review were included.

2.29 A large number of references, principally literature reviews, but also evidence submitted in the stakeholder consultation, provided useful contextual information whilst not providing quantitative evidence. These sources have been used in the short prefaces to each of the three sub-questions and in the discussion sections.

2.30 This left the following outstanding issues to be considered:

Treatment of evidence from closely related neutral grassland communities (GB)

2.31 In addition to MG3 and associated upland MG8 communities, studies investigating the relevant management interventions on three closely related species-rich mesotrophic (neutral) grasslands in lowland situations, have also been included within this review, where these are managed as hay meadows, these are:

- MG4 *Alopecurus pratensis–Sanguisorba officinalis* (meadow foxtail–great burnet).
- MG5 *Cynosurus cristatus–Centaurea nigra* (crested dog's-tail–knapweed).
- MG8 *Cynosurus cristatus–Caltha palustris* (crested dog's-tail–marsh marigold).

Treatment of evidence from related European grasslands

2.32 MG3 *Anthoxanthum odoratum–Geranium sylvaticum* (sweet vernal-grass and wood crane's-bill) grassland is the British representative of Continental Europe's *Polygono-Trisetion* alliance. Meadows within this alliance are widely distributed throughout the sub-montane and montane zones of western and central Europe and are managed under similar low input systems on well drained, relatively fertile mineral soils (Rodwell *et al.* 2007). Since these meadows are analogous to MG3, relevant evidence from studies on the following grassland types are included:

- *Polygono-Trisetion* alliance
- *Lathyro-Trisetenion* sub alliance, in particular the following associations:
  - *Geranium sylvatici-Trisetetum*
  - *Meo-Festucetum.*
- *Campanulo-Trisetenion* sub alliance
- *Alchemillo-Trisetenion* sub alliance.

2.33 In addition, the lowland counterparts to these montane meadows, equivalent to the British NVC types MG4, MG5 and MG8, within the orders *Arrhenatheretalia* and *Molinietalia* and within the following alliances are included:

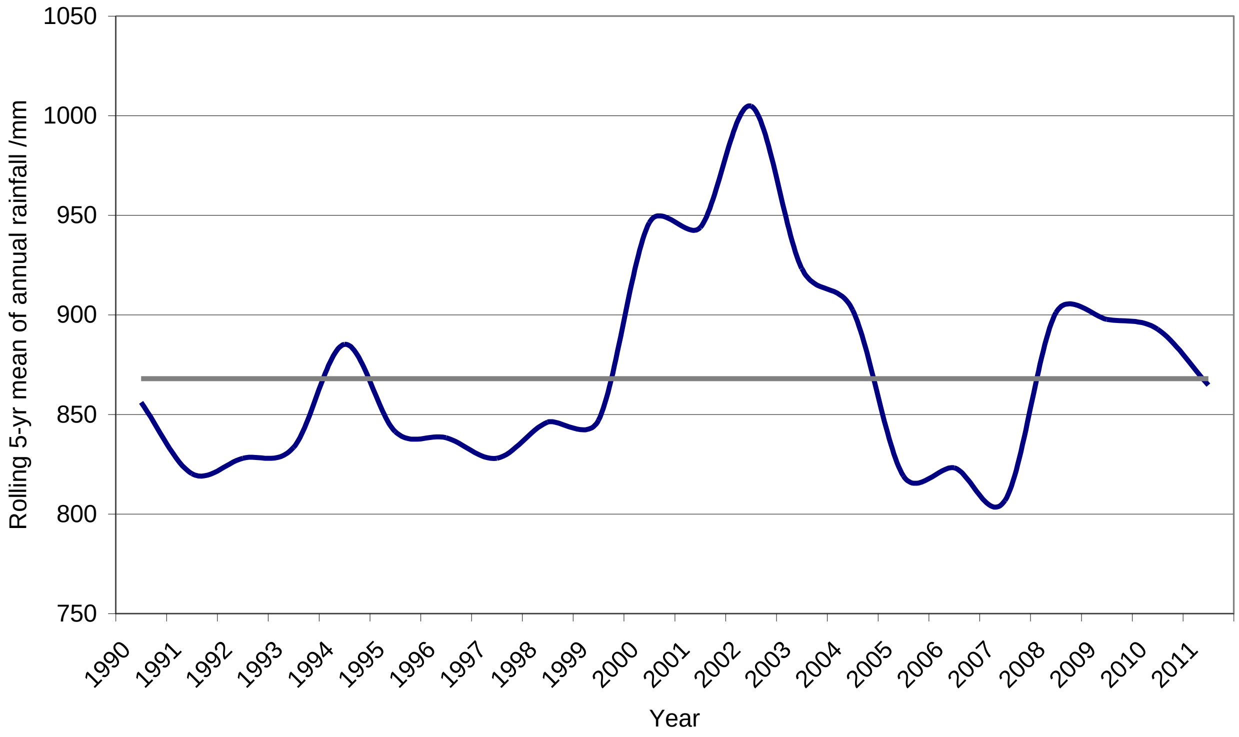
- *Cynosurion* includes vegetation analogous to MG5
- *Alopecurion* includes vegetation analogous to MG4
- *Calthion* includes vegetation analogous to MG8.

2.34 A comprehensive description of British lowland grassland types and their European context is provided in Rodwell *et al.* (2007).

Weather conditions during study period

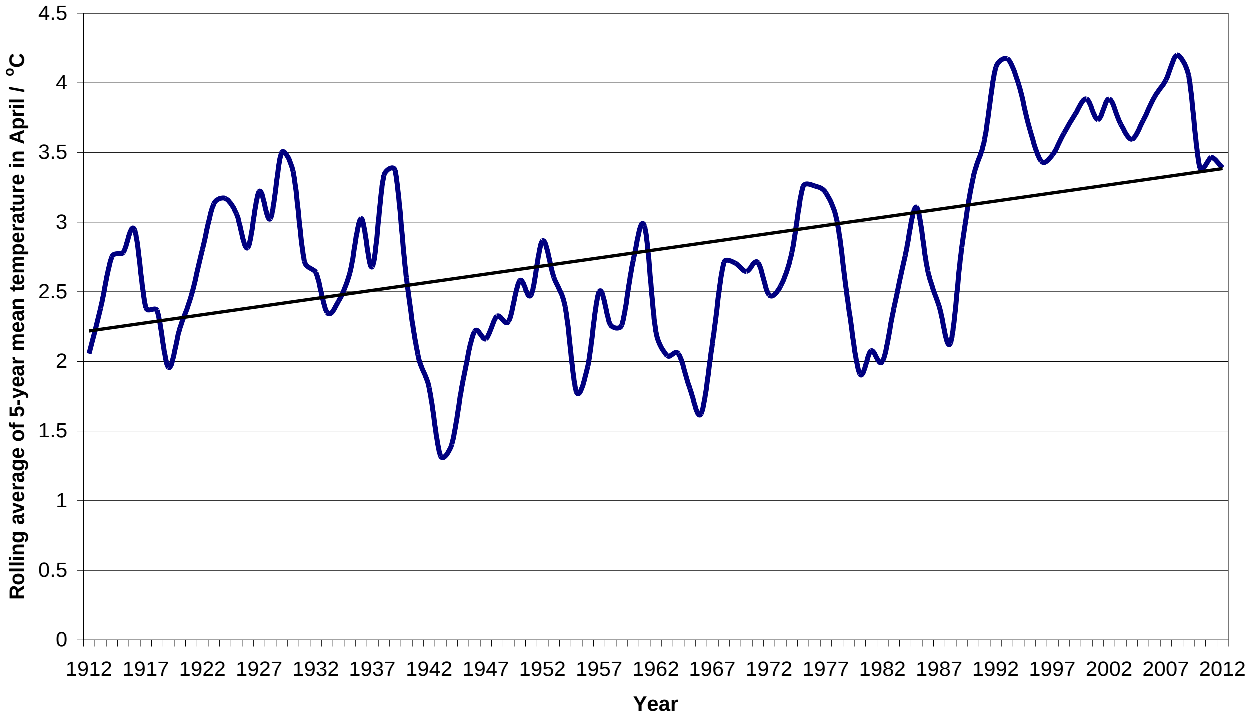
2.35 Bradford was selected as the meteorological station with the longest verified record of precipitation and rainfall in the Pennine area. Experimental field data needs to be viewed in the context of prevailing weather conditions. While there has been no consistent trend in rainfall amounts for the Bradford area in recent years, stochastic variation has occurred, which could have substantially affected vegetation composition. Climatic conditions will of course vary according to altitude and position within the Pennines.

2.36 Figure 2 shows a moving average for a 5-year period based on rainfall data from the meteorological station at Bradford. Note in particular the unusually wet period between 2000 and 2004.



Source: **www.metoffice.gov.uk/climate/uk/stationdata/bradforddata.txt**

Figure 2 A rolling five-year mean of annual rainfall over the past 30 years at Bradford. The horizontal line indicates the long term mean value (1912-2011)



Source: http://www.metoffice.gov.uk/climate/uk/stationdata/bradforddata.txt

Figure 3 Mean April temperatures over the past 100 years at Bradford. The straight line indicates the long-term trend in temperatures

2.37 When considering available evidence from the literature, it is necessary to be aware of the timing of experimental trials because botanical data gathered during unusually wet or dry periods is likely to have altered its composition due to hydrological or temperature related drivers, which may have interactive effects with the treatments applied. Similarly weather conditions may affect the timing and productivity of bird breeding, so have been taken into account when reviewing these studies too. For example, the mean temperature in April can determine the start of the growing season and there is considerable variation in temperature from year to year (see Figure 3).

2.38 Figure 3 illustrates a tendency for spring temperatures to have increased over the past 100 years. The optimal dates for shut-up and cutting might for example be different in trials conducted post 1991 compared to those executed during the "cold" period prior to this date.

2.39 Three of the evaluated studies noted a potential effect of atypical weather conditions.

Deviation from traditional upland hay meadow management

2.40 Similarity to a typical upland-hay-meadow management regime as described under *Definitions and descriptions* in Section 1, was assessed and any significant deviations noted, for example where meadows were not aftermath grazed, for example, in the Park Grass experiment.

3 What types, rates of application and timing/periodicity of nutrient and lime applications maintain the floristic diversity and breeding bird populations of upland hay meadows?

Introduction

3.1 The purpose of nutrient application, whether organic or inorganic, is to maintain or increase the yield and nutritive value of the crop. Cutting the crop for hay removes nutrients from the system, which were traditionally returned in meadows by light dressings of farm yard manure (FYM) (Rodwell, 1992). Occasional light dressings of lime also formed part of the traditional management of upland hay meadows. Lime offsets the losses of calcium caused by leaching and cropping of herbage. This enhances nutrient availability by reducing acidity thereby encouraging grass growth (Tallowin, 1998). It has been suggested this practice has declined over the last thirty years (Bradshaw, 2009). Within the context of background deposition of acidifying pollutants (see Section 6.4) lime application may have wider benefits in reducing acidity and maintaining diversity.

3.2 Across a range of related semi-natural lowland grasslands, high species richness has been found to be associated with low soil fertility (Pilgrim *et al.* 2007; Janssens *et al.* 1998), with phosphorus being considered the key limiting nutrient (Walker *et al.* 2004). The floristic diversity of species-rich hay meadows is partially due to the relatively low fertility of the soil making it difficult for any species to become dominant (Gamble & St. Pierre, 2010). Critchley *et al.* (2002) state that compared to other mesotrophic grasslands in England, the MG3 community tends to occur on soils with low levels of extractable P and K with typical soil nutrient values for MG3 meadows, of Olsen's extractable P 7.7 mg kg^{-1}, Total N 0.9 %, K is 96 mg kg^{-1} and pH is 6.4. A number of studies of hay meadows in the Pennines have suggested that recent declines in floristic diversity and an increase in the frequency of weedy and nutrient demanding species in species-rich hay meadows, are indicative of increased nutrient availability (Hewins *et al.* 2005; O'Reilly 2010; Starr-Keddle 2012). However, some landowners refute this relationship and assert that the observed declines are due to more restrictive nutrient inputs required by the Higher Level Stewardship grassland options.

3.3 This section examines available evidence on the effect of different rates and forms of nutrients, specifically FYM inorganic fertiliser NPK (and its constituent parts) and lime applications, on upland hay meadows and related neutral grassland types and the breeding bird populations they sustain. Studies which look at the effect of different timings of applications, for example of spring, autumn or winter applications, and frequencies, for example annual, biennial or triennial, on both floristic diversity and breeding bird populations are also included. Only the direct impacts of these interventions are considered for breeding birds, for example, nest destruction.

3.4 A number of studies refer to changes in positive indicator or key character species. These are variably defined depending on the specific study, but their presence in sufficient number and frequency usually denotes that the habitat is of high quality and good condition, (Robertson & Jefferson, 2000).

3.5 All inputs whether FYM or inorganic have been converted into kg ha^{-1} yr^{-1} of Nitrogen (N), Phosphorus (P) and Potassium (K) to enable easy comparison between studies.

The studies and their applicability

3.6 Twenty-two studies, eighteen UK based and four from mainland Europe, provide evidence on sub question (a). Summary descriptions of each study and their findings can be found in Appendix 2.

3.7 Four studies, including the 130 year nutrient addition treatments at the Park Grass Experiment reported in Crawley *et al.* (2005) [2+], the Hochberg & Zopf (2011) [2-] and Honsova *et al.* (2007) [1+] studies and the small-scale experiment at Tadham Moor Kirkham, Mountford & Wilkins (1996) [1+] examined nutrient input under cutting management with no aftermath grazing. This slightly reduces their direct applicability to upland hay meadows, where grazing by livestock will influence nutrient cycling by grazing and dunging and encourage establishment opportunities in the sward through trampling. Furthermore the findings of Hochberg & Zopf (2011) [2-] in particular should be treated cautiously due to the confounding and likely balancing effect, of increasing number of cuts with increased nutrient inputs.

3.8 Whilst the Tadham Moor study conforms to the related NVC types MG4, MG5 and MG8, included within this review, the underlying soils are peat, not mineral, and are also subject to seasonal flooding, hence reducing the relevance of the evidence for MG3 hay meadows which typically overlie more freely draining mineral soils. Peat soils are commonly deficient in plant-available P compared with mineral soils (Brady, 1990). All of the other experimental studies evaluated in this section overlie mineral soils.

3.9 The study undertaken by Jeangros, Sahli & Jacot (2003) [2-] had a number of limitations which reduce its applicability and reduced its score. Firstly, only treatment two allowed comparison of the impacts of manure alone with fertiliser. Secondly, it is likely that the full impacts of manure treatment may not have become fully apparent in the six-year time period of the study due to potentially slower release of both N and P.

Presentation of the evidence

3.10 Due to the multi-factorial nature of sub-question (a) the question has been further sub-divided into a series of five subsidiary questions as follows:

1) What quantity/rate of nutrients maintains the sward composition of upland hay meadows?
2) Does the type/form in which nutrients are supplied result in different impacts on either botanical composition or breeding bird populations of upland hay meadows?
3) Does the timing of application (for example, spring/autumn/winter) effect either botanical composition or breeding bird populations?
4) Does the frequency of application (for example, annual/biennial/triennial etc) effect botanical composition or breeding bird populations?
5) Is application of lime consistent with maintaining upland hay meadow sward composition and if so what regime?

3.11 Under each sub-sub question a short summary of the evidence is provided underpinned by a more detailed analysis of the evidence which has been used to derive evidence statements, capturing the nature and strength of the evidence.

3.12 Paragraphs 3.54 to 3.58 synthesizes the overall evidence base for sub-question (a) and draws conclusions on what constitutes sustainable nutrient management on the basis of this. Paragraphs 3.59 to 3.63 sets out recommendations for further research based on identification of gaps in the evidence base.

What quantity/rate of nutrients maintains the sward composition of upland hay meadows?

3.13 Thirteen studies provide evidence on this sub-sub-question, nine are UK based and four are from mainland Europe, they comprise:

- Four randomised control experiments (Kirkham *et al*. (2012) [1+]; Smith *et al.* (1996) [1++]; the large scale experiment at Tadham Moor [1++] as reported in the following references. N.B these have been evaluated together to avoid double counting the one study on which they are based, Mountford, Lakhani & Kirkham (1993); Tallowin *et al*. (1994); Tallowin (1996); the small scale experiment at Tadham [1++] as reported in Kirkham, Mountford & Wilkins (1996) and Tallowin *et al*. (1994).
- Five non-randomised control experiments (Lawes, Gilbert & Masters (1882) [2+]; Crawley *et al.* (2005) [2+]; Aerts, de Caluwe & Beltman (2003) [2+]; Honsova *et al.* 2007 [1+]; and Hochberg & Zopf (2011) [2-].
- Three correlative studies (Critchley, Fowbert & Wright (2007) [2-]; Starr-Keddle (2011) [2-] and Starr-Keddle (2012) [2-]).

Summary of evidence

3.14 Few studies assess the impact of low rates of Nitrogen ≤ 25 N kg ha^{-1} on the floristic diversity of species rich hay meadows, with just one study providing evidence specifically on MG3. This indicates that FYM inputs at 12 t ha^{-1} $year^{-1}$ may maintain floristic diversity on MG3 meadows which have a history of inputs at this rate, but that botanical enhancements (increases in the cover of positive indicator species) occurred at the lower rate of 6 tonnes FYM ha^{-1} $year^{-1}$.

3.15 Overall the available evidence shows that that under increased nutrient availability competitive grasses increased in cover, usually at the expense of smaller, slower growing forbs with rates of c. 18 kg N ha^{-1} yr^{-1} or greater to leading significant reductions in floristic diversity across a range of neutral grasslands.

3.16 The evidence suggests that botanical responses to nutrient applications are driven by which ever macro-nutrient is growth limiting in the grassland in question and potentially to the historic nutrient regime.

Analysis and evidence statements

Nitrogen (N)

3.17 The majority (7/9) of experimental studies examined the impacts of applying ≥ 50 N kg ha^{-1} yr^{-1}, principally on yield but also on species richness and/or the ratio of grasses to forbs. Only two studies, the Tadham Moor Large Scale Experiment reported by Mountford, Lakhani & Kirkham (1993) and Tallowin (1996) [1++] and Kirkham *et al*. (2012) [1+] examined the impact of agriculturally low rates of fertiliser application, i.e. ≤ 25 N kg ha^{-1} annually on floristic diversity of species rich meadows. Furthermore only Kirkham *et al*. (2012) [1+] examined the impact of very low rates of nutrient application (from FYM and equivalent rates of inorganic fertiliser) specifically on the MG3 community in addition to a lowland MG5 meadow. Application rates in this study ranged from just under 18 kg N ha^{-1} yr^{-1} to as little as 4.4 kg N ha^{-1} yr^{-1}. All other evidence is derived from related neutral grassland types, MG5 or MG4 from the UK or from hay meadows in Europe analogous to either MG3, MG4 or MG5.

3.18 Consistent evidence is provided from seven studies (Kirkham *et al*. (2012) [1+]; Smith *et al.* (1996) [1++]; Tadham Moor Large Scale Experiment [1++] (Lawes, Gilbert & Masters (1882) [2+]; Crawley *et al.* (2005) [2+]; Aerts, de Caluwe & Beltman (2003) [2+] and Honsova *et al.* 2007 [1+]) showing that annual applications of Nitrogen, at rates of 17.6 kg ha^{-1} $year^{-1}$ or greater, lead to significant reductions in species richness in species-rich neutral hay meadows.

3.19 All seven of the above studies, plus one study by Jeangros, Sahli & Jacot (2003) [2-] showed that under increased nutrient availability competitive grasses increased in cover, usually at the expense of smaller, slower growing forbs. Only one study Hochberg & Zopf (2011) [2-] suggested that botanical quality and species richness could be maintained under high inputs of N. However this was under a two or three hay cut regime, in which removal of biomass effectively balanced the nutrients applied reducing its applicability to typical upland hay meadow management.

3.20 From this we draw the following evidence statements:

- There is strong evidence from seven studies (two [1++], two[1+] and three [2+]) to indicate that annual applications of Nitrogen, at rates of 17.6 kg ha^{-1} $year^{-1}$ or greater, lead to significant reductions in species richness in MG3 and related neutral grassland types.
- There is strong evidence from eight studies (two [1++], two[1+], three [2+] and one [2-]) that under increased nutrient availability competitive grasses increased in cover, usually at the expense of smaller, slower growing forbs.

3.21 With respect to MG3 specifically evidence from Kirkham *et al*. (2012) [1+] found that FYM inputs at 12 t ha^{-1} $year^{-1}$ (equivalent to 9 kg N ha^{-1}, 10 kg P ha^{-1} and 69 kg K ha^{-1} annually) maintained vegetation quality on the Cumbrian study site where historical inputs had been at this level. However, enhancement of botanical quality (specifically increase in percentage cover of positive indicators) occurred under lower application rates of 6 tonnes FYM ha^{-1} $year^{-1}$or less (equivalent to 4.4 kg N ha^{-1}, 5 kg P ha^{-1} and 35 K kg ha^{-1} yr^{-1}). In contrast at the Welsh MG5 study site where there was no recent history of nutrient application, floristic quality was compromised at rates of FYM application of ≤ 4 tonnes FYM ha^{-1} annually equivalent to 0.6 kg N ha^{-1}, 0.9 kg P ha^{-1} and 7 kg K ha^{-1}. The study authors suggest that in light of these findings the nutrient regime of any given meadow should be informed by its soil nutrient status, grass utilisation, past fertility management and conservation objectives rather than prescription programmes.

3.22 From this we draw the following evidence statement:

- There is moderate evidence from one [1+] study that for MG3 meadows FYM inputs at 12 t ha^{-1} $year^{-1}$ (equivalent to 9 kg N ha^{-1}, 10 kg P ha^{-1} and 69 kg K ha^{-1} annually) maintain vegetation quality on meadows where inputs have been at a similar level historically, but that enhancement of botanical quality is achievable under lower nutrient rates of 6 tonnes FYM ha^{-1} $year^{-1}$ or less (equivalent to 4.4 kg N ha^{-1}, 5 kg P ha^{-1} and 35 K kg ha^{-1} yr^{-1}).
- There is strong evidence from one [1+] study on MG3 indicating that the nutrient regime of any given meadow should be informed by its soil physical and chemical status and past fertility management.

The role of Phosphorus (P) and Potassium (K)

3.23 Evidence suggest that vegetation responses to nutrient inputs are largely dictated by whichever macro nutrient is in shortest supply and is limiting growth. Two studies, the Tadham Moor Large Scale Experiment [1++] (reported in Mountford, Lakhani & Kirkham (1993), (Tallowin *et al*. (1994) and Tallowin (1996)) and Crawley *et al.* (2005) [2+], both on MG5 grassland found that when P is applied in combination with N then reductions in species richness are more significant than when N is applied alone. This effect is apparent at application rates as low as 25 kg N ha^{-1} and circa 13 kg P ha^{-1} yr^{-1}. In contrast Aerts, de Caluwe & Beltman (2003) [2+] reported that after 11 years of inputs on a riverine grassland in the Netherlands addition N either alone or in combination with P, led to lower species diversity and higher biomass. No such effects were observed with additions of the non-limiting nutrient (P) on its own.

3.24 Evidence specific to MG3 meadows from two correlative studies, Starr-Keddle (2011) [2-] and Starr-Keddle 2012 [2-] suggests a significant association between increased availability of soil extractable P and lower botanical quality (specifically higher cover of competitive, nutrient demanding species, and decreasing species richness). However, both the study authors and hay meadow review panel note that the confounding influence of other in-field management operations has not been accounted for in either study thereby reducing their reliability.

3.25 In their analysis of monitoring data from the North Pennines Environmentally Sensitive Area Critchley, Fowbert & Wright (2007)[2-] found that shifts in species composition notably a reduction in number of forb species were associated with lower levels of soil extractable K. This finding was specific to the very small number of species-rich upland hay meadows (n =16) monitored in the sample reducing the reliability of this evidence.

3.26 From this we draw the following evidence statements:

- There is strong evidence from three studies (one [1++] and two [2+]) that botanical responses to nutrient applications are driven by whichever macro-nutrient is growth-limiting in the grassland in question, with even small additions of the limiting nutrient, for example circa 13 kg P ha^{-1} yr^{-1} , significantly reducing species richness.
- There is limited evidence from two correlative studies (both [2-]) on MG3 meadows of a significant association between increased availability of soil extractable P and lower botanical quality (specifically higher cover of competitive, nutrient demanding species, and decreasing species richness).
- There is limited evidence from one correlative study (2-) that shifts in species composition over a 15-year period, notably a reduction in number of forb species were associated with lower levels of soil extractable K.

Does the type/form in which nutrients are supplied result in different impacts on either botanical composition or breeding bird populations of upland hay meadows?

3.27 Four studies two randomised control trials Kirkham *et al.* accepted with corrections [1+], Edwards & Younger (2006) [1++] and one non-randomised control trials Crawley *et al.* (2005) [2+] and one non-systematic review ADAS (1993) [4-] provide evidence of impacts of the different forms of fertiliser on vegetation composition.

3.28 Two studies, one correlative/observational Small (2002) [2++] and one systematic review Vickery *et al.* (2001) [3++] provide evidence of impacts on breeding birds.

3.29 Six studies took place in the UK whilst one is from Switzerland.

Summary of evidence

3.30 Available evidence on the differential impacts of different forms of nutrient on floristic diversity is limited to two studies and one non-systematic review. This evidence is equivocal and its reliability is compromised by the fact that in no single study can rates of FYM and inorganic fertilizer be said to be directly equivalent.

3.31 Available evidence suggests that there are benefits associated with the moderate application of FYM in winter for breeding birds, through increasing the abundance and accessibility of soil-dwelling invertebrates by bringing them closer to the surface.

Analysis and evidence statements

Botanical evidence

3.32 Kirkham *et al*. (2012) [1+] found that inorganic fertilisers were apparently no more harmful to vegetation quality at the MG3 and MG5 study sites than equivalent FYM, and sometimes less so. Indeed inorganic treatments were slightly more species-rich with respect to positive indicators at a given level of N or P input than FYM. However the study authors acknowledge that these discrepancies may be attributed to the inorganic treatments receiving less nutrients (especially P) than their FYM comparators over the course of the experiment, due to the initial model used to specify equivalent amounts of inorganic N, P and K underestimating their actual supply in the FYM treatments in the first seven years of the experiment. Hence the impact on botanical composition might have been expected to be less than if a truly equivalent rate had been applied despite the authors' efforts to control for this in modelling.

3.33 In contrast findings from the post 1905 FYM treatments of the Park Grass Experiment on MG5 grassland reported by Crawley *et al.* (2005) [2+] indicate that FYM has a slightly less harmful effect on species richness than equivalent rates of inorganic fertiliser. According to multivariate modelling which controlled for rates of N, P and K application, applying FYM rather than mineral fertilisers added two species on average. No reasons are provided for this differential impact. Whilst it is possible that FYM genuinely had a less deleterious impact on species richness, it is also possible that over the duration of the experiment the FYM plots received less NPK than the inorganic fertiliser plots, leading to non-equivalence of nutrient supply. No testing of the actual nutrients supplied in the FYM applied annually took place and it is not possible to verify this retrospectively.

3.34 ADAS (1993) [4-] in a non-systematic literature review focused the impacts of nutrient additions on unimproved grassland state that they did not expect inorganic fertilisers to differ from organic fertilisers in their effect on species diversity when applied at equivalent rates.

3.35 Edwards & Younger (2006) [1++] tested the hypothesis that application of FYM may facilitate return of seed of desirable MG3 species. However, their study concluded that very few of the species which remained viable in cattle manure were of conservation interest.

3.36 From this we draw the following evidence statement:

- Evidence on the differential impacts of different forms of nutrient on floristic diversity is very limited and equivocal with the two [1+] studies available showing small but contradictory effects. The reliability of the evidence is compromised by the fact that in no study were rates of FYM and inorganic fertilizer truly equivalent.

Ornithological evidence

3.37 Vickery *et al.* (2001) [3++] state that moderate use of FYM may benefit grassland birds by increasing the abundance of soil-dwelling invertebrates, or their accessibility by bringing them closer to the surface. They report that winter field use by lapwings, starlings, redwing and fieldfare is positively associated with frequent addition of FYM on permanent grassland but that benefits decrease under high applications and would be expected to decrease if the livestock have been recently dosed with broad-spectrum avermectin wormers. Similarly Small (2002) [2++] found a strong association in two surveys included in their analysis of relationships between birds and surface features, between occurrence of lapwing and newly applied FYM.

3.38 From this we draw the following evidence statement:

- There is moderate evidence from two studies (one [3++] and one [2++]) that FYM application increases the abundance and availability of invertebrate prey for grassland birds, although these benefits will be reduced under high applications and are likely to decrease if the livestock have been recently dosed with broad-spectrum avermectin wormers.

Does the timing of application (ie seasonality) effect either botanical composition or breeding bird populations?

3.39 Four studies provide evidence on this question (one randomised control experiment Kirkham, Mountford & Wilkins (1996) [1++], two correlative/observational studies Lawes, Gilbert &

Masters (1882) [2+] and Baines, (1990) [2++] and one review Simpson & Jefferson (1993) [4-] which summarises expert opinion).

Summary of evidence

3.40 There is little evidence available on the effect of different timings of application of nutrients on MG3 meadows or the birds they support. Available evidence indicates that the timing of nutrient inputs has no effect on floristic diversity but that agricultural operations which take place in spring (including application of FYM and/or inorganic fertilizer) result in reduced breeding success in lapwing.

Analysis and evidence statements

Botanical evidence

3.41 At Tadham Moor varying the proportions of the total N applied annually between spring and mid-summer (after hay cutting) had no significant effect on either species richness or species diversity of the vegetation Kirkham, Mountford & Wilkins (1996) [1++], although the authors' suggest that this finding may be attributable to the overriding effect of replacing P and K, in both spring and mid-season.

3.42 In their review of expert evidence Simpson & Jefferson (1993) [4-] report that timing or manure application varies considerably from place to place but that evidence suggests that both winter and spring applications of FYM allow opportunity for efficient utilisation of nutrients, subject to satisfactory soil conditions. No evidence was presented, on different biological impacts of spring versus autumn or winter application, with the exception of it being reported that too high a rate of application of FYM in spring can smother and physically scorch herbage, particularly in very dry conditions. A similar effect was reported from the Park Grass Experiment by Lawes, Gilbert & Masters (1882) [2+], where initial annual application rates of 35 tonnes ha^{-1} $year^{-1}$ in spring caused 'adverse effects' to the sward from smothering. However, these negative impacts are more a reflection of rate of input not timing.

3.43 From this we draw the following evidence statement:

- There is no specific evidence related to the effect of different timings of application of nutrients on upland hay meadows. Available evidence is restricted to a [1++] study on a related neutral grassland type (MG5) and a review [4-], both of which suggest no significant effect of timing (ie season) of FYM or inorganic fertiliser application on botanical composition.

Ornithological evidence

3.44 Baines (1990) [2++] found that reduced lapwing productivity on improved meadows was attributable to higher proportion of clutches being destroyed and a lower proportion of clutches being replaced due to more intensive management, namely more agricultural activities (ie field operations in the spring) and the production of a faster growing sward that leaves insufficient time for laying of replacement clutches.

3.45 From this we draw the following evidence statement:

- There is moderate evidence from one [2++] study of a deleterious impact of spring field operations, (including FYM application and inorganic fertilizer applications), on breeding lapwing in upland meadows

Does the frequency of application (for example, annual/biennial/triennial etc.) affect botanical composition or breeding bird populations?

3.46 Only one study, a UK based randomised control experiment Kirkham *et al*. (2012) [1+] provided evidence on this question.

Summary of evidence

3.47 Only one study provided evidence on this question it showed no detectable impact on botanical composition of triennial compared to annual application of nutrients at correspondingly lower amounts. No studies examined the impact of application frequency on breeding waders.

Analysis and evidence statements

3.48 Kirkham *et al*. (2012) [1+] showed that once the mean amount of nutrients supplied annually over the duration of the experiment (12 years) had been accounted for there was no detectable impact of triennial compared to annual application at correspondingly lower amounts on botanical composition.

3.49 From this we draw the following evidence statement:

- There is limited evidence from one [1+] study on MG3 grassland of no significant effect on botanical composition of annual or triennial nutrient application, provided the overall nutrients supplied over a given period are the same.

Is application of lime consistent with maintaining upland hay meadow sward composition and if so what regime?

3.50 Four studies provide evidence for this question, comprising one randomised control study (Kirkham *et al*. (2012) [1++], one non-randomised control study Crawley *et al.* (2005) [2+], one correlative study Askew (1993) [2+] and one review Tallowin (1998) [3++]. All studies were UK based.

Summary of evidence

3.51 According to the evidence occasional liming to maintain/achieve a pH of around 6 is consistent with maintaining vegetation quality on MG3 hay meadow with a past history of lime application.

Analysis and evidence statements

3.52 Kirkham *et al*. (2012) [1++], found that liming alone had little or no detrimental effect on vegetation on either the upland MG3 meadow or lowland MG5 meadow. Liming reduced botanical quality of vegetation when applied in conjunction with annual FYM at the lowland meadow site, but not at the upland site. In an early analysis of botanical data from meadows in the Pennine Dales ESA. These findings are supported by Askew (1993) [2+] who identified presence of lime applications as a factor distinguishing meadows with conservation interest and by Tallowin (1998) [3++] who, whilst reporting a paucity of information on the impact of lime applications on neutral grassland, concludes that where lime has historically been applied on upland hay meadows then this tradition should continue, providing that only lime and not phosphatic slag is used. Crawley *et al.* (2005) [2+] reported that lime had no significant effect on species richness on the MG5 grassland in the Park Grass Experiment except on plots receiving nitrogen in the form of ammonium sulphate, which has a strong acidifying effect, where species richness increased sharply in response to liming as pH increased.

3.53 From this we draw the following evidence statement:

- There is strong evidence from three studies (one [1++], one [2+] and one [3++]), to suggest that occasional liming is consistent with maintaining vegetation quality on MG3 hay meadow with a past history of lime application. A further [2+] study on a related neutral grassland type, MG5, also indicates that lime has no deleterious impact on species richness.

Conclusions on nutrient regimes

3.54 There is strong evidence showing that nutrient applications of c. 18 kg N ha^{-1} yr^{-1} or greater led to significant reductions in floristic diversity in upland hay meadows and meadows on related neutral grassland types.

3.55 The limited available evidence specific to FYM inputs indicates that rates of 12 tonnes ha^{-1} $year^{-1}$ (equivalent to 9 kg N ha^{-1}, 10 kg P ha^{-1} and 69 kg K ha^{-1} annually) may be sustainable on MG3 meadows which have a history of inputs at this rate, but that botanical enhancements (increases in the cover of positive indicator species) occurred at the lower rate of 6 tonnes FYM ha^{-1} $year^{-1}$.

3.56 However, there is strong evidence to suggest that botanical responses to nutrient applications are driven by which ever macro-nutrient is growth limiting in the grassland and potentially by historic nutrient inputs. As a consequence the nutrient regime of any given meadow should be informed by its soil nutrient status, grass utilisation, past fertility management and conservation objectives.

3.57 The evidence suggests that the amount of nutrients applied (rate) is the single most important factor influencing botanical response, with the evidence for any additional differential impacts of form (FYM versus inorganic fertilizers) being very limited and equivocal. Similarly the little evidence which does exist for MG3 and related grassland types suggests there is no significant effect of either different timings and or frequencies of nutrient inputs on floristic diversity. Occasional liming to maintain a pH of around 6 appears consistent with maintaining vegetation quality on MG3 hay meadow with a past history of lime application.

3.58 In contrast evidence for breeding birds suggests that there are benefits associated with FYM application through increasing prey abundance and availability, and with avoidance of any agricultural operations (including nutrient inputs) in spring when lapwing are breeding. Whilst no studies examined the impact of application frequency on breeding waders, as a general principle less frequent applications might be predicted to beneficial in reducing overall disturbance to nests and fledglings.

Evidence gaps and research recommendations

3.59 The one study which examined the impacts of very low (<20 kg N ha^{-1} yr^{-1}) rates of N application (in both inorganic and organic forms) on floristic diversity revealed that only very low rates ≤10 kg N ha^{-1} yr^{-1} are likely to be sustainable, and that the botanical responses to these treatments in part reflect conditioning of the sites to historic nutrient and lime inputs.

3.60 Despite best efforts no studies are considered to have compared truly equivalent rates of FYM and inorganic fertilizer.

3.61 Few studies examined the roles of P (or K) specifically in influencing floristic diversity, with no studies specific to MG3 meadows.

3.62 There was almost no evidence on impact of seasonality of nutrient input on species-rich grasslands and their breeding birds and very little on the impacts of different periodicities (frequency) of nutrient application.

3.63 The following areas would therefore merit further investigation:

- Examination of the impacts of very low rates of N application ≤20 kg N ha^{-1} yr^{-1} on floristic diversity (with directly equivalent FYM treatments) across a range of MG3 meadows with different nutrient management histories.
- Exploration of the role of P in influencing floristic diversity on MG3 meadows.
- Investigation of the impact of different seasonality of nutrient input on species-rich grasslands and its impact on both botanical composition and breeding birds.
- Further investigation of the impact of different periodicity (frequency) of nutrient application.

4 What management methods or approaches control rushes (*Juncus* spp.) in upland hay meadows and maintain the floristic diversity of the meadows?

Introduction

4.1 Concern has been expressed by ecologists and farmers about the gradual ingress of the sharp-flowered and soft rushes (*Juncus acutiflorus* and *J.effusus*) and to a lesser extent compact rush (*J. conglomeratus*) over the hill grasslands, pastures and meadows of certain upland areas. Data from Countryside Survey (Lindsey Maskell, pers. comm.) indicate that between 1998 and 2007 there was an increase in soft rush *Juncus effusus* nationally, alongside increases in the frequency of plant species with higher Ellenberg moisture requirements. In certain areas, notably Teesdale, rush species in particular soft rush, *J.effusus* and sharp-flowered rush *J.acutiflorus*, are reported to have increased noticeably in the last 10 years to an extent that the area of grassland (grazing) is viewed by landowners and botanists to be severely reduced in pastures and on hill-sides, and the quality of resulting hay crops compromised. O'Reilly (2010) reports that rushes have increased alongside creeping buttercup *Ranunculus repens*, meadowsweet *Filipendula ulmaria* and creeping bent *Agrostis stolonifera* all species that do well in damp conditions. Local botanists are particularly concerned about the ingress of rush into small base-rich flushes where they may competitively exclude a number of rare and declining species (Bradshaw, pers.comm).

4.2 As perennials of damp and waterlogged fields, rushes spread through rhizomes and prolific seeding (13000 seeds per flower head), making them rapid colonisers of disturbed habitat. Rushes are tolerant of a wide range of pH (for example, soft rush 3 - 7, articulated rush 4.5 - 9, sharp flowered rush 3 - 5) and moderately tolerant of annual cutting, grazing and trampling. Creeping rushes, namely (jointed rush and sharp flowered rush) are reported as being more readily grazed than tussock rushes (hard, soft and compact) (RSPB, 2007).

4.3 Reasons for the increase in abundance of sharp flowered and soft rushes in Teesdale are not well understood and have been variably assigned to changing weather patterns and changes in aspects of land management (for example, reduced application of lime, sub-surface drains falling into disrepair and not being replaced, larger, heavier and softer-mouthed continental stock and a ban on spraying). This section examines available evidence for rush control measures consistent with maintenance of botanical diversity.

The studies and their applicability

4.4 Six studies provide evidence on this sub-question comprising three randomised controlled experiments, Mercer, Reavey & Morgan (2008) [1+] Merchant (1995) [1++] Wolton (2000) [1-], one correlative study Cherril (1995) [2+], one part observational and part experimental study Smolders *et al.* (2008) [2-] and one guidance document representing expert opinion RSPB (2007) [4-]. Five were from the UK whilst one was from The Netherlands. Summary descriptions of each study and their findings can be found in Appendix 2.

4.5 None of the studies were conducted on MG3 grassland or considered the maintenance of floristic diversity directly, instead focusing on the decrease in rush vigour. Despite this the various control measures trialled are still considered to have direct relevance and applicability to management of rushes within MG3 grassland.

4.6 Several studies are likely to have been too short to have fully tested the efficacy of the control measure, namely Wolton (2001) [1-] who examined impact of the different cutting treatments over one growing season and Smolders *et al.* (2008) [2-] who looked at the response of rush biomass to lime additions over three months.

Summary

4.7 There was little available evidence on rush control on species-rich grasslands and no evidence *relating* to their control within upland hay meadows. Most studies focused on soft rush, *Juncus effusus*.

4.8 Evidence suggests that mowing rushes flush with the ground at least twice during the summer can reduce their vigour and where only one cut is possible, a late summer cut is most effective. Herbicide by weed wiping application can also be effective, although not without danger to other vegetation.

Analysis and evidence statements

4.9 Two studies sought to explain reasons for rush infestations. Cherril (1995) [2+] report that agriculturally improved grasslands in the uplands may suffer more from infestation of *J. effusus* due to the greater availability of rush seed in adjacent upland habitats. Smolders *et al.* (2008) [2-] found in a field survey that growth of *J. effusus* was highly correlated with Olsen' P. However when lime was applied to ex-situ field soil from an arable field to reduce soil P there was no observed reduction in soft rush biomass.

4.10 With respect to control measures Mercer, Reavey & Morgan (2008) [1+] found that late spring/early summer applications of glyphosate were more effective in reducing rush growth than those in late summer/autumn, but that there were no significant differences between the three different concentrations of glyphosate tested. Results suggest that treatment needs to be ongoing to be effective and that even careful application of herbicide can significantly affect non-target vegetation. The RSPB guidelines [4-] also mention the use of herbicide, specifically MCPA and glyphosate, as a possible rush control mechanism, using a weed-wiper, but warn of the likelihood that it will kill non-target vegetation.

4.11 Two studies examined the impact of cutting, Merchant (1995) [1++] and Wolton (2000) [1-] both found that cutting down to ground level is more effective in reduced tussock mass and vigour than cutting at half the height. Multiple cuts during the growing season are most effective, but where only a single cut is possible a later August cut is preferable. RSPB (2007) [4-] guidelines advise similar, but with the first summer cut taking place after the last wader chicks have fledged (exact timing is dependent on species present) which should be as close to the ground as possible without causing bare soil. Use of grazing as a management tool to control rushes is also suggested, ideally with cattle with grazing following a single cut reported as being sufficient in certain instances. Care is advised in avoiding creation of bare ground by poaching, scalping vegetation when cutting and permanently saturated soil all of which will allow rush seeds in the seed bank the chance to establish.

4.12 From this we draw the following evidence statements:

- There is strong evidence from three studies (one [1++], one [1-] and one [4-]) that mowing rushes flush with the ground at least twice during the summer can reduce rush vigour and that where only one cut is possible a late summer cut is most effective.

- There is moderate evidence from two studies (one [4-] and one [1+]) that herbicide use by weed wiping application can also be effective, although not without danger to other vegetation.

Conclusions on rush control

4.13 There was little available evidence on rush control on species-rich grasslands and no evidence relating to their control within upland hay meadows.

4.14 Available evidence suggests that mowing rushes flush with the ground at least twice during the summer can reduce their vigour and where only one cut is possible a late summer is most effective. Herbicide by weed wiping application can also be effective, although not without damage to other vegetation. Care should be taken to avoid poaching and creation of bare ground, which abundant rush seed will quickly exploit.

Evidence gaps and research recommendations

4.15 Overall there was a paucity of evidence for rush control on species-rich grasslands and no evidence relating to their control within upland hay meadows.

4.16 There is clear need to both identify reasons for increases in rush species within upland hay meadows and for research to identify sustainable, non-damaging, control measures on upland hay meadows.

5 What spring-grazing levels, timing of shut-up/closure for hay and cutting dates maintain the floristic diversity and breeding bird populations of upland hay meadows?

Introduction

5.1 This question deals both with the effects of different spring grazing regimes, (grazing intensity and duration), and the timing of cutting for field dried hay (not silage) on botanical composition and breeding birds.

5.2 Sheep numbers in England rose throughout the 1980s as headage-based subsidy payments encouraged producers to increase numbers of breeding ewes (Defra 2010). The collapse of breeding wader populations in many areas of moorland-edge enclosed pastures has been largely attributed to these increases alongside associated intensification of land use, changes to the composition and structure of the vegetation being pivotal influences of grazing pressure on birds (Fuller, 1996). National quota limits forced a ceiling on ewe numbers during the 1990s, before changes to subsidy eligibility rules in 2000 and Foot and Mouth Disease in 2001 resulted in a sharp decline in ewe numbers - although the rate of decline was much greater outside the Less Favoured Areas (Defra 2010). Nationally, sheep numbers have now reduced to the levels of the early 1980's and cattle numbers continue to decline due largely to the reductions in the dairy herd (Silcock, Brunyee & Pring, 2012). Average stocking densities have fallen in each upland region between 2004 and 2009 with the proportion of livestock units derived from sheep has increasing.

5.3 Upland hay meadows have been created by, and are maintained through, appropriate upland livestock enterprises. Grazing intensity and period have a large impact on biomass off-take and selectivity which are both important determinants of floristic composition. Recent declines in the diversity and character of MG3 meadows have been linked to changes in the management of sheep in the spring, with more sheep being kept in the grasslands beyond the normal removal date when the sward is shut for the growth of the hay crop (Critchley, Fowbert & Wright 2007). Indeed recent UK data suggest that whilst overall stocking densities have fallen in upland areas, finer scale changes in grazing regime including summer grazing on the hill starting later have led to more intensive use of in-bye land (including hay meadows) in spring (Silcock, Brunyee & Pring, 2012). Furthermore, (Bradshaw, evidence submitted as part of this review) reports that winter grazing levels on Teesdale meadows is higher than in the past due to sheep having been removed from the hills under agri-environment scheme options for moorland management.

5.4 With respect to hay cutting, traditionally field-cured hay formed the main grass-fodder crop in upland areas, essential for feeding stock in the winter months. Timing of hay cutting is greatly influenced by environmental factors such as climate, altitude and aspect. Three or four consecutive days of good weather are required. Pre-mechanisation hay cutting took place over months, not weeks, allowing considerable temporal variation in cutting dates each year depending on the weather (Smith & Jones, 1991). Concerns have been expressed about overall homogeneity in hay cutting date. Earlier finishing dates are considered to limit opportunities for breeding birds to lay replacement clutches (for example, waders), or rear later broods (for example, corncrakes and yellow wagtails) to make up for poor early weather conditions or nest/chick losses due to meadow management or predation (Brown & Grice, 2005).

5.5 Tighter restrictions on the start of hay cutting (notably restricting cutting to the 8th July or later within the Pennine Dales ESA, in response to declining populations of yellow wagtails) are thought to have resulted in an overall homogenisation of the botanical composition of meadows with increases in the frequency of annual species including yellow rattle, *Rhinanthus minor*, eyebright, *Euphrasia sp*, soft brome, *Bromus hordaeceus*, changing forget-me-not *Myosotis discolour*, and lesser trefoil, *Trifolium dubium* reported in a number of studies (O'Reilly, 2010; Bradshaw, *pers comm*.) Traditionally cutting the meadows earlier, before the seeds of many of these species had seeded, would have controlled their populations.

5.6 Only the direct impacts of grazing and mowing, ie nest destruction due to grazing are considered for breeding birds alongside evidence on sward height preferences for nesting in spring.

The studies and their applicability

5.7 Twenty one studies provided evidence on this sub-question (four randomised control experiments, 14 correlative or observational studies, one modelling study, one meta-analysis and one review). Fifteen were from the UK and six were from continental Europe. Summary descriptions of each study and their findings can be found in Appendix 2.

5.8 A considerable number of studies on the impacts of hay cutting on breeding waders were from meadow grasslands in mainland Europe. Care was taken to ensure the species studied were also characteristic of upland hay meadows and that the management interventions investigated were also relevant to this study, ie timing of hay cutting date and spring grazing intensity. For these reasons these non-UK studies are deemed directly applicable in terms of quantifying the scale of the impact of cutting, but not for informing precise hay cutting date as this is specific to local climate.

5.9 Studies examining the impact of cutting dates tended to consistently apply either the traditional mid to late July, or early (mid-June) to late (September) extremes. Such consistently applied and divergent cutting management is not truly representative of historical cutting regimes as these varied considerable with season (Smith & Jones, 1991), nor of the more homogenised July hay cutting which prevailed under the ESA. Furthermore the impact of these different hay cutting dates was invariably examined in combination with other treatments, ie grazing and/or nutrient input, hence the impact per se of the cutting date was sometimes difficult to factor out. These issues reduce the usefulness of these studies.

Presentation of evidence for sub-question (c)

5.10 Due to the multi-clause nature of sub-question (c), and the number of studies which provide evidence, the question has been further sub-divided into two subsidiary questions as follows:

1) Which spring grazing levels and shut-up dates maintain floristic diversity and breeding bird populations of upland hay meadows?
2) What cutting date maintains floristic diversity and breeding bird populations of upland hay meadows?

5.11 Under each sub-sub question a short summary of the evidence is provided underpinned by a more detailed analysis of the evidence which has been used to derive evidence statements, capturing the nature and strength of the evidence.

5.12 The conclusions section synthesizes the overall evidence base for sub-question (c) and draws conclusions on what constitutes sustainable nutrient management on the basis of this. The recommendations for further research based on identification of gaps in the evidence base are then listed.

Which spring grazing levels and shut-up dates maintain floristic diversity and breeding bird populations of upland hay meadows?

5.13 Eleven studies, ten from the UK and one from the Netherlands, provide evidence on this question comprising:

- Three randomised control experiments (Smith *et al.* (1996) [1+], Smith *et al.* 2012 [1++] and Smith & Rushton (1994) [1++]).
- Five correlative or observational studies (Pacha & Petit (2008) [2++], Beintema & Müskens (1987) [2++], Court *et al.* (2001) [3+], Devereux *et al.* (2004) [2+], Shrubb (1990) [2++] and Small (2002) [2++]).
- One review Fuller (1996) [3+].
- One modelling study Small (2002) [2++].

Summary of evidence

5.14 Two of the three studies on MG3 meadows looked at the impact of cessation of grazing or exclusion of animals in spring or in the aftermath. Whilst these indicate the importance of spring grazing per se in maintenance of floristic diversity in the MG3 community, probably by reducing competition of grasses, they do not provide quantitative evidence on the impact of different spring grazing intensities and durations. Such evidence is limited to one study. This suggests that grazing in spring to an average sward height of 5-6 cm rather than 3-4 cm and that shutting up meadows before the 15th May will maintain floristic diversity.

5.15 The MG3 study also points to an important interaction between spring temperature (T-sum), date at which meadows are shut-up and sward development in any given year suggesting that in warm and wet spring conditions the more vigorous early growth of the plants is likely to be greatly affected by different shut dates, whilst in cold springs date of shut-up may make little difference. The scope to use T-sum to inform the date at which meadows are best “shut-up” should be explored in future.

5.16 Whilst there is substantial evidence proving a relationship between trampling by livestock and losses of nests in ground-nesting birds, which increase with grazing intensity and duration, most of the studies evaluated are correlative. None specify a specific sustainable stocking rate for breeding birds although one study presents a “standardised trampling value” per type of livestock and per bird species from their data (survival rate per animal per hectare per day) which can be used to determine likely losses over a given grazing period.

5.17 There is a clear dichotomy in the preferred grazing intensities of the breeding birds of upland hay meadows between lapwing which prefer a moderate level of grazing to retain a short sward into late spring and the lighter grazed, more heterogeneous vegetation preferred by other breeding birds (snipe, redshank, curlew, whinchat and skylark).

Analysis and evidence statements

Botanical evidence

5.18 Both Smith & Rushton (1994) [1++] and Smith *et al.* (1996) [1+] report that the most extreme vegetation response in MG3 meadows, resulting in significant declines in species number, is elicited by the complete cessation of grazing.

5.19 Smith *et al.* (1996) [1+] report that number of species was significantly higher ($p<0.05$) under the traditional grazing regime of both autumn and spring grazing indicating an important role of spring grazing per se. Furthermore Smith & Rushton (1994) [1++] report that removal of livestock in either spring or autumn produced significant differences in species composition, favouring different groups of species. Interestingly autumn grazing alone with no spring grazing favoured a suite of grasses (sweet vernal-grass *Anthoxanthum odoratum*, rye grass *Lolium perenne*, rough meadow-grass *Poa trivialis* and crested dog's-- tail *Cynosurus cristatus*) whilst spring grazing alone favoured a suite of herbs (wood crane's-bill *Geranium sylvaticum*, melancholy thistle *Cirsium heterophyllum* and great burnet *Sanguisorba officinalis*). These findings suggest an important role of spring grazing in reducing competition by grasses.

5.20 Smith & Rushton (1994) [1++] found that species which have a high nuclear DNA content, which appears to enable growth to begin under low spring temperatures, were associated with the un-grazed treatment. The authors suggest that meadows which are not grazed in spring may provide a niche for early vernal species such as wood anemone *Anemone nemorosa*.

5.21 From this we draw the following evidence statements:

- There is strong evidence from two studies (one [1++] and one [1+]) that cessation of grazing, even where hay cutting is continued, leads to a reduction in floral diversity.
- There is strong evidence from two studies (one [1++] and one [1+]) that spring grazing per se is important in maintaining botanical composition of species-rich MG3 meadows.
- Smith *et al.* 2012 [1++] found that whilst the more intensive grazing treatment (defined by maintenance of an average sward height of 3-4 cm) and later shut-up dates had no effect on species richness, they did reduce diversity as defined by the Simpson and Shannon diversity indices, and increased the apparent (Ellenberg) fertility of the grassland, with particularly significant responses($p \leq 0.011$) associated with the latest shut-up date (27th May). Over four years the higher intensity grazing treatment significantly reduced similarity to MG3b ($p=0.013$), decreased both Simpson ($p= 0.029$) and Shannon diversity ($p = 0.023$) indices whilst increasing Ellenberg fertility score ($p=0.021$). At the high grazing intensity there was a significant interaction with shut-up date, with species richness progressively decreasing with later shut-up date ($p=0.017$). Pacha & Petit (2008) [2++] found that species richness in upland hay meadows was negatively correlated with high grazing intensity ($p<0.01$).
- The Smith *et al.* 2012 [1++] study also reported a number of significant year to year differences in response to treatments and it is suggested that these are linked to variability in spring climate, specifically the over whelming influence of accumulated temperature (T-sum) ie the cumulative sum of the daily mean air temperature above a threshold (in this case 5.6^{o}C) starting from 1 January each year on sward growth. Delaying the date at which sheep are removed delays maturation of the sward, since grazing constantly promotes new leaf growth rather than development of flowers and seeds, as demonstrated by the significant reduction in the hay rattle populations in the 15th and 27th May shut-up dates ($p=0.018$) and taller height in late May of a number of other key community character species under the earlier shut-up date and low intensity grazing treatment (maintenance of an average sward height of 5-6 cm). These finding suggest that in warm and wet spring conditions the more vigorous early growth of the plants is likely to be greatly affected by different shut-up dates. In cold springs date of shut-up may make little difference.

5.22 From this we draw the following evidence statements:

- There is moderate evidence from one [1++] study that if spring grazing is prolonged (with closing date after 15th May) species diversity is reduced and species associated with more eutrophic conditions (Ellenberg N values) increase.
- There is moderate evidence from one [1++] study that grazing to an average of 5-6 cm is better than 3-4 cm in terms of retaining floristic diversity, with another study [2++] indicating that increased grazing intensity is negatively correlated with species richness.
- There is moderate evidence from one [1++] study of an important interaction between accumulated spring temperature (T-sum) in any given year and the rate of sward

development and spring grazing regime, in particular shut-up date, and impact on botanical composition.

Ornithological evidence

5.23 The impacts of spring grazing on breeding waders and passerines has been well researched generally though little specific evidence derives from upland hay meadows. Beintema & Müskens (1987) [2++] found that young cattle caused the most damage by trampling especially when considered in terms of grazing equivalents (LU). Sheep did little harm per individual, but damage increases with stocking density. However, the reduction in nesting success with increased density is less than for the equivalent cattle grazing pressure. Trampling risk was higher for redshank with over 50% of nest losses due to trampling compared to 23% for lapwing. They present a "standardised trampling value" per type of livestock and per bird species from their data (survival rate per animal per hectare per day) which can be used to determine likely losses over a given grazing period.

5.24 Two studies report general association between increased grazing intensity and negative impacts on breeding birds. Shrubb (1990) [2++] found that the percentage of lapwing nests in grassland lost to trampling in any year was significantly correlated with the overall densities of both sheep and cattle on English and Welsh grassland. Court *et al.* (2001) [3+] suggests that increased stocking levels may increase the loss of yellow wagtail nests through trampling, although no quantitative data on changing stocking rates were provided.

5.25 The spring sward height preferences of bird species breeding in grassland varies, with a pronounced dichotomy reported by Fuller (1996) [3+] between lapwing which benefit from a moderate to high level of grazing, maintaining low but not structurally uniform vegetation and the other principal breeding birds of meadows, snipe *Gallingo gallingo*, redshank *Tringa tetanus,* curlew *Numenius phaeopus*, whinchat *Saxicola rubetra* and skylark *Alauda arvensis*, preferring lighter grazed, tussocky vegetation. Small (2002) [2++] similarly reported a strong association between the presence of lapwing and short swards in the first three weeks in June was detected in the Pennine Dales ESA but with medium swards earlier in the season, which may indicate avoidance of trampling. Devereux *et al.* (2004) [2+] found that lapwing foraging rates declined significantly (p<0.001) as sward height increased from just under 2 cm to 10 cm , due to sward height restricting accessibility of the chicks' insect prey.

5.26 From this we draw the following evidence statements:

- There is strong evidence from three studies (two [2++] and one [3+]) proving a relationship between trampling by livestock and losses of nests in ground-nesting birds, which increase with grazing intensity and duration, though no specific stocking levels are advised.
- There is a moderate evidence (one [2++], one [2+] and one [3+]) of a clear dichotomy in the preferred grazing intensities of the breeding birds of upland hay meadows between lapwing which prefer a moderate level of grazing to retain a short sward into late spring, and the lighter grazed, more heterogeneous vegetation preferred by other breeding birds (snipe, redshank, curlew, whinchat and skylark).

What cutting date maintains floristic diversity and breeding bird populations of upland hay meadows?

5.27 Twelve studies provide evidence on this sub-sub question, seven are from the UK whilst five are from mainland Europe and focus on impacts of cutting date on breeding birds. They comprise:

- Two randomised control experiments (Smith *et al.* (1996) [1++], Smith, Pullan & Shiel (1996) [1+]).

- Eight correlative or observational studies (Smith & Jones (1991) [2+], Broyer (2009) [2+], Court *et al.* (2001) [3+], ADAS (1996) [2++], Breeuwer *et al.* (2009) [2+], Kruk, Noordervliet & ter Keurs (1996) [2++], Wilson (1991) [3+] and Greubler *et al.* (2012) [2+]).
- One meta-analysis Humbert *et al.* (2012) [3-].
- One modelling study Green *et al.* (1997) [2+].

Summary of evidence

5.28 Studies comparing hay cutting dates indicate that hay cutting date around the 21st July maintains MG3 grassland in the short term. However, historically the period over which hay-cutting took place extended from July to September, with actual cutting dates varying significantly with the season. With the arrival of mechanisation hay cutting now takes place within a far shorter window with most meadows cut by early August with the result that later flowering species may seldom have the opportunity to set seed within the meadow. Periodic late cutting dates may be helpful in mimicking past management.

5.29 Evidence from a large number of studies shows that cutting of meadows prior to the peak fledging date of the bird studies reduced nest success. For yellow wagtails, which nest later than the breeding waders which use meadows, evidence suggests that delaying cutting until after 8th July enhances breeding success in the short term. Accumulated spring temperature (T-sum) have been shown to influence nesting and fledging in any one year and subject to further research could be used to inform the timing of hay cut under variable spring temperatures to enable better protection for breeding birds.

Analysis and evidence statements

Botanical evidence

5.30 Smith & Jones (1991) [2+] report that between the years 1947 and 1986, hay cutting start dates showed little variation around the 1st July on the five farms studied. In contrast, hay cutting finish dates varied considerably with time, becoming far earlier in later decades as the window for hay cutting was shortened due to mechanisation. Historic data indicate that pre-mechanisation the frequency of very late cutting was as regular as two in every five years on some farms. A significant relationship between sward composition and order of cutting was found on three of the six farms surveyed ($p<0.03$) indicating a definite effect of cutting date. However, this effect was masked on farms where artificial fertiliser had been applied as this had the greatest effect on composition.

5.31 Smith *et al.* (1996) [1++] also detected an effect of cutting date on botanical composition over a four year period with consistent cutting on 21st July maintained the MG3 community, whilst a consistently early September cut tended to shift the sward towards semi-improved grassland. Ruderal species were significantly ($p<0.001$) more abundant with successively earlier hay cuts, whilst stress-tolerating ruderals were favoured by the 21st July hay cut ($p<0.05$). The latest hay cut (1st September) was significantly associated with increasing abundance of competitor species ($p<0.001$) and species with persistent seeds ($p<0.01$) or which are capable of vegetative spread ($p<0.05$).

5.32 Smith, Pullan & Shiel (1996) [1+] found a significant effect of cutting date on seed return from hay for 17 of the 23 species, reflecting species specific differences in the timing of seed production and the amount of seed produced. Grasses produced significantly more seed at the end of the summer with a 20 fold increase in the grass:forb seed ratio (highly significant increase in grasses and decrease in forbs both ($p<0.0001$). The traditional time for hay cutting (21st July) resulted in more seed than the June cut, with nearly equal amounts of forb and grass seed. Smith & Jones (1991) [2+] report on a phenological study of an MG3 meadow that whilst great burnet, *Sanguisorba officinalis*, knapweed *Centaurea nigra* and meadowsweet, *Filipendula ulmaria* have little ripe seed by 21st August and may need intermittent late cuts to allow regeneration by seed. Humbert *et al.* (2012) [3-] found no overall significant effect on plant species richness of delayed mowing in their meta-analysis, but this result was confused by the inclusion of a number of studies where the 'early' cut was in July/August.

5.33 Timing of hay cut effects sward composition in two ways, by influencing the competitive interactions between species through actual removal or biomass and by seed return and resultant regeneration from seed. The evidence does not allow identification of the relative importance of these factors.

5.34 From this we draw the following evidence statements:

- There is moderate evidence from two studies (one [1++] and one [1+]) on the same meadow that a hay cutting date consistently applied on or around the 21st July maintained botanical composition of MG3 grassland in the short term (for example, less than 3 years).
- There is no direct or quantifiable evidence on the importance of periodic late cutting on botanical composition of MG3 meadows.

Ornithological evidence

5.35 Three studies examined the impact of timing of hay cut on yellow wagtails in the Pennine Dales. Court *et al.* (2001) [3+] cite earlier cutting dates of hay meadows, especially where there was a switch to silage, as one of the main reasons for the long term decline in yellow wagtail populations in the Yorkshire Dales, especially when the species fidelity to nesting site is factored in. Wilson (1991) [3+] attribute a nest failure of 31% of surveyed sites in two Pennine Dales to early cutting, whilst ADAS (1996) [2++] report that peak fledging date in Pennine Dales meadows is the last week of June, with approximately 70% of birds fledging prior to the 7th July. The impact of cutting in any one year varying with both the timing of the breeding season and the timing of cutting, this varied widely with spring temperature and rainfall.

5.36 The effect of meadow mowing date on the breeding success of whinchats was considered in two European studies Broyer (2009) [2+], Gruebler *et al.* (2012) [2+]. which both found lower nest survival with early hay making Green *et al.* (1997) [2+] explored effects on breeding success of altering mowing practices on corncrake *Crex crex* through modelling found that moving the mowing date from the end of June to the beginning of September resulted in a very large increase in productivity, but even using an intermediate date of the model (beginning of August) almost doubled the productivity in most iterations of the model presented.

5.37 Kruk, Noordervliet & ter Keurs (1996) [2++] examined the relationship between mowing and hatching dates of grassland waders (lapwings *Vanellus vanellus*, black-tailed godwits *Limosa limosa* and redshanks *Tringa tetanus*) in The Netherlands over an eight year period as influenced by spring temperatures. Both median hatching dates and median mowing dates were closely correlated with T-sums and significant relationships were found for all three species of breeding wader studied ($p<0.05$), with great differences in mowing and hatching dates between years, which were explained by spring temperatures. Although the negative effects of early mowing on the breeding success of waders were smaller as a consequence of this correlation, mowing dates still need to be delayed by an average of 1-2 weeks in order to ensure that required recruitment of chicks is met. T-sum could usefully be used to predict peak hatching for wader species to inform safe cutting date in each year.

5.38 Breeuwer *et al.* (2009) [2+] report that postponement of mowing date alone on land under agri-environmental agreement was insufficient to maintain or increase meadow bird densities since other aspects of meadow management, namely drainage and nutrient inputs were judged to be indirectly affecting bird densities by reducing both the total amount of invertebrate prey available and its accessibility to the birds.

5.39 From this we draw the following evidence statements:

- There is strong evidence from eight (four [2+], two [2++] and two [3+]) studies to show that cutting of grassland prior to the peak fledging date (this varied according to species) reduced nest success in a range of breeding birds of meadows.
- There is strong evidence from three studies (one [2++] and two [3+]) showing that delayed cutting of meadows in the Pennine Dales can enhance breeding success of yellow wagtails in the short term.
- There is limited evidence from one study [2++] that T-sum could be used to inform timing of hay cut under variable spring temperatures to better protect breeding birds.

Conclusions

5.40 Evidence indicates that spring grazing per se is important for maintenance of floristic diversity in the MG3 community, probably through reducing competition of grasses. Quantitative evidence on the impact of different spring grazing intensities and durations is limited to one study which suggests that grazing to an average sward height of 5-6 cm rather than 3-4 cm and that shutting up meadows before the 15th May will maintain floristic diversity. This study also points to an important interaction between spring temperature (T-sum), date at which meadows are shut-up and sward development in any given year, with significant effects on botanical composition. The scope to use T-sum to inform the date at which meadows are best "shut-up" should be further explored.

5.41 Whilst there is substantial evidence proving a relationship between trampling by livestock and nest losses of nests in ground-nesting birds, which increase with grazing intensity and duration, most of the studies evaluated are correlative. None specify a sustainable stocking rate for breeding birds, although one study presents a "standardised trampling value" per type of livestock and per bird species from their data (survival rate per animal per hectare per day) which can be used to determine likely losses over a given grazing period.

5.42 There is a clear dichotomy in the preferred grazing intensities of the breeding birds of upland hay meadows between lapwing which prefer a moderate level of grazing to retain a short sward into late spring and the lighter grazed, more heterogeneous vegetation preferred by other breeding birds (snipe, redshank, curlew, whinchat and skylark).

5.43 Studies comparing hay cutting dates indicate that consistently cutting on the 21st July maintains MG3 grassland in the short term (over four years). However, the window of time in which hay cutting takes placed is significantly shorter than in the period before mechanisation, with most meadows cut by early August instead of cutting extending into September. Periodic late cutting may be helpful in mimicking this past management and allowing return of later seeding species, however no direct or quantifiable evidence exists to support this assertion.

5.44 Evidence from a large number of studies shows that cutting of meadows prior to the peak fledging date of the bird studies reduced nest success. For yellow wagtails, which nest later than the breeding waders which use meadows, evidence suggests that delaying cutting until after 8th July enhances breeding success in the short term. Accumulated spring temperature (T-sum) have been shown to influence nesting and fledging in any one year and subject to further research could be used to inform the timing of hay cut under variable spring temperatures to enable better protection for breeding birds.

Evidence gaps and research recommendations

5.45 Available evidence suggests that there may be merit in using T-sum to inform both meadow shut-up dates and hay cutting times as a way of encouraging seasonally appropriate variability in meadow management, rather than specifying specific cut off dates.

5.46 The feasibility of determining and applying a threshold T-sum, to inform the time at which meadows are shut-up in any given year should be investigated across a range of MG3 sites and impacts on botanical composition and breeding birds assessed.

5.47 There is no evidence to quantify the importance of periodic regeneration by seed of some of the medium to longer lived perennials of hay meadows. The importance of intermittent late cuts in enabling this regeneration is assumed due to the longer window for hay cutting pre-mechanisation but is not proven.

5.48 Research or modelling would be useful on the importance of regeneration by seed in maintaining populations of long-lived perennials within MG3 meadows to inform long term hay cutting strategies.

5.49 Available evidence suggests that the historical management patterns and the climatic context in which that management takes place, for example, prolonged period of high spring rainfall, could be important in informing meadow management regimes today and in the future.

5.50 Investigation of the historical management of hay meadows and their changing climatic and environmental context.

6 Wider issues: consideration of the influence landscape scale processes on upland hay meadows biodiversity

Landscape scale factors and processes

6.1 There are a number of processes that operate at the landscape scale that will also impact directly and indirectly on the flora and fauna of the meadows. Furthermore, the biodiversity value of any one field is strongly influenced by its surroundings, whilst changes within any individual field can impact on the biodiversity value of the wider landscape (McCracken & Tallowin, 2004).

6.2 Consequently assessments of the biodiversity impact of changes to agricultural management practices need to be considered at both the field and wider landscape scale. In particular the contributions of, and interactions between, other farmed and non-farmed habitats, for example, road-side verges, needs to be considered.

6.3 The relative impact of these processes will need to be accounted for in management guidance and agri-environment scheme targeting strategies. Key considerations are described below:

Atmospheric deposition of pollutants

6.4 Between 1860 and 1995 the global creation of reactive nitrogen (all forms of nitrogen that are biologically or photochemically active) increased from 15 to156 Tg N year^{-1}. Between 1995 and 2005, it increased further reaching 187 Tg N year^{-1} (Galloway *et al.* 2008). With continued population growth and the consequent increase in food production, emissions of reactive nitrogen are likely to increase further (Tilman, 1999). In Europe nitrogen deposition has shown a slight decline between 1980 and 2003 (Fagerli & Aas, 2008), but in many areas of the UK levels of deposition remain above those that are known to have an impact on semi-natural ecosystems. The critical load is ''a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur, according to present knowledge'' (Nilsson & Grennfelt, 1988).

6.5 For species-rich mountain hay meadows the critical load is 10-20 kg N ha^{-1} yr^{-1}. Exceeding the critical load is likely to lead to a general increase in competitive grasses and a decline in forbs, resulting in eventual reductions in species diversity. These changes are in contrast to sulphur emissions which have been reduced by between 90 and 70% since the 1970s leading to rapid declines in deposition (Fowler, 2007). Reduced sulphur deposition has led to reduced levels of acidity in terrestrial and freshwater habitats. The Countryside Survey soil analysis has shown a significant increase ($p<0.05$) in the pH of topsoil in the neutral grassland broad habitat from a mean of pH 5.52 in 1978 to pH 6.14 in 2007 (RoTAP, 2012).

Habitat fragmentation

6.6 The pattern and relative proportions of unimproved and improved fields may also be significant factor in sustaining viable populations at a landscape scale for some species. Research by Small (2002) indicates that although breeding waders may tolerate certain levels of agricultural intensification, particularly if in-field wet areas are maintained, there may be thresholds above which the likelihood of wader occurrence drops off sharply. For most wader species, a decline in density was predicted when surrounding habitat was close to 40% improved grassland in the Pennine Dales ESA.

6.7 Similarly the life-history strategies of certain MG3 species indicates that traditional meadow management may rarely allow regeneration by seed (Smith & Rushton, 1991). Whilst many of these species are perennials, it is hypothesised that the long-term persistence of populations within meadows may partly depend on dispersal of propagules from elsewhere in the landscape, for example roadside verges or lightly grazed banks within hay meadows themselves, especially where species-rich meadows are highly fragmented. The value and relative stability of these habitat fragments in providing refugia for species-rich hay meadow communities and key species is recognised by O'Reilly (2010) and Pacha (2004).

Temporal variation in management

6.8 Hay cutting now takes place over a significantly shorter period compared to 50 years ago (Smith & Jones, 1991), leaving far fewer meadows uncut in August and early September. The homogenisation of hay cutting dates within a few short weeks is likely to have consequences for botanical composition over the medium to long term, with the same July seeding species benefiting from regeneration opportunities year on year, whilst later seeding species are disadvantage. Furthermore, loss of the flower-rich hay meadow resource within the landscape into August and September is likely to have a significant and deleterious impact on certain bird and invertebrate species which feed in them. Raine (2006) report that maintaining hay meadows with seeding plants throughout the breeding season is important in providing a continuous supply of granivorous food resource to species such as linnet and twite (Raine, 2006). Twite, are found to actively select fields with a higher percentage of flowering food plants (Raine, 2006).

Inter-relationship with management of open moorland

6.9 Stocking restrictions on the open fells in spring, aimed at improving breeding success of waders nesting on open moorland have led to increased stocking densities in the in-bye meadows and grazing continuing later into May than was commonly practiced in the past. The inter-relationship between the open moorland and enclosed in-bye must be considered when changes to management practices are proposed to either. Stocking increases on in-bye and the balance of stock shifts in favour of more sheep and fewer cattle in these areas.

7 Conclusions

What management regimes maintain the floristic diversity and populations of breeding birds within upland hay meadows?

7.1 Overall the evidence evaluated provides support for a recognisable traditional annual management cycle as described in Section 1 under Definitions and description, but with:

- more meadow specific tailoring of nutrient input regimes according to soil nutrient status, past history and management objectives;
- less uniformity of hay cutting dates at the landscape scale than has been the case in the last 20 years to mimic the longer window for hay cutting that existed in the past when botanical diversity was higher;
- more flexibility to respond to spring weather conditions in any one year, for example by early shut-up of meadows in warm springs, though further work is required to inform this.

What types, rates of application and timing/periodicity of nutrient and lime applications maintain the floristic diversity and breeding bird populations of upland hay meadows?

7.2 There is strong evidence showing that nutrient applications of c. 18 kg N ha^{-1} yr^{-1} or greater led to significant reductions in floristic diversity in upland hay meadows and meadows on related neutral grassland types. The limited available evidence specific to FYM inputs indicates that rates of 12 tonnes ha^{-1} $year^{-1}$ (equivalent to 9 kg N ha^{-1}, 10 kg P ha^{-1} and 69 kg K ha^{-1} annually) may maintain current diversity on MG3 meadows which have a history of inputs at this rate, but that botanical enhancements (increases in the cover of positive indicator species) occurred at the lower rate of 6 tonnes FYM ha^{-1} $year^{-1}$.

7.3 However, there is strong evidence to suggest that botanical responses to nutrient applications are driven by which ever macro-nutrient is growth-limiting in the grassland and potentially by historic nutrient inputs. As a consequence the nutrient regime of any given meadow should be informed by its soil nutrient status, grass utilisation, past fertility management and conservation objectives.

7.4 The evidence suggests that the amount of nutrients applied (rate) is the single most important factor influencing botanical response, with the evidence for any additional differential impacts of form (FYM versus inorganic fertilizers) being very limited and equivocal. Similarly the little evidence which does exist for MG3 and related grassland types suggests there is no significant effect of either different timings and or frequencies of nutrient inputs on floristic diversity. Occasional liming to maintain a pH of around 6 appears consistent with maintaining vegetation quality on MG3 hay meadow with a past history of lime application.

7.5 In contrast evidence for breeding birds suggests that there are benefits associated with FYM application through increasing prey abundance and availability, and with avoidance of any agricultural operations (including nutrient inputs) in spring when lapwing are breeding. Whilst no studies examined the impact of application frequency on breeding waders, as a general principle, less frequent applications might be predicted to be beneficial in reducing overall disturbance to nests and fledglings.

What management methods or approaches control rushes (*Juncus* spp.) in upland hay meadows and maintain the floristic diversity of the meadows?

7.6 There was little available evidence on rush control on species-rich grasslands and no evidence relating to their control within upland hay meadows.

7.7 Available evidence suggests that mowing rushes flush with the ground at least twice during the summer can reduce their vigour, and where only one cut is possible a late summer cut is most effective. Herbicide by weed wiping application, can also be effective, although not without damage to other vegetation. Care should be taken to avoid poaching and creation of bare ground, which abundant rush seed will quickly exploit.

What spring-grazing levels, timing of shut-up/closure for hay and cutting dates maintain the floristic diversity and breeding bird populations of upland hay meadows?

7.8 Quantitative evidence on the impact of different spring grazing intensities and durations is limited to one study, which suggests that grazing to an average sward height of 5-6 cm rather than 3-4 cm and that shutting up meadows before the 15th May will maintain floristic diversity. This study also points to an important interaction between spring temperature (T-sum) and sward development in any given year and date at which meadows are shut-up, with significant effects on botanical composition particularly likely in warm, wet years. The scope to use T-sum to inform the date at which meadows are best "shut-up" should be further explored.

7.9 Whilst there is good evidence proving a relationship between trampling by livestock and losses of nests in ground-nesting birds, which increase with grazing intensity and duration, most of the studies evaluated are correlative. None specify a sustainable stocking rate for breeding birds, although one study presents a "standardised trampling value" per type of livestock and per bird species from their data (survival rate per animal per hectare per day) which can be used to determine likely losses over a given grazing period.

7.10 There is a clear dichotomy in the preferred grazing intensities of the breeding birds of upland hay meadows between lapwing which prefer a moderate level of grazing to retain a short sward into late spring and the lighter grazed, more heterogeneous vegetation preferred by other breeding birds (snipe, redshank, curlew, whinchat and skylark).

7.11 Studies comparing hay cutting dates indicate that consistently cutting on the 21st July maintains MG3 grassland in the short term (over 4 years). However, the window of time in which hay cutting takes place is significantly shorter than in the period before mechanisation, with most meadows cut by early August instead of cutting extending into September. Periodic late cutting may be helpful in mimicking this past management and allowing return of later seeding species, however no direct or quantifiable evidence exists to support this assertion.

7.12 Evidence from a large number of studies shows that cutting of meadows prior to the peak fledging date of the bird studies reduced nest success. For yellow wagtails, which nest later than the breeding waders which use meadows, evidence suggests that delaying cutting until after 8th July enhances breeding success in the short term. Accumulated spring temperature (T-sum) has been shown to influence nesting and fledging in any one year and subject to further research could be used to inform the timing of hay cut under variable spring temperatures to enable better protection for breeding birds.

Research recommendations

7.13 Assessment of the available evidence indicates that the following areas would benefit from further research:

- Examination of the impacts of N application ≤20 kg N ha^{-1} yr^{-1} on floristic diversity (with directly equivalent FYM treatments) across a range of MG3 meadows with different nutrient management histories.
- Exploration of the role of P in influencing floristic diversity on MG3 meadows.
- Investigation of the impact of different seasonality and periodicity of nutrient input on MG3 meadows and their impacts on both botanical composition and breeding birds.
- Trialling of sustainable, non-damaging rush control measures (including the use of lime) on MG3 meadows.

- The feasibility of determining and applying a threshold T-sum, to inform the time at which meadows are shut-up in any given year. This should be investigated across a range of MG3 sites and impacts on botanical composition and breeding birds assessed.
- Determination of the importance of regeneration by seed in maintenance of populations of long lived perennials within MG3 meadows.
- Investigation of the historical management of hay meadows and their changing climatic and environmental context.

8 Glossary of terms

Term	
Botanical composition	The relative proportion of all the species which make up the sward.
Ellenberg N	Ellenberg N values estimate the position along a productivity/macro-nutrient availability gradient at which a species reaches peak abundance. The Ellenberg N Index consists of allocating a N score to each plant species, so that the overall mean score for the community lies on a scale of nutrient poor (1) to nutrient rich (10). Calculating mean values for sampled vegetation allows spatial or temporal changes in productivity to be inferred.
Floristic/Botanical diversity	to include both species evenness (relative abundance) and species richness (number of species/unit area).
FYM	'Farmyard manure'; manure consisting of animal excreta incorporated with bedding material, usually straw, which has been stored to allow some rotting to take place prior to spreading on the land.
Hay meadow	Grassland where grazing animals are excluded for all or part of the year in order to grow a crop of herbage for hay.
In-bye	Enclosed grassland, often surrounding farm buildings.
Inorganic	Fertiliser produced by mining rock or by industrial process.
K	Potassium
K_2O	Potash
Mg, MgO	Magnesium, magnesium oxide
Lime	Lime has no precise chemical meaning and is used to describe various materials, most commonly calcium carbonate $CaCO_3$ as limestone or chalk but sometimes also calcium oxide (CaO,) which is also called burnt or quicklime, and calcium hydroxide $Ca(OH)_2$, which is also known as hydrated or slaked lime. Even basic slag and other industrial by-products with a high base content are sometimes referred to as "lime" but such materials should not be treated as equivalent as they may supply other nutrients besides calcium.
N	Nitrogen
National Vegetation Classification (NVC)	A phytosociological classification describing the plant communities of the British Isles.
P, PO_4^{3-}	Phosphorus, phosphate
P_2O_5	Phosphorus pentoxide
Pasture	Grassland which is grazed by livestock and not shut-up for part of the year for hay production.
S, SO_3	Sulphur or equivalent amount of sulphur expressed as sulphur trioxide.

Table continued…

Term	
Slurry	Semi-fluid mixture of animal faeces and urine deposited in buildings where livestock (principally cattle, pigs and poultry) are housed with little or no bedding. Slurry is normally stored before field spreading.
Species richness	Total number of non-native and native taxa per plot (excluding lichens, mosses and liverworts but counting species recorded to genus only or amalgamations of two taxonomically difficult species). This is a simple measure of plant diversity. Increases in plant diversity may not always be beneficial for habitats.
T-sum	The temperature sum is the cumulative sum of the daily mean air temperature above a threshold value (usually 5.5^{o}C) starting from 1 January each year. Sometimes referred to as day-degrees or accumulated heat units.
Vegetation quality	Reflects both the overall plant-species diversity and the frequency of those species that are characteristic of the habitat. In the case of this evidence review, characteristic species are taken to be those listed as community constants in the published description of the MG3 community (Rodwell, 1992).

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Appendix 1 Details of evaluated studies

Table A Details of evaluated studies

Study	Duration	Country	Study type & quality	Sub-question
ADAS (1993)	NA	UK	4-	a
ADAS (1996)	NA	UK	2++	c
Aerts, de Caluwe & Beltman (2003)	11 yrs	Netherlands	2+	a
Askew (1993)	2 years	UK	2+	a
Baines (1990)	3 yrs	UK	2++	a
Breeuwer (2009)	12 yrs	Netherlands	2+	c
Broyer (2009)	1 yrs	France	2+	c
Cherril (1995)	NA	UK	2++	b
Court *et al*. (2001)	1 yrs	UK	3+	c
Crawley *et al*. (2005)	107 yrs	UK	2+	a
Critchley *et al*. (2002)	NA	UK	2-	a
Critchley, Fowbert & Wright (2007)	15 yrs	UK	2-	a and c
Devereux *et al*.(2004)	1 day	UK	2+	c
Edwards & Younger (2006)	1-2 yrs	UK	1++	a
Fuller (1996)	NA	UK	3+	c
Green *et al*. (1997)	1 yr	Scotland/Eire	2+	c
Gruebler *et al*.(2012)	1 yr	Switzerland	2+	c
Hochberg & Zopf (2011)	39 and 18 yrs	Germany	2-	a
Honsova *et al*. (2007)	15 yrs	Czech Republic	1+	a
Humbert *et al*.(2012)	NA	Europe	3-	c
Jeangros, Sahli & Jacot (2003)	6 yrs	France	2-	a
Kirkham *et al*. (2012)	12 yrs	UK	1++[a] or 1+[b]	a
Kirkham *et al*. (2008)	6 yrs	UK	1+	a
Kirkham, Mountford & Wilkins (1996)	8 yrs	UK	1++	a
Kruk, Noordevliet & ter Keurs (1996)	8 yrs	Netherlands	2++	c

Table continued…

Study	Duration	Country	Study type & quality	Sub-question
Lawes, Gilbert & Masters (1882)	8 yrs	UK	2+	a
Mercer, Reavey & Morgan (2008)	4 yrs	Ireland	1+	b
Merchant (1995)	3 yrs	UK	1++	b
Mountford, Lakhani & Kirkham (1993)	8 yrs	UK	1++	a
O'Brien (2002)	2 years	UK	2+	c
Pacha & Petit (2008)	NA	UK	2++	c
RSPB management guidelines (2007)	NA	UK	4-	b
Shrubb (1990)	NA	UK	2++	c
Simpson & Jefferson (1996)	NA	UK	3++	a
Small (2002)	6 yrs	UK	2++	a and c
Smith & Jones (1991)	1 yr	UK	2+	c
Smith & Rushton (1994)	5 yrs	UK	1++	c
Smith *et al*. (1996)	4 yrs	UK	1++[c] or 1+[d]	a and c
Smith, Pullan & Shiel (1996)	1 yr	UK	1+	a and c
Smith *et al*. (2012)	5 yrs	UK	1++	c
Smolders *et al*. (2008)	3 months	Netherlands	2-	b
Starr-Keddle (2011)	NA	UK	2-	a
Starr-Keddle (2012)	NA	UK	2-	a
Tallowin *et al*. (1994)	NA	UK	1++	a
Tallowin (1996)	7 yrs	UK	1++	a
Tallowin (1998)	NA	UK	3++	a
Wilson (1991)	1 yrs	UK	3+	c
Vickery *et al*. (2001)	NA	UK	3++	a

[a] assessed as 1++ for lime component of study; [b] assessed as 1+ for FYM and inorganic equivalent components of study. [c] assessed as 1++ for fertiliser component of study; [d] assessed as 1+ for the grazing component of the study.

Appendix 2 Summary descriptions of evaluated studies with key findings relevant to the review

Sub-question (a) What types, rates of application and timing/periodicity of nutrient and lime applications maintain the floristic diversity and breeding bird populations of upland hay meadows?

The studies

Twenty-two studies, eighteen UK based and four from mainland Europe, provide evidence on sub-question (a). For the purposes of clarity studies have been split into those which focus on botanical composition and those which focus on impacts on breeding birds.

Botanical studies

ADAS (1993) [4-] undertook a literature review which summarised information on the known nutrient requirements of grassland, the main sources and forms of fertiliser (inorganic and organic), and differences in their impact. Whilst the focus of the review was unimproved grassland of nature conservation value, particularly hay meadows there was relatively little information available for this grassland type, so it was necessary to consider data from more intensively managed grassland. They reported that it is likely that lower nutrient inputs will increase species diversity, and that there is no evidence to indicate differences in the effectiveness of inorganic compared to organic fertilisers of the same NPK analysis in their effect both on grass growth and on sward botanical diversity.

Aerts, de Caluwe & Beltman (2003) [2+] studied the effects over 11 years of experimentally increased N and P supply on botanical composition of a riverine meadow in The Netherlands which was mown and aftermath grazed. The four treatments comprised: an unfertilised control; N only; P only and N + P together. N and P were applied in granular form twice a year in the form of NH_4NO_3 (100 kg N ha^{-1}) and NaH_2PO_4 (50 kg P ha^{-1}). Species richness was found to be highest under the non-fertilised control (22 species per plot). Addition of N resulted in a significant ($P<0.05$) reduction in species diversity and evenness with a strong reduction in the number of legumes and a strong increase in grasses on the riverine grassland. Addition of the growth limiting nutrient for this grassland (N), either alone or in combination with P, led to lower species diversity and higher biomass. No such effects were observed with additions of the non-limiting nutrient (P), on its own.

Askew (1993) [2+] analysed botanical and management data from a sample of meadows in the ESA in 1987 and 1989 to identify management associated with meadows of high or low conservation interest. Applications of lime was one of several management factors found to be important in distinguishing meadows with conservation interest.

Critchley, Fowbert & Wright (2007) [2-] analysed botanical monitoring data from a sample of upland hay meadows within the Pennine Dales Environmentally Sensitive Area (ESA) to assess change in vegetation composition over a 15 year period and its relationship with management practices including inorganic fertiliser, FYM rates and lime applications. They found a significant increase ($p <0.05$) in Ellenberg N values between 1987 and 2002 in the modified species-rich sample, (grasslands with close similarity to MG3). Furthermore Ellenberg N-values were more likely to increase at higher soil pH ($p<0.05$) and extractable P ($p<0.01$). In contrast, change in species composition of species-rich MG3 meadows over the 15 year time scale studied was found to be associated with lower soil extractable K values ($p<0.01$).

Edwards & Younger (2006) [1++] studied the extent to which manure may be beneficial in maintaining or improving plant diversity in MG3 by the return of viable seed of species of conservation interest back to the meadows in the dung of cattle. They showed that whilst the hay of MG3 meadows contains viable seed of many species, far fewer seeds remain viable after passing through the digestive system of cattle. Furthermore very few of these species were of conservation interest, with a high occurrence of grasses. FYM was found to be a poor means of seed dispersal for most herb species but had some value for dispersing seed of meadowsweet *Filipendula ulmaria* and great burnet *Sanguisorba officinalis*, which seem to be resistant to damage.

Hochberg & Zopf (2011) [2-] examined responses in the botanical composition of three mountain meadows in Germany over an 18 year period to different cutting and fertiliser applications. Treatments were:

1) Three cuts annually with the first cut at silage stage, plus application of optimal amount of NPK fertiliser according to the yield (N was applied at between 130 to 200 kg ha^{-1} yr^{-1}, P applied at between 25 and 30 kg ha^{-1} yr^{-1} and K applied at 149 - 220K kg ha^{-1} yr^{-1}).
2) Two cuts annually with the first cut at hay stage, 60 kg N ha^{-1} yr^{-1},P and K applied to replace that lost in the hay cuts; 3. one cut at beginning of July, without N fertilization but P and K to replace that lost in the hay cut.

Over the course of the experiment the proportion of herbs declined linearly from treatments with high to low nutrient inputs, whilst legumes showed the reverse trend. Total species number was stable and the grassland community was reported to have been maintained under all nutrient treatments. However the confounding influence of the cutting regime should be recognised in interpreting these results, as treatment 1 whilst under higher NPK input was subject to three cuts annually, treatment 2 under intermediate NPK input had two cuts annually whilst treatment 1 under no N and low PK input had one cut alone.

Honsova *et al.* (2007) [1+] examined how plant species richness and composition of an alluvial meadow in the Czech Republic changed in relation to additions of NPK over 40 years. Treatments implemented in1966 were: an unfertilised control; P applied at 40 kg ha^{-1} yr^{-1} and K applied at 100 kg ha^{-1} yr^{-1}; four treatments with N applied at between 100 and 400 kg ha $^{-1}$ yr^{-1} with 40 kg P ha^{-1} yr^{-1} and 100 kg K ha^{-1} yr^{-1} (rates of 300 and 400 N kg ha^{-1} yr^{-1} were added in 1975). From 1990 onwards the N application rates were reduced by half giving a control, PK only; N50PK; N100PK; N150PK and N200PK. The meadow was managed by cutting alone. Cover of herbs and species richness were highest in the unfertilised control, followed by the P and K only treatment. Both these treatments differed significantly from all treatments supplying N although no specific p values was given. Species richness ranged from 24 species/m^2 in the control to 8 species/m^2 in the treatment supplying 200 kg N ha^{-1} yr^{-1}, 40 kg K ha^{-1} yr^{-1} and 100 kg K ha^{-1} yr^{-1}. The tall grasses, meadow foxtail *Alopecurus pratensis*, and meadow grass *Poa pratensis*, dominated the swards in all treatments with N. Where P and K were applied alone they had no significant effect on species richness. This was attributed to N being the nutrient which limited growth of grasses at the study site.

Jeangros, Sahli & Jacot (2003) [2-] studied the impact of manure on its own and in combination with liming agents, and inorganic fertilisers, on botanical composition of a meadow in the Swiss Jura over a period of six years. Treatments applied were:

1) Ammonium nitrate 100 kg ha^{-1} yr^{-1}, Triple P 110 kg ha^{-1} yr^{-1}, 125 kg K ha^{-1} yr^{-1};
2) Manure 15 tonnes ha^{-1} yr^{-1};
3) Manure 15 tonnes ha^{-1} yr^{-1} + rock phosphate 135 kg ha^{-1} yr^{-1}; and
4) Manure 15 tonnes ha^{-1} yr^{-1} plus calcified seaweed 2.78 tonnes ha^{-1} yr^{-1}.

Botanical composition changed significantly over five years in response to both inorganic and manure treatments, with non-legume forbs significantly decreasing. Grasses increased by 10% in all treatments with the exception of application of manure only.

Kirkham et al. (2012) quantified the effects of FYM treatments and inorganic fertiliser supplying equivalent amounts of NPK on botanical composition of one upland and one lowland hay meadow over a 12-year period. The aim of this study was in to inform sustainable nutrient regimes on MG3 and MG5 meadows. The effects of different periodicities of application were examined, to determine whether inorganic fertiliser or FYM, applied either triennially, or at correspondingly lower rates annually, differs in its impacts. The effect of lime, on its own and in combination with FYM, were also examined. Specific treatments were as follows 6, 12 or 24 tonnes ha^{-1} yr^{-1} applied annually or triennially, or the inorganic equivalents to applying 12 or 24 tonnes FYM ha^{-1} either annually or triennially over the 12 years. The highest rate of FYM applied at 24 tonnes ha^{-1} annually equates to inorganic application of c.17 kg N ha^{-1} yr^{-1}, 17 kg P ha^{-1} yr^{-1} and 138 kg K ha^{-1} yr^{-1}, whilst the lowest rate of inorganic supplied, equivalent to FYM applied at 12 tonnes ha^{-1} triennially was 3 kg N ha^{-1} yr^{-1}, 4 kg P ha^{-1} yr^{-1} and 23 kg K ha^{-1} yr^{-1}. Lime was applied either alone or with 12 tonnes FYM ha^{-1} annually or triennially.

Impacts on MG3 meadow - At the MG3 meadow FYM at 24 tonnes ha^{-1} yr^{-1} (equivalent to 17.6 kg N ha^{-1}, 20 kg P ha^{-1} and 138 kg K ha^{-1}) significantly reduced total species-richness and richness of positive indicator species and increased aggregate cover of negative indicator species in the MG3 meadow. Under FYM inputs at 12 tonnes ha^{-1} yr^{-1} (c 9 kg N ha^{-1}, 10 kg P ha^{-1}, and 69 kg K ha^{-1} annually) vegetation quality was maintained by continuing this treatment (FYM had historically been applied at this rate). However, vegetation quality was enhanced under treatments supplying around 4.4 kg N ha^{-1} yr^{-1}, 5 kg P ha^{-1} yr^{-1} and 34.5 kg K ha^{-1} yr^{-1} (ie the low rate annual FYM treatment of 6 tonnes ha^{-1} yr^{-1}, the medium FYM rate of 12 tonnes ha^{-1} applied every three years and its inorganic equivalent). Swards under these treatments had a significantly higher percentage cover of positive indicator species compared to the annual FYM application at 12 tonnes ha^{-1} yr^{-1}. Despite effects on species richness, most treatments retained a close affinity to MG3b after 12 years of inputs, with the exception of the high rate of annual FYM 24 tonnes ha^{-1} yr^{-1} which moved to a position intermediate between MG3a and MG3b, MG3a representing the less species rich sub-community of MG3.

Impact on MG5 meadow - At the lowland MG5 meadow which had no recent history of nutrient input, rates equivalent to only ≤ 4 tonnes FYM ha^{-1} yr^{-1} were sustainable. FYM application at 12 tonnes FYM ha^{-1} yr^{-1} was detrimental. There was little evidence of vegetation adapting to initially damaging fertility inputs at either meadow. The authors considered that responses of vegetation may in part reflect historic adaptations to nutrient and lime inputs.

FYM versus Inorganic fertilisers - Inorganic fertilisers were apparently no more detrimental to vegetation quality than equivalent FYM, and sometimes less so. The best-fit model for species-richness in the upland meadow showed a significant difference in response between FYM and inorganic treatments ($p<0.024$). Inorganic treatments were slightly more species-rich with respect to positive indicators at a given level of N or P input than FYM (by 0.75 and 0.62 Positive Indicator species per m^2 according to the N and P models respectively).

However the authors acknowledge that discrepancies between FYM and inorganic counterparts could be largely accounted for by lower amounts of P supplied in the inorganic 'equivalent' treatments than in corresponding FYM treatments between 1999 and 2006. From 2007 onwards, adjustments were made to correct this. Despite this over the course of the experiment inorganic treatments received less nutrients (especially P) than their FYM comparators, hence the impact on botanical composition might have been expected to be less than if a truly equivalent rate had been applied. The authors state that remaining differentials between the two nutrient forms might have narrowed further, following the corrections to rate, with a longer duration of study, and that revised estimates of both N and P availability may not have fully accounted for the likely cumulative residual effects of FYM.

Periodicity of application - Once the mean amount of nutrients supplied annually over the duration of the experiment (12 years) had been accounted for, there was no detectable impact of triennial, compared to annual, application at correspondingly lower amounts on botanical composition.

Impact of lime - Liming alone had little or no detrimental effect on vegetation on either the upland MG3 meadow or lowland MG5 meadow. Liming reduced botanical quality of vegetation when applied in conjunction with annual FYM at the lowland meadow site, but not at the upland site.

The **Tadham Moor Study** examined the effects of inorganic fertiliser treatments on flower rich hay meadows corresponding to the National Vegetation Classification types MG5 and MG8 in the Somerset levels. It comprised two experiments: the large-scale experiment reported in **Mountford, Lakhani & Kirkham (1993) [1++], Tallowin *et al*. (1994) [1++]** and **Tallowin (1996) [1++]** and the small-scale experiment reported in **Kirkham, Mountford & Wilkins (1996) [1++]**.

The large-scale experiment examined the effects on botanical composition of five inorganic N treatments applied annually: 0, 25, 50, 100 and 200 kg ha^{-1} yr^{-1} over eight years, with P and K applied on all plots except the control, in amounts sufficient to replace that removed in the hay crop. The plots were managed by a summer hay cut and aftermath grazing. Addition of nitrogen fertiliser at levels as low as 25 kg ha^{-1} yr^{-1} (and with other nutrients applied at very low rates only to replace that lost by hay cutting, c 9 kg P ha^{-1} yr^{-1} and c 60 kg K ha^{-1} yr^{-1}) led to reduced botanical diversity and an increased abundance of competitive species, particularly the grasses Yorkshire fog *Holcus lanatus* and perennial rye grass *Lolium perenne*, after seven years. The extent and speed of changes reflected the amount of N applied, significant reductions in species number occurred within two years under inputs of 100 or 200 N kg ha^{-1} yr^{-1}, three years with inputs of 50 N kg ha^{-1} yr^{-1} and 6 years under 25 N kg ha^{-1} yr^{-1}. The number of flowering plants of species indicative of MG8 declined in response to fertiliser input. Meadow thistle *Cirsium dissectum*, ragged robin *Lychnis flos cuculi*, cuckoo flower *Cardamine pratensis*, greater bird's-foot trefoil *Lotus pedunculatus* and meadowsweet *Filipendula ulmaria* almost completely disappeared in plots receiving high N inputs. Prior to 1986 these were all abundant, but after seven years of fertiliser applications they were only common on the control plots receiving no inputs. Low growing forbs and sedges declined significantly in abundance on plots receiving fertiliser.

A wider range of N, P and K inputs were applied within the **small-scale experiment** over a period of four years under cutting management alone. The experiment aimed to determine the impact of different rates of N between 0 and 200 kg ha^{-1} yr^{-1}, in combination with different rates of P up to 75 kg ha^{-1} yr^{-1} and K up to 200 kg ha^{-1} yr^{-1} under a management regime of two hay cuts with no aftermath grazing. Treatments that included N applied at 25 kg ha^{-1} yr^{-1} with both P and K replaced at c 13 kg P ha^{-1} yr^{-1} and between 56 to 106 kg K ha^{-1} yr^{-1}) significantly reduced ($p<0.05$) Simpson's index of botanical diversity compared to the control after just one year. Within two years species diversity was significantly lower on plots receiving N100 with the high rate of P at 75 kg ha^{-1} yr^{-1} than on those receiving the same amount of N but with replacement P and K only ($p<0.01$). Ordination studies indicated that botanical change was in fact influenced to a greater extent by P than by N. Where P was applied without N changes in species richness and diversity were minimal even at the high application rate of 75 kg P ha^{-1} yr^{-1}. Varying the proportions of the total N applied annually between spring and mid-summer (after hay cutting) had no significant effect on either species richness or species diversity of the vegetation. However, the authors suggest that this finding may be attributable to the overriding effect of replacing P and K, in both spring and mid-season.

In the **Park Grass Experiment**, different combinations of fertilisers have been applied annually since 1856 to MG5 grassland cut for hay each year and their effects compared with those of farmyard manure and an unfertilised control. **Lawes, Gilbert & Masters (1882) [2+]** report the impacts of initial treatments in which nitrogen was applied annually in three amounts (48, 96 and 144 kg ha^{-1}) as ammonium sulphate and in two amounts as sodium nitrate (48 and 96 kg ha^{-1}) together with P supplied at 35 kg ha^{-1} and K supplied at 225 kg ha^{-1}. Application of FYM at 35 tonnes ha^{-1} annually was included in the initial treatments but discontinued after eight years, this is equivalent to 240 kg N ha^{-1}, 45 P kg ha^{-1} and 350 kg K ha^{-1}, thereby supplying higher rates of nutrients than the inorganic equivalents. The early nutrient input treatments of the Park Grass Experiment, both FYM and combinations of NPK quickly caused significant change in the proportions of the grasses, legumes in the herbage. Nitrogen fertiliser suppressed legumes and other forbs and PK fertilisers without N encouraged legumes. Ammonium sulphate alone or with P K fertilisers eliminated the legumes, leaving a herbage with 90% or more grasses. Initial annual application rates of FYM at 35 tonnes/ha/year caused "adverse effects" to the sward from smothering. These early treatments allow little comparison with the inorganic treatments due to non equivalence of the rates of nutrients applied (the annual FYM treatment supplied higher annual rates of all macro-nutrients N, P and K compared to the inorganic treatments).

In 1905 three farmyard manure treatments were reintroduced to the **Park Grass Experiment**, only one of which (Plot 19) supplying FYM alone is relevant to this review. This supplied FYM at 35 tonnes per ha^{-1} every four years equivalent to at 240 kg N ha^{-1}, 45 kg P ha^{-1} and 350 K kg ha^{-1}. Between 1903 and 1964 sub-plots of most treatments were limed at 2.24 tonnes ha^{-1} every fourth year. From 1965 a new liming scheme was introduced, to produce soils at pHs of 4, 5, 6 and 7 on four sub-plots within each treatment. **Crawley *et al.* (2005) [2+]** report the long term impact on plot species richness of the FYM treatments as well as long standing fertiliser and liming treatments. Species richness in 2000 was greatest on the control plots (<40) and lowest in plots were the soil was strongly acidified by the long-term input of ammonium sulphate supplying 144 N kg ha^{-1} yr^{-1} (<4). There was a roughly linear decline in mean species richness with N application rate for both types of N. Species richness was highest in the control plots, declining progressively in the following order of treatments: plots receiving P alone, sodium nitrate or ammonium sulphate on their own, N and K together (the minus P plot), FYM , P and K together and finally the largest reduction in species richness are associated with adding N and P, and NPK together. The maximum depression of species richness occurs when N is applied as ammonium sulphate which lowers soil pH. Only N ($p<0.00001$) and P ($p<0.00001$) had significant main effects on species richness. There was no significant interaction between N and P application ($p=0.14$) the effect of adding N and P together was additive and was responsible for the greatest reduction in species richness attributable to nutrients.

Impact of lime - Lime had no significant effect on species richness in the Park Grass Experiment except on plots receiving nitrogen in the form of ammonium sulphate, which has a strong acidifying effect. On these plots species richness increased sharply in response to liming as pH was increased.

FYM versus Inorganic fertilisers - FYM has a slightly less deleterious effect on species richness than equivalent rates of inorganic fertiliser. According to multivariate modelling, adding P loses six species on average, adding N loses about two species for every 50 kg ha^{-1} applied, ammonium N loses three more species than would the same rate of N as sodium nitrate (because of the effect on soil pH), using FYM rather than mineral fertilisers added two species on average. No reasons are provided for this differential impact. Whilst it is possible that FYM applied at equivalent rates genuinely had a less deleterious impact on species richness, it is also possible that over the duration of the experiment the FYM plots received less NPK than the inorganic fertiliser plots, leading to non-equivalence of nutrient supply.

Simpson & Jefferson (1996) [4-] conducted a non-systematic review of the agricultural and ecological literature for information relating to the use and impact of farmyard manure on the floristic composition of neutral grassland hay meadows, both unimproved and improved. Timing of manure application was found to vary considerably from place to place, ranging from February to April, and from September to December. Evidence suggests that winter and spring applications of FYM allow opportunity for efficient utilisation of nutrients, subject to satisfactory soil conditions. However, no reference was made, or evidence presented, of different biological impacts of spring versus autumn or winter application, with the exception of it being reported that too high a rate of application of FYM in spring can smother and physically scorch herbage, particularly in very dry conditions.

Smith *et al.* (1996) [1++] in a four year study (1989 - 1993) of an MG3 meadow at Gillet Farm, Upper Teesdale examined the interacting effects of different grazing, fertiliser and cutting date treatments on sward composition. The fertiliser component of the study included two treatments; no fertiliser or 80 kg N ha^{-1} plus 40 kg ha^{-1} of P and K, applied in mid-April in each year. Addition of fertiliser at rates of 80 kg N ha^{-1} yr^{-1} and 40 kg P ha^{-1} yr^{-1} significantly reduced the number of species within MG3 grassland over a four year period by between 12 and 21% ($p<0.001$). Fertiliser use led to a significant increase in the abundance of competitive species ($p<0.001$) and those that could reproduce vegetatively ($p<0.001$) and were able to rapidly capitalise on increased nutrient availability, and significant decreases in species with stress-tolerator ($p<0.01$), ruderal ($p<0.001$) and stress-tolerant-ruderal strategies ($p<0.001$).

Starr-Keddle (2011) [2-] conducted a small scale correlative study of 12 meadows in Teesdale to determine if there were differences in species richness, diversity, composition and soil nutrient levels between meadows that had received chemical fertiliser inputs in the past and those which had not. The study also examined whether there were differences in botanical composition and soil nutrients at the centre and edges of fields. Soil P, K and Mg levels were significantly greater in meadows which had received fertiliser. However, no significant difference was detected between fertilised and non-fertilised meadows in terms of species richness and diversity. Irrespective of fertiliser applications, the edges of fields were significantly more species rich than the centres ($p<0.024$) and had lower phosphorus levels ($p<0.001$). Furthermore an ordination analysis indicated that a number of characteristic species of MG3 meadows tended to be associated with the edges of the meadows and with lower phosphate levels (for example, lady's mantle, *Alchemilla xanthochlora*, wood crane's-bill *Geranium sylvaticum*, melancholy thistle *Cirsium heterophyllum*, great burnet *Sanguisorba officinalis*). The authors and reviewers note that other in-field management operations, for example, cutting/grazing and FYM applications are likely to have confounded the analysis in this study.

Starr-Keddle (2012) [2-] compared early botanical surveys with later botanical surveys and analysed change over time in relation differing histories of fertiliser addition in a large scale correlative study of 97 meadows in Upper Teesdale. A highly significant decline in mean species number and other measures of botanical quality (all $p<0.001$) for 64% of Upper Teesdale meadows was detected between the baseline and later survey dates. For the majority of meadows this was accompanied by a highly significant increase in Suited Species Nutrient score and Ellenberg fertility index ($p<0.001$). This decline was apparent across all fertiliser categories analysed even in meadows receiving no inorganic fertiliser, indicating that nutrient inputs from FYM or/and from atmospheric N deposition may be having a significant impact.

Tallowin (1998) [3++] collated and evaluated information relevant to the use of lime application on semi-natural grasslands from the literature and from management information from neutral grassland SSSIs. Nutrient and liming information was presented for five MG3 grassland SSSIs from a wider survey of management practices. Of these only one SSSI had a history of lime application whilst four had a history of FYM application, with one also receiving basic slag in the past. Although based on a very small sample of MG3 SSSIs, the survey indicates that lime application is not always part of the traditional management of species rich upland hay meadows. Tallowin states 'that the generality of lime use appears to be less than that of FYM, and that the small liming effect of FYM may assist in the maintenance of this type of neutral grassland'. Furthermore 'where there is a tradition of lime use on an MG3 meadow then this tradition should continue, providing that only lime and not phosphatic slag is used'.

Ornithological evidence

Baines (1990) [2++] examined the role of predation, food and agricultural practice in determining the breeding success of lapwings on improved and unimproved upland grasslands. 22% of lapwing clutches laid on improved meadows were destroyed by farm machinery compared to 8% on unimproved meadows ($p<0.02$). Reduced lapwing productivity on improved meadows was attributable to higher proportion of clutches being destroyed and a lower proportion of clutches being replaced due to more intensive management, namely more agricultural activities (ie field operations in the spring) and the production of a faster growing sward that leaves insufficient time for laying of replacement clutches.

Small (2002) [2++] investigated which habitat and surface features were significantly related to the distribution of five wader species in the Pennine Dales. A strong association was found in two surveys between occurrence of lapwing and newly applied FYM.

Vickery *et al.* (2001) [3++] reviewed the range of potential mechanisms by which the agricultural intensification of lowland neutral grasslands may impact on bird populations in Britain. They found evidence that organic fertilisers provide extra food for decomposer communities and that grassland soil invertebrate populations generally benefit from moderate applications of organic manures as do earthworms, though these decrease under high applications and would be expected to decrease if the livestock have been recently dosed with broad-spectrum avermectin wormers. The authors' state that moderate use of FYM may benefit grassland birds by increasing the abundance of soil-dwelling invertebrates, or their accessibility by bringing them closer to the surface. They report that winter field use by lapwings, starlings, redwing and fieldfare is positively associated with frequent addition of FYM on permanent grassland.

Sub-question (b) What management methods or approaches control rushes (*Juncus* spp) in upland hay meadows and maintain the floristic diversity of the meadows?

The studies

Six studies provide evidence on this sub-question (three randomised controlled experiments, one correlative study, one part observational and part experimental study and one literature review). Five were from the UK whilst one was from The Netherlands.

Cherril (1995) [2+] used stratified sampling to investigate the distribution and extent of infestation of soft rush *Juncus effusus* in improved grasslands in the River Tyne catchment in order to explain levels of infestation. Agriculturally improved grasslands in the uplands were significantly more infested by *J. effusus* than either improved grasslands in the marginal uplands or lowlands. The reasons for this finding are not clear and may reflect local factors and the greater availability of rush seed in adjacent upland habitats. Qualitative consideration of management records (as provided by the Farm Business Survey and consisting of the proportions of cut/grazed and permanent/temporary grassland) did not explain infestation patterns.

Mercer, Reavey & Morgan (2008) [1+] assessed the effectiveness of using a weed wiper to control rush growth on two study sites in County Fermanagh. At the first study site, a reclaimed bog, the effect of weed wiping in May, with three concentrations of glyphosate herbicide (72, 90 and 120 g.a.i. I-1) in one or two consecutive years was assessed. At the second study site, a species-rich unimproved wet grassland, the effect of weed wiping with glyphosate (at 120 g.a.i. I-1) in either late spring/early summer or late summer/autumn in one, two or three consecutive years was examined. Late spring/early summer applications of glyphosate were more effective in reducing rush growth than those in late summer/autumn. There was no significant effect two years after application, suggesting that treatment would need to be ongoing to be effective. It should also be noted that a corresponding significant decrease in grass biomass after weed-wiping of rushes, showing that even careful application of herbicide can significantly affect non-target vegetation. The study revealed no significant differences in rush control in the three different concentrations of glyphosate.

Merchant (1995) [1++] examined the vigour of soft rush, *J. effusus*, in response to three severities of defoliation (uncut, cut at half the green stem height, and cut at ground level) in all possible combinations at two cutting dates (end of June and end of August). Treatments were imposed over two consecutive years and rush vigour assessed in year three. Cutting at half the height of green stems either once or twice annually had no effect on subsequent tussock mass or vigour, while cutting down to ground level reduced tussock mass and vigour in the next year's growth ($p<0.05$). However, a large number of green living stems remained on all treatments indicating considerable potential for regeneration. Whilst there was no significant effect of number or timing of cuts, the results indicate that cutting rushes to ground level twice during the growing season was more effective at reducing rush vigour. Where only a single cut is possible, a later August cut is preferable.

Smolders *et al.* (2008) [2-] examined the relationship between nutrient availability, specifically P, and soft rush, *J. effusus* on a former agricultural field, on which top soil had been removed two years previously. In addition two ex-situ experiments were conducted using soil from an ex-arable site. The first investigated the extent to which liming reduces P availability and the second sought to determine whether reducing P liming controls soft rush *J. effusus*. Growth of *J. effusus* on moist or wet soils seems to be strongly determined by the Olsen-P concentration in the soil. Experimental addition of lime to ex-situ field soil was shown to reduce soil available P (Olsen' P) but this effect did not translate to reduction in soft rush biomass over the three month period following lime application. Findings of the observational field survey confirmed that rush biomass in the field was highly correlated with Olsen' P.

Wolton (2000) [1-] investigated the effectiveness of different cutting regimes as a method of controlling soft rush *J. effusus* on wet neutral grassland over mineral soils in Devon. The effects of; first cut (May, July, August or September); cutting height (flush with the ground or at 8 cm above the ground) and altering the interval between cuts (fortnightly or monthly cuts) were assessed. Cutting rush flush with the ground is more effective than cutting at a height of 8 cm. If only a single cut is possible, then cutting after mid-summer is more effective than before mid-summer, but this is not the case if multiple cuts are made. Cutting at monthly intervals in some instances appears more effective than cutting fortnightly. No tests of significance were applied.

RSPB (2007) [4-] Two short documents consisting of an information and advice note, and rush management guidelines set out the wildlife value of rushes and management options for rush control to improve habitat quality for breeding waders. Although detailed information about control of rush infestations (over 30% cover in grasslands) is provided no direct evidence is provided to support these hence the negative score for this reference. The guidelines advise a summer cut, after the last wader chicks have fledged (exact timing is dependent on species present) which should be as close to the ground as possible without causing bare soil which allows rush seeds in the seed bank the chance to establish. It is suggested that this will be more effective if followed after 4-8 weeks by another cut. Use of grazing as a management tool to control rushes is suggested, with grazing following a single cut reported as being sufficient in certain instances. Cattle are reported to be better than sheep at suppressing rushes. Creeping rushes, namely (articulated rush and sharp flowered rush) are reported as being more readily grazed than tussock rushes (hard, soft and compact). The RSPB guidelines also mention the use of herbicide, specifically MCPA and glyphosate, as a possible rush control mechanism, using a weed-wiper, but warn of the likelihood that it will kill non-target vegetation unless there is a significant height difference between this and the rushes. Care is also advised in avoiding poaching and permanently saturated soil so ensuring appropriate stocking rates and sufficient drainage.

Sub-question (c) What spring-grazing levels, timing of shut-up/closure for hay and cutting dates maintain the floristic diversity and breeding bird populations of upland hay meadows?

The studies

Twenty one studies provided evidence on this sub-question (four randomised control experiments, 14 correlative or observational studies, one modelling study, one meta-analysis and one review). Fifteen were from the UK and six were from continental Europe. For the purposes of clarity studies have been split into those which focus on botanical composition and those which focus on impacts on breeding birds.

Botanical studies

Critchley, Fowbert & Wright (2007) analysed botanical monitoring data from a sample of upland hay meadows within the Pennine Dales Environmentally Sensitive Area (ESA) to assess change in vegetation composition over a 15 year period and its relationship with management practices, including: livestock type, timing of grazing (autumn, winter, spring); changes in grazing intensity; Foot and Mouth Disease effect from 2001; closing date (before 15 May or after 15th May); cutting date (pre 15th July, 15th – 22nd July, post 22 July) and crop type (hay, haylage or silage).

Humbert *et al.* (2012) [3-] undertook a meta-analysis of experimental and observational studies to determine the effect of delayed mowing on plants and invertebrates of semi-natural grasslands. No overall significant effect was detected of delayed mowing on plant species richness, but this result is likely to be confounded by the inclusion of a number of studies where the 'early' cut was in July/August, hence the negative scoring of this meta-analysis. A significant positive effect of delaying the first mowing date was found for invertebrate species richness ($p=0.009$).

Pacha & Petit (2008) [2++] investigated vegetation change in 47 upland hay meadows over a period of two decades in relation to management practices and isolation, with a focus on wood crane's-bill, *Geranium sylvaticum*. Meadow quality declined significantly between the two survey periods with declines in species richness ($p<0.01$) and a 40% loss of sites supporting wood crane's-bill *G.sylvaticum*. Species richness was found to be negatively correlated with high grazing intensity ($p<0.01$) and inorganic fertiliser application ($p<0.01$). Meadow quality, as described by a derived habitat quality index, was negatively correlated with both fertiliser application ($p<0.05$) and level of isolation ($p<0.01$).

Smith & Rushton (1994) [1++] investigated the response of an MG3a meadow in Ravenstonedale, Cumbria to excluding grazing during specific periods of the year over a five year period. Four grazing treatments were applied: no grazing; spring grazing only (no grazing from the time of the hay cut until January; autumn grazing only (no grazing from January until the hay cut) and a control in which included traditional spring and autumn grazing. The most extreme vegetation response was elicited by the complete cessation of grazing, which was the only treatment for which there was a significant change in the number of species, a 25 % decrease. A distinct group of species, particularly grasses soft brome *Bromus hordaceus*, red fescue *Festuca rubra*, meadow foxtail *Alopecurus pratensis*, cock's-foot *Dactylis glomerata* and Yorkshire fog *Holcus lanatus* became dominant under this treatment. Removal of livestock in either spring or autumn produced significant differences in species composition, favouring different groups of species. Autumn grazing alone favoured a suite of grasses (sweet vernal-grass *Anthoxanthum odoratum*, rye grass *Lolium perenne*, rough meadow grass *Poa trivialis* and crested dog's-tail *Cynosurus cristatus*). Spring grazing alone favoured a suite of herbs (wood crane's-bill *Geranium sylvaticum*, melancholy thistle *Cirsium heterophyllum* and great burnet *Sanguisorba officinalis*). Grazing in the spring and autumn was essential for the maintenance of white clover *Trifolium repens*. Species which have a high nuclear DNA content, which appears to enable growth to begin under low spring temperatures were associated with the un-grazed treatment. The authors suggest that meadows which are not grazed in spring may provide a niche for early vernal species such as wood anemone *Anemone nemorosa*.

Smith & Jones (1991) [2+] compared past and present practice in hay cutting times on meadows at five farms in the Yorkshire Dales and Cumbria, and analysed vegetation data to determine if there was any association with sequence of cutting. The authors also undertook a phenological study of common meadow species in one MG3 meadow at Bowberhead Cumbria to assess likely impact of changes in cutting date on these species. Between the years 1947 and 1986, hay cutting start dates showed little variation around the 1st July on the five farms studied. In contrast, hay cutting finish dates varied considerably with time, becoming far earlier in later decades as the time it takes to make hay significantly shortened, with the advent of mechanisation in the 1960s. Historic data indicate that pre-mechanisation the frequency of very late cutting was as regular as two in every five years on some farms. A significant relationship between sward composition and order of cutting was found on three of the six farms surveyed ($p<0.03$). However, on the other three farms, where artificial fertiliser had been applied, this had the greatest effect on composition masking any effect of cutting order.

The phenological study from an MG3b meadow in Cumbria found that ripe seed are present at different times for different species. Red fescue *Festuca rubra*, cock's-foot *Dactylis glomerata*, red clover *Trifolium pratense* and rough hawkbit *Leontodon hispidis*, produce seed from early August, whilst great burnet, *Sanguisorba officinalis*, knapweed *Centaurea nigra* and meadowsweet, *Filipendula ulmaria* have little ripe seed by 21st August. The authors suggest intermittent late cuts may be needed to enable adequate seed production and return for these species if early cuts are the norm.

Smith *et al.* (1996) examined the interacting effects of different grazing, fertiliser and cutting date treatments on sward composition in a four year study on an MG3b meadow at Gillet Farm, Upper Teesdale. Three grazing treatments were applied as follows: no grazing, autumn grazing with cattle between September to October; and autumn grazing plus spring grazing for 1 week in early/mid May with sheep. Three hay cutting dates were applied as follows: 14th June; 21st July; 1st September. The herbage was cut, turned once and dried on the experimental plots prior to its removal. Fertiliser treatments were described and evaluated under sub-question (a) of this review.

Impact of grazing treatments - Complete cessation of grazing caused considerable changes in vegetation in the MG3b studies over four years. The number of species was significantly higher ($p<0.05$) under the traditional grazing regime of both autumn and spring grazing, at the smallest spatial scale vegetation in which botanical composition was assessed.

Impact of cutting dates - After four years no significant effect of cutting dates alone on overall species number was found. Cutting on 21st July maintained the MG3 community, whilst an early September cut tended to shift the sward towards semi-improved grassland. Seven species showed significant changes in their cover with cutting date but response were split almost equally between the three cut dates. Ruderal species were significantly ($p<0.001$) more abundant with successively earlier hay cuts, whilst stress-tolerating ruderals were favoured by the 21st July hay cut ($p<0.05$). The latest hay cut (1st September) was significantly associated with increasing abundance of competitor species ($p<0.001$) and species with persistent seeds ($p<0.01$) or which are capable of vegetative spread ($p<0.05$).

Smith, Pullan & Shiel (1996) [1+] studied the seed shed from the hay of an MG3b meadow at Gillet Farm, Upper Teesdale in the following summer after application of three different hay cutting dates (14th June; 21st July and 1st September), three grazing regimes; no grazing; autumn grazing; autumn and spring grazing and a plus/minus fertiliser treatment. The quantity of seed produced through the summer changes with the timing of seed production and the amount of seed produced by different species. Grasses produced significantly more seed at the end of the summer with a 20 fold increase in the grass:forb seed ratio (highly significant increase in grasses and decrease in forbs both ($p<0.0001$). The overall forb:grass seed ratio was highest in June and lowest in September. The traditional time for hay cutting (21st July) resulted in significantly more seed than the June cut, with nearly equal amounts of forb and grass seed. Seventeen species showed significant differences in the amount of seed extracted at different cut dates. In addition, four species showed a significant response to the different grazing treatments applied.

Smith *et al.* (2012) [1++] investigated the effect of duration and intensity of spring grazing on plant species diversity and composition, and the performance of key community character species in an MG3b meadow in Wensleydale. They also considered the ecological mechanisms underlying plant growth and development in the experiment, particularly the link with spring temperature. Two grazing intensities, comprising grazing to maintain an average sward height of either 3-4 cm (high intensity) and 5-6 cm(low intensity), and four shut-up dates (1st February, 1st May, 15th May and 27th May) were applied to the study site in spring and early summer for five years. Detailed temperature recording on site enable plant performance and sward growth to be related to accumulated temperatures throughout the five years of the experiment. Whilst more intensive grazing and later shut-up dates had no effect on species richness, they did reduce diversity as defined by the Simpson and Shannon diversity indices, and increased the apparent (Ellenberg) fertility of the grassland. These changes were particularly evident with the latest shut-up date (27th May) which significantly reduced Simpson (p=0.001) and Shannon diversity (p=0.001) and Shannon evenness (p=0.011). The later the shut-up date the later that flowering was initiated in a number of key community character species (hay rattle *Rhinanthus minor*, red clover *Trifolium pratense*, pignut *Conopodium majus*) which resulted in delayed seeding. Swards with the two earlier shut-up (1st February and 1st May) dates showed significantly greater similarity to MG3b vegetation (p=0.005) than swards from the later shut-updates.

Interaction of management with spring weather - The study reported a number of significant year to year differences in response to treatments and it is suggested that these are linked to variability in spring weather considered below. Over four years the higher intensity grazing treatment significantly reduced similarity to MG3b (p=0.013), decreased both Simpson (p= 0.029) and Shannon diversity (p = 0.023) indices whilst increasing Ellenberg fertility score (p=0.021). At the high grazing intensity there was a significant interaction with shut-up date, with species richness progressively decreasing with later shut-up date (p=0.017). The influence of spring temperatures on sward development and its interaction with spring grazing intensity and date of shut-up was also considered. Plant growth, as measured by sward height was almost entirely explained by accumulated temperature (T-sum), ie the cumulative sum of the daily mean air temperature above usually 5.6^{o}C starting from 1 January each year. The transition from bud to flower to ripe seed is most rapid in warm springs, but does not start until the field is shut-up for hay since grazing constantly promotes new leaf growth but does not encourage development of flower stems, flowers and seeds. As a consequence delaying the date at which sheep are removed delays maturation of the sward. This led to a significant reduction in hay rattle populations in the 15th and 27th May shut-up dates (p=0.018). Similarly by late May key community character species, particularly hay rattle R. minor, but also pignut *C. majus*, wood crane's-bill *G. sylvaticum*, red clover *T. pratensis*, and greater burnet *S. officinalis* were all taller under the earlier shut-up date and low intensity grazing treatment. The authors suggest that in warm and wet spring conditions the more vigorous early growth of the plants is likely to be greatly affected by different shut dates. In cold springs date of shut-up may make little difference

Ornithological studies

ADAS (1996) [2++] monitored populations of breeding waders and yellow wagtails in land under agreement in the Pennine Dales ESA and sought to detect population changes between 1991-1995. The main focus of the yellow wagtail work was to examine the timing of nesting and fledging in relation to the timing of grass cutting. They found a clear preference for yellow wagtails to nest to meadows within the Pennine Dales ESA. They also found that peak fledging date in Dales is the last week of June, with approximately 70% of birds fledging prior to the 7th July. Over the survey period a quarter of nests failed due to cutting, with the impact of cutting in any one year varying with both the timing of the breeding season and the timing of cutting, this vary widely with spring temperature and rainfall. The 8th July cutting date for the ESA falling just after the peak fledging period is judged to offer considerable protection for the breeding population on agreement land.

Beintema & Müskens (1987) [2++] explored the effects of predation and trampling by sheep and cattle as causes of nest loss, and identify their significance in the population dynamics of meadow-bird species (wading birds) on Dutch meadow grasslands. They found that the impact of grazing management exceeds losses due to predation, particularly at high stock densities. Young cattle caused the most damage by trampling for most bird species, especially when considered in terms of grazing equivalents (LU). Sheep did little harm per individual, but damage increases with stocking density. However the reduction in nesting success with increased density is less than for the equivalent cattle grazing pressure. Trampling risk was higher for redshank with over 50% of nest losses due to trampling compared to 23% for lapwing. They present a “standardised trampling value” per type of livestock and per bird species from their data (survival rate per animal per hectare per day) which can be used to determine likely losses over a given grazing period.

Breeuwer *et al.* (2009) [2+] assessed the effectiveness of Dutch agri-environment schemes in maintaining (and increasing) breeding bird species of meadows by analysing changes in the density of these species on land inside and outside agreement over a 12 year period. The main interventions investigated were postponement of mowing (and other disturbing agricultural activities, such as manure application) until the end of May or June to reduce chick and egg mortality. Postponement of mowing date alone on land under agreement was insufficient to maintain or increase meadow bird densities. Other aspects of meadow management, namely drainage and nutrient inputs are likely to be indirectly affecting bird densities by reducing both the total amount of invertebrate prey available to the birds and its accessibility. They suggest that in order to increase chick survival to sufficiently high levels, it would also be necessary to raise groundwater levels and to reduce fertilization to allow for the development of an open vegetation structure.

Broyer (2009) [2+] investigated the effect of meadow mowing date on the breeding success of whinchats in alluvial floodplain and upland meadows in France. Hatching success of whinchat *Saxicola rubetra*, is negatively correlated ($r = -0.503$, $p=0.024$) with early hay making, and also with meadow passerine territory density, suggesting that lowland areas with high densities of passerines may be acting as population sinks.

Court *et al.* (2001) [3+] undertook a targeted survey of breeding yellow wagtails in 10 areas within the Yorkshire Dales National Park and compared their findings with the limited historical data available to determine whether the species had significantly declined. The findings indicate that increased stocking levels may increase the loss of yellow wagtail nests through trampling, no quantitative data on changing stocking rates were provided. Earlier cutting dates of hay meadows, especially where there is a change from hay to silage, as one of the main reasons for the long term decline in yellow wagtail populations in the Yorkshire Dales, especially when the species fidelity to nesting site is factored in.

Devereux *et al.* (2004) [2+] investigated the effect of grassland sward height and soil moisture on two declining bird species, lapwing and starling. (NB Only the lapwing experiment is reported). The lapwing observations were made on grasslands on the Isle of Islay during early to mid May. Lapwing foraging rates declined significantly ($p<0.001$) as sward height increased from just under 2 cm to 10 cm. Since there was no difference in the number of surface invertebrates found (through pitfall traps) in long and short swards, this suggests that sward height was restricting accessibility of the chicks’ insect prey

Fuller (1996) [3+] undertook a review of the relationships between grazing, principally by sheep and bird populations. Although the review focused mainly on open upland habitats it also considered certain impacts of grazing on bird use of in-bye land, including hay meadows, and best available evidence on the sward structure preferences for a number of breeding waders. Grazing pressure was found to affect different species in different ways, with precise mechanism being species specific. There is a pronounced dichotomy in the sward height preferences of bird species breeding in grassland. Lapwing benefit from a moderate to high level of grazing, maintaining low but not structurally uniform vegetation. In contrast the other principal breeding birds of meadows snipe *Gallingo gallingo*, redshank *Tringa tetanus*, curlew *Numenius phaeopus*, whinchat *Saxicola rubetra* and skylark *Alauda arvensis*, prefer lighter grazed, tussocky vegetation.

Green *et al.* (1997) [2+] explored effects on breeding success of altering mowing practices on corncrake *Crex crex* through modelling. The findings of intensive studies of breeding biology and success, and studies of the effects of mowing on nest and chick survival studied in several areas in

Scotland and Ireland informed the construction of the simulation model of nesting and chick-rearing for this species. Mowing from the inside of the meadow (inside out) towards the outside resulted in a substantial increase in corncrake *Crex crex*, productivity compared to outside-in mowing, especially when the mowing date is early. Moving the mowing date from the end of June to the beginning of September resulted in a very large increase in productivity, but even using an intermediate date of the model (beginning of August) almost doubled the productivity in most iterations of the model presented.

Gruebler *et al.* (2012) [2+] investigated whinchat nest success in Swiss hay meadows which were either early or late mown, or were early mown but where nests were protected. Early hay cuts lead to low nest survival (10%) of whinchat. There was no significant difference in nest survival between nests protected in early-mown fields and unprotected nests in late mown fields (70%).

Kruk, Noordervliet & ter Keurs (1996) [2++] examined the relationship between mowing and hatching dates of grassland waders (lapwings *Vanellus vanellus*, black-tailed godwits *Limosa limosa* and redshanks *Tringa tetanus*) in The Netherlands over an eight year period as influenced by spring temperatures. They report that the date at which a critical T-sum of 180^{o}C was reached varied between 30 January and 30 March. Both median hatching dates and median mowing dates were closely correlated with T-sums. Significant relationships were found for all three species of breeding wader studied ($p<0.05$), with great differences in mowing and hatching dates between years, which were explained by spring temperatures. Although the negative effects of early mowing on the breeding success of waders were smaller as a consequence of this correlation, mowing dates still need to be delayed by an average of 1-2 weeks in order to ensure that required recruitment of chicks is met. The difference between median mowing date in a particular year and the date for achieving the required recruitment showed that mowing date was too early in 5/8 years for lapwings and in 3/8 years for redshanks. These results suggest that safe mowing dates would have been 1-2 weeks later than current dates and that T-sum could usefully be used to predict peak hatching for wader species to inform safe cutting date in each year.

O'Brien (2002) [2+] surveyed breeding lapwing in large scale field survey in Northern Britain in order to determine the relationship between field occupancy rate across a range of land uses and aspects of habitat management namely, sward height, area covered by rush and maximum area flooded. The probability that lapwings occurred in a field was negatively associated with vegetation height, a feature consistent across regions and between land use categories and positively associated with the area flooded, although this varied between regions.

Shrubb (1990) [2++] examined the impact of various agricultural changes, including increases in grazing intensity on the nesting of lapwings in England and Wales between 1962 and 1985 from analysis of BTO nest-record cards. The percentage of grassland nests lost to trampling in any year was significantly correlated with the overall densities of both sheep and cattle on English and Welsh grassland.

Small (2002) [2++] used GIS and modelling to identify habitat features which were related to wader distribution (curlew, lapwing, oystercatcher, redshank and snipe) in an initial study area, and tested the models to see if the conclusions could be applied to the Pennine Dales as a whole. The study sought to complement existing research on wader productivity in relation to agriculture, with a focus on wader distribution at the landscape level. A strong association between the presence of lapwing and short swards in the first three weeks in June was detected. The relationship was also noted for redshank in two specific survey areas, but not in the 26 wider Pennine Dales ESA squares. There was also an association of redshank and lapwing with medium swards early in the season, which may indicate avoidance of trampling.

Wilson (1991) [3+] surveyed yellow wagtail populations in Littondale and Arkengarthdale and assessed breeding success in relation to hay cutting. A nest failure rate for attributable to early cutting of 31% (13 sites) was reported.

Appendix 3 Evidence statements categorised according to the strength of the evidence base

We found strong evidence showing:

- There is strong evidence from seven studies (two [1++], two [1+] and three [2+]) to indicate that annual applications of Nitrogen, at rates of 17.6 kg ha^{-1} $year^{-1}$ or greater, lead to significant reductions in species richness in MG3 and related neutral grassland types.
- There is strong evidence from eight studies (two [1++], two [1+], three [2+] and one [2-]) that under increased nutrient availability competitive grasses increased in cover, usually at the expense of smaller, slower growing forbs.
- There is strong evidence from one [1+] study on MG3 indicating that the nutrient regime of any given meadow should be informed by its soil physical and chemical status and past fertility management.
- There is strong evidence from three studies (one [1++] and two [2+]) that botanical responses to nutrient applications are driven by which ever macro-nutrient is growth limiting in the grassland in question, with even small amounts of the limiting nutrient, for example circa 13 kg P ha^{-1} yr^{-1} significantly reducing species richness.
- There is strong evidence from three studies (one [1++], one [2+] and one [3++]), to suggest that occasional liming is consistent with maintaining vegetation quality on MG3 hay meadow with a past history of lime application. A further [2+] study on a related neutral grassland type, MG5, also indicates that lime has no deleterious impact on species richness.
- There is strong evidence from three studies (one [1++], one [1-] and one [4-]) that mowing rushes flush with the ground at least twice during the summer can reduce rush vigour and that where only one cut is possible a late summer is most effective.
- There is strong evidence from two studies (one [1++] and one [1+]) that cessation of grazing, even where hay cutting is continued, leads to a reduction in floral diversity.
- There is strong evidence from two studies (one [1++] and one [1+]) that spring grazing per se is important in maintaining botanical composition of species-rich MG3 meadows.
- There is strong evidence from three studies (two [2++] and one [3+]) proving a relationship between trampling by livestock and nest losses of nests in ground-nesting birds, which increase with grazing intensity and duration, though no specific stocking levels are advised.
- There is strong evidence from eight (four [2+], two [2++] and two [3+]) studies to show that cutting of grassland prior to the peak fledging date (this varied according to species) reduced nest success in a range of breeding birds of meadows.
- There is strong evidence from three studies (one [2++] and two [3+]) showing that delayed cutting of meadows in the Pennine Dales can enhance breeding success of yellow wagtails in the short term.

We found moderate evidence showing:

- There is moderate evidence from one [1+] study that for MG3 meadows FYM inputs at 12 t ha^{-1} $year^{-1}$ (equivalent to 9 kg N ha^{-1}, 10 kg P ha^{-1} and 69 kg K ha^{-1} annually) maintain vegetation quality on meadows where inputs have been at a similar level historically, but that enhancement of botanical quality is achievable under lower nutrient rates of 6 tonnes FYM ha^{-1} $year^{-1}$ or less (equivalent to 4.4 kg N ha^{-1}, 5 kg P ha^{-1} and 35 K kg ha^{-1} yr^{-1}).

- There is moderate evidence from two studies (one [3++] and one [2++]) that FYM application increases the abundance and availability of invertebrate prey for grassland birds, although these benefits will be reduced under high applications and would be expected to decrease if the livestock have been recently dosed with broad-spectrum avermectin wormers.
- There is moderate evidence from one [2++] study of a deleterious impact of spring field operations, (including FYM application and inorganic fertilizer applications), on breeding lapwing in upland meadows.
- There is moderate evidence from two studies (one [4-] and one [1+]) that herbicide by weed wiping application, can also be effective, although not without danger to other vegetation.
- There is moderate evidence from one [1++] study that if spring grazing is prolonged (with closing date after 15^{th} May) species diversity is reduced and species associated with more eutrophic conditions (Ellenberg N values) increase.
- There is moderate evidence from one [1++] study that grazing to an average of 5-6 cm is better than 3-4 cm in terms of retaining floristic diversity, with another study [2++] indicating that increased grazing intensity is negatively correlated with species richness.
- There is moderate evidence from one [1++] study of an important interaction between accumulated spring temperature (T-sum) in any given year and the rate of sward development and spring grazing regime, in particular shut-up for date, and impact on botanical composition.
- There is a moderate evidence (one [2++], one [2+] and one [3+]) of a clear dichotomy in the preferred grazing intensities of the breeding birds of upland hay meadows between lapwing which prefer a moderate level of grazing to retain a short sward into late spring, and the lighter grazed, more heterogeneous vegetation preferred by other breeding birds (snipe, redshank, curlew, whinchat and skylark).
- There is moderate evidence from two studies (one [1++] and one [1+]) on the same meadow that a hay cutting date consistently applied on or around the 21st July maintained botanical composition of MG3 grassland in the short term.

We found limited evidence showing:

- There is limited evidence from two correlative studies (both [2-]) on MG3 meadows of a significant association between increased availability of soil extractable P and lower botanical quality (specifically higher cover of competitive, nutrient demanding species, and decreasing species richness).
- There is limited evidence from one correlative study (2-) that shifts in species composition over a 15-year period, notably a reduction in number of forb species were associated with lower levels of soil extractable K.
- Evidence on the differential impacts of different forms of nutrient on floristic diversity is very limited and equivocal with the two [1+] studies available showing small but contradictory effects. The reliability of the evidence is compromised by the fact that in no study were rates of FYM and inorganic fertilizer truly equivalent. There is no specific evidence on the effect of different timings of application of nutrients on upland hay meadows. Limited available evidence is restricted to a [1+] study on an related neutral grassland type (MG5) and a review [4-], both of which suggest no significant effect of timing (i.e. season) of FYM or inorganic fertiliser application on botanical composition.
- There is limited evidence from one [1+] study on MG3 grassland of no significant effect on botanical composition of annual or triennial nutrient application, provided the overall nutrients supplied over a given period are the same.
- There is no direct or quantifiable evidence on the importance of periodic late cutting on botanical composition of MG3 meadows.
- There is limited evidence from one study [2++] that T-sum could be used to inform timing of hay cut under variable spring temperatures to better protect breeding birds.

Catalogue Code: NEER