Review of the effectiveness of on-site habitat management to reduce atmospheric nitrogen deposition impacts on terrestrial habitats

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ADOLYGIAD O EFFEITHIOLRWYDD RHEOLAETH CYNEFIN AR SAFLE I LEIHAU EFFEITHIAU DYDDODIAD NITROGEN ATMOSFFERIG AR GYNEFINOEDD DAEAROL

1. O ystyried fod effeithiau dyddodiad N ar gynefinoedd yn y DU yn bellgyrhaeddol, mae'n hanfodol deall sut y gallai mesurau rheolaeth cynefin liniaru'i effeithiau a hyrwyddo adferiad. Mae'r prosiect yma yn adolygu effeithiolrwydd dulliau rheoli tir 'ar safle' i liniaru effeithiau dyddodiad nitrogen ar gynefinoedd sensitif; mae'n asesu pa effaith y mae mesurau rholaethol presennol yn eu cael ar ymateb cynefin i ddyddodiad nitrogen; mae'n ystyried sut y gallai mesurau gael eu heffeithio gan newid hinsawdd; mae hefyd yn argymell dulliau rheoli realistig ac ymarferol ar gyfer gwahanol fathau o gynefinoedd a allai gael eu defnyddio i liniaru effeithiau nitrogen neu gyflymu adferiad.
2. Cafodd potensial rheolaeth i liniaru effeithiau dyddodiad N ei ystyried ar draws y cynefinoedd eang canlynol: collddail, coetir cymysg a choetir yw & choetir conwydd (naturiol); glaswelltir niwtral; glaswelltir calchaidd; glaswelltir asidaidd; rhostir corwrychoedd; cors; twyni tywod a llaciau arfordirol; cynefinoedd arfordirol eraill. Yn achos pob cynefin, roeddem yn gallu nodi technegau rheolaethol gyda rhywfaint o botensial i liniaru effeithiau dyddodiad N.
3. Gallai technegau rheolaeth wella addasrwydd cynefin (e.e. rheoli rhywogaethau trechol), cael gwared â nitrogen o'r system, neu'r ddau.
4. Fodd bynnag mae i'r holl dechnegau rheolaeth hefyd ganlyniadau na fwriadwyd sy'n golygu y gallai eu defnyddio wrthdaro gyda blaenoriaethau cadwraethol eraill.
5. Ceir ystod o gynlluniau a llawlyfrau yn y DU sy'n rhoi cyngor ar reoli cynefin. Cafodd y technegau canlynol eu hadolygu yn fanwl: pori; torri; llosgi; gwrteithiad; calchu; rheolaeth hydrolegol; rheolaeth coed a phrysgwydd; aflonyddu.
6. Gallai rheolaeth bresennol fod eisoes yn atredu i ryw raddau effaith dyddodiad N.
7. Mae'n annhebygol y bydd rheolaeth N yn gwneud cynefinoedd yn fwy agored i newid hinsawdd. Mae cyfatebolrwydd yn yr opsiynau rheolaeth sydd eu hangen i fynd i'r afael â dyddodiad N a newid hinsawdd. Bydd angen i amlder neu ddwysedd mesurau fel pori, torri neu losgi gynyddu. Gallai amrywiaeth lleol mewn newid hinsawdd arwain at roi pwyslais ar opsiynau rheolaeth gwahanol yn y gogledd orllewin gwlypach a'r de ddwyrain sychach.
8. Bydd newid hinsawdd yn newid sensitifrwydd cynefin i ddyddodiad N, trwy newidiadau yn y prosesau ecosystem. Yn gyffredinol, bydd newid hinsawdd yn gwneud coetiroedd yn llai sensitif i ddyddodiad N, ond bydd yn gwneud rhostiroedd yn fwy sensitif i ddyddodiad N. Nid yw'r effeithiau ar gynefinoedd eraill wedi'u cloriannu hyd yma.
9. Mae rhywfaint o botensial i liniaru effeithiau dyddodiad N trwy reolaeth ar safle er bod hyn yn amrywio'n fawr rhwng cynefin ac ymarfer rheoli. Mae'n debygol y gallai mân newidiadau mewn rheolaeth a chadw at ganllawiau addas wella rhywfaint ar addasrwydd cynefin a / neu lwyddo'n well i gael gwared â N.
10. Nid yw'r rhan fwyaf o ymarferion rheoli yn cael gwared â swmp arwyddocaol o N (ac eithrio cael gwared â biomas neu uwchbridd). Yn ogystal, byddai rheolaeth i ddwysedd addas i gael gwared â digon o N i atredu'n llwyr yr N a ychwanegir gan dyddodiad

atmosfferig, yn debygol o ddifrodi'r cynefin gan arwain at nifer o ganlyniadau na fwriadwyd.

11. Mae angen gwneud rhagor o ymchwil i ddarganfod effeithiau arferion rheolaethol unigol ar swmp N mewn gwahanol gynefinoedd. Mae angen gwneud ymchwil pellach hefyd er mwyn archwilio'r posibilrwydd o ddefnyddio technegau rheolaethol gwahanol i gael gwared â N o safleoedd.
12. Yn achos safle unigol lle mae N wedi'i nodi yn bwysau, gall rheolwr edrych ar y rheolaeth bresennol a chymharu hynny gyda'r argymhellion rheolaethol yn yr adroddiad er mwyn gwneud newidiadau lle bo hynny'n addas.
13. Mae'r holl argymhellion rheolaethol sy'n cael gwared â N o'r safle yn ei symud i rywle arall ac mae posibilrwydd y byddai'r argymhellion yn rhoi canlyniadau na fwriadwyd. O ganlyniad nid oes ffordd arall o leihau faint o N sydd wedi'i ddyddodi ar safle a dim ond drwy reolyddion gollyngiad y gellir gwneud hyn.

EXECUTIVE SUMMARY

11. Given the widespread impacts on habitats in the UK it is essential to understand how habitat management measures could mitigate N deposition impacts and promote recovery. This project reviews the effectiveness of ‘on-site’ land management methods to mitigate nitrogen deposition impacts on sensitive habitats; assesses what effect current management practice has on habitat response to nitrogen deposition; considers how measures may be affected by climate change; and recommends realistic and practical management measures for different habitat types which could be used to mitigate nitrogen impacts or speed recovery.
12. The potential for management to mitigate N deposition impacts was considered across the following broad habitats: broadleaved, mixed and yew woodland & (natural) coniferous woodland; neutral grassland; calcareous grassland; acid grassland; dwarf shrub heath; bog; coastal dunes and slacks; other coastal habitats. For all habitats we were able to identify management techniques with some potential to mitigate N deposition impacts.
13. Management techniques may improve habitat suitability (e.g. control dominant species), remove nitrogen from the system, or both.
14. However, all management techniques also have unintended consequences meaning that their implementation might conflict with other conservation priorities.
15. There are a range of schemes and handbooks providing habitat management advice in the UK. The following techniques were reviewed in detail: grazing; cutting; burning; fertilisation; liming; hydrological management; scrub and tree management; disturbance.
16. Current management may already be partially offsetting the impact of N deposition.
17. Management for N is unlikely to make habitats more vulnerable to climate change. There is complementarity in the management options required to tackle N deposition and climate change. The frequency or intensity of measures such as grazing, cutting or burning will all need to increase. Regional variation in climate change may lead to different emphasis of management options in the wetter north west and the drier south east.
18. Climate change will alter habitat sensitivity to N deposition, via changes in ecosystem processes. Overall, climate change will make woodlands less sensitive to N deposition, but will make heathlands more sensitive to N deposition. Effects on other habitats have not yet been evaluated.
19. There is some potential for mitigating the impacts of N deposition through on-site management although this varies greatly between habitat and management practice. It is likely that small changes in management and adherence to appropriate guidelines could partially improve habitat suitability and/or increase N removal.
20. The majority of management practices do not remove significant quantities of N (with the exception of removing biomass or topsoil). Furthermore, management of a suitable intensity to remove sufficient N to fully offset N added by atmospheric deposition is likely to damage the habitat and result in a number of unintended consequences.
21. Further research is needed to determine the impacts of individual management practices on the N budget in different habitats. Further research is also needed to explore the potential for novel management techniques to remove N from sites.

22. For an individual site where N is identified as a pressure, a manager can look at current management and compare this with the management recommendations in the report to make changes where appropriate.

23. All management recommendations that remove N from the site move it elsewhere and have the potential for unintended consequences. Consequently there is no substitute for reducing the amount of N deposited onto a site which can only be achieved through emission controls.

TECHNICAL SUMMARY

Introduction

Globally the deposition of reactive nitrogen (N) has more than doubled over the last one hundred years and in the UK only small declines in N deposition are predicted in the next ten years. The potential loss of biodiversity as a result of N deposition has important implications for both environmental and agricultural policy. Given the widespread impacts on habitats in the UK it is essential to understand how habitat management measures could reduce N deposition impacts and promote recovery. In order to explore how on-site habitat management could be used to mitigate atmospheric N impacts on terrestrial habitats this project addressed the following aims:

- Review the effectiveness of 'on-site' land management methods to reduce nitrogen deposition impacts on sensitive habitats and species or to aid recovery;
- Assess what effect current management practice, used by the conservation bodies, has on habitat response to nitrogen deposition (reduces, exacerbates or prevents impacts);
- Consider how measures may be affected by climate change or management in response to climate change, in the near-term, or may affect habitat vulnerability to climate change;
- Recommend realistic and practical management measures for different habitat types which could be used to reduce nitrogen impacts or speed recovery and to discuss their effectiveness;

Review of the effectiveness of 'on-site' land management methods to reduce nitrogen deposition impacts on sensitive habitats and species or to aid recovery

This chapter reviews on-site management methods and their potential effect on N deposition impacts. The state of knowledge of N impacts in the habitat is briefly summarised and evidence for how management practices in that habitat might be able to mitigate adverse N impacts is reviewed. The broad habitats and management options considered are summarised in table E1.

Managing for any single issue (e.g. N, climate change, biodiversity) in isolation may result in unintended and undesirable outcomes. Many studies which have recommended increased intensification of management have failed to monitor the impacts on the full range of species and functions. Unintended consequences of management to mitigate N impact were identified for all methods. These included damage to plants, insects, animals and birds; impacts on water quality, loss of soil C stocks, changes in N cycling, acidification, loss of seedbanks, visual blight. These may be habitat-type and management specific.

The use of case study sites or experiments to separate N deposition and management effects was explored. Potential data sources were identified and it was concluded that although we believe it is possible to disentangle the effects of N deposition and management in some of the data sources, individual data sources will require considerable analysis and interpretation in order to separate the effects of these two. It is possible that management has already changed in response to N deposition within impacted sites but managers are not necessarily aware that they are working towards addressing N deposition impacts.

Table E1 Summary of broad habitats and the potential for on-site land management methods to mitigate nitrogen deposition impacts on habitat suitability or to remove N from the system. A question mark means there is insufficient evidence to draw a conclusion on the potential of this method. An evidence score of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Broad habitat	Management method	Potential to mitigate N impacts on habitat suitability	Potential to remove N from the system	Strength of evidence
Broadleaved, mixed and yew woodland & (natural) coniferous woodland	Grazing and Browsing	Medium	Low	2
	Litter removal	High	Medium	1
	Thinning or harvesting	Low	Medium	2
	Burning	Low	High	3
Neutral grassland	Grazing	Medium	Low	3
	Cutting	Medium	High	2
	Liming	Medium	Low	3
	Introduction of hemi-parasitic species	High	Low	2
	Hydrological management	Low	Medium	3
	Carbon addition	Medium	Low	3
	Turf stripping	Low	High	3
Calcareous grassland	Grazing	Medium	Low	3
	Cutting	Medium	High	2
	Sheep folding	?	Medium	3
	Glycophosphate control of *Brachypodium rupestre*	Low	Low	2
Acid grasslands	Grazing	Medium	Low	1
	Burning	Low	High	3
	Liming	Medium	Low	3
	Cutting	Medium	High	2
Dwarf shrub heath	Turf stripping	High	High	2
	Rotavating	Low	Low	2
	Grazing	Medium	Low	2
	Cutting	High	High	1
	Burning	High	High	2
Fen, marsh and swamp	Grazing	Low	Low	3
	Cutting	High	High	2
	Burning	Medium	High	3
	Hydrological management	Medium	Medium	3
	Topsoil removal	Medium	High	3
Bogs	Hydrological management	Medium	Medium	3
	Burning	?	High	3
Coastal dunes and slacks	Grazing	High	Low	1
	Cutting	Low	High	1
	Burning	?	High	3
	Hydrological management	Medium	Medium	2
	Turf stripping and topsoil removal	High	High	2
	Dune mobilisation	High	Low	2
Other coastal habitats	Grazing	Medium	Low	3
	Cutting	?	High	3

Assessment of effects of current management practice, used by the conservation bodies, on habitat response to nitrogen deposition

This chapter assesses the effect of current management practice, used by the conservation bodies, on habitat responses to N deposition. Of the habitats considered in the previous chapter, six are included here (acid grassland, calcareous grassland, dwarf shrub heath, bog, coastal dunes and woodland). These habitats were selected for more detailed study because they are known to be sensitive to N deposition and there is sufficient information on management practices and their impact on N cycling for review. To compile current management practice lists, conservation agency publication lists were searched, conservation agency habitat specialists were consulted, and agri-environment scheme handbooks were used. Only management practices prescribed for habitat conservation, as opposed to restoration and creation, were considered. In total, nine broad categories of management practice were identified (Table E2).

Table E2 Habitats and topics of current management recommendations by UK conservation agencies, set out in nine broad management classes

	Grazing	Cutting	Burning	Fertilisation	Liming	Hydrological Management	Scrub removal	Tree removal	Disturbance
Acid grassland	✓	✓	✓	✓	✓	✓	✓	✓	✓
Calcareous grassland	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dwarf shrub heath	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bog	✓	✓	✓	✓	✓	✓	✓	✓	✓
Coastal Dunes	✓	✓		✓	✓	✓	✓		✓
Woodland	✓	✓		✓		✓	✓	✓	✓

Grazing

Current recommendations to graze habitats may result in minor removal of N off-site in animal live-weight gain, with slightly increased N losses as a result of leaching due to nitrate accumulation. However these losses are not sufficient to offset the impacts of atmospheric addition. Leaching also has negative implications for water quality with losses likely to be highest in winter. Management of grazing stock so that they are removed at night has the potential to provide some reduction in N from the site but this has not been quantified. The main benefit of grazing is to open up the canopy and reduce the dominance of competitive species, thus increasing light availability for species which are poorer competitors in the lower canopy. However, increasing the intensity of grazing has the potential to alter species composition reducing species less tolerant of grazing, and excess grazing may also be detrimental to flora and fauna. Grazing with a mix of sheep or ponies and cattle offers the best potential to both reduce sward height and remove areas of tall vegetation.

Cutting

Cutting clearly removes N in above-ground biomass in all habitats where it is used and, as long as cuttings are removed from sites, has the potential to mitigate against N deposition impacts. In some habitats there is the potential for increased decomposition and reduced leaching to offset some of this benefit but further research is needed to determine the magnitude of these changes.

However, replacing current grazing management with cutting presents practical difficulties and may result in changes in species composition. If cuttings are not removed then cutting could potentially exacerbate the impacts of N deposition. If cutting is used as a management tool the timing of the cut could be used to maximise N offtake although care needs to be taken to avoid adverse effects on seed set of species of conservation interest.

Burning

Overall, burning removes N from vegetation, increases N leaching from soil, and increases habitat suitability for heather in some cases. Given these responses, the current management practice of prescribed burning in dwarf shrub heath has the potential to reduce adverse responses to N deposition. However, burning needs to be carefully managed and can have unintended consequences for wildlife and water quality. It is also not suitable in all situations (e.g. close to urban areas) and so careful consideration should be given to the site characteristics and situation before burning.

In both acid and calcareous grasslands, burning removes standing and litter biomass, but is unlikely to reduce the dominance of competitive species since these are often adapted for rapid re-establishment after fire (e.g. *Brachypodium rupestre* in calcareous grasslands). Current advice, i.e. to consider vegetation composition, is appropriate for the management of habitat responses to N deposition. Given the sensitivity of woodland ground flora to fire, and the inconsistent effects on soil N, the prescription of no burning in forests should be continued.

Fertilisation

In general the addition of fertilisers, and especially N fertilisers, is likely to exacerbate the effects of N deposition.

Liming

Liming mitigates against the acidification effects of N deposition in habitats with acid soils. However, liming should be used with caution since it alters many aspects of soil N cycling, often increases the availability of other nutrients, changes vegetation species composition and can increase leaching of dissolved organic carbon with water quality impacts. Liming soils has the potential to increase eutrophication effects. There should be a clear understanding of the desired endpoint if considering liming as a management option, and unintended consequences on species of conservation interest should be considered.

Hydrological management

Drainage of wet habitats is likely to exacerbate impacts of N deposition by increasing rates of mineralisation and reducing losses of N through denitrification. Current recommendations to avoid drainage therefore seem the most suitable management to minimise N impacts. Rewetting of habitats could potentially increase N losses by denitrification but will have potentially deleterious, implications for botanical species composition, although often the main aim of such management measures is to reinstate particular favourable hydrological regimes. However, care needs to be taken to consider whether the nutrient status and geochemical composition of waters used to rewet the site are appropriate and do not exacerbate impacts of N deposition on the site.

Scrub and tree management

Removing scrub by cutting, topping or mowing has the potential to remove large amounts of N from grassland, heathland or bog sites. It also increases light levels reaching the smaller stature stress-tolerant species and has the potential to reduce rate of N deposition. There is the potential for mineralisation and decomposition rates to be increased but no data are available on how much rates are likely to be impacted.

In conservation woodlands, current advice on tree management is generally not to remove living trees. This strategy seems also to be the best for minimising impacts on the N cycle because although removing trees would increase N offtake and leaching it is also likely to increase mineralisation and decomposition, making more N available as well as causing considerable damage to the habitat. Deadwood management recommends that deadwood be left *in situ*, since wood has a low N content this is unlikely to cause an exacerbating effect.

Disturbance

In most habitats soil disturbance is generally not recommended except in some very specific situations. Considering the large number of unintended consequences, in the majority of cases, it seems appropriate to continue to avoid disturbance. In some habitats, these techniques may provide a viable option in some cases. Turf stripping in dwarf shrub heath and peat cutting in bogs represent a major removal of N from the system with the potential to mitigate N deposition impacts, however this is a destructive and expensive technique and, in the case of bogs, the unintended consequences outweigh benefits. In coastal dunes however, it represents a relatively cost-effective management option over the longer term, and may be one of the more sustainable methods of recreating the conditions required for early successional habitats to persist on larger sites.

Summary

A number of management practices currently recommended in conservation guidelines and agri-environment schemes have the potential to reduce the impacts of N deposition on sites of conservation importance. In many sites we may not see the full impact of N deposition. Small changes to recommended management have the potential to further reduce the impact of N deposition. However, all management measures have unintended consequences and it is likely to be very rare that management at a level of intensity that will not be damaging to the habitat will offset N deposition inputs.

How measures may be affected by climate change or management in response to climate change, in the near-term, or may affect habitat vulnerability to climate change

This chapter explores how N mitigation measures will be affected by climate change, how habitat sensitivity will be affected by climate change, and how management can tackle both climate change and N deposition. We conclude that the majority of management activities used to mitigate the adverse effects of N on habitat suitability or on N storage in ecosystems, will also help to moderate some of the adverse effects of climate change (with the possible exception of some woodland management recommendations).

A review of climate change impacts on habitat sensitivity to N deposition showed that impacts differed for each nitrogen process, i.e. plant uptake, immobilisation in soil, denitrification and leaching (Table E3). Managers only have control over some of these processes (plant uptake), but need to be aware of others (long-term N immobilisation in soil).

Table E3 Summary of climate change impacts on N processes which govern the losses of N from habitats as part of the Simple Mass Balance (SMB) critical load.

Nitrogen process (SMB term)	Sensitivity of SMB critical load to this process	Importance for management	Management potential to alter N losses
Nitrogen uptake and removal from the system via cutting etc. (Nu)	Med-High	High, progress can be made over short timescales	High potential, by increasing intensity or frequency of grazing, cutting or burning
Long-term N immobilisation in soil (Ni)	Med-High	High, but a longer term issue – alters resilience of natural systems	Limited potential, but managers should be aware of management activities which might affect soil N stocks
Denitrification (Nde)	Low	Low, denitrification may be beneficial	Low
Nitrogen leaching in runoff (Nleaching)	High	Low – High, depending on UK location	Low

There is considerable complementarity in the management options required to tackle both issues, due to similar impacts of climate change and N deposition in many habitats. In order to maintain or improve habitat suitability under both drivers, the frequency or intensity of measures such as grazing, cutting or burning will all need to increase. Increasing the frequency or intensity of management will also lead to greater N removal. However, cutting with biomass removal and some disturbance measures remain the only methods which will actively reduce accumulated N stocks. The need for monitoring and possible subsequent hydrological management of wetland systems is likely to increase in importance. Working with natural processes is likely to make management for climate change and N deposition impacts easier and cheaper in the long-run, particularly for coastal habitats. Regional differences in climate change within the UK may lead to different emphasis of management options in the wetter North and West compared with the drier South and East.

Recommending realistic and practical management measures for different habitat types which could be used to reduce nitrogen impacts or speed recovery

This chapter describes the recommendations for management strategies with the potential to mitigate the impacts of N deposition on individual habitats. The management recommendations should be considered as general advice and suitability for individual sites will need to consider conservation objectives and circumstances. The conditions at the site prior to management to mitigate N deposition impacts are an important consideration and may impact on the suitability of different management strategies, their likelihood of success and the rate of recovery.

Management recommendations were drafted based on chapters 2 to 4 of this report and were then presented to Habitat Specialists from the Countryside Council for Wales, Natural England, Scottish Natural Heritage and the Northern Ireland Environment Agency. The management recommendations made are all based on measures that can be implemented within a site of conservation interest.

Table E4 Summary of management recommendations which could be used to reduce nitrogen impacts or speed recovery for each habitat. In the current practice column 'Yes' indicates that this is in line with current recommendations and practice, 'No' indicates that this is a novel management technique, and Sometimes indicates that it is currently recommended under some advice. A confidence of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Habitat	Recommendation	Justification	Confidence	Current practice?
General	Well managed according to guidelines	Increases resilience	2	
	No N addition	Avoids adding N to the site	1	Sometimes
	No supplementary feeding	Avoids adding N to the site	1	Sometimes
Woodland	Continue to retain deadwood	Low quantities of N, high conservation	2	Yes
	Litter removal (lowland only)	Removes N from the site	3	No
Acid grasslands	Graze to sward height guidelines	Increases light availability	1	Sometimes
	Mixed stock grazing	Increases light availability	1	Sometimes
	Winter grazing	Increases light availability	2	Sometimes
	Stock removal at night	Removes N from the site	3	No
	Lime at low levels where suitable	Reduces acidification impacts	3	No
	Continue to avoid installation of new drainage	No benefits by changing advice	1	Yes
	Continue scrub management	Removes N and increases light availability	1	Yes
	Continue to avoid large-scale disturbance	No benefits by changing advice	1	Yes
Calcareous grasslands	Graze to sward height guidelines	Increases light availability	1	Sometimes
	Consider mixed stock grazing	Increases light availability	1	Sometimes
	Consider winter grazing	Increases light availability	2	Sometimes
	Consider stock removal at night	Removes N from the site	3	No
	Continue to avoid installation of new drainage	No benefits by changing advice	1	Yes
	Continue scrub management	Removes N and increases light availability	1	Yes
	Continue to avoid large-scale disturbance	No benefits by changing advice	1	Yes
Dwarf shrub heath	Grazing	Increases light availability	2	Sometimes
	Stock removal at night	Removes N from the site	3	No
	Use cutting where burning not possible but remove cuttings	Removes N and increases light availability	1	Sometimes
	Use burning where appropriate	Removes N and increases light availability	1	Sometimes

	Define burn frequency relative to dwarf shrub heath growth	Removes N and increases light availability	1	Sometimes
	Use high intensity burns where appropriate	Removes N and increases light availability	1	No
	Avoid installation of new drainage	No benefits by changing advice	1	Yes
	Continue scrub management	Removes N and increases light availability	1	Yes
	Consider turf stripping in heavily impacted sites	Removes N from the site	2	Yes
Bog	Graze where appropriate	Increases light availability	1	Sometimes
	Burn where already used for conservation	Removes N and increases light availability	2	Yes
	Enable water table fluctuation	Maximises N loss	2	No
	Continue scrub management	Removes N and increases light availability	1	Yes
Coastal dunes and slacks	Continue or introduce grazing where appropriate	Increases light availability	1	Sometimes
	Use cutting where grazing is not possible	Removes N and increases light availability	1	Sometimes
	Remove all cuttings	Removes N from the site	1	Sometimes
	Restore natural water regimes	Increases site resilience	1	Sometimes
	Continue scrub management	Removes N and increases light availability	1	Yes
	Remobilisation of dune systems	Restores natural N cycling	2	Sometimes

Conclusion

There is some potential for reducing the impacts of N deposition through on-site management although this varies greatly between habitat and management practice. It is likely that small changes in management and adherence to appropriate guidelines could reduce the impacts of N deposition on habitat suitability and could increase N removal and may already be doing so. The majority of management practices do not remove significant quantities of N. Furthermore, management of a suitable intensity to remove sufficient N to fully offset N added by atmospheric deposition is likely to damage the habitat and result in a number of unintended consequences.

Further research is needed to determine the impacts of individual management practices on the N budget in different habitats. Further research is also needed to explore the potential for novel management techniques to remove N from sites. Novel management techniques are litter removal in woodlands, stock removal at night in grasslands, liming in acid grassland, high intensity burns in heathland, and water table management in bogs.

For an individual site where N is identified as a pressure, a manager can look at current management and compare this with the management recommendations in the report to either: include new management techniques not currently in use on the site, or continue doing those which will be of benefit in reducing N impacts and ensure that current guidelines are adhered to. Changes to management must consider the conservation objectives of the site and unintended consequences of the management practices. All management recommendations that remove N from the site move it elsewhere and have the potential for unintended consequences. Consequently there is no substitute for reducing the amount of N deposited onto a site which can only be achieved through emission controls.

For an individual site where N is identified as a pressure, a manager can look at current management and compare this with the management recommendations in the report to make changes where appropriate.

1. INTRODUCTION

Globally the deposition of reactive nitrogen (N) has more than doubled over the last one hundred years as a result of agricultural intensification and increased burning of fossil fuels by traffic and industry (Galloway *et al.* 2008; Fowler *et al.* 2005). Atmospheric deposition of reactive N has the potential to enrich the N content of soils, resulting in increased plant growth and hence competition for light (Bobbink *et al.* 1998; Hautier *et al.* 2009) and other resources, and to acidify soils reducing the number of species that can tolerate these conditions and coexist (Schuster and Diekmann, 2003). The potential loss of biodiversity as a result of N deposition has important implications for both environmental and agricultural policy. Globally, the deposition of reactive N is set to increase in the future due to increased demand for food from the expanding global population (Tilman *et al.* 2002; Dentener *et al.* 2006). In the UK only small declines in N deposition are predicted in the next ten years (RoTAP, 2012). Given the widespread impacts on habitats in the UK (Stevens *et al.* 2011a; Emmett *et al.* 2011) it is essential to understand how habitat management measures could reduce N deposition impacts and promote recovery.

In order to explore how on-site habitat management could be used to reduce atmospheric N impacts on terrestrial habitats this project will address the following aims:

- To review the effectiveness of 'on-site' land management methods to reduce nitrogen deposition impacts on sensitive habitats and species or to aid recovery;
- To assess what effect current management practice, used by the conservation bodies, has on habitat response to nitrogen deposition (reduces, exacerbates or prevents impacts);
- To consider how measures may be affected by climate change or management in response to climate change, in the near-term, or may affect habitat vulnerability to climate change;
- To recommend realistic and practical management measures for different habitat types which could be used to reduce nitrogen impacts or speed recovery and to discuss their effectiveness;
- To recommend how the methods could be tested in a demonstration trial; giving recommendations for the design of a trial.

This report is presented in five sections. Section 1 provides a brief introduction to the impacts of N deposition on ecosystem processes. Section 2 addresses the first objective of the project by reviewing management options available for reducing nitrogen deposition impacts on habitats. In section 3 we identify current management practices used by conservation agencies and in agri-environment schemes and discuss how these might impact on habitat responses to N deposition. Section 4 discusses how measured to reduce impacts of N deposition might interact with climate change. In section 5 we provide recommendations for continuation of current management practices or for changes to current management practice based on discussion with habitat specialists. The final objective, to recommend how methods could be tested in a demonstration trial is published in a separate report.

1.1 Introduction to N deposition effects on ecosystem processes

1.1.1 The nitrogen cycle

After carbon (C), oxygen and hydrogen, N is the most abundant element in the tissue of living organisms. The vast majority of N in the atmosphere is present as unreactive N_2 gas, but to be incorporated into living tissue it must be in "reactive" form. For brevity, reactive N is referred to in this report simply as N. Reactive N mainly consists of reduced N (ammonia gas, NH_3, and its dissolved form, NH_4^+) or oxidised N (N oxides and their dissolved forms such as nitrate, NO_3^-).

Large amounts of N are needed for plants and animals to grow – for example, the N removed in silage in a typical two-cut system amounts to 200-400 kg N ha^{-1} yr^{-1} (McCalman, 2012). Farmers have to pay attention to replacing this N efflux if they are to maintain productivity, by spreading slurry, incorporating N-fixing plants such as clovers, or applying artificial N fertiliser. Natural systems without inputs of anthropogenic N typically have a much lower rate of N input, from biological N fixation and the effects of lightning, of the order of 3-5 kg N ha^{-1} yr^{-1} (DeLuca *et al.* 2008). Following the invention of artificial N fixation (Haber-Bosch process) and the release of reactive N during burning of fossil fuels, the total planetary flux of reactive N has more than doubled. This is a global average; the increase in N inputs in the UK is considerably greater. Even in ecosystems where no N fertiliser is applied, atmospheric pollution results in typical UK deposition rates of 10-15 kg N ha^{-1} yr^{-1} in the lowlands and 15-25 kg N ha^{-1} yr^{-1} in upland areas (RoTAP, 2012). A recent modelling study suggests that this extra input has approximately doubled plant productivity in unfertilised semi-natural ecosystems since pre-industrial times (Tipping *et al.* 2012).

When assessing the effects of this extra N on habitats and species, it is useful to distinguish between effects of habitat management on the N budget for a site, and effects of management on the processes that affect habitat suitability for particular species. The N budget consists of the flows into and out of the site and the stocks of N in the soil, vegetation and animals. A simplified version of this budget is illustrated in Figure 1.1, in which the solid arrows represent flows of N. The main ways that aspects of this cycle affect habitat suitability for species are shown by dashed arrows.

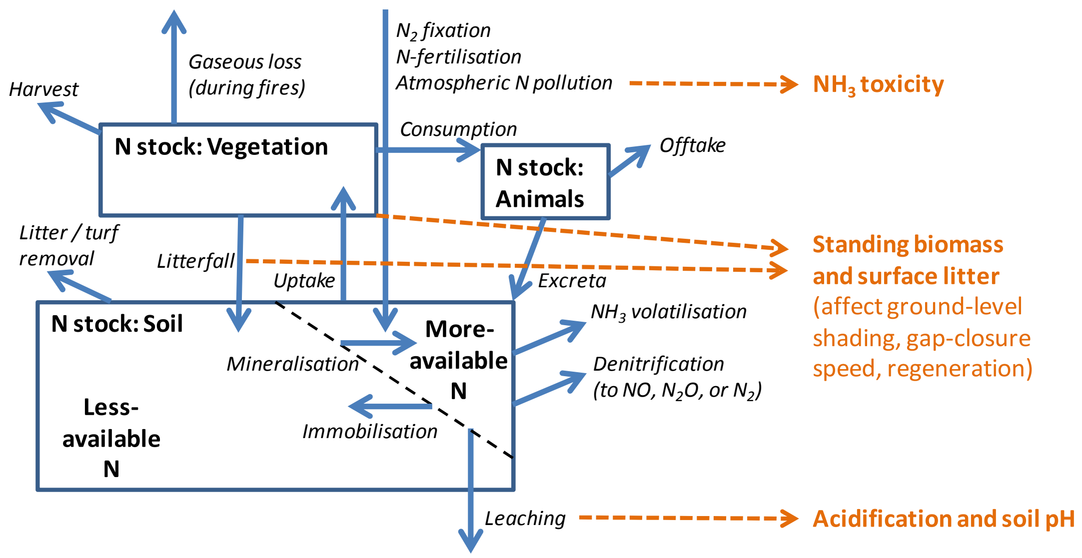


Figure 1.1 Simplified diagram of the terrestrial nitrogen cycle and its influences on processes that can affect biodiversity. Solid arrows represent flows of N and dashed arrows link aspects of the cycle to habitat suitability.

The stock of N in an ecosystem, in particular in the soil, is much greater than the annual fluxes in and out. Much of the N in soil is bound up in organic matter and so not immediately available to plants, although there is a gradual transfer to usable N through mineralisation. In most habitats, the N leaching rate and other losses have increased far less than the input rates (Phoenix *et al.* 2012), so large amounts of anthropogenic N have accumulated in the soil. Some of the loss pathways of reactive N from an ecosystem can themselves cause damage, to the site or elsewhere. Leaching results in soil acidification and can pollute downstream ecosystems. Nitrous oxide (N_2O) is a potent greenhouse gas. Some N export routes are less damaging, and one option for mitigating N pollution is to increase the offtake of N in livestock, biomass, litter or soil. However, net export in livestock, biomass or litter is likely to be small (see Section 3.3), and soil and litter removal can be problematic. There are management options to mitigate some impacts of N deposition via site management, but in general these do not remove the problem, which can only come about through reductions to N inputs.

1.1.2 Oxidised and reduced nitrogen

One of the simplifications in the diagram is that reduced and oxidised N are not distinguished. Reduced N, particularly when in the form of gaseous ammonia, is more toxic to plants and lichens than is nitrate, and for this reason a low concentration of ammonia gas, 1 $\mu g\ NH_3\ m^{-3}$, is considered the critical level above which effects on ecosystems occur (Cape *et al.* 2009). Reducing atmospheric ammonia concentrations involves local and national measures to limit emissions, which come mainly from intensive livestock units, but there is some potential for on-site or near-site management (see section 1.1.6).

1.1.3 Acidification

Sulphur (S) and N pollution are the main causes of acid rain. Through effective international agreements, sulphur emissions have greatly reduced across Europe since the 1980s. In the UK, 73% of the area of sensitive habitats received acid deposition in excess of the acidity critical load in 1996, and this declined to 54% of the area of sensitive habitats by 2007 (DEFRA, 2012). However, some sensitive ecosystems have limited capacity to replace the calcium and other base cations that were leached during the period of excessive acid deposition, and are recovering only slowly (Evans *et al.* 2012). Rates of N deposition have not reduced as much, and N continues to be a source of acidifying compounds. Although most UK systems are slowly starting to recover, residual soil acidity from historical S deposition, coupled with continuing inputs of N are still causing loss of biodiversity. The most acid-sensitive habitats are those with little calcium in the soil, such as acid grassland, bog and heath. Although the acid soil in these habitats supports distinctive species, they can become too acid for many species. Species richness generally declines with pH, and this explains some of the clear pattern of decreasing species richness with more N deposition observed on acid grassland sites (Stevens *et al.* 2004).

Acidification occurs when N is leached from the soil or utilised by organisms. If all of the N deposited on ecosystems is retained in vegetation and soil, as is often the case, acidification does not occur, neither does the N pollution of watercourses. However, retention of N within the terrestrial ecosystem causes both short-term and long-term problems.

1.1.4 Effects on productivity and light availability

Plant productivity in many ecosystems is limited by N availability, so additional N increases the growth of plants. This apparently beneficial effect actually underpins one of the main reasons why N pollution reduces biodiversity. The plant species that respond most vigorously to the extra N tend to be more competitive, taller-growing species, and shorter-growing species are likely to be shaded out (Hautier *et al.* 2009). Species that have increased their range across the UK in recent decades include those that are taller, whereas shorter species are more likely to be threatened or rare (Ken Thompson, *pers com*). Increased litter production also reduces the amount of light at ground-level. The variety of ways in which plant species fill gaps in vegetation is one mechanism that underpins plant diversity in habitats such as grasslands (Grime, 1973). Increased productivity and litterfall mean that gaps close more quickly.

It is difficult to separate the effects of increased plant growth due to eutrophication from the relaxation of management, which is more commonly reported as a reason for loss of habitat condition. Pollution by N and reductions in grazing or woodland management are likely to have synergistic effects, and the encroachment by competitive species and loss of low-growing species are likely to be exacerbated by both. Damage by N occurs over long time scales, with a gradual loss of species over decades, and is therefore difficult to observe on a particular site. However, compelling evidence is available from national surveys that chronic N pollution is having severe adverse effects on UK plant and lichen diversity (Emmett *et al.* 2011).

1.1.5 Effects on biota other than plants and lichens

Although much of N impacts research has focused on plant diversity, effects on other organisms have been observed. Increased standing biomass and litter production can directly affect invertebrates that require open ground (Wallisdevries and Van Swaay, 2006). Studies have shown adverse effects of N deposition on mycorrhizal hyphal density (e.g. Nilsson *et al.* 2007) and occurrence of fruiting bodies of ectomycorrhizae (e.g. Brandrud and Timmermann, 1998). There is less conclusive information on effects of N deposition on soil fauna or on mammals (Bobbink and Hettelingh, 2011). However, there is limited evidence for changes in important microbial groups (Payne *et al.* 2013) and it seems likely that a reduction in plant diversity will adversely affect the diversity of other organisms, due to reductions in the structural diversity of the habitat and in the variety of food substrates.

1.1.6 Summary of management interventions

Potential options available to reduce N impacts on a site are, broadly:

- Reducing the flows of N onto the site.
- Increasing N removal from the site in plant material, animal biomass, litter or soil.
- Increasing N removal in water and gaseous flows.
- Reducing effects on ground-level light availability.
- Changing the biogeochemical processing of N.
- Increasing soil pH.

Different types of management will now be assessed against these options and in relation to the N cycle and its effects on biodiversity.

2 REVIEW OF THE EFFECTIVENESS OF 'ON-SITE' LAND MANAGEMENT METHODS TO REDUCE NITROGEN DEPOSITION IMPACTS ON SENSITIVE HABITATS AND SPECIES OR TO AID RECOVERY

This task reviews on-site management methods and their potential effect on N deposition impacts. For each of the broad habitat types listed below (Table 2.1), we briefly summarise the state of knowledge of N impacts in the habitat, then review the evidence for how management practices in that habitat might be able to mitigate adverse N impacts. We also consider the unintended consequences for other habitat components. Lastly, we explore the potential of existing long-running datasets and experiments as information sources for further analysis which might be useful in separately distinguishing impacts of N deposition from impacts of altered land management. These two drivers have previously been very difficult to disentangle.

Table 2.1 Broad habitat types included in the review

Broad habitat
1 Broadleaved, mixed and yew woodland & (natural) coniferous woodland
2 Neutral grassland
3 Calcareous grassland
4 Acid grassland
5 Dwarf shrub heath
6 Fen, marsh, and swamp
7 Bog
8 Coastal dunes and slacks
9 Other coastal habitats

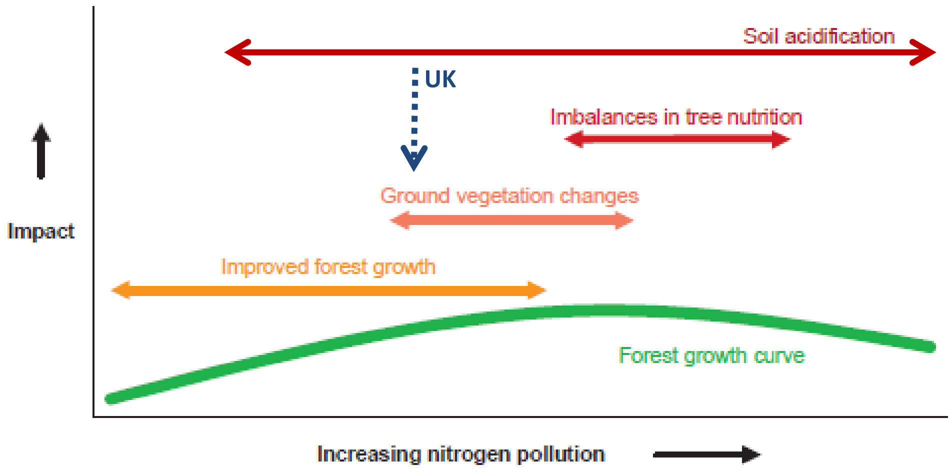
For each of the broad habitats listed in Table 2.1, the aims of this section are:

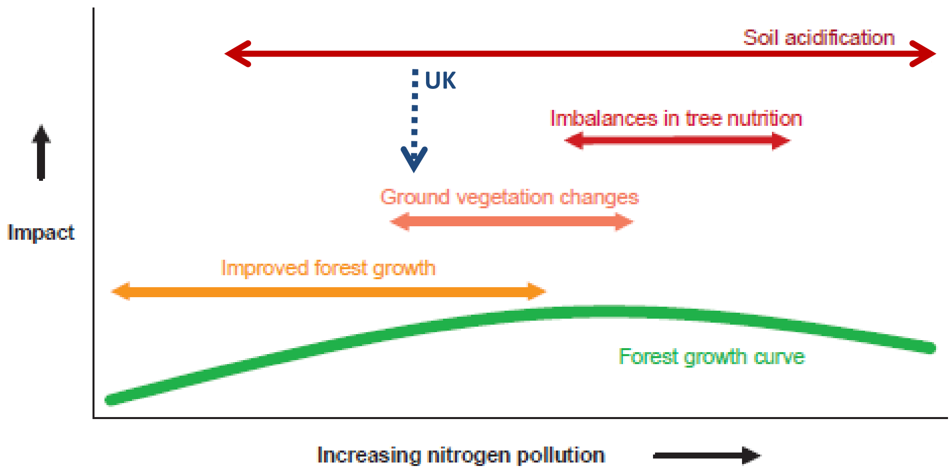
- To review the effectiveness of 'on-site' land management methods to reduce N deposition impacts on sensitive habitats and species or to aid recovery.
- To evaluate the risks to other management objectives.
- To investigate the potential for the use of case study sites.

2.1 Broadleaved, mixed and yew woodland & (natural) coniferous woodland

This section focuses on non-productive woodland and includes ancient and semi-natural woodland and plantations on ancient woodland sites. The effects of N deposition on woodland habitats are reviewed in detail in Bobbink and Hettelingh (2011).Empirical critical loads for these habitats are based on changes in the most sensitive components: ground flora, soil processes and nitrate leaching. Elevated N deposition to woodlands can affect soil processes (e.g. soil acidification, N immobilisation and accumulation, mineralisation, nitrification, nitrate leaching, litter decomposition), tree growth, nutrition and sensitivity to biotic and abiotic stress (Bobbink *et al.* 1996), and biodiversity (e.g. effects on macrofungi, mycorrhiza, epiphytic lichens and algae, ground vegetation). Data from 1205 semi-permanent vegetation plots from 23 understorey resurvey studies along a large N deposition gradient across deciduous temperate forests in Europe suggested N deposition could be one of the indirect drivers of change in understorey plant communities (Verheyen *et al.* 2012). However, management-related alterations in the canopy structure and composition appeared to play a more important role. The study concludes that if the N that has accumulated over decades in soils becomes available to plants then its impact will increase. Nitrogen is an essential growth nutrient so reactive N deposition will initially enhance tree growth when N availability is limiting. However, once N availability begins to exceed the demands for tree growth, there are a range of adverse effects (Figure 2.1).Species composition of ground flora will change in favour of N tolerant species, usually exhibiting faster growth rates, that out compete N sensitive species. At higher deposition levels, soils start to become N saturated, leading to leaching of nitrate into surface and groundwater supplies and soil acidification. These changes are progressive and can start to occur fairly early on, long before the system is fully N saturated. If deposition levels increase further or remain high, imbalances in tree nutrition may occur, leading to detrimental impacts on tree growth and increasing susceptibility of trees to insect attack and drought (Bobbink *et al.* 1996).

Figure 2.1 A schematic representation of the impacts of increased pollution on forest ecosystems (based on Gundersen, 1999). The dotted arrow shows approximately where UK forests currently fit along the nitrogen saturation curve.





The internal N status of a forest stand (important for determining the retention capacity) reflects historical N deposition and management practice (Emmett, 2002). Soil has a finite capacity to accumulate N, so that as exposure increases retention will decrease and the system will start to 'leak' N. For mature coniferous forests Gundersen *et al.* (1998) derived three classes of nitrate leaching risk:

Low risk: N limited systems with forest floor C:N>30

Moderate risk: Intermediate systems with forest floor C:N 25-30

High risk: N saturated systems with forest floor C:N<25

The Forestry Commission practice guidelines for managing ancient and native woodlands in England (FC, 2010) identify diffuse pollution and inappropriate management as two of the threats to these habitats. They also describe the ecological benefits of different types of woodland management:

- *Thinning and cutting understorey:* releases understorey, enhances ground flora, diversifies species composition, and releases veteran trees.
- *Felling and coppicing:* creates canopy gaps for ground flora and a sheltered woodland edge, and a temporary open phase.
- *Restocking and regenerating:* changes to a more natural mix of species, creates a thicket stage habitat and establishes the next generation of trees.
- *Opening up rides:* enhances woodland edge, restores remnant grassland or heathland habitat, and creates links between bigger patches of open habitat.
- *Managing deer and grazing:* reduces damage to ground flora, allows a shrub layer and understorey structure to develop, and prevents loss of palatable tree species.
- *Conserving deadwood and veteran trees:* conserves micro-habitats that are used by a large proportion of woodland species; remedies an unnatural characteristic of managed woodland, and ensures continuity through the centuries into the future.

While there are plenty of studies examining the impact of different management regimes in woodlands, few studies have focused on management to mitigate the impacts of excessive N deposition. Gundersen *et al.* (2006) list five mechanisms that may help alleviate N saturation in temperate forest ecosystems:

- Reducing N inputs
- Increasing N uptake
- Increasing N export in harvest
- Restoring soil N retention
- Improving catchment-scale N removal in the riparian zone.

A number of authors (e.g. Fenn *et al.* 2010; Prietzel and Kaiser 2005; Rothe *et al.* 2002) conclude that reductions in N deposition represent the only long-term sustainable method of reducing impacts. However, understanding how site management interacts with N pollution can help develop strategies to mitigate damage in the short- and medium-term. These site management options are discussed below.

2.1.1 Grazing and Browsing

Reported impacts of grazing/browsing in woodlands indicate advantages and disadvantages with respect to offsetting N deposition, affecting tree growth, ground flora and soils. Deer numbers and thus grazing pressures are increasing and need to be managed to protect ground flora in British Woodlands (Kirby 2001). Most vegetation types contain some species that may be sensitive to grazing. General trends linked to high deer populations include a reduction in *Rubus fruticosus* and all other growing herbs and ferns (other than bracken) and increases in grasses and lower-growing species. Deer browsing in young coppice woodland in eastern England reduced canopy cover and the density and cover of understorey vegetation, while increasing grass cover (Gill and Fuller, 2007). However, both browsing and shading can reduce understorey vegetation, so one may confound the impact of the other. The authors found that the abundance of bird species using the understorey was significantly higher in areas where deer were excluded. Improving the understorey cover for birds is likely to be most successful if combined with deer management (Gill and Fuller, 2007).

Trend data for Wytham Woods (Corney *et al.* 2008) suggest that changes in soil pH and nutrient status and deer browsing combined can change species richness and composition leading to an increase in grass species. Deer preferentially browsed *Rubus fruticosus*in shaded (i.e. closed canopy) areas helping to alter the shrub layer and competitive interactions between species leading to an increase in grass species.

Deer browsing also impacts on soils. Litter decomposition rates in native regenerating birch woodland in the Highlands of Scotland were significantly reduced by deer browsing(Harrison and Bardgett 2003). Browsing reduced litter quality, suggesting that herbivores can reduce rates of nutrient cycling in this habitat, and potentially mitigating adverse effects of N deposition impacts on ground flora. In a regenerating woodland in northern Britain growth of *Betula pubescens* was N limited in browsed areas reflecting lower N mineralisation rates (- 50%) and lower N availability. Tree growth rates and the quantity and quality of litter returned to the soil were all lower in browsed areas compared with unbrowsed areas. Both these studies suggest that deer browsing can help restrict the impacts of N deposition on soil N status. On the downside however, browsing itself can cause similar, deleterious effects on the understorey vegetation to excess N deposition.

Unintended consequences

- Elimination of grazing sensitive species
- Changes in species composition

2.1.2 Litter removal

Litter removal can reduce the amount of N in the ecosystem, but it also depletes the soil of other important nutrients, so the amount removed would need to be optimized. A litter removal experiment over a 16 year period, in an acidophilous mixed oak-pine woodland in southern Poland (Dzwonko and Gawronski, 2002), resulted in substantial impoverishment of the soil, with plots containing significantly less P, Mg, Ca and lower cation exchange capacity (CEC). However, vascular plants and bryophytes colonised these plots much more frequently, increasing species richness, although not abundance of the dominant species nor character of the vegetation. In the control plots (no litter removal) vegetation changed from acidophilous to neutrophilous, and vascular plants and mosses disappeared, due to the thick litter layer impeding seed germination and development, and competition by dominant species.

Six years of intensive prescribed litter raking in N saturated Scots pine forest in southern Germany reduced the soil N pool by 450 kg ha^{-1} (equivalent to 75 kg N ha^{-1} $year^{-1}$) (Prietzel and Kaiser 2005). The removed N was approximately 11% of the original pools down to 100 cm soil depth, and forest floor N pools were reduced by 40%. The bolewood was estimated to sequester only 22 kg N ha^{-1}. Therefore in forest ecosystems subject to elevated N deposition and eutrophication prescribed litter-raking could provide an effective tool to (a) maintain biotopes for endangered ground vegetation species adapted to N limitation and frequent ecosystem disturbance; (b) achieve a more balanced nutritional status of the forest stand and keep nitrate concentrations in seepage water low.

Unintended consequences

- Potential but unstudied effects of litter removal include: removal of base cations leading to acidification, impacts on fungi and other decomposer organisms including grounddwelling invertebrates, with potential consequences for some woodland birds. There has been no research in this area.

- Compromises the buffering capacity of soils by removal of base cations in the litter. There has been no research in this area.
- Reduces the CEC of the system, limiting the soils capacity to retain nutrients on exchange sites.

2.1.3 Thinning or harvesting

Although the focus of this report is on non-productive (i.e. non-commercial) forest, it may be useful to note that estimates of N removal by harvesting in productive UK forests, are in the order of 2.9 kg N ha^{-1} yr^{-1} for coniferous woodland and 5.9 kg N ha^{-1} yr^{-1} for broadleaved woodland (Hall *et al.* 2003).

A meta-analysis of forest management and soil C (Johnson and Curtis 2001) showed that on average, forest harvesting had little or no effect on soil C or N. However, significant effects of harvest type and tree type, deciduous versus evergreen, were identified; sawlog harvesting increased (+18%) soil C and N, contrasting a 6% decrease with whole-tree harvesting. This positive effect of sawlog harvesting appeared to be restricted to coniferous species. Fertilisation and naturally invading vegetation associated with N fixation increased soil C and N overall. In an ancient deciduous woodland in Cumbria, the characteristic ground flora changed considerably over 18 years at sites left unmanaged, or cleared and replanted, becoming clearly distinct from that of a traditionally managed wood (Barkham 1992).

Thinning will alter the forest canopy and thus the amount of light accessible to ground flora. In 20 beech woodlands across the UK vegetation cover tended to be greater (>50%) where the canopy gap fractions exceeded 9% Kennedy and Pitman (2004). Observations also indicated that the response to thinning may take time: two years was not sufficient, whereas after five years gaps were dominated by swards of *Holcus* and *Agrostis* grass species, which may not be desirable. That study also showed that the effects of light on ground flora can vary according to the age, structure and management of woodlands. At some mature tree sites the age of the trees had resulted in lower branch dieback and openings in the canopy permitting mosses to colonise the forest floor at some sites, or brambles (*Rubusspp.*).Although brambles can suggest N enrichment, Kennedy and Pitman (2004) found no significant relationship between incoming N deposition (estimated from national deposition databases) and ground flora composition. There was however, a relationship between weighted Ellenberg N score mean site values and the average distance to the edge of the woodland, indicating the importance of local N sources in determining ground flora species composition.

Hardtle *et al.* (2003) also examined the effects of light and soil conditions on the species richness of ground vegetation in three types of deciduous forest in northern Germany. In moist forests of alder-ash, species richness of the ground vegetation was positively correlated with soil moisture, while light and nutrient supply appeared to have no effect. In meso- to eutrophic beech forests, where many ground cover species are shade tolerant, species richness was determined by nutritional status (closely correlated with soil activity and base and N supply) rather than light. By contrast, in acidophyte beech and mixed beech-oak forests, species richness did respond to canopy closure and interior light conditions. This study also highlights how effects of soil moisture, nutrient supply and light conditions on ground flora depend on the type of forest community. It should also be appreciated that N as a nutrient is key to light harvesting, being a fundamental component of the Rubiscoenzyme. This means that increasing light levels can trigger similar responses in woodland ground level to N eutrophication, encouraging graminoids at the expense of lower plants and herbs.

Unintended consequences

- Changes in ground flora composition; loss of species
- Impacts on habitat/food/breeding requirements for birds, mammals and invertebrates
- Habitat fragmentation (e.g. if excessive thinning/harvesting)
- Disruption to "shelter belts" where woodland edges provide protection to areas within from near-source pollution (e.g. pig/poultry farms)

2.1.4 Burning

Fire has been used to reduce the size of soil N pools in other countries. In simulated scenarios prescribed fires every 15 years or so, combined with 50-75% reductions in N deposition, were the most effective treatment for N saturated catchments. Prescribed fires at longer intervals (e.g. 30-60 years), if accompanied by reductions of 25-50% in N deposition, also reduced ecosystem N (Southern California, Fenn *et al.* 2010). However, this approach is of limited use when the bulk (60-80%) of the site N capital is stored in the mineral soil. Also, prescribed forest fires can be difficult to implement in locations at the urban/natural area interface.

Prescribed burning can impact total C and N pools more than a combination of prescribed burning and thinning (northern Alabama, Nobles *et al.* 2009). Although, the review by Johnson and Curtis (2001) showed no overall effect of fire on soil C or N until ten years had elapsed, by then both soil C and N had significantly increased. Interestingly, soil C was lower following prescribed fires whereas wildfires increased soil C.

Prescribed fire is not likely to be a management option for removing N from UK woodland ecosystems, since they contain sensitive ground vegetation and epiphytic lichen communities which would be adversely impacted by fire. Fire is not a naturally occurring phenomenon in UK woodlands.

Unintended consequences

- Changes in ground flora composition; loss of species
- Impacts on habitat/food/breeding requirements for birds, mammals, invertebrates etc.
- Pollution swapping (transfers to atmospheric N or leaching).
- Burned areas look unsightly

2.2 Neutral grasslands

In neutral grasslands the majority of investigations concerned with the impacts of N on species composition and soil chemistry have been primarily concerned with agricultural fertiliser addition rather than atmospheric N deposition. However, many of these studies are useful in determining N deposition impacts.

The consequences of fertiliser addition to neutral grasslands are well established, and include a reduction in species richness and diversity, and an increase in dominance of a few agriculturally desirable and competitive species such as *Lolium perenne* and *Trifolium repens* (Kirkham *et al.* 1996). The Park Grass experiment at Rothamsted, England, the world's longest running ecological experiment is in lowland neutral grassland. In the Park Grass experiment over 150 years of fertiliser additions (including applications of N alone in the form of ammonium sulphate and sodium nitrate) have led to reduced species richness and a domination by grasses (Silvertown *et al.* 2006). Changes have also been observed in control plots which have shown declines in species richness associated with increasing atmospheric N deposition (Goulding *et al.*

1998). A long running experiment in a wet neutral grassland at Tadham Moor, Somerset has shown similar results. At Tadham Moor the grassland species composition was shown to be very sensitive to N addition. Nitrogen addition at a rate of 25 kg ha^{-1} N yr^{-1} encouraged the spread of agriculturally productive grasses within two years. At 50 kg N ha^{-1} yr^{-1} species richness was significantly reduced within three years (Mountford *et al.* 1993). Moreover, after five years of fertiliser application, the balance of plant species in the seed bank had changed in favour of species that were more competitive under fertile conditions (Kirkham and Kent, 1997). There were also clear impacts of N addition on soil N cycling. Kirkham and Wilkins (1993) showed that between 1987 and 1990 soil nitrate concentrations and total mineral N increased with N addition and rates of nitrification were also higher in plots receiving larger amounts of N. Other studies in mainland Europe have also shown increases in biomass and reductions in species richness with N addition (Beltman *et al.* 2007; Honsova *et al.* 2007).

Neutral grasslands are traditionally managed with a hay cut in early summer followed by aftermath grazing in the autumn.

2.2.1 Grazing

Grazing in hay meadows is traditionally carried out by sheep, horses or cattle after the hay crop has been collected after hay has been cut (aftermath grazing). Other neutral grasslands are grazed year round and managed as pasture. In neutral grasslands grazing as a potential tool to reduce the impact of N inputs has received considerably less investigation than cutting although lessons can be learnt from acid (section 1.4) and calcareous grasslands (section 1.3). Hynšt and Šimek investigated the impact of ammonium addition on selected soil properties of pasture grassland with and without cattle grazing. The found nitrate accumulation increased with increasing ammonium addition, this effect increased until a threshold was reached after which it stopped increasing. Under grazing the threshold for increase was higher leading to increased nitrate accumulation. This nitrate could then be available for leaching as seen in acid grasslands (see McGovern, 2011). Increased grazing intensity or longer grazing periods in neutral grasslands could lead to overgrazing, reduced botanical diversity (Pacha and Petit, 2008) and may impact on ground nesting birds (Beintema and Müskens, 1987).

Unintended consequences

- Loss of grazing intolerant species
- Changes in species composition
- Loss of ground nesting birds
- Changes in N cycling due to grazing rates
- Supplementary feeding is a source of nutrients and a seed source of undesirable plant species

2.2.2 Cutting

Both the timing and frequency of cutting have the potential to impact on N management. Čámská and Skálová (2012) investigated the impact of timing of cutting on the impact of N addition testing the hypothesis that early mowing would counteract the N addition by creating space for less competitive species. The *Arrhenatherion elatioris* community they were working in is a mesophilic meadow community traditionally managed by cutting once in late May and once in mid-August with an additional cut in autumn in some areas. Nitrogen addition rates were 56 kg N ha^{-1} yr^{-1}. The early cut was conducted two weeks earlier than usual. As expected N application increased nitrophious species and tall graminoids. However although cutting early reduced the abundance of tall herbs it did not increase the abundance of smaller herbs and grasses. They also raised the concern that cutting early may impact on seed production.

Working in Germany, Pavlů *et al*. (2011) investigated the result of cutting either twice or four times per year combined with N application levels of 0, 60, 120, 240 kg N ha^{-1} yr^{-1}. Their study was conducted in a *Lolio-Cynosuretum* meadow which had previously been intensively managed. The experiment was conducted over a 20 year period. Cutting four times per year reduced the sward height enabling dominant grasses with high nutrient demands to be replaced with other less nitrophilous grasses, Cutting frequency had a stronger effect on species composition than N because some species are better adapted to defoliation so the number of cuts was important for determining species composition.

A number of studies have investigated the potential for cutting to be used as a restoration tool to reduce levels of stored N in the soil or reduce the impacts of N inputs however; many of the studies conclude that N removal by defoliation is very slow. Bakker *et al*. (2002) found that after 25 years of annual cutting for restoration of a Nardo-Galion saxatilis grassland species characteristic of eutrophic soil were still present whilst after 13 years of cutting in a neutral grassland Hejcman *et al*. (2010) concluded that the restoration of low productivity cannot be achieved by cutting.

Unintended consequences

- Loss of species intolerant of cutting
- Changes in species composition
- Loss of ground nesting birds if cuts are not timed appropriately
- Timing and frequency of cutting may adversely affect seed production and species composition.

2.2.3 Liming

Occasional liming is part of the traditional management regime for hay meadows but in experimental investigations results have been mixed indicating that the impact of liming is dependent on the starting pH of the soil. Kirkham *et al*. (2008) investigated the impact of liming in combination with organic and inorganic fertilisers at four hay meadow sites in the UK. Fertilisers were added at low levels and lime was added to achieve a target pH of 6.0. They found mixed effects of lime on vegetation. At Pentwyn, a lowland meadow in Wales there was a significant negative effect of liming combined with manure. The strong change observed at this site was in contrast to changes at other sites possibly reflecting the long history of no lime input at the site and the larger change in soil pH as a consequence of liming. However, liming led to increased capacity for nutrient uptake and biomass production which in combination with fertilizer inputs led to reduced species richness and an increase in the Ellenberg N score. These results contrast with those observed in the Park Grass experiment where the long-term addition of ammonium sulphate resulted in a strong acidification of soils (pH 5.8 to 3.5) and a reduction in species richness from 50 to one or two species over 100 years. Here the addition of lime resulted in an increase in species numbers to around 15 (Goulding *et al.* 1998).

Unintended consequences

- Changes in species composition
- Increase in nutrient availability
- Reduction in soil carbon (C) stocks and potentially leaching losses

2.2.4 Introduction of hemi-parasitic species

The hemi-parasite *Rhinanthus* species attach to host roots by haustoria extracting water, nutrients, minerals and C compounds. *Rhinanthus* species are typically found in low productivity vegetation and there have been a number of investigations into whether *Rhinanthus* occurs in low productivity vegetation or if it is responsible for reducing productivity. The potential for *Rhinanthus* species to restore species poor grasslands has been investigated and a number of studies have shown that that they can reduce productivity by on average 41 % (Ameloot *et al.* 2005). Studies have concluded that *Rhinanthus* species probably have a positive effect on the recruitment and establishment of less competitive species within a grassland sward (Bullock and Pywell, 2005) which may mitigate the eutrophying effects of N deposition. However, hemi-parasite litter has very high N concentration and because of the short-life cycle is commonly returned to the ground before hay can be removed. An experiment in Belgium investigated the effect of *Rhinanthus angustifolius* and *minor* on N cycling. N uptake by grasses was significantly reduced by the presence of *Rhinanthus* species and tracer studies revealed that N was less available to plants in parasitized plots (Ameloot *et al.* 2008). This is backed by another study that showed increases in N mineralisation caused by the high quality parasite litter did not result in increased productivity (Bardgett *et al.* 2006). An intended consequence of introducing hemi-parasites such as *Rhinanthus* species is a decline in productivity of grasses because this is the mechanism by which forb diversity is increased; this necessitates a trade-off between grassland production and biodiversity conservation.

Unintended consequences

- Changes in species composition

2.2.5 Hydrological management

In wet meadows raising the water table has been used to reduce N mineralisation and decrease above-ground biomass production. It was expected that this would result in increased species richness. However, in experimental plots there was only a small reduction in biomass and few wet species became established (Oomes *et al.* 1996). The reason for the lack of successful restoration may be the lack of a seed source (Bakker *et al.* 1997) or alternatively Grevilliot *et al.* (1998) suggest it may be that there are few species in the community which are adapted to survive in regularly disturbed wet communities like wet meadows which also benefit from high nutrient status.

Unintended consequences

- Changes in species composition
- Increase in undesirable sedges or rushes

2.2.6 Carbon addition

A novel method for the reduction of impact of N input developed in recent years has been the use of C addition to immobilise N in the soil. The addition of a readily accessible C source stimulates soil microbial activity resulting in the increased immobilisation of N. The addition of C has been shown to reduce biomass production increasing the potential for small stature stress tolerant species to increase as competition for light is reduced (Eschen *et al.* 2007). Spiegelberger *et al*. (2009) investigated this with the addition sawdust to grazed and ungrazed grasslands in the Alps. Over a three year period they found that in both the grazed and ungrazed grasslands biomass of grasses and the majority of forbs was reduced by up to 25 % although species evenness and richness were unaffected. The tall unpalatable herb *Veratrum album* increased slightly. Tilston *et al*. (2009) also investigated the potential of this method for restoring agricultural fields in Hungary. They found that sucrose led to mobilisation of N from organic pools and consequent immobilisation by microbial biomass whereas sawdust immobilised N into another N pool. Experiments on this method to date have only been short term and longer term consequences need to be fully investigated.

Unintended consequences

- Potential for un-researched consequences for the soil microbial community and soil fauna.

2.2.7 Turf stripping

Turf removal followed by reseeding has been suggested as a way to increase species diversity in productive grasslands (Pywell *et al.* 2007) however, this extreme and expensive methods of grassland restoration met with limited success in restoring a wet grassland impacted by N deposition. Jansen and Roelofs (1996) used sod cutting in a *Cirsio-Molinietum* grassland impacted by eutrophication. The authors suggest that the attempt was unsuccessful because prolonged inundation resulting from the sod cutting caused anaerobic conditions. This changed the chemistry of deep groundwater and led to higher nutrient availability in the root zone. Tallowin and Smith (2001) also investigated the removal of the topsoil in a *Cirsio-Molinietum* grassland. They found that after four years dry matter yields were comparable to a *Cirsio-Molinietum* meadow but results for the abundances of individual species were mixed. Turf stripping can also remove the seed bank (Dorland *et al.* 2005a). Turf stripping has been more widely investigated for heathlands and is discussed more fully in section 2.5.1.

Unintended consequences

- Unsuitable for many areas e.g. those with archaeological interest
- Costly management
- Disposal of cut turves risks moving the pollution problem elsewhere
- Removal of species of high conservation interest
- Alteration of hydrological regimes
- Reduction of some rare species
- Loss of desirable seed bank
- Disturbance of soil food-webs and may affect important micro-organisms such as mycorrhizas

2.3 Calcareous grassland

Effects of N deposition on calcareous grasslands are less well documented than other grassland types. This is surprising given their importance for nature conservation but there have been several recent studies investigating impacts. Evidence from N addition experiments suggest that N deposition may increase dominance of the grass *Brachypodium rupestre* leading to consequent reductions in species richness (e.g. Bobbink, 1991; Bobbink and Willems, 1987; Willems *et al.* 1993). Other studies have shown reductions in species richness in the absence of *B. rupestre* (e.g. Jacquemyn *et al.* 2003). Bennie *et al*. (2006) used a temporal study showing changes in species composition of calcareous grasslands in southern England between 1952-53 and 2001-03. They found a decline in species richness, a decrease in species associated with infertile conditions and an increase in species typical of more mesotrophic grasslands. These changes indicate an effect of nutrient enrichment.

Long-term N additions (35, 70 and 140 kg N ha^{-1} yr^{-1} from 1990 to the present day) to calcareous grassland on shallow carboniferous soil at Wardlow Hay Cop have shown declines in vascular plant and bryophyte cover (Carroll *et al.* 2003; Carroll *et al.* 2000), changes in N turnover (Carroll *et al.* 2003; Morecroft *et al.* 1994) and significant losses of soil base cations and increases in aluminium and manganese in the highest N treatments (Horswill *et al.* 2008).

Another study from southern Germany that used permanent plots showed similar results. However, in this case changes were mainly attributed to reduced grazing intensity (Hagen, 1996). However, this is not the case for all studies and several experimental, time-series or gradient studies have not observed reductions in species richness although several report changes in species composition (Diekmann *et al.* submitted; Maskell *et al.* 2010; Van den Berg *et al.* 2011; Wilson *et al.* 1995). This evidence is complemented by evidence from national vegetation surveillance data which shows changes in the probability of individual species occurence with increasing N deposition (Henrys *et al.* 2011; Stevens *et al.* 2011a).

In the UK, calcareous grasslands are typically managed by grazing but there have been few studies specifically assessing the interaction between management and N inputs.

2.3.1 Grazing

There has been little investigation of the interaction between grazing and N addition in calcareous grasslands although this has been suggested as a management strategy to reduce N deposition impacts (Wilson *et al.* 1995) one experimental study in eastern Belgium did investigate this. The experimental site had not been fertilised for over 20 years, was grazed by cattle in the summer and was characterised by high pH and low soil phosphorus (P) content. Ammonium nitrate was applied at rates of 0, 30, 60 and 90 kg N ha^{-1} yr^{-1}. Cattle grazing was applied at a rate of 15 cows per hectare. The study found an interaction between management and N addition. Grazing increased species richness over the three years of the experiment and was more effective at maintaining species diversity under N addition than no grazing was but it did not counter the negative effects of N addition (Jacquemyn *et al.* 2003). As in other grazed habitats, overgrazing can have a negative impact on diversity (Pacha and Petit, 2008) and trampling from grazing animals can have a negative impact on ground nesting birds (Beintema and Müskens, 1987). Supplementary feeding should be avoided to prevent import of nutrients.

Unintended consequences

- Loss of grazing intolerant species
- Changes in species composition
- Loss of ground nesting birds
- Changes in N cycling due to grazing rates
- Supplementary feeding is a source of nutrients and a seed source of undesirable plant species

2.3.2 Cutting

The same experiment described in section 2.3.1 also considered the impact of mowing on species richness under different N regimes. Mowing took place after seed had been set for most species. Mowing appeared to have less of an impact on competitive interactions and there was consistently low diversity in fertilised and mown plots compared to plots that were repeatedly grazed. Results suggested that mowing once a year was insufficient to maintain high diversity as nutrient levels increased (Jacquemyn *et al.* 2003). A seven year UK study looked at interactions of N deposition with cutting using mesocosms from a calcareous grassland in the Peak District

(Jones, 2005). The study showed that both heavy (6 cm) and light (11 cm) clipping with two cuts per year significantly increased both species richness and Simpsons evenness index compared to the uncut control. However there were no interactions with N deposition. Cutting twice per year removed between 20 and 60 kg N ha^{-1} yr^{-1} depending on the cutting height.

Unintended consequences

- Loss of cutting intolerant species
- Changes in species composition
- Loss of ground nesting birds if cuts are not timed appropriately
- Timing and frequency of mowing may adversely affect seed production and species composition.

2.3.3 Sheep folding

Sheep folding is the practice of bringing stock off downland and putting them on arable land overnight. It is a traditional practice that was formerly commonplace in downland areas (Walker *et al.* 2001). Since sheep produce dung mainly at night this has been suggested as a possible practice for removing nutrients from the soil (Gibson, 1995). Unfortunately there is only anecdotal evidence to suggest that the practice removes nutrients and increases floristic diversity (Chalmers *et al.* 2000; Gibson, 1997).

2.3.4 Glycophosphate control of Brachypodium rupestre

Brachypodium rupestre is a species frequently associated with high levels of N deposition (Bobbink and Willems, 1987). *B. rupestre* spreads clonally and can produce dense stands. Glycophosphate, a broad-spectrum, non-selective, foliar-applied herbicide, is sometime applied for *B. rupestre* control. Hurst and John (1999) conducted an experimental trial to examine the effectiveness of Glycophosphate for *B. rupestre* control. They monitored the plant community on four stands of *B. rupestre* for five years following treatment. They found that *B. rupestre* dominance was initially considerably reduced by the Glycophosphate treatment but the treated areas did not establish vegetation similar to the surrounding vegetation. *B. rupestre* re-invaded all of the treated areas and the authors felt it was likely that it would come to dominate the grassland sward again in the future. In more nutrient rich sites re-colonisation of *B. rupestre* was more rapid than in nutrient poor sites.

Unintended consequences

- Loss of non-target species
- Recovery of *B. rupestre*

2.4 Acid grasslands

Acid grasslands are among the most thoroughly studied habitats with regards to N deposition. National and European surveys have demonstrated clear declines in species richness of acid grasslands with increasing levels N deposition (Duprè *et al.* 2010; Maskell *et al.* 2010; Stevens *et al.* 2004; Stevens *et al.* 2010), changes in species composition (Stevens *et al.* 2006; Stevens *et al.* 2011b) and changes in soil chemistry, primarily related to acidification (Stevens *et al.* 2009; Stevens *et al.* 2006; Stevens *et al.* 2011b). Changes in species composition include a shift to increased dominance by grasses and reductions in sensitive forb species such as *Euphrasia officinalis* and *Campanula rotundifolia* (Stevens *et al.* 2011c). Further field surveys in the Netherlands have shown the importance of high soil ammonium concentrations in determining the distribution of Red-List plant species found in acid grasslands (De Graaf *et al.* 2009; Kleijn *et al.* 2007). Experiments in water cultures, containers and mini-ecosystems have also revealed the ammonium sensitivity of some characteristic species of acid grasslands (De Graaf *et al.* 1998; van den Berg *et al.* 2005a; van den Berg *et al.* 2008). In montane acid grassland communities such as *Racomitrium* heath N deposition is also a very clear driver of species composition, moss growth and cover, and moss tissue chemistry (Armitage *et al.* 2012; Jones, 2005; Pearce and van der Wal, 2002; Pearce *et al.* 2003; van der Wal *et al.* 2005).

Long-term N additions (35, 70 and 140 kg N ha^{-1} yr^{-1} from 1990) to acid grasslands at Wardlow Hay Cop show declines in bryophyte abundance and trends for reduced cover of some vascular plant species at higher levels of N addition (Carroll *et al.* 2000; Morecroft *et al.* 1994). Flowering has also been dramatically reduced by N addition (Phoenix *et al.* 2012). Impacts on soil N processing (Morecroft *et al.* 1994; Phoenix *et al.* 2003), the N and enzyme concentrations in vascular plant and bryophyte tissues (Arroniz-Crespo *et al.* 2008; Phoenix *et al.* 2003) and soil pH and cation exchange capacity (Horswill *et al.* 2008) have also been observed. At Pwllpeiran acid grassland N additions have resulted similar changes with a reduction in lichen abundance, increases in foliar N concentrations of vascular plants and bryophytes and an increase in nitrate leaching (Emmett, 2007; Phoenix *et al.* 2012).

Henrys *et al.* (2011) identified five lowland acid grassland species (*Cerastium arvense*, *Cerastium semidecandrum*, *Trifolium arvense*, *Vicia lathyroides* and *Viola canina*) which showed negative relationships with N deposition in their national distribution. They also reported an increase in Ellenberg N score for lowland acid grasslands but not for upland acid grasslands. Three terricolous lichen species also showed negative relationships with N deposition when their national distribution was analysed (Stevens *et al.* 2012).

In the UK acid grasslands are typically managed by grazing by sheep, cattle and horses with additional grazing by wild deer and rabbits (Sanderson, 1998).

2.4.1 Grazing

Pwllpeiran acid grassland is a long-term N addition experiment in north Wales. It is one of the few experiments specifically designed to investigate interactions between N deposition and management. Nitrogen additions are made at realistic levels of N (10, 20 kg N ha^{-1} yr^{-1}), in the form of wet reduced and oxidised deposition. Grazing paddocks were stocked at 'light' or 'heavy' grazing pressure: Light = ESA - 30% (670 grazing days yr^{-1}, equivalent to 1.87 sheep ha^{-1}); Heavy = ESA + 24% (1280 grazing days yr^{-1}, equivalent to 3.74 sheep ha^{-1}). Here *Vaccinium myrtillus* was found to decline under the lower grazing intensity treatment and with oxidized N but not in the higher grazing intensity treatment. Grazing intensity also impacted on lower plants changing the completive balance between species with different light requirements and affecting their sensitivity to N. These results suggests that heavy grazing may mask the effects of N addition and may change the control of vegetation composition from nutrient (bottom up) to grazing (top down) control (Phoenix *et al.* 2012; UKREATE, 2010). Grazing intensity didn't change N cycling or losses but in a separate transect study removing grazing completely caused an increase in leaching (Emmett *et al.* 2001). A mesocosm study using intact cores from Pwllpeiran and clipping to simulate grazing showed that some moss species were able to tolerate higher N levels under more severe clipping treatments but in the field total moss cover declined under higher grazing pressure (Emmett *et al.* 2004a; Jones, 2005).

McGovern (2011) revisited a long-term grazing experiment on Snowdon to look at interactions between grazing and N deposition. The experiment had three grazing treatments – normal grazing where sheep were allowed free access but were mostly removed in the winter, summer only grazing and no grazing. The experiment ran between 1957 and 1981 and when it ended all plots were fenced to exclude grazers. The results were in agreement with those from Pwllpeiran indicating that the removal of grazing increases N losses by leaching.

In montane *Racomitrium* heath there is evidence to suggest that grazing exacerbates the impact of N deposition. Van der Wal *et al*. (2003) present a model whereby N deposition increases grass and sedge performance whilst at the same time impacting negatively on *Racomitrium* performance through toxicity. Grass growth increases shading further reducing *Racomitrium* growth. The increased grass growth attracts more herbivores which increases trampling, again negatively impacting on *Racomitrium* performance. The increased grazing leads to fecal enrichment which further exacerbates fertilization leading to a feedback loop. Pearce *et al*. (2010) conclude that removal of grazing may result in an improvement in *Racomitrium* condition where the moss mat remains, even under existing levels of N deposition but restoring dmaged areas may require more intervention. However, field evidence from Pwllpeiran and mesocosm studies suggest that light levels of grazing may benefit *Racomitrium* by opening up the canopy which increases light levels and the ability of *Racomitrium* to process ammonium, thus reducing ammonium toxicity (Emmett *et al.* 2004a; Jones, 2005; Jones *et al.* 2002a).

As in other grazed habitats, overgrazing can have a negative impact on diversity (Pacha and Petit, 2008) and trampling from grazing animals can have a negative impact on ground nesting birds (Beintema and Müskens, 1987). Supplementary feeding of should be avoided to prevent import of nutrients.

Unintended consequences

- Loss of grazing intolerant species
- Changes in species composition
- Loss of ground nesting birds
- Changes in N cycling due to grazing rates
- Supplementary feeding is a source of nutrients and a seed source of undesirable plant species

2.4.2 Burning

Burning provides a means of removing above-ground biomass and is a traditional form of management in heathlands (section 2.5) and grasslands (e.g. in damper rush pastures and fen meadows). Burning is often used as a management tool to control spread of gorse (*Ulex* spp.). Burning of grasslands is often carried out using large uncontrolled fires with some areas burnt as frequently as every year. Studies suggest that burning has the potential to reduce litter accumulation which can lead to the dominance of species such as *Molinia caerulea* (Tucker, 2003) and contribute to the replacement of dwarf shrubs with grasses (Aerts, 1990). These effects are similar to those seen with high N inputs and burning removes nutrients but the potential as a management tool may not be long-term because *Molinia* recovers rapidly from fire (Grant *et al.* 1963) and can come to dominate the sward rapidly necessitating further burning (Tucker, 2003). Burning is also often unpopular with the general public because it generates greenhouse gasses, particulates and other pollutants, leaves areas looking unsightly and generates safety concerns (Stevens *et al.* 2011d).

Unintended consequences

- Changes in ground flora composition; loss of species
- Impacts on habitat/food/breeding requirements for birds, mammals, invertebrates etc.
- Pollution swapping (transfers to atmospheric N or leaching).

- Leaves areas looking unsightly

2.4.3 Liming

Liming is traditionally used to increase pH and presents a mitigation option for reducing acidification impacts of N deposition (Stevens *et al.* 2011d). However, although the potential for liming has been investigated in neutral grasslands (see section 2.2.3) there have been few investigations in acid grasslands. In a study using intact grassland cores Johnson *et al*. (2005) found strong increases in soil pH with lime addition in an upland acid grassland (from pH 5.3 to 8, and 7.8 for lime and N addition together). They also found a significant interaction between liming and N addition (compared to control and N addition alone) for biomass and tissue nutrient concentrations of *Agrostis capillaris* as well as in microbial biomass and respiration rates. Liming has been shown to increase mineralisation of organic matter leading to increased losses of C in upland grasslands (Rangel-Castro *et al.* 2004).

Unintended consequences

- Changes in species composition
- Increase in nutrient availability
- Reduction in soil C stocks, and potentially leaching losses

2.4.4 Cutting

Results from an experimental N addition in North Wales where 35 and 70 kg N ha^{-1} yr^{-1} is added in combination with a single or double cut suggest that additional cutting does remove more N. The double cut treatment resulted in higher biomass removal. Vegetation removed from the double cut treatment also had a slightly higher C:N ratio and soils tended to have lower extractable nitrate concentrations and plant available N although differences were not statistically significant after three years of treatment application (Stevens, unpublished data). A seven year UK mesocosm study also looked at interactions of N deposition with cutting in an acid grassland using mesocosms from a U4/H18 grassy heath at Pwllpeiran (Jones, 2005). The study showed that both heavy (~6 cm) and light (~11 cm) clipping, mimicking selective grazing by sheep, and with two cuts per year, significantly increased both species richness and Simpsons Evenness index compared to the uncut control. There were significant interactions with N deposition and cutting on the abundance of a number of moss species, discussed further under grazing (Section 2.4.1 above). Cutting twice per year removed 7 - 34 kg N ha^{-1} yr^{-1} depending on the cutting height, which varied according to the palatability of vegetation species. Although cutting is not a normal management in acid grasslands in the UK the results suggest that biomass removal can be used to remove N from the soil, although benefits are likely to be slow.

Unintended consequences

- Loss of cutting intolerant species
- Changes in species composition
- Loss of ground nesting birds if cuts are not timed appropriately
- Timing and frequency of cutting may adversely affect seed production and species composition.

2.5 Dwarf shrub heath

Heathlands were one of the first ecosystems in which the deleterious impacts of N deposition were recognised, with heathlands in areas of high N deposition, particularly the Netherlands, showing increasing dominance by competitive grasses at the expense of *Calluna vulgaris* (common heather, hereafter '*Calluna*'). Most deposited N is retained within the heathland system with high immobilisation and little leaching (Pilkington *et al*. 2005). N increases the growth of *Calluna* but makes it more vulnerable to frost (Carroll *et al*. 2009), drought or heather beetle attack (Power *et al*. 1998) which in turn may open the canopy and allow grass invasion (Bobbink *et al*. 2010). The most strongly affected ecosystem components above ground are lichens and bryophytes (Pilkington *et al*. 2007a, Edmondson *et al*. 2010), which decline in abundance from low levels of deposition and are a major contributor to reduced overall plant species richness. Impacts may be greater with reduced rather than oxidised N (van den Berg *et al*. 2008) and ecosystem recovery may be very slow, even after total cessation of deposition (Power *et al*. 2006; Edmondson *et al*. 2013). Impacts below-ground parallel those above-ground with changed microbial biomass (Johnson *et al*. 1998), microbial community structure (Payne *et al*. 2012) and enzyme activity (Johnson *et al*. 1998). In addition to abundant experimental evidence for impacts of N (Bobbink *et al*. 1998, Phoenix *et al*. 2012) there is evidence for reduced species richness and community change from time-series (Ross *et al*. 2012) and spatial gradient studies (Caporn *et al*. 2009).

The term heathlands encompasses a range of habitats: dry and wet, upland and lowland. As such there are important differences between ecosystem structure and function which determine both their sensitivity to N and their requirements for habitat management. Lowland heathlands are generally anthropogenic ecosystems with sub-climax plant communities and low nutrient conditions maintained by the active removal of nutrients by fire, turf stripping, grazing and removal of plant material (Webb 1998). Traditional management served to remove nutrients from the ecosystem; in many cases the current more eutrophied state of heathlands is a combination of both enhanced deposition and reduced removal by management with restoration focusing on active nutrient removal (Mitchell *et al*. 2000). While management is also required for continued existence of some upland heathlands, others are climatically-constrained climax communities which do not require human activity for their continued existence. The role of management is therefore distinctly different in the two types of habitats; in sub-climax heathlands management is essential for continued existence, while in climax heathlands management is used to maintain or improve condition. Heathland management for N deposition has typically focussed on three aims: 1) to sustain the heather community 2) increased richness of characteristic heathland plant species, 3) the removal of N from the system. We consider five possible management interventions which may help achieve these aims: turf stripping, rotavating, burning, mowing and grazing.

2.5.1 Turf-stripping

Many lowland heaths have traditionally been managed by turf (sod) cutting, indeed many heathlands owe their origin to such activity (Webb 1998). Turf stripping is common practice in some areas of the UK (e.g. parts of Cheshire). As most deposited N is retained in the soil it is clear that turf cutting is a very effective way of removing N from the system and may reduce productivity for considerable periods of time (Diemont 1994). In one lowland heath study the nutrient removal by turf cutting was equivalent to <176 years of atmospheric deposition (Härdtle *et al*. 2006). Turf cutting is the most effective way to rapidly remove nutrients from the ecosystem. Studies comparing turf cutting with less intensive management interventions have found that nutrient removal is several times greater (Härdtle *et al*. 2006, 2007) and similar results have been found for comparisons involving functionally similar deep burning (Barker *et al*. (2004). Turf cutting favours species which have a persistent seed-bank at depth. Several studies have found that, at least in the short-term, cutting favours *Calluna* over invasive graminoid species such as *Molinia caerulea* (hereafter '*Molinia*') and *Deschampsia flexuosa* (hereafter '*Deschampsia*') whose seeds are only found in the surface layers (and in the case of *Deschampsia* are not persistent; Diemont 1990). Turf cutting may thus be effective at both removing N and shifting the balance from invasive grasses towards *Calluna*. However recent studies have revealed an increasing number of less desirable side-effects and caveats.

There are clearly situations in which turf cutting is inadvisable. Most UK upland heathlands have not been traditionally turf cut and it would be inappropriate, as well as extremely costly, to instigate such management. Similarly, there are situations where extensive soil disturbance is undesirable, for instance in areas with archaeological interest (Britton *et al*. 2000a). Disposal of large quantities of N-enriched turves presents a potential problem with the cost of transport alone being considerable (Britton *et al*. 2000a).

The effects of cutting on species of conservation interest are a key cause for concern. Turf cutting will remove vegetative material and seeds of non-target as well as target plants; dispersal limitations of these species therefore become critical to their probabilities of re-establishment after cutting. van den Berg *et al*. (2003) found that turf cutting depth was negatively correlated with *Arnica montana* germination and establishment, suggesting that although cutting is successful at removing nutrients it may also reduce the abundance of such sensitive species. As impacts may be related to removal of the buffering capacity this effect may be ameliorated by liming (van den Berg 2003), preventing the accumulation of ammonium in the soil (Dorland *et al*. 2004). Dorland *et al*. (2005a) concluded that turf cutting allowed return of acid-tolerant typical species but acid-sensitive species required the addition of lime. An important determinant of efficacy is the depth of cutting with very deep cutting being both less effective, due for instance to modified soil moisture levels (Diemont and Linthorst Homan 1989; Diemont 1990), as well as more costly (Niemeyer *et al*. 2007).

A key, but little studied issue in heathland management and restoration is the effect of interventions on mycorrhizas, which may be particularly important to ericoid species such as Calluna (Diaz *et al*. 2006). As well as seeds, turf cutting will remove mycorrhizal fungi limiting the ability of some species to re-colonise. Vergeer *et al*. (2006) found that most arbuscular mycorrhizal fungi spores were removed by cutting and numbers were still reduced after 2.5 years.

Overall the research suggests that although turf cutting may be highly successful at the removal of nutrients there may be important trade-offs against the conservation of ecosystem function and rare species. Cutting success requires careful design and implementation and may necessitate additional interventions such liming. Given the complex interactions between multiple ecosystem components it is not clear that cutting is a desirable management approach to N deposition in any but the most damaged lowland heathlands.

Unintended consequences

- Unsuitable for many areas e.g. those with archaeological interest
- Costly management
- Disposal of cut turves risks moving the pollution problem elsewhere
- Removal of species of high conservation interest
- Alteration of hydrological regimes
- Reduction of some rare species
- Loss of desirable seed bank

- Disturbance soil food-webs and may affect important micro-organisms such as mycorrhizas
- Turf striping is likely to result in significant C emissions, particularly in more organic soils (Alonso *et al.* 2012).

2.5.2 Rotavating

A similar but less intensive management intervention is rotavating in which soil layers are mixed but not removed. Rotavating may minimise some of the disadvantages of turf-stripping (principally high cost and waste) while achieving some of the same effects (Britton *et al*. 2000a). As with turf cutting, rotavating may benefit *Calluna* relative to *Deschampsia* through the presence of a large seed-bank (Britton *et al*. 2001). However, recolonisation by invasive grasses can be rapid (Britton *et al*. 2000a) and there is no direct nutrient removal, which is unlikely to make this a viable long-term solution in areas of high N deposition. Results from a Dutch experiment have shown that such treatment may be ineffective at returning degraded grass-dominated heath to dwarf-shrub domination but may still reduce productivity (Diemont and Linthorst Homan 1989; Diemont 1994). Any advantages of rotavating for N impact amelioration are currently insufficiently proven.

Unintended consequences

- Unsuitable for many areas e.g. those with archaeological interest
- Removal of species of high conservation interest
- Disturbance soil food-webs and may affect important micro-organisms such as mycorrhizas
- Rotavation is likely to result in significant C emissions, particularly in more organic soils (Alonso *et al.* 2012).

2.5.3 Grazing

Many heathlands are, or have historically been, grazed by livestock and rabbits. Grazing serves to keep the sward structurally diverse preventing shading effects, creates areas of bare ground through trampling, and if livestock are removed at night may remove nutrients (Marrs 1993; Britton 2000a). It has therefore been suggested that grazing may be an appropriate management approach to N deposition. In a Dutch study Bokdam and Gleichman (2000) found that (unrestricted) grazing re-distributed nutrients but did not remove high atmospheric inputs. Grazing did increase species richness but did not reduce grass cover. The impacts of grazing are likely to depend on stocking density, timing, type of stock, and duration of grazing period; Alonso *et al*. (2001) suggest that *Calluna* is able to out-compete grasses under increased nutrient supply but this may be reversed by over-grazing. A review of lowland heath data by Bullock and Pakeman (1997) found that grazing generally increased cover of grasses, forbs, bryophytes and lichens while reducing cover of dwarf shrubs with an overall increase in species richness. Recently a systematic review of the evidence for impacts of grazing on lowland heath has shown that grazing can result in an increase of the ratio of grassland to ericoid shrub cover, in contrast to manager's expectations (Newton *et al*. 2009). Grazing may be a desirable management option in some heathlands but N export is limited and is unlikely to be sufficient to produce substantive amelioration of N deposition impacts.

Unintended consequences

- Loss of grazing intolerant species

- Changes in species composition
- Loss of ground nesting birds
- Changes in N cycling due to grazing rates
- Supplementary feeding is a source of nutrients and a seed source of undesirable plant species

2.5.4 Cutting

Some areas of UK upland and lowland heath are managed by mowing. Vegetation cutting or mowing has potential to export nutrients if the cuttings are removed. The impacts of vegetation cutting on species composition appear limited. In a Dutch experiment Diemont and Linthorst Homan (1989) found that mowing without biomass removal did not change vegetation; while with biomass removal some dwarf shrub vegetation was established in *Molinia*-, but not in *Deschampsia*-dominated degraded heathland. In experiments in which N treatment was stopped prior to management, Power *et al*. (2001) found that management by burning or mowing removed a previously-observed acceleration of plant decomposition with N treatment but did not remove the effect of previous N treatment on *Calluna* shoot length, canopy density and height. Nutrient export is unlikely to be sufficient to remove large proportions of accumulated atmospheric deposition (Härdtle *et al*. 2006, 2007). Barker *et al*. (2004) found that high intensity mowing removed 23% of total N and low intensity mowing 16%, considerably less than the 82% removed by deep burning. Most deposited N is in the soil rather than the vegetation so management solely of above-ground vegetation will inevitably have limited short-term impact (e.g. Britton *et al*. 2000a). Mowing though can have other benefits since the collected heather brash, including seed from winter mowing is often sold for use in revegetation of heathland and degraded moorland. In an experiment on lowland heath, N addition increased the growth and advanced the maturity of *Calluna* which appeared to affect the re-growth after subsequent mowing; the regeneration of new shoots from cut stems and roots was slowed in N treated plants compared with water treated controls (Ray, 2007).

Unintended consequences

- Loss of cutting intolerant species
- Changes in species composition
- Loss of ground nesting birds if cuts are not timed appropriately
- Timing and frequency of cutting may adversely affect seed production and species composition.

2.5.5 Burning

Many UK heathlands are managed by burning, in particular to regenerate young vigorous growth and dominance of the *Calluna* plants on grouse moors (Grant *et al*. 2012). Recent research on managed upland heath in the English Peak District, an area subjected to some of the highest N deposition in the UK, shows that following a typical managed burn *Calluna* cover steadily increases but almost all other plant species, following a short-term increase, are out-competed and removed (Harris *et al*. 2011). These authors recommend short rotation of burning to avoid complete dominance of *Calluna* if plant diversity is a priority target. On an upland heath in north Wales Pilkington *et al*. (2007b) found that burning also removed, in combustion, significant amounts of accumulated N from the vegetation and litter but did not reduce the N stores in the soil. However, they also found that burning increased N leaching for at least two years. These authors suggest that burning may be a suitable management approach for moderately polluted heathlands but in heavily polluted sites required burning frequency might be unrealistically high and burning may also imperil water quality. Post-burning increase in nutrient leaching has also been reported from German lowland dry heath (Mohamed *et al*. 2007). There is some evidence that burning may ameliorate the impacts of N deposition on plant communities. In a Scottish montane heath experiment with N addition and pre-treatment burning Britton and Fisher (2007) showed that N had little impact on plant communities of burned plots but considerable impacts on unburned plots reducing species richness and changing community composition. In English lowland heath burning did not remove the effect of previous N treatment on *Calluna* growth (Power *et al*. 2001). N enhanced post-burning *Deschampsia* seedling establishment and number of Calluna seedlings (Barker *et al*. 2004). Given relative growth rates and mixed evidence for the effect of N on *Calluna* seedlings it is possible that burning may encourage dominance by *Deschampsia* (Barker *et al*. 2004). However in a German dry heathland burning produced conditions more favourable to *Calluna vulgaris* compared to *Deschampsia flexuosa* (Mohamed *et al*. 2007). In experiments on upland *Calluna* moorland in north Wales, N additions accelerated growth and the transition through the developmental phases (pioneer, building, mature) (Carroll *et al.* 1999). When these plots were eventually burnt after 11 years of N addition vegetation surveys showed greater values for height, cover and shoot extension of regenerating *Calluna* for at least three years in the lower N addition plots than in high N treatments (Pilkington *et al*. 2007b). If this is a general response to elevated N deposition then the burning frequency on moorlands may need to be increased to avoid plants entering the degenerate phase (when re-growth is much poorer). Burning may be an appropriate management response to N deposition but more evidence is desirable.

Unintended consequences

- Changes in ground flora composition; loss of species
- Impacts on habitat/food/breeding requirements for birds, mammals, invertebrates etc.
- Pollution swapping (transfers to atmospheric N or leaching).
- Leaves areas looking unsightly

2.5.6 Combinations of treatments and influence of other variables

In practice different management options are often combined, but the impacts of such multiple interventions are complex and effects often difficult to predict (Vandvik *et al*. 2005). Ross *et al*. (2003) tested various combinations of burning followed by cutting or herbicide treatment in UK upland wet heathland under two grazing regimes. They found that burning increased *Molinia* dominance, when followed by cutting there was either little impact or increased *Molinia* but burning followed by herbicide (Fusilade) gave some short-term reduction in *Molinia*. Burning reduced *Calluna* cover with little additional effect of cutting or herbicide.

There is also the possibility for important climate and local environment-related differences in post-disturbance succession which mean that similar interventions may have quite different effects in different sites (Sedláková and Chytrý 1999; Britton *et al*. 2000b). For instance Britton *et al*. (2001) suggest an interaction between cutting frequency, required to maintain high *Calluna* cover under N deposition, and precipitation. Complex interactions between management impacts mean that combinations of interventions may have non-additive impacts which confound simple prescriptions for management.

2.6 Fen, marsh and swamp

Fens and other wetlands fed by lateral water inputs differ from bogs, in that they are a) adapted to some level of nutrient and other solute input from adjacent areas of land or water, and b) more likely to be affected by elevated nutrient inputs from sources other than nutrient deposition, in particular agricultural runoff. Nevertheless, a number of studies have demonstrated vegetation sensitivity to experimentally elevated N inputs at levels relevant for evaluating N deposition impacts. These impacts tend to be clearest in base-poor systems, where *Sphagnum* and other bryophyte species have been shown to accumulate, and to be negatively impacted by, moderate rates of N addition (Hogg *et al.* 1995; Francez and Loiseau, 1999; Malmer *et al.* 2003; Gunnarson *et al.* 2004; Wiedermann *et al.* 2007). In a number of these studies, reductions in bryophyte cover were associated with increased vascular plant cover. These responses in general correspond to those recorded in bog systems, and provided the basis for a critical load range for valley mires, poor fens and transition mires of 10-15 kg N ha^{-1} yr^{-1} (Bobbink and Hettelingh, 2011).

Rich fens are characterised by large lateral inputs of groundwater with high base cation concentrations, although in their natural state they remain fairly nutrient-poor, and are typically N-limited (Verhoeven and Schmitz, 1991). Vegetation comprises brown mosses and calcicolous small sedges, but enhanced levels of N input (whether from deposition or agricultural runoff) favour the growth of tall graminoids, with associated loss of diversity (e.g. Verhoeven and Schmitz, 1991). Bobbink and Hettelingh (2011) note the relative scarcity of field experiments on rich fens with levels of N addition relevant to assessing deposition impacts, and conclude that short-term vegetation responses to enhanced N deposition may be small (Paulissen *et al.* 2004). However some studies have demonstrated negative effects of enhanced N on the cover of productivity of brown mosses, and positive effects on vascular plants (e.g. Dorland *et al.* 2008; Bergamini and Pauli, 2001). On this basis, Bobbink and Hettelingh (2011) define a critical load range for rich fens of 15-30 kg N ha^{-1} yr^{-1}, with a low confidence level ('expert judgement'). In the UK, The Fen Management Handbook (McBride *et al.* 2011) recognises N deposition as a significant source of nutrient enrichment, particularly for base-poor fens, and follows the empirical critical loads approach described above to define threshold deposition levels. They consider aerial nutrient pollution likely to be most significant in proximity to intensive livestock units or major roads.

There are few (if any) studies that have explicitly examined the role of management in mitigating the effects of N deposition on fens or other ground/surface water fed wetlands. However, due to the widespread effects of agricultural nutrient runoff on fens, there is a substantial body of research on management techniques to mitigate against these effects or to restore damaged ecosystems, the practicalities of which are reviewed in detail by McBride *et al*. (2011). Some of these techniques have relevance in relation to atmospheric N deposition, whilst others do not.

2.6.1 Grazing

Grazing occurs widely in moderately drained fens and fen meadows, and low-intensity grazing is now widely used as a tool in conservation-managed wetlands. The aims of grazing in these sites include a reduction in the growth of dominant graminoids, and the maintenance of a low, open vegetation canopy in which rarer species can survive. The effectiveness of these measures is open to debate (e.g. Middleton *et al.* 2006 and references therein), and may be influenced by nutrient status; Proulx and Mazumder (1998) concluded that grazing would increase species-richness in nutrient-rich sites, but decrease species-richness in nutrient-poor sites. Grazing animals may be ineffective at maintaining areas of poor grazing quality within mosaic landscapes, particularly at low stocking densities, because animals tend to target areas with more palatable species. At higher stocking densities or over longer periods, animals may be forced to graze more nutrient-poor areas (e.g. Güsewell *et al.* 2007), but these higher stocking levels may also cause ground disturbance and subsequently lead to increased rates of N mineralisation. In terms of nutrient management, N removal off-site in animal biomass is generally relatively small. In complex habitats which include nutrient-rich vegetation types, or where high nutrient forage is available there is also risk that grazing animals will transfer N from nutrient-rich to nutrient-poor areas. Kirkham (2006) found that nutrient transfers from improved to uniproved habitats could be up to 19 kg N ha^{-1} yr^{-1} depending on the fertility level of the improved habitat in relation to the unimproved one. Any feed supplements introduced will increase overall nutrient loadings. Overall, Stammel *et al*. (2003) concluded that grazing was less effective than mowing in calcareous fens, while Middleton *et al*. (2006) advocated the use of grazing only in nutrient-rich fens, and at low stocking densities, noting that these low stocking densities may be insufficient to halt biodiversity losses without additional measures. It appears unlikely that grazing will provide any significant, specific benefits in terms of mitigating N deposition impacts to fens or other wetlands.

Unintended consequences

- Loss of grazing intolerant species
- Changes in species composition
- Loss of ground nesting birds
- Changes in N cycling due to grazing rates
- Supplementary feeding is a source of nutrients and a seed source of undesirable plant species
- Grazing may affect structure of the substrate

2.6.2 Cutting

Biomass removal by mowing represents a widely used historic form of wetland management, which can represent an important removal mechanism for N and other nutrients. Verhoeven *et al*. (1996) note that regular mowing has been able to maintain the N balance of managed Dutch fens despite very high N deposition levels. This is supported by available UK data from a C budget study of a managed fen meadow in the Somerset Levels (Lloyd, 2006) which estimated annual hay crop removal of C at around 200 g C m^{-2} yr^{-1}. Assuming a mean C/N ratio of 20 g g^{-1} for biomass this would give an annual N removal of 100 kg N ha^{-1} yr^{-1}, well in excess of deposition. Olff *et al*. (1994) found that long-term hay removal was associated with reduced N mineralisation rates in fen meadows. While biomass N removal rates will likely be lower in less productive, less regularly harvested semi-natural fen ecosystems, it is nevertheless clear that this form of management can provide an effective measure for mitigating against atmospheric (or other) N inputs.

As well as removing moderate amounts of N, and thus maintaining balance with inputs, regular mowing tends to remove comparatively large amounts of P and potassium (K). These removals may be in excess of long-term inputs, with the consequence that fens subject to historic management tend to be P limited, whereas less managed sites may remain N limited, (Koerselman *et al*. 1990; Verhoeven and Schmitz, 1992; Verhoeven *et al*. 1996). In fens also subject to intensive drainage, and hence reduced base cation supply from lateral water inputs, K limitation can also occur (Venterink *et al*. 2009). Long-term management of fens by mowing is therefore likely to make them insensitive to additional N inputs (e.g. Kirkham *et al*. 1996). The instigation of P or K limitation through management may therefore allow rare species to persist under elevated N inputs (Wassen *et al*. 2005), although the responses of individual sites to these changes may be difficult to predict in the context of the other ecological impacts of regular biomass removal. Mowing also limits the dominance of individual tall graminoids, maintaining an open vegetation structure, reducing litter accumulation on the ground surface and increasing light levels to low-growing vascular plants and bryophytes, and thus has multiple potential benefits in terms of species diversity. In a degraded, N-impacted poor fen valley mire, Hogg *et al*. (1995) recorded an increase in *Sphagnum* cover following summer cutting of *Molinia*.

Unintended consequences

- Loss of cutting intolerant species
- Changes in species composition
- Loss of ground nesting birds if cuts are not timed appropriately
- Timing and frequency of cutting may adversely affect seed production and species composition.

2.6.3 Burning

Prescribed burning is occasionally used in Europe, and more widely in North America, to reduce standing biomass and encourage the establishment of low-growing species in fens. Burning generally takes place when water levels are high, i.e. during winter or early spring (Middleton *et al.* 2006), to avoid burning the underlying peat. At these times, most plant N is likely to be stored in below-ground biomass, and so burning may be less effective than summer mowing in terms of N removal. On the other hand, because vehicles are not required, the risk of ground disturbance leading to enhanced N mineralisation may be somewhat reduced.

Unintended consequences

- Changes in ground flora composition; loss of species
- Impacts on habitat/food/breeding requirements for birds, mammals, invertebrates etc.
- Pollution swapping (transfers to atmospheric N or leaching).
- Leaves areas looking unsightly

2.6.4 Hydrological management

Fens (and other wetlands fed by lateral water inputs) are highly heterogeneous with regard to their hydrology, levels of nutrient input from surrounding land areas, on-site management and successional stage, and it is thus extremely difficult to draw generalised conclusions about their sensitivity to N deposition. Historic drainage lowers water tables, reducing habitat suitability for wetland species and increasing organic matter mineralisation rates, which can induce ‘internal eutrophication’. At the same time, drainage can isolate fens from base-rich groundwater supplies, shifting them towards poor fen or bog conditions. Water management for conservation generally aims to raise water levels, reduce or redirect inputs of nutrient-enriched agricultural runoff, and/or re-introduce lateral seepage of base-rich groundwater into the fen. All of these activities will influence nutrient status, potentially lowering the input load of N from hydrological sources, and therefore increasing the proportional importance of deposition as a residual source of N input. This has a number of implications. A site with large quantities of hydrological N inputs may need very little additional atmospheric N to cause the critical load to be exceeded, but it is difficult to compensate for large N inputs by management. Conversely, once hydrological inputs are reduced, management activities (such as biomass removal) may be more effective in reducing the pool of accumulated N. Shifts in hydrochemistry brought about by water management may alter N cycling, changing pH may alter P availability, but also rates of N mineralisation, altering the ability of the system to process atmospherically deposited N.

Unintended consequences

- Managing water levels may alter nutrient inputs to the site
- Changes to species composition

2.6.5 Topsoil removal

In cases of extreme nutrient enrichment of former fen wetlands (i.e. conversion to farmland), attempts have been made to restore semi-natural fen vegetation by large-scale removal of nutrient-enriched surface peat. Rasran *et al*. (2007) applied this approach experimentally to a fen in Northern Germany and recorded significant ecological benefits through reduced nutrient levels, suppression of resident agricultural grassland species, and re-establishment of rare species, aided by transfer of seed-rich hay from another site. The approach forms a part of the major Anglsey-Lleyn Fens EU-LIFE restoration project, being undertaken by CCW. However, while this method may be effective for severely nutrient-enriched systems, given the level of associated disturbance it is doubtful whether it would be appropriate for mitigating against the more moderate effects of N deposition.

Unintended consequences

- Unsuitable for many areas e.g. those with archaeological interest
- Costly management
- Disposal of cut turves risks moving the pollution problem elsewhere
- Removal of species of high conservation interest
- Alteration of hydrological regimes
- Reduction of some rare species
- Loss of desirable seed bank
- Disturbance soil food-webs and may affect important micro-organisms such as mycorrhizas

2.7 Bogs

Peat bogs are a widespread semi-natural habitat in the UK with considerable evidence for the deleterious impacts of N deposition. N addition experiments have frequently shown an increase in the biomass of vascular plants (Heijmans *et al*. 2001) and reduced *Sphagnum* productivity and cover (Gunnarsson and Rydin 2000; Berendse *et al*. 2001; Bubier *et al*. 2007; Sheppard, 2011). Both shading by increased vascular plant cover (Bubier *et al*. 2007) and direct toxicity may be important factors in the decline of mosses (Heijmans *et al*. 2001). N deposition may shift bogs from N-limitation to P and K-limitation with P and K availability being an important determinant of impacts (Aerts *et al*. 1992; Bragazza *et al*. 2004; Limpens *et al*. 2004; Phuyal *et al*. 2008). There is experimental evidence that *Molinia caerulea* is particularly favoured by high N deposition (Tomassen *et al*. 2003a). Time-series studies have shown vegetation changes consistent with the experiments with a general decline in *Sphagnum* and expansion of N-tolerant vascular plants such as *Molinia caerulea* in sites receiving high N deposition (Hogg *et al*. 1995). There is evidence for differential impacts of reduced versus oxidised and dry versus wet N deposition (Sheppard *et al*. 2011). N deposition impacts are apparent below-ground with modified microbial community structure (Gilbert *et al*. 1998), biomass (Payne *et al*. 2013; Bragazza *et al*. 2012) and enzyme activity (Bragazza *et al*. 2012).

A survey of UK bogs (National Vegetation Classification M19) as part of the Terrestrial Umbrella project shows a significant negative correlation of plant species richness with N deposition, although in relative terms this trend is less strong than that found in other habitats. Graminoid cover is positively correlated with N deposition particularly species such as *Eriophorum vaginatum*. Forb and lichen species richness are negatively correlated with N, in particular species such as the lichen *Cladonia portentosa* (Caporn *et al*. 2012).

Peatlands are the UK's largest soil C store, storing more than forty times more C than all UK vegetation combined (Milne and Brown 1997). There is evidence that this C storage function may be imperiled by N deposition. In a Canadian peatland Bubier *et al*. (2007) found that net ecosystem exchange was reduced by N addition with reduced moss photosynthesis and increased litter accumulation more than compensating for enhanced vascular plant photosynthesis. On a European scale Bragazza *et al*. (2007) showed enhanced decomposition rates of peat accumulated under high N deposition leading to increased C release through both CO_2 and DOC. Experimental results show important interactions with temperature, N form and PK availability (Kivimaki *et al*. in press). Methane fluxes may be enhanced through increased cover of sedges in N-impacted peatlands (Nykänen *et al*. 2002). Palaeoecological data show that peatlands receiving high N deposition may be accumulating little or no C (Gunnarsson *et al*. 2008).

There has been little research directly addressing mitigation options for N deposition in bogs, but existing evidence provides some evidence on the possible roles of current management practices in reducing or exacerbating N impacts.

2.7.1 Hydrological management

A large proportion of UK bogs have been drained, intentionally by the digging of ditches (grips) and unintentionally through the formation of erosion gullies due to vegetation loss. Restoration of these damaged bogs is now a major focus of conservation and scientific efforts (Bain *et al*. 2011). Although not directly tested by field experiment there is a general opinion that drier peatlands are more vulnerable to N deposition. Current critical loads guidance suggests using the low end of the range (5 kg ha^{-1} yr^{-1}) for sites with low water table and high end of the range (10 kg ha^{-1} yr^{-1}) for sites with high water table. This recommendation is primarily based on observations of greater impacts in drier areas of N addition experiments (Bobbink and Hettelingh 2011). The assumed mechanism behind this response is that reduced surface wetness and N deposition have additive impacts, particularly by imposing physiological stress on *Sphagnum* species. However there is also some conflicting evidence; in a meta-analysis Limpens *et al*. (2011) found that higher annual precipitation was associated with greater N-induced suppression of *Sphagnum* production, a good explanation for this result is currently lacking. Studies of N addition experiments experiencing natural drought have given varied results. Carfrae *et al*. (2007) showed branching and length of photosynthetically active material in *Sphagnum capillifolium* were reduced by N input with this effect more pronounced when the water-table was low but reversible when wetter conditions returned. Impacts of N deposition on *Sphagnum* productivity and decomposition in a bog in Italy were reduced in the hot summer of 2003 (Gerdol *et al*. 2007). Interactions between N impacts and water table lowering may be complex, for instance Fritz *et al*. (2012) suggested that reduced *Sphagnum* stem density due to N deposition increases vulnerability to drought and Aldous (2002) found that *Sphagnum* retention of deposited N was reduced in a drought phase. Restoration of bogs may increase methane emissions in the short-term (Waddington and Day 2007) and be particularly severe in N impacted sites (Carter *et al*. 2012) particularly where these have greater sedge cover (Nykänen *et al*. 2002). It is expected that over several decades this will be more than offset by reduced CO_2 emissions (Bain *et al*. 2011).

Unintended consequences

- Restoration of bogs will increase methane emissions in the short-term, but may be offset by long-term CO_2 sequestration. However the timescales of these changes are not known.
- Emissions of other greenhouse gases are likely to be particularly severe in N impacted sites (Carter *et al*. 2012), and where there is high sedge cover.

2.7.2 Burning

Many UK moorlands are managed by burning, particularly to promote new heather growth for grouse and some of these moorlands are on blanket bog (i.e. where peat exceeds 0.5 m). As discussed by Harris *et al.* (2011) burning of *Calluna*-dominated moorlands may be advantageous in order to maintain plant species richness (see section 2.5.5). However, burning on blanket bog and wet heaths, particularly *Sphagnum*-rich sites is not generally encouraged under the Heather and Grass burning code (DEFRA, 2007). We are not aware of any data on the interaction of burning with N deposition impacts but research on upland heathlands (discussed in section 1.5) may be relevant. Burning in peatlands is of unproven benefit for N impact amelioration. There is also the possibility for deleterious consequences including the loss of C through direct combustion and promotion of aeolian and fluvial erosion, the loss of sensitive species of plants and animals (for instance some Sphagnum species and meadow pipit: Worrall *et al*. 2010) and the promotion of burning-tolerant species, especially some bryophytes. Pollution swapping may occur, with re-deposition of emitted N oxides on other parts of the heathland in large systems and enhancement of N leaching. These processes have not been studied in bogs, but Cresser *et al*. (2004) identified higher runoff NO_3 concentrations in areas of a blanket bog catchment affected by burning.

Unintended consequences

- Changes in ground flora composition; loss of species
- Impacts on habitat/food/breeding requirements for birds, mammals, invertebrates etc.
- Pollution swapping (transfers to atmospheric N or leaching).
- Leaves areas looking unsightly
- Burning in peatlands risks the loss of C through direct combustion and promotion of aeolian and fluvial erosion.

2.8 Coastal dunes and slacks

It is now widely accepted that N deposition has contributed to over-stabilisation of dune systems in Europe. A number of studies from the UK and the continent provide evidence of the impacts of N deposition on dry dune grasslands and dune slacks. These two habitats are discussed separately below. In dune grasslands, two N deposition gradient surveys in the UK suggest impacts on a wide range of parameters. Jones *et al*. (2004) reported increases in plant above-ground biomass in mobile and semi-fixed dunes, and in fixed dune grassland there were declines in species richness, declines in soil available N and increases in soil C:N ratio. Declines in species richness were shown in a later study on decalcified dune grassland (SD12) (CEH, unpublished data). A gradient study in the Baltic showed lower species richness of lichens, increased cover of tall grasses, particularly *Carex arenaria*, and higher rates of soil mineralisation with N (Remke *et al*. 2009a,b), but only in acidic dunes not in calcareous dunes, suggesting that acidic systems are more sensitive to N than calcareous systems (see also Jones *et al*. 2002b). Further evidence is provided by a number of manipulation experiments, including N x grazing experiments at Newborough Warren, North Wales and on the continent (see also section 2.8.1 below). In contrast to the gradient studies the UK and Dutch experiments showed no changes in species composition (ten Harkel and van der Meulen 1996; Plassmann *et al*. 2009; Phoenix *et al*. 2012). However, the UK N addition treatments show significant accumulation of N in the moss biomass, and to a lesser extent in the grass biomass (Plassmann *et al*. 2009), and increases in N accumulation in below-ground tissue of *Carex arenaria* (Hodges 2006). A Dutch mesocosm experiment showed increases in biomass of *Carex arenaria* with N (van den Berg *et al*. 2005b). Leachate fluxes in the UK experiment showed that the majority (90%) of N is stored within the soil-plant system, and relatively little was lost through leaching (CEH, unpublished data). The Dutch N x grazing study reported leaching losses varying from 0 to 70% depending on the degree of soil development and interactions with grazing. In general, leaching was lower in older soils (ten Harkel *et al.* 1998). Although leaching losses vary, the majority of N is stored in older dune grasslands. This suggests the potential for long-term consequences of N accumulation in this habitat, and a chronosequence study shows correlations of faster soil development with higher N deposition (Jones *et al*. 2008).

There is less evidence of N impacts on dune slacks. Two UK gradient studies, one focusing on rare species, showed no correlation of slack species richness with N (Jones *et al*. 2004; Jones 2007). However cover of individual species: *Carex arenaria* and *Hypochaeris radicata* showed positive correlations with N (Jones *et al*. 2004). A seed bank study suggests N increases seed germination (Plassmann *et al*. 2008), with possible consequences for long-term composition of seed banks, an important reserve of species richness in naturally dynamic systems. High N deposition may increase groundwater dissolved organic N (DON) contents (Jones *et al*. 2002b), but there is as yet no evidence that details the impacts on elevated N in dune groundwater on slack habitats.

Phosphorus limitation is likely to be a major factor altering response of dune habitats to N deposition as it is controlled chemically by soil pH and may be altered by management. Phosphorus is optimally available between pH 6 and 7.5 (Kooijman *et al*. 1998). Both the Newborough and the Dutch N x gradient studies were N or N and P co-limited (CEH, unpublished data; ten Harkel and van der Meulen 1996). However, while P limitation may prevent immediate adverse effects on species composition, N continues to accumulate, and has the potential to alter species composition in the longer term (Rowe *et al*. 2011).

In the UK, dune systems are predominantly managed by grazing, although other techniques such as mowing have been trialled, and a consideration of the importance of hydrological regimes and water chemistry is now recognised for dune slacks (Rhind and Jones 2009). Since dunes are naturally dynamic systems, a further management technique is to reinstate natural mobility. Although widely practiced on the continent, this is in its infancy in the UK, however smaller scale management techniques of turf stripping and dune slack re-profiling have been trialled.

2.8.1 Grazing

Grazing is the most common dune management technique. In the north and west of the UK, there is still agricultural grazing on many sites, predominantly by sheep (Boorman 1989). However, in much of the rest of the UK dune sites are smaller making stock grazing difficult, or managed grazing has ceased for a variety of reasons. Over the last few decades there has been a drive to re-instate grazing for conservation purposes, where agricultural grazing can no longer be maintained. Common livestock used for conservation grazing include heritage breeds of sheep (Soay), cattle (Highland cattle, Belted Galloway, Dexter) and ponies (Tolhurst and Oates 2001). The high botanical diversity of many dune sites is maintained by rabbit grazing (Ranwell 1960), although rabbit numbers in turn are facilitated by the presence of large stock (Bakker *et al*. 2009).

There is one, long-running N x grazing study in the UK (Plassmann *et al*. 2009; Phoenix *et al*. 2012), set up in 2003 at Newborough Warren, North Wales on a slightly decalcified area of fixed dune grassland (SD8/SD12 transition) which combines realistic N (0, +7.5, +15 kg N ha^{-1} yr^{-1}) and P addition (+10 kg P 0 kg N; +10 kg P +15 kg N ha^{-1} yr^{-1}) treatments nested within 3 grazing treatments managed by exclosures (grazed by ponies, cattle, sheep and rabbits; rabbit-grazing only; ungrazed). The effects of grazing dominate over N effects on species composition, vegetation structure and soils. However, there are some important implications for management of N impacts and of N accumulation from this experiment. Nitrogen and P co-limitation mean that species composition has hardly changed, however soil processes are altered: soil available N and P turnover are slower in the grazed treatments, and are higher in the N+P treatments. Leaching losses are higher by a total flux of around 1 – 2 kg N ha^{-1} yr^{-1} in the fully grazed treatments compared with ungrazed: In the ungrazed treatment, leaching losses range from 2.0 – 3.6 kg N ha^{-1} yr^{-1}, while in the grazed treatment, leaching losses are higher, ranging from 3.9 – 4.7 kg N ha^{-1} yr^{-1}. However, this finding differs from the Dutch experiment where leaching losses were slightly higher in the ungrazed treatments, 15% of inputs compared with <5% of inputs in the grazed exclosure (ten Harkel *et al*. 1998). It is not straightforward to explain these differences. The Dutch experiment was unreplicated, and compared only +/- rabbit grazing, with N applied in the form of ammonium sulphate. The Newborough experiment was replicated (N=6 for each N treatment), and compared combined stock and rabbit grazing with ungrazed, with N applied as ammonium nitrate. Other Dutch work suggests that the size of grazers has an impact on rates of N mineralisation (Bakker 2003), which may also alter leaching rates. The lower mineralisation rates in grazed treatments at Newborough (Ford *et al*. 2012) match the pattern expected from Bakker (2003).

The main effect of grazing is to mitigate some of the adverse effects of N, by reducing the dominance of aggressive or tussocky species and opening up the canopy, thus increasing botanical diversity (Hewett 1985; Plassmann *et al*. 2010). However, grazing does not usually remove much N from the system. The fluxes of N removed by grazers depend on their live-weight gain, whether they are taken off site, and whether supplementary feed is provided on-site. Since live-weight gain is low on the poor quality grazing of most dune systems, if supplementary feed is provided, it is likely that grazing livestock are a net source of N to the dune system (even accounting for elevated leaching losses) rather than a net sink.

The main take-home message is that even where grazing and P limitation prevent rapid changes in plant composition, N is still accumulating in the system, altering soil processes and building up the potential for change in the future, which is likely to involve reductions in species richness and accelerated succession.

Grazing can have a number of adverse effects. High grazing pressure may damage fragile habitats, particularly those with a high lichen component, and any form of stock grazing may be inappropriate for some of these communities such as SD11 *Carex arenaria - Cornicularia aculeata* community. Supplementary feeding of stock should be avoided other than with salt blocks as hay, silage etc. import nutrients to a highly oligotrophic habitat. Other grazing practices can also cause net nutrient import, where stock are grazed on-site during the day but housed off-site at night and receive supplementary food there. Some stock types e.g. ponies may congregate in slack areas and preferentially dung in these areas, which may lead to localised nutrient enrichment.

Unintended consequences

- Loss of grazing intolerant species
- Changes in species composition
- Loss of ground nesting birds
- Changes in N cycling due to grazing rates

- Supplementary feeding is a source of nutrients and a seed source of undesirable plant species
- Grazers may redistribute nutrients into sensitive habitats

2.8.2 Cutting

Some mowing experiments have been conducted on dunes, at Newborough and at Braunton Burrows. Mowing has broadly similar effects to grazing, although it lacks the disturbance element which benefits germination of annuals. Mowing leads to reduced dominance of tall herbs and perennial grasses, and increases in small herbs (Hewett, 1985). Removal of N is dependent on whether the cut biomass is removed off-site. If it remains on site, then cutting only mitigates some of the effects of N deposition, through opening up the canopy. Mowing has been used to reduce nutrient pools in the Netherlands, but with limited success. A dune slack was mown every year since 1977, but species still disappeared as a result of successional changes linked to pH, organic matter accumulation and groundwater levels (Sival and Grootjans, 1996). Mowing can also encourage the activity of natural grazers such as rabbits, by reducing the height of the canopy to the level they prefer (Anderson and Romeril, 1992). There are disadvantages to mowing. The mowing experiment in dry dunes at Braunton reported numerous problems with uneven terrain and with wear and tear to machinery (Breeds and Rogers 1998). Cutting with machinery may lead to soil compaction, and over time may also modify geomorphological features by flattening hummocks and filling hollows. For practical reasons, mowing is unlikely to be applied as a large-tool management technique on dunes; its use is restricted mainly to slacks. No studies have assessed the N budget associated with mowing and removal of cuttings off-site.

Unintended consequences

- Loss of cutting intolerant species
- Changes in species composition
- Loss of ground nesting birds if cuts are not timed appropriately
- Cutting with machinery may damage surface topography and soils
- Timing and frequency of cutting may adversely affect seed production and species composition.

2.8.3 Burning

Accidental burns happen occasionally at dune sites. In principle these may result in some loss of N from the system through ash and NO_2 in the smoke plume transported off site and through increased leaching. An accidental fire at Newborough Warren improved the structure and composition of the affected vegetation (Rhind and Sandison 1999) and there is evidence that certain moss species such as *Ceratodon purpureus* and *Campylopus introflexus* can dominate after burns (Ketner Oostra *et al*. 2006). The consequences of burning in dunes are largely unknown, and there have been no scientific studies on dunes looking at the quantity of N removed, the long-term consequences for soils, and only a few studies examining short- to medium-term effects on vegetation.

Unintended consequences

- Changes in ground flora composition; loss of species
- Impacts on habitat/food/breeding requirements for birds, mammals, invertebrates etc.

- Pollution swapping (transfers to atmospheric N or leaching).
- Leaves areas looking unsightly
- Some moss species can be invasive after fire.

2.8.4 Hydrological management

Hydrological management is only recently being considered in dune systems due to greater appreciation of both the potential for nutrient inputs via groundwater (Jones *et al*. 2005; 2006), but also the consequences of climate-mediated changes in water tables (Davey *et al*. 2010; Curreli *et al*. 2013) which have important consequences for the chemical regime of dune slacks. Declining water tables lead to a reduction in the natural buffering of dune slack soils by winter groundwater, exacerbating acidification effects. The hydrological regime can be an important control on denitrification in early successional communities (Grootjans *et al*. 2004). Hydrological management in the context of predicted climate change impacts is likely to focus on elevating site water tables. This will include techniques such as blocking or re-routing existing drainage ditches which control water levels and managing vegetation to reduce evapotranspirative losses, primarily by removing trees or scrub. If groundwater is rich in nutrients then elevating water tables has the potential to increase nutrient inputs to the site.

Unintended consequences

- Managing water levels may alter nutrient inputs to the site
- Changes to species composition.

2.8.5 Turf stripping and topsoil inversion

Turf stripping is primarily used in dune slacks as a management technique with a dual purpose: to remove accumulated soil organic matter and nutrients and to chase a falling water table. On the continent this also serves to remove decalcified soil layers and the closer contact with the water table brings the benefits of improved buffering of soil layers by carbonate rich groundwater in winter, which benefits base-loving pioneer species. While it has been extensively used on the continent and at very large scale (e.g. Sand Dune and Shingle Network, 2011), in the UK it has only been conducted at small scale, albeit at a number of sites, and without any formal scientific monitoring. In particular, there have been no attempts to quantify the amount of soil N removed, or the long-term trajectories of vegetation recovery. In dry dunes, topsoil inversion (deep-ploughing) has been trialled at Talacre Warren in North Wales (Jones *et al*. 2010). This inverts the soil profile, burying nutrient rich soil layers below mineral sand. However, sand winnowing and rejuvenation of undesirable perennials from rhizomes and persistent roots in the initial trial meant that it was not a success and removal of organic material and its stock of soil N off-site is preferable (Jones *et al*. 2012a). Both turf stripping and topsoil inversion remove or reduce the seed bank, this may be desirable in some situations in removing non-target species, but may be a significant barrier to recolonisation of target species. Therefore, a further consideration relevant to both these techniques is how to manage subsequent recolonisation if the bulk of the soil seed bank is removed.

Unintended consequences

- Unsuitable for many areas e.g. those with archaeological interest
- Costly management
- Disposal of cut turves risks moving the pollution problem elsewhere
- Removal of species of high conservation interest

- Alteration of hydrological regimes
- Reduction of some rare species
- Loss of desirable seed bank
- Disturbance soil food-webs and may affect important micro-organisms such as mycorrhizas

2.8.6 Dune mobilisation

Facilitating natural dynamic processes in dunes is increasingly seen as the most robust and viable long-term management strategy for adapting to climate change, sea level rise and over-stabilisation. Dynamic dune systems with active dune processes produce a self-regulating system where migrating mobile dunes slowly envelop older habitats, but create new secondary dune slacks and mobile and semi-fixed dune habitat in their wake which are the most important habitat for the majority of dune specialist plant, insect and vertebrate species. A mosaic of older fixed dune and dune slack habitat combined with younger successional stages creates a highly heterogenous mix of habitats supporting a wide range of species. This does not directly remove stored N from the system, but is a more effective way of recreating early successional habitat than topsoil inversion discussed above. The formation of new dune slack habitat by such natural processes automatically adapts to changes in hydrological regime caused by climate change for example (Davy *et al*. 2010), avoiding the need for other interventions.

Reinstating natural dynamics is non-trivial and is strongly dependent on prevailing climatic conditions (Jones *et al*. 2010), but can be achieved through a number of techniques at varying scales. One option is beach nourishment, which injects extra sand into the sediment system, which both maintains beach profiles preventing erosion and provides sand for enhanced dune mobility and burial of vegetation inland. At Talacre Warren in North Wales 150,000 m^3 of sand from navigation dredging operations was pumped on to the foreshore in 2003. New foredunes are now developing and sand is now being channelled into hind dune areas creating new mobile dunes (Rhind and Jones 2009). Larger-scale remobilisation, by reactivating blow-outs or carefully selected stabilised dunes is now being considered for a number of sites in Wales, identified during a scoping study (Houston and Dargie 2010). Some remobilisation is starting at Kenfig dunes in South Wales (Pye and Blott 2011).

Remobilisation of dunes may potentially over-run other habitats of conservation importance, but can be avoided by careful selection of locations. The considerable experience in stabilising mobile dunes gained in previous decades means that run-away dune mobility is highly unlikely.

Unintended consequences

- Run-away dune mobility
- Limitations imposed by local dune alignment and current climatic conditions may restrict the value of dune remobilisation as a management tool

2.9 Other Coastal Habitats

This section covers the three remaining UK BAP priority habitats occurring in terrestrial coastal regions with vegetation communities, namely: coastal saltmarsh, maritime cliff and slopes, and coastal vegetated shingle.

2.9.1.1 Coastal saltmarsh

Coastal saltmarshes occur in the upper vegetated portions of intertidal mudflats, and consist of a limited number of salt tolerant species adapted to regular immersion by tides. Natural saltmarsh systems comprise successional stages, determined by the frequency of seawater inundation. Low to mid marsh is typically species-poor, while mid to upper marsh is more diverse. Saltmarsh habitats are currently threatened by land claim, erosion and sediment dynamics. Furthermore, saltmarshes are affected by N inputs from rivers, sea and the atmosphere. Saltmarsh habitats experience open nutrient cycles, with significant exports and imports through surface water. There are high levels of total N within the saltmarsh system and large inputs and outputs. In general the net N balance can be negative or positive, depending on the condition of the marsh (Boorman and Hezelden, 2012). These exchanges are considerably larger than the defined critical load of 20 – 30 N kg ha^{-1} yr^{-1} (Hall *et al.* 2011). In the UK, N deposition exceeds critical loads in just 0.9 % of the total saltmarsh area, but in 11 % of the area in Northern Ireland.

Despite high levels of productivity, saltmarsh is still regarded as N-limited (van Wijnen and Bakker 1999) and susceptible to the impacts of N deposition such as vegetation growth and rates of succession. However, the evidence presently available indicates that for responses to occur, N levels would need to be significantly higher than the defined critical loads (Boorman and Hezelden, 2012). The age of a saltmarsh is probably a significant factor determining the response of the vegetation, such that the pioneer and lower marshes are likely to show a positive growth response to increases in N loading while the higher marshes with closed plant communities are likely to show a decrease in species diversity. In addition, eutrophication of coastal waters can result in the rapid growth of certain fast-growing algal species (Pedersen and Borum, 1996) and algal mats have been observed to smother the germination and growth of pioneer saltmarsh species (Boorman 2003). However, the sensitivity of saltmarsh to N deposition cannot be reliably estimated due to the low number of experimental studies in this habitat (Bobbink and Hettelingh 2011), indeed the critical levels for this habitat are based upon expert judgment (Hall *et al*. 2011).

Saltmarshes in the UK are primarily managed by commercial grazing or for wildfowl conservation.

2.9.1.2 Coastal Vegetated Shingle

Shingle is defined as sediment of particle size greater than 2 mm and less than 200 mm. The vegetation communities which occur on the shingle depend primarily upon substrate stability, followed by water availability and substrate matrices. The first plant species to colonise shingle are nutrient-loving pioneer ruderals tolerant of salt water inundation, but are overwhelmed by storm conditions and re-establish as conditions become suitable. Where the shingle beach is stable from spring to autumn it can support summer annuals, if the beach is stable for a longer period of time, short lived perennials can establish. On more stable shingle, salt-tolerant species occur, and further landward shingle is replaced by heath, scrub and grassland communities.

In the pioneer shingle communities, large quantities of nutrients are supplied by organic matter derived from the sea, rather than atmospheric deposition. As such, little research has concentrated on the impacts of N deposition on this habitat. However, stable vegetated sites can contain many lichens and bryophytes, which are sensitive to the effects of N deposition. Due to the dependence of these shingle habitats on substrate stability, current management recommendations are focused toward minimising anthropogenic disturbance. Due to the sparse vegetation cover in this habitat, the grazing of domestic stock is restricted because grazing can cause loss of species, even in larger shingle sites (Doody and Randall, 2003). Community compositional shifts could also occur due to the fertilization enrichment in this otherwise nutrient- poor environment. There is no literature available to inform the viability of management for the mitigation of N deposition. However, the response to N deposition and management of successive habitats developed on stable shingle, such as scrub, heath and grassland, may be similar to the responses covered in those sections of this report. Shingle is generally not directly managed, other than at the seaward edge with beach nourishment, but grazing by stock would damage the sensitive lichen communities.

2.9.1.3 Maritime Cliff and Slopes

Maritime cliff and slope encompasses the cliff-top area receiving salt spray deposition, and extends seaward to the supralittoral zone. Maritime cliffs can broadly be classified into two groups: 'hard cliffs' are vertical or steeply sloping and generally support few higher plants, 'soft cliffs' are less stable and form shallower slopes more easily colonised by vegetation. On exposed hard cliffs with little soil development, lichens are often the predominant vegetation, but ledges can support some flora. Beyond the rock crevice pioneer vegetation communities, maritime grassland, scrub and heath also occur on cliff-tops. On the northern and south-western coasts of the UK, maritime vegetation such as saltmarsh and sand dunes can occur on cliff-tops.

At present, there are no studies documenting the effect of N deposition in this habitat. Rock and cliff habitats may be sensitive to N deposition, since these often occur in remote regions adapted to low nutrient supply, with relatively little anthropogenic disturbance. However, bird colonies may substantially increase N inputs in these environments, which could exceed those via anthropogenic deposition.

Some maritime cliffs are managed by grazing with livestock or for conservation purposes.

2.9.1.4 Grazing

Currently, saltmarshes are primarily managed by commercial grazing for provision of high-value products such as saltmarsh lamb and saltmarsh beef. Where they are important for bird conservation they are heavily grazed by wildfowl such as geese, often in combination with livestock grazing. Grazing also has implications for the role of saltmarsh in coastal protection, through consolidation of the soil and as a physical barrier. Management efforts in the south and east of the UK are concentrated on erosion prevention and on managed realignment sites. Cutting and grazing techniques have not been used specifically to mitigate against potential effects of N deposition. Grazing alters the vegetation structure directly through feeding and indirectly by altering the conditions for vegetation growth (Kiehl *et al.* 2007), and at low intensity increases vegetation patchiness and biodiversity (Bakker, 1985; Olsen *et al*. 2011). While grazing decreases above-ground biomass, below-ground biomass is increased (Olsen at al. 2011). Therefore grazing could be used to manage vegetation responses to N deposition should they occur, though the interactions between the two factors have not been experimentally tested.

Maritime cliffs and slopes tend to be inaccessible to grazing, though in some countries, human activities such as tourism have had negative effects on vegetation cover of maritime grassland and heath communities (Sawtschuk *et al.* 2010). However cliff tops are occasionally grazed by stock, usually sheep, but other grazers have been suggested for conservation grazing of these habitats (Oates *et al*. 1998; Oates 1999). Where they are grazed they usually support high rabbit densities also through the facilitating effect of maintaining a low sward height. No management techniques have been applied to this habitat specifically with the aim of mitigating N deposition effects, though vegetation communities beyond pioneer vegetation may respond similarly to other habitats.

2.9.1.5 Cutting

The cutting of saltmarsh for hay has been practiced on saltmarshes both in Europe and America in the past, but is rarely practiced in Britain, and is a way of controlling the coarse vegetation characteristic of the higher marsh levels (Boorman 2003). Cutting could in principle be used to manage vegetation responses to N deposition should they occur, though the interactions between the two factors have not been experimentally tested.

Unintended consequences

- Grazing saltmarshes may damage creek structures
- Grazing saltmarshes reduces their effectiveness at wave attenuation.

2.10 Conclusion

A number of management practices currently recommended in conservation guidelines and agri-environment schemes have the potential to reduce the impacts of N deposition on sites of conservation importance. In many sites we may not see the full impact of N deposition because many of these practices are already in use. Small changes to recommended management have the potential to further reduce the impact of N deposition. The majority of management practices do not remove significant quantities of N. Furthermore, it is likely to be very rare that management at a level of intensity that will not be damaging to the habitat will fully offset N deposition inputs or increase habitat suitability sufficiently.

Managing for any single issue (e.g. N, climate change, biodiversity) in isolation may result in unintended and undesirable outcomes. Many studies which have recommended increased intensification of management have failed to monitor the impacts on the full range of species and functions. Unintended consequences of management to mitigate N impact were identified for all methods. These included damage to plants, insects, animals and birds; impacts on water quality, loss of soil C stocks, changes in N cycling, acidification, loss of seedbanks, visual blight. These may be habitat-type and management specific.

2.11 The potential use of case study sites or experiments to separate N deposition and management effects.

Separating the effects of N deposition and management is non-trivial. It requires the ability to separately attribute change to the two drivers. There are three main approaches: 1) A spatial gradient approach, 2) Temporal change analysis and 3) Experimental manipulations.

In the spatial gradient approach, sites are selected along gradients of N deposition and of management intensity, effectively including both as continuous variables in a statistical analysis. This approach has been widely applied to explore N deposition and other pollutant impacts in a range of habitats (e.g. Maskell *et al*. 2010; Stevens *et al*. 2004; Jones *et al*. 2004; Edmondson *et al*. 2010), but not yet for management impacts. Selection of sites should seek to control for other likely co-varying factors such as temperature, rainfall, other pollutants including ozone, and is more powerful if analyses are conducted within a single habitat type. While information on pollution and climatic driving variables has been collated and calculated historically across the UK, there remains a major challenge in collating appropriate management information both currently and particularly historically for the multiple sites required for this approach to be most effective.

Temporal change analysis can be applied where data are available for two or more points over time. Changes in the measured parameters can then be interpreted in the light of known changes in driving variables such as N deposition, climate change and management. A major disadvantage of this approach is that many driving variables co-vary over the same period. The difficulties are highlighted by Jones *et al*. (2008) in a chronosequence study which looked at changes in rates of soil development at a single site over time, where changes in temperature and N deposition co-varied and their impact on soil development could not be statistically separated, although both were significant when analysed independently. Analysis of change in vegetation composition provides a little more flexibility, by examining the characteristics of species increasing or decreasing according to their ecological requirements, most simply by the use of Ellenberg indicator values (e.g. McGovern *et al*. 2011).

Experimental manipulations are the most rigorous, using experimental sites in which one or both of the desired factors (N deposition or management) have been experimentally manipulated and where information about the other factor has also been recorded. For example, the acid grassland N x grazing experiment at Pwllpeiran has manipulated both N and grazing intensity over 15 years, and allows separate differentiation of the two factors (Emmett *et al*. 2007). The disadvantage of this approach is that there are relatively few experiments which have run over sufficient duration to reliably separate N and management effects, and they are restricted to a few habitats. The majority of suitable experiments were funded through Defra's UKREATE N research consortium, summarised in Table 2.2; an overview of N impacts from these experiments is available in Phoenix *et al*. (2012).

2.11.1 Potential data sources and feasibility

2.11.1.1 ECN and ECBN

The environmental change network (ECN) comprises 12 sites, across a range of habitats in the UK which have been monitoring vegetation, soils and climate and other data since 1992. Additional sites are included in the Environmental Change Biodiversity Network (ECBN; also know as the Long Term Monitoring Network) proposed in 2006, and slowly growing, with much lower monitoring effort than in the core ECN sites. Spatial gradient analysis in the ECN sites is constrained by the fact that the sites comprise different habitats, and are mostly located in areas of high N deposition in the uplands or in south-east England, providing little opportunity to define a sufficient N gradient, and insufficient replication by habitat. They offer most promise in looking at temporal change, although the opportunity to identify N impacts is unfortunately also limited in this case because N deposition has decreased during the monitoring period. Vegetation responses to decreases in N deposition show long lags due to accumulated N in soil and vegetation pools. However, bryophytes and lichens respond more quickly to changes in atmospheric inputs and analysis of this component of the vegetation may allow some interpretation of the effects of management on N impacts, if replicate sites within the same vegetation type, but with different management regimes can be identified. In theory the ECBN sites will allow both spatial and temporal change analysis, since the ECBN was specifically designed to monitor biodiversity across a network whose locations take into account climate, air pollution and management gradients. However, there are only 40 ECBN sites currently, divided across a range of habitats, which means there is insufficient replication of any individual habitat to statistically separate effects of co-varying factors in a spatial gradient analysis.

2.11.1.2 Countryside Survey

The CEH countryside survey has sampled over 5 time points: 1978, 1984, 1990, 1998 and 2007, across a range of habitats, with 591 1x1 km squares sampled in the most recent survey in Great Britain, and a further 288 0.5x0.5 km squares surveyed in Northern Ireland. This unique datas*et* allows both spatial gradient and temporal change approaches. Several publications have already reported on effects of N deposition across a range of habitats (e.g. Maskell *et al*. 2010; Smart *et al*. 2004). CS data provides probably the best opportunity to disentangle N deposition and management signals from existing data. But this has not been attempted yet due to the difficulty of obtaining relevant management data for each location (and historical changes in management over time).

2.11.1.3 Floodplains Meadows Partnership

The Flood Plain Meadows partnership (http://www.floodplainmeadows.org.uk/) holds an extensive database with long-term management and floristic monitoring data from flood plain meadows across the UK. The network covers a reasonable breadth of N deposition but lower levels are unlikely to be covered due to the habitat distribution. Management manipulations have also been conducted at a smaller number of sites focussed on cutting regimes and nutrient or lime additions. The detailed botanical data held together with management information make this a potential source of information for distinguishing impacts of N addition in this community. Little is currently known regarding how sensitive this community is to N deposition.

2.11.1.4 Site-specific datasets

Temporal change analysis

McGovern *et al*. (2011) applied a temporal change analysis to explain change in vegetation and soils at Snowdon over a 40 year period and discerned that the main signal of change in vegetation related to soil recovery from acidification, and that changes in land use had no significant effect. Jones *et al*. (2008) looked at climatic, N pollution and topographical influences on soil development over time in a sand dune system at Newborough Warren. Other vegetation data exist from this site including changes in vegetation due to grazing based on permanent quadrats established in 1987, with repeated monitoring data available (Plassmann *et al*. 2010).

National Nature Reserves

Long term management and vegetation records from National Nature Reserves may provide the opportunity to further develop this approach if there are sufficient good quality data available.

Long-running manipulation experiments

Park Grass Experiment

The Park Grass Experiment is the longest running experiment on grassland in the world. The experiment is on a neutral grassland in Hertfordshire and was established in 1856. Experimental additions of N, P, K, and organic fertilisers are made, singly and in combination with liming. There are also control plots which have been managed but not received nutrient or lime additions. Management is principally by a hay cut in mid-June with some variation due to grazing and second cuts being introduced at different times during the experiment's history. Rothamsted Research also collects long-term measurements of N deposition. The experiment has been used to investigate impacts of nutrients on vegetation (e.g. Silvertown, 1987) and the control plots have been used to identify long-term impacts of N deposition on soils (e.g. Goulding *et al.* 1998).

N x management manipulation experiments

Five experiments in the Defra UKREATE consortium have N x management treatments (Table 2.2). These experiments span acid and dune grasslands, lowland and upland Calluna heath and alpine heath, with management treatments of grazing for the grassland communities and burning for the heaths. In the grassland experiments, grazing has been continuous. In the heathland experiments burning (experimentally controlled or accidental) has been a one-off event, with N additions and monitoring continuing afterwards. Many of these experiments are relatively long running, and offer a unique opportunity to examine how management may alter responses to N. While individual experiments have published many papers, there has been no co-ordinated attempt to synthesise N and management responses across multiple experiments as yet.

The BEGIN experiment provides a network of three experiments located in acid grasslands in differing climatic zones (Trefor, Wales; Fusa municipality, Norway; Bordeaux, France). These experiments have been running for six years and investigate the N x management treatments focusing on cutting and removal of biomass.

N-only manipulation experiments

Four further experiments in the Defra UKREATE consortium have N only treatments (Table 2.3) covering acid and calcareous grassland, lowland heath and bogs. Other N addition experiments exist in a range of habitats throughout Europe. These may be of some use in providing extra information on trajectories of change in un-managed systems in statistical comparison of results against other sites where management has taken place.

2.11.1.5 Summary of 2.11

Although we believe that it is possible to disentangle the effects of N deposition and management in some of these data sources this is a non-trivial undertaking and individual data sources will require considerable analysis and interpretation in order to potentially separate these effects. It is possible that management has already changed in response to N deposition within impacted sites but managers are not necessarily aware that they are working towards addressing N deposition impacts.

Table 2.2. Experimental sites from the Defra UKREATE nitrogen research network, in which management and N deposition have been manipulated. Adapted from Phoenix *et al*. (2012)

	Site name (Abbreviated code)	Vegetation type: NVC classification	Soil type	N treatment rates (kg N ha^{-1} yr^{-1})	N form (as solution unless stated)	Management treatments	Year started	Duration of N treatments	Background N dep. (kg N ha^{-1} yr^{-1})
Heath	Ruabon (RUH)	Upland heath: H12 *Calluna –Vaccinium*	Peaty podzol	0,40,80,120 0,10,20,40, 120	NH_4NO_3	Controlled burn	1989 1998	22 13	25
	Thursley (TLH)	Lowland heath: H2 *Calluna - Ulex minor*	Podsol, over lower greensand	0, 7.7, 15.4 0, 30	$(NH_4)_2SO_4$	Uncontrolled burn, Controlled burn	1989-1996 1998	7 13	20
	Culardoch (CAH)	Low Alpine Heath: H13 *Calluna-Cladonia*	Sub-alpine podsol	0, 10, 20, 50	NH_4NO_3	Clipping, Burning	2000	11	11
Acid Grassland	Pwllperian (PAG)	Upland acid grassland	Shallow ferric stagnopodzol	0, 10, 20	$NaNO_3$ $(NH_4)_2SO_4$	Sheep grazing: Light, Heavy	1996	15	17
Sand dune	Newborough (NDG)	Fixed sand dune grassland: SD8 *Festuca – Galium*	Para-rendzina	0, 7.5, 15	NH_4NO_3	Ungrazed; Rabbit grazed; Large Stock (ponies, cattle)	2003	8	11

Table 2.3. Experimental sites from the Defra UKREATE nitrogen research network, in which N deposition only has been manipulated. Adapted from Phoenix *et al*. (2012)

	Site name (Abbreviated code)	Vegetation type: NVC classification	Soil type	N treatment rates (kg N ha^{-1} yr^{-1})	N form (as solution unless stated)	Management treatments	Year started	Duration of N treatments	Background N dep. at site (kg N ha^{-1} yr^{-1})
Heath	Budworth (BLH)	Lowland heath: H9 *Calluna –Deschampsia*	Humo ferric podzol	0,20,60,120	NH_4NO_3	None	1996	15	28
Bog	Whim (WBO)	Ombrotrophic bog: M19, *Calluna-Eriophorum*	*Sphagnum* peat	0, 8,24,56 for wet dep.	NH_4Cl $NaNO_3$	None	2002	9	10
				NH_3 transect 4-70	NH_3 gaseous		2002	9	
Grass land	Wardlow acid grassland (WAG)	Acid grassland: U4e *Festuca-Agrostis-Galium*	Paleo-argillic	0, 35, 70, 140	NH_4NO_3	None	1990[1]	12	34
				0, 35, 140			1995[2]	16	
	Wardlow calcareous (WCG)	Calcareous grassland: CG2d *Festuca –Avenula*	Rendzina	0, 35, 70, 140	NH_4NO_3	None	1990[1]	12	34
				0, 35, 140			1995[2]	16	

3 ASSESSMENT OF EFFECTS OF CURRENT MANAGEMENT PRACTICE, USED BY THE CONSERVATION BODIES, ON HABITAT RESPONSE TO NITROGEN DEPOSITION.

This chapter assesses the effect of current management practice, used by the conservation bodies, on habitats responses to N deposition. Of the habitats considered in the previous chapter, six are included here (acid grassland, calcareous grassland, dwarf shrub heath, bog, coastal dunes and woodland). These habitats were selected for more detailed study because they are known to be sensitive to N deposition and there is sufficient information on management practices and their impact on N cycling for review. In section 3.1 the current management practices for each habitat are described, and in section 3.2 the effect on habitat responses to N deposition are discussed. Where common management practices are discussed there is some overlap between sections 2 and 3.

3.1 Current management practice

3.1.1 Introduction

To compile current management practice lists, conservation agency publication lists were searched, conservation agency habitat specialists were consulted, and agri-environment scheme handbooks were used. Only management practices prescribed for habitat conservation, as opposed to restoration and creation, were considered. In total, nine broad categories of management practice were identified; whether the management practice is currently used or not for a given habitat is presented in Table 3.1. Current management practice in each habitat is discussed in detail in the sub-sections below. Note that management advice from different schemes is at times contradictory.

Table 3.1 Habitats and topics of current management recommendations by UK conservation agencies, set out in nine broad management classes

	Grazing	Cutting	Burning	Fertilisation	Liming	Hydrological Management	Scrub removal	Tree removal	Disturbance
1. Acid grassland	✓	✓	✓	✓	✓	✓	✓	✓	✓
2. Calcareous grassland	✓	✓	✓	✓	✓	✓	✓	✓	✓
3. Dwarf Shrub Heath	✓	✓	✓	✓	✓	✓	✓	✓	✓
4. Bog	✓	✓	✓	✓	✓	✓	✓	✓	✓
5. Coastal Dunes	✓	✓		✓	✓	✓	✓		✓
6. Woodland	✓	✓		✓		✓	✓	✓	✓

3.1.2 Broadleaved, mixed and yew woodland & (natural) coniferous woodland

Minimum intervention is required to manage woodland for conservation. Prescriptions state that grazing can be used to maintain rides and to manage scrub, or woodlands should not be grazed. Cutting and burning of the understorey vegetation is not used, fertiliser is not applied and site hydrology should not be modified. Disturbance should be minimised. Tree removal should be minimised and standing dead wood should also be protected and left on site. Management prescriptions and advice are summarised in Table 3.2 and presented in full in Appendix 1.

Table 3.2 Current management prescriptions for broadleaved, mixed and yew woodland.

Management Category	Management sub-category	Current Prescriptions
Grazing	General	Do not graze. Protect vulnerable trees from grazing. Consider controlled grazing. Maintain rides and glades within woodland by grazing or cutting.
	Timing	Do not graze in winter.
	Intensity	
	Stock type	Use mature cattle if possible. Sheep, goats or horses may be used.
	Stock management	
	Supplementary feeding	Do not supplementary feed.
Cutting	General	Do not cut. Cutting is only permitted to maintain the scrub and grass mosaic and for control of weeds.
	Timing	
	Intensity	
	Litter removal	
Burning	General	Do not burn
	Timing	
	Intensity	
	Litter removal	Avoid burning brash.
Fertilisation		Do not apply fertiliser. Minimise the use of fertiliser.
Liming		
Hydrological management		Do not install new drainage or modify existing drainage. Keep streams clear of brash. Restore site drains. Ensure wetland features are protected.
Scrub management		Do not cultivate within 6 m of woodland edge. Remove thick vegetation and brash. Use pulling or grazing to control bramble, bracken, wood small-reed and rhododendron.
Tree management		Limit felling to 10% of area in any five year period. Manage for a minimum of 10% open space. Retain and protect native woodland. Maintain high forest management. Use rotational coppicing. Maintain good canopy. Retain all deadwood. Trees must be left on site to decompose. Do not manage trees 1 Mar to 31 Aug. Fell selected trees and leave fallen wood. Once felled the cut trees must be cleared from the site. Protect older trees. Protect hollow trees. Ensure the removal of forest products does not deplete site fertility or soil carbon over the long term. Avoid removing stumps.
Disturbance	General	Restrict unnecessary disturbance to soils. Minimise compaction and erosion. Conserve and enhance carbon stocks.
	Turf stripping	
	Cultivation	
	Litter removal	

3.1.3 Calcareous grassland

Grazing, cutting and burning in winter in uplands, are used to manage calcareous grassland for conservation. Grazing is recommended all year or summer only, at low stocking densities although the timing of grazing may vary between sites. Cuttings can be removed or grazed. Trees and scrub should be controlled. Fertiliser is not permitted, or is limited to low levels of farm yard manure (FYM) only. Large-scale disturbance should be avoided Management prescriptions and advice are summarised in Table 3.3 and presented in full in Appendix 2.

Table 3.3 Current management prescriptions for calcareous grassland.

Management Category	Management Sub-category	Current Prescriptions
Grazing	General	Manage by grazing only.
	Timing	Graze all year. Graze summer only. No winter grazing. No spring grazing. Low summer grazing.
	Intensity	Maintain a varied sward height. 1 - 15 cm. 20% <7cm. 75% <10 cm. No upper sward height range. 2 to 10 cm (autumn). 75% 3 cm to 50 cm (summer), 50% 2 cm to 10 cm (winter). 2 to 10 cm (winter) and 2 to 15cm (summer).Do not increase current stocking level. 0.25 - 0.5 LSU/ha (all year). 0.15 - 0.6 LSU/ha (summer). 0.75 LSU/ha (winter).
	Stock type	Sheep, cattle, horses and rabbit. 30% of LSU cattle 15% of LSU sheep. Graze upland with cattle during summer.
	Stock management	Make sure that grazing is evenly distributed. No poaching is permitted. No heavy poaching. Movement of stock between the habitat and improved grassland should be limited. 5 to 10% bare ground.
	Supplementary feeding	Do not supplementary feed. Supplementary feeding allowed but move feeders often.
Cutting	General	Manage areas of dense rushes by cutting. Management must include grazing and/or cutting for hay.
	Timing	Cut rushes in winter. Cut in summer then autumn, or summer then spring. *Upland*: Do not cut in summer.
	Intensity	Cut close to the ground and certainly under half-stem height
	Litter removal	Aftermath graze with cattle. Remove cuttings.
Burning	General	*Upland*: Do burn small portions of the site on rotation. Do not burn where *Molinia* is present.
	Timing	*Upland*: Do not burn 01 Apr to 31 Aug Do burn in January, February or March
	Intensity	*Upland*: Do not burn an entire site. Do not burn the same area every year
	Litter removal	
Fertilisation		Fertiliser not permitted. FYM permitted but synthetic fertiliser not permitted. Do not increase current FYM applications. Maximum 15 kg N $ha^{-1}yr^{-1}$as FYM. Apply only early in growing season. Apply only when ground is dry. *Upland*: Do not apply fertiliser. Do not apply within 6m of top bank of a watercourse
Liming		Continue adding lime if you already do so. Do not apply lime in summer. Only apply lime with consent.
Hydrological management		Do not install new drainage or modify existing drainage.
Scrub management		Scrub must be controlled. Prevent scrub encroachment by grazing, mowing or topping. Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal. Remove the cut material.
Tree management		Trees must be controlled. Fallen deadwood must be retained. Remove the cut material.
Disturbance	General	Avoid poaching or creating wheel ruts.
	Turf stripping	Do not carry out any earth moving activities.
	Cultivation	Cultivation and chain harrowing not permitted. Do not roll or chain-harrow in spring and summer.
	Litter removal	

3.1.4 Acid grassland

Grazing and cutting are the main techniques used to manage acid grassland for conservation. The use of fertiliser is not permitted or is restricted to FYM only. Lime may be added, but not in summer. Drainage may not be installed or modified and disturbance such as cultivation is not permitted. Scrub should be controlled. Management prescriptions and advice are summarised in Table 3.4 and presented in full in Appendix 2.

Table 3.4 Current management prescriptions for acid grassland.

Management Category	Management Sub-category	Current Prescriptions For Acid Grassland
Grazing	General	Land must be maintained by grazing. Manage by grazing only. Manage areas of dense rushes (i.e. where over 50% of the vegetation is rushes) by grazing each year.
	Timing	Graze all year. Graze summer only. No winter grazing. Graze upland with cattle during summer.
	Intensity	Maintain a varied sward height and >15% bare ground. Minimum 75% < 3 to 20 cm (or 10 cm if drought prone) in summer and 60% of 2 to 10 cm in winter. Do not increase current stocking level. 0.2 - 0.75 LSU/ha (all year) 0.4 - 1.0 LSU/ha (summer). Use lower stock density with less than 50% Agrostis-Festuca grassland.
	Stock type	Sheep, cattle, horses and rabbit. 30% of LSU cattle 15% of LSU sheep
	Stock management	Make sure that grazing is evenly distributed. No poaching is permitted. No heavy poaching.
	Supplementary feeding	Do not supplementary feed.
Cutting	General	Maintain by cutting and aftermath grazing. Cutting is an acceptable method of weed control in small areas. Manage areas of dense rushes by cutting and/or grazing each year.
	Timing	Cut up to 1/3 of the area of rushes between 15 March and 31 July. Cut 15 Jul to 15 Mar. Do not cut before 01 Jul. Cut after 01 Aug. *Upland*: Do not cut in summer.
	Intensity	Between 1 August and 31 March inclusive, achieve an open mix of rushes and grass pasture, by cutting between a third and two thirds of your rushes in a random pattern, and/or by grazing to remove and thin between a third and two thirds of your rushes.
	Litter removal	Rushes may be controlled by cutting and the cuttings removed
Burning	General	Do not burn.
	Timing	
	Intensity	
	Litter removal	
Fertilisation		Fertiliser not permitted. No other type of fertiliser (besides FYM) may be applied. Add only early in growing season. Maximum 15 kg Nha^{-1} FYM or maximum FYM 2.5 $tonnesha^{-1}yr^{-1}$ and only where grassland is cut..
Liming		Continue adding lime if you already do so. Do not apply lime 01 Apr to 01 Aug. Only apply lime with consent.
Hydrological management		Do not install new drainage or modify existing drainage
Scrub management		Scrub/trees must be controlled. Prevent scrub encroachment by grazing, mowing or topping
Tree management		Fallen deadwood must be retained
Disturbance	General	
	Turf stripping	Do not carry out any earth moving activities
	Cultivation	Cultivation and chain harrowing not permitted. Do not roll or chain-harrow in summer.
	Litter removal	

3.1.5 Dwarf shrub heath

The main conservation aims for both lowland and upland dwarf shrub heath habitat are: to maintain structural diversity in vegetation stands, to prevent scrub or tree encroachment, and to control against nutrient addition. General prescriptions for management of heather include: avoid producing a *Calluna* monoculture, encourage a range of dwarf-shrub species, ensure that all phases of *Calluna* development are present, maintain a substantial proportion of tall heather more than 20 cm tall, 25% heather in all four growth stages, 5% of total area of heather should not receive heather management, and manage on 20 year rotation. Management also includes maintenance of grass, tree, scrub, bare ground, forbs, bryophyte and lichen communities.

Grazing, burning and cutting are all used to manage vegetation in uplands and lowlands, although burning is not recommended for wet heath. Current recommendation states that undisturbed wet heaths and blanket mires require little management and should be left completely alone as far as possible. The timing of burning is governed by legislation (Heather and Grass Burning Code and Regulations 2007). In order to maintain low nutrient status of this habitat, water inputs should be nutrient poor, supplementary feeding should not be conducted on site, and no fertiliser of any kind is used. Some level of disturbance in lowland heath is suggested in some cases in order to improve the habitat for reptiles, invertebrates and some plants. Among regions of the UK, management recommendations are similar. Management prescriptions and advice are detailed in full in Appendix 3, and summarised in Table 3.5.

Table 3.5 Current management prescriptions for dwarf shrub heath.

Management Category	Management Sub-category	Current Prescriptions For Dwarf Shrub Heath
Grazing	General	Use moorland for agricultural livestock production. Ensure the sward is longest in summer and shorter in spring and autumn. Ensure a significant proportion of the shoot tips of heather are unbrowsed. *Upland*: Maintain current grazing practice, provided grazing practice has not recently altered, and not causing deterioration. Favourable condition may result from absence of grazing. *Lowland*: Avoid overgrazing. Maintain dwarf-shrub species.
	Timing	Do not graze 01 Nov to 28 Feb and 01 Apr to 31 Aug. Graze cattle and/or sheep 1 Jun to 31 Aug, sheep 01 Mar to 31 Oct (wet). Graze cattle and/or sheep 1 Mar to 31 Oct (dry).
	Intensity	Consider impacts of livestock and other grazing animals. Reduce stock density over winter. *Upland*: Winter stocking rates reduced by 25% and all hogs, cattle and horses removed. Reduced stocking density compared to lowland. *Lowland*: Manage stock density on wet heath.
	Stock type	Cattle, sheep, ponies. Minimum 30% cattle. *Upland*: Cattle, sheep. *Lowland*: Minimum 15% sheep.
	Stock management	*Upland*: Shepherding is required.
	Supplementary feeding	Do not supplementary feed or use silage. Haylage is permitted. Move feeding sites regularly. *Upland*: Supplementary feeding allowed. Lowland: Supplementary feeding not allowed on site.

Management Category	Management Sub-category	Current Prescriptions For Dwarf Shrub Heath
Cutting	General	Cut heather. Cut fire breaks. *Upland*: Do not cut large areas of old heather; saturated, steep and rocky ground, wet areas and bogs; old heather adjacent to roads. Cut every 10-20 years for heather growing alone or in mixtures with grass. *Lowland*: Do not cut. Establish a cutting rotation which allows Stands to go through all growth stages and creates a diverse structure.
	Timing	Cut 01 Oct to 31 Mar. *Upland*: Cut 01 Oct to 15 Apr or 01 Aug to 15 Apr. *Lowland*: Cut 01 Sep to 15 Apr.
	Intensity	*Lowland*: Cut every 10-20 years for heather growing alone or in mixtures with grass.
	Litter removal	Remove brash. If brash removal impractical, produce finely chopped material.
Burning	General	Do not burn wet, shaded, humid areas; vegetation on rocky areas; and stands with well developed heather layering, old rank (mature and degenerate, >20cm tall) heather, and which have not been burnt for long periods (more than 40 years). Do burn stands of continuous, evenly-structured, dense, tall heather on dry substrates. *Upland*: Do not burn flushes and valley mires, grass-heath mosaics, bracken, where stock tend to congregate, where the grazing pressure exceeds 1.5 ewes per hectare (dry). Do burn, fire breaks where accidental fires are likely, in patches as small as possible (dry). Do not burn where *Molinia* is present at more than 20-30% cover, areas dominated by cotton-grass *Eriophorum* spp, or wetter, steeper, higher altitude location (wet). Do burn small patches (wet). *Upland*: Do not burn on deep peat (>0.5m) *Lowland*: Do not burn vegetation, follow the Grass and Heather Burning Code and Regulations.
	Timing	Burn 1st Oct to 31st Mar/15th Apr/30th Apr. *Lowland*: Burn 01 Nov to 15 Mar or 01 Nov to 31 Mar.
	Intensity	Burn when 20 to 30 cm, allow some patches to grow to 40 cm or more, rotation 10-15 yrs. *Upland*: Burn on a regular rotation. Burn sufficient total area to prevent concentration of livestock on recently burnt patches. *Lowland*: Burn maximum 25% in 5 years. Rotation 12-20 years. Rotation longer on slopes, above gullies and cloughs, and at the moorland edge. Rotation shorter on some flat or gently sloping ground.
	Litter removal	*Lowland*: Remove after burning.
Fertilisation		Do not apply fertiliser, slurry, farmyard manure, calcified seaweed, sewage sludge, waste paper sludge, poultry litter.
Liming		Do not apply lime.
Hydrological management		Existing drainage systems can be maintained, but not widened, deepened or extended. Do not clear ditches 01 Mar and 31 Aug. *Upland*: Any water inputs should be acidic and nutrient poor. Lowland: Restore original hydrology of wet heaths by blocking ditches.

Management Category	Management Sub-category	Current Prescriptions For Dwarf Shrub Heath
Scrub management		The spread of scrub/trees must be controlled. Control scrub by cutting. Do not remove stumps. Do not control scrub 01 Mar to 31 Aug. Removal of western gorse on dry heath is not permitted. Control bracken by spraying, bruising or cutting in spring and summer, follow up with grazing. Removal of western gorse on dry heath is not permitted *Lowland*: Prevent scrub and gorse encroachment by grazing with cattle, sheep, goats or ponies. Do not allow bracken or scrub to encroach >20% of area. Gorse: rotational cutting or burning on 10-12 year rotation, strip litter, graze by ponies or goats. Bracken: control in early stages of invasion by cutting, rolling or crushing; cut as low as possible in mid-June and again in late July and a 3rd cut may be made in August; remove cut material; initial winter burn to remove litter. Birch: light grazing by sheep or cattle or cut down trees, treat stumps, remove cut scrub. Grass: turf stripping or light grazing by cattle. Rhododendron: remove.
Tree management		Protect and retain all in-field and veteran trees and native woodland. Remove all pines. Maximum 15% tree/scrub cover *Lowland*: Keep narrow shelterbelts of trees. Maintain areas of permanent open water and remove encroaching trees. Cut pine in the winter months, remove some/most pines over two metres.
Disturbance	General	Do not damage/disturb. *Upland*: Use low ground pressure vehicles. *Lowland*: Create bare ground patches 1m square.
	Turf stripping	*Lowland*: Control grass by turf stripping. Create sandy tracks 2-3 m wide by scraping and turf stripping mid-April to mid-May.
	Cultivation	Do not plough, cultivate, re-seed or harrow. Do not plough or cultivate any land within two metres of a watercourse or a wetland habitat.
	Litter removal	

3.1.6 Bog

Light grazing, hydrological management and scrub removal are all used to manage bogs for conservation. When grazing, it is important to avoid overgrazing and poaching, for example by shepherding and by avoiding supplementary feeding of stock. Maintenance and blocking of drains is permitted in order to maintain high water tables, and scrub should be managed especially when affecting hydrology. Some degree of disturbance occurs in the extraction of peat for domestic use, which is sometimes permitted at low levels. Burning and cutting are generally not recommended, and fertiliser and lime are not applied. Management prescriptions and advice are summarised in Table 3.6 below, are presented in full Appendix 4.

Table 3.6 Current management prescriptions for bogs.

Management Category	Management Sub-category	Current Prescriptions For Bogs
Grazing	General	Graze where possible, and where grazed in the past. *Blanket bog*: Favourable condition may also result from a complete absence of stock grazing. *Lowland raised bog*: Avoid overgrazing; remove grazing if poaching is evident.
	Timing	Graze in summer. Remove or reduce stocking density in winter.
	Intensity	Do not increase current stocking level.
	Stock type	Cattle, or cattle and sheep can be used to control purple moor grass. Minimum 30% LSU cattle per year, minimum 15% LSU sheep per year. *Blanket bog*: Livestock can also include ponies
	Stock management	*Blanket bog*: Shepherd sheep to ensure the area is grazed evenly, or as desired.
	Supplementary feeding	Avoid supplementary feeding, but may be required in winter. *Blanket bog*: Do not supplementary feed using silage, but haylage is permitted
Cutting	General	Cutting is generally discouraged. *Lowland raised bog*: Do not cut.
	Timing	
	Intensity	
	Litter removal	
Burning	General	Burning is not recommended but may be justified in extreme situations. *Blanket bog*: Do not burn exposed peat, deep peat, or areas dominated by *Molinia* or *Eriophorum*.
	Timing	Do not burn in summer. Burning Jan to Feb is least damaging.
	Intensity	*Blanket bog*: Minimum 20 year rotation length.
	Litter removal	Avoid burning brash on bog surface
Fertilisation		Do not apply fertiliser of any kind.
Liming		Do not apply lime.
Hydrological management		Do not install new drainage or modify existing drainage. *Blanket bog*: Maintenance of existing drains permitted. Blocking of drains permitted. Maintain water table at surface in winter, maximum 10 cm below the surface during the summer and preferably close to the surface. *Lowland raised bog*: No digging or clearing out ditches. Retaining rainfall to maintain high water table throughout the year.
Scrub management		The spread of scrub/trees must be controlled. Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal. Pull when ground less susceptible to damage (in summer when water is low, or in winter with mild frosts). Graze late spring to control birch. *Blanket bog*: Control common gorse by cutting or burning. *Lowland raised bog*: Introduce grazing to control heather and scrub. Clear woodland and seedling trees when affecting hydrology.
Tree management		The spread of scrub/trees must be controlled. Seedlings can be left onsite or removed. Brash can be disposed of onsite in blocked drainage or man-made pool system. *Blanket bog*: Control common gorse by cutting or burning.
Disturbance	General	Prevent physical disturbance.
	Turf stripping	Do not remove peat. Peat cutting maximum 0.1 ha for domestic use only. *Blanket bog*: Peat banks may be cut, carefully replace turfs with vegetation side uppermost.
	Cultivation	Do not plough, cultivate or reseed.
	Litter removal	N/A

3.1.7 Coastal dunes and slacks

Grazing and cutting are used to manage coastal sand dunes for conservation, trees and scrub must be controlled, and hydrological management is important. Grazing stocking densities are very low, and some site sizes are not large enough to sustain grazing. Burning is not used, and fertiliser must not be added. Management prescriptions and advice are summarised in Table 3.7 and presented in full in Appendix 5.

Table 3.7 Current management prescriptions for coastal sand dunes.

Management Category	Management Sub-category	Current Prescriptions for Coastal Sand Dunes
Grazing	General	Extensive/ light grazing or mowing regime.
	Timing	
	Intensity	Maintain a range of sward heights (20% less than 5cm, 40% less than 10cm). Maintain less than 70% cover of grasses in wet hollows. Low stocking densities, 0.5 to 0.75 LSU/ha.
	Stock type	Graze with cattle, sheep, goats or ponies. Minimum 30% of LSUs must be cattle and 15% of LSUs must be sheep in each year.
	Stock management	
	Supplementary feeding	Do not supplementary feed.
Cutting	General	Extensive/light grazing or mowing regime. Cut rushes when greater than 1/3rd of area.
	Timing	Cutting not permitted in summer.
	Intensity	
	Litter removal	
Burning	General	
	Timing	
	Intensity	
	Litter removal	
Fertilisation		Do not add fertiliser.
Liming		
Hydrological management		Maintain existing drainage and flood pattern. New drainage not permitted. Lowering of the water table is not desirable. Ideal winter water table maximum 0 to 50cm above ground level. Ideal summer water table maximum 50 to 100cm below ground level.
Scrub management		Scrub must be controlled.
Tree management		Trees must be controlled.
Disturbance	General	
	Turf stripping	
	Cultivation	
	Litter removal	Retain accumulation of seaweed and wood debris.

3.2 Grazing

This section outlines the current use of grazing as a management tool for habitat conservation in the selected habitats and describes the impact of grazing on habitat responses to N deposition.

3.2.1 Current management

Grazing is currently used as a management tool in woodland, acid grassland, calcareous grassland, dwarf shrub heath, bogs and coastal sand dunes. Current agri-environment scheme and conservation management handbooks provide advice and prescriptions regarding the timing, intensity, stock type and stock management.

3.2.1.1 Broadleaved, mixed and yew woodland & (natural) Coniferous woodland

Current management advice in woodland is to either to not graze, or to consider controlled grazing. Grazing is mainly used to maintain open areas in the woodland. Winter grazing is not recommended. Stock types can include sheep, goats, horses or mature cattle. Supplementary feeding is not recommended (see Table 3.2).

3.2.1.2 Acid grassland

Acid grassland is primarily managed by grazing, and is also required to control rushes where they form part of the sward. Grazing is all year or summer only. Sward height prescriptions vary. Livestock include sheep, cattle and horses. Stock should be managed such that grazing is evenly distributed, and no poaching is permitted. Supplementary feed is not allowed (see Table 3.3).

3.2.1.3 Calcareous grassland

In general, calcareous grassland is primarily managed by grazing. Grazing is recommended all year with lower intensity in summer, or summer only although there are variations on this in practice. The aim of management is to maintain a varied sward height from around 1 - 15 cm, while some sources do not prescribe an upper sward height range. Livestock include sheep, cattle and horses. Relatively more cattle than sheep should be used, and uplands should be grazed with cattle during summer. Prescribed stocking rates are low (0.25 - 0.5 LSU/ha), and current stocking levels should not be increased. Stocks should be managed such that grazing is evenly distributed, and no heavy poaching is permitted. Movement of stock between calcareous grassland and improved grassland should be limited. In some cases supplementary feed is not allowed, but if allowed, supplementary feeders should be moved often (see Table 3.4).

3.2.1.4 Dwarf shrub heath

Current advice for dwarf shrub heath is that it is grazed to create a diverse structure in spring and autumn, while ensuring a significant proportion of the shoot tips of heather are un-browsed. In uplands current grazing practice should be maintained, provided grazing practice has not recently altered, and is not causing deterioration. Some agri-environment schemes require that the moorland is used for agricultural livestock production, but favourable conservation condition may result from absence of grazing. Grazing should be used to maintain 25-90% dwarf-shrub species in lowland, and overgrazing should be avoided. Dwarf shrub heath is mostly grazed in summer and not winter, stock density over winter should be reduced. Uplands are grazed for shorter periods than lowlands. Stocking rates should consider impacts of livestock and other grazing animals. In uplands all pigs, cattle and horses should be removed in winter, and in general should have reduced stocking density compared to lowland areas. Cattle, sheep and ponies are commonly used and in uplands and shepherding is required. It is currently advised that supplementary feed is not used, haylage is permitted but feeding sites should be moved regularly (see Table 3.5).

3.2.1.5 Bog

Current advice in bogs is to graze where possible, and where grazed in the past. In blanket bog, favourable condition may also result from a complete absence of stock grazing. In lowland raised bog, overgrazing should be avoided by removing grazing if poaching is evident. Bogs should be grazed in summer with reduced stocking density in winter. Cattle, or cattle and sheep can be used, with relatively more cattle than sheep. Livestock can also include ponies. In blanket bog, shepherding should be used to ensure the area is grazed evenly and supplementary feeding should be avoided, but may be required in winter. In lowland raised bog supplementary feeding with haylage is permitted(see Table 3.6).

3.2.1.6 Coastal dunes and slacks

It is desirable for most coastal dunes (where size allows) to be managed using a light grazing regime. The aim is to maintain a range of sward heights and maintain less than 70% cover of grasses in wet hollows. Dunes are grazed with cattle, sheep, goats or ponies and low stocking densities around 0.5 to 0.75 LSU/ha, with relatively more cattle than sheep. Supplementary feeding should be avoided (see Table 3.7).

3.2.2 Impacts of grazing

Grazing provides very limited removal of above-ground N (typically < 1 kg N ha^{-1} yr^{-1} in most unimproved grassland systems). It's main impact is on habitat suitability by creating bare ground and increasing light availability to low-growing plants. As such, it has been suggested as a mechanism to reduce N deposition impacts in some habitats (Wilson *et al.* 1995). The magnitude of N removal depends on several factors, including the live weight gain of stock and the management of stock regarding the location of dunging. Also, an additional input of N to the system can occur if the stock is provided with supplementary feed, which is more likely to be used when stock are kept at high densities, and may well counteract any advantages of N removal in live-weight gain. Furthermore, transfer of nutrients onto the site from more intensively managed grasslands can result from stock movements (Kirkham, 2006). Variations in grazing timing and intensity, and instock type and management will have implications for N removal, N processes and habitat suitability.

3.2.2.1 Above-ground N loss

The most immediate action of grazing is the removal of above-ground vegetation biomass. The amount of biomass removed depends upon stock type, stock density and timing. Stock type is important because selectivity and feeding mechanisms vary among stock types (Ritchie and Olff, 1999) (see section 3.3.2.4). The timing of grazing will impact upon the quality and quantity of above-ground vegetation available for offtake. The N content of vegetation is typically highest in autumn and winter when vegetation is not actively growing. This will decline through the spring and summer due to growth dilution (Stevens *et al.* 2012).

Unlike cutting, the removal of vegetation biomass by grazing does not translate to an equivalent removal of N, because the majority of N is returned in urine and dung. Woodmansee (1979) estimated that about 17 to 20% of N taken up by large grazers is stored in animal tissues whereas 40% is lost is lost through volatilisation of ammonia from urine and faeces. The actual offtake of N depends on stock type, stock density, timing and management. Stock type is important because of different dunging physiology and habits. Cattle will dung randomly over the sward creating an area which the cows will avoid. Sheep also dung randomly although there will be concentrations in areas where animals rest (Crofts and Jefferson, 1999). Exclusion of livestock often leads to increases in populations of wild grazers such as voles, while a certain level of livestock grazing may be required to facilitate other grazers such as rabbits. The concentration of N in faeces among grazing animals, even between the largest (cattle) and smallest (voles) is between 20 and 355 g N kg^{-1}, but a greater mass of dung, and thus greater mass of N (Cows typically excrete 48 g N day^{-1}), is returned by an equivalent density of voles than cattle (Bakker *et al.* 2004). Management is also important because, if stock remains on site, the effect of grazing is to redistribute rather than remove nutrients (Bokdam and Gleichman, 2000). On the other hand, the practice of sheep folding, moving stock off land overnight can result in a net export of N, because stock disproportionately produce dung at night. Management of stock provides the potential to help mitigate the impacts of N deposition but there has not been any research into how effective this method is (see section 2.3.3).In a modelling study Berendse *et al.* (1985) found competition between *Erica tetralix* and *Molinia caerulea* changed with increasing N inputs giving *Molinia* a competitive advantage. In wet heathlands and bog grazers favour *Molinia* over *Erica* so there is potential for grazing to mitigate the impact of N addition. However, the low grazing intensity used in a heathland was insufficient to remove N added by deposition and they predicted that *Erica* would not become the dominant species. Other studies have found similar results in grasslands and heathlands (see sections 2.4.1; 2.3.1; 2.5.3) suggesting that although grazing has the potential to mitigate the impacts of N addition to some extent it is not sufficient to remove N deposited at higher levels of deposition.

In general, the amount of N removed by grazers in live-weight gain is low, typically < 1 kg N ha^{-1} yr^{-1} for stock on unimproved grassland, due to the poor quality forage. The exception is saltmarsh grassland where the nutritional content of the vegetation is high. However, as far as we know, no research has quantified the N removal by stock in saltmarsh grassland.

3.2.2.2 Below-ground N loss

The majority of studies concerned with the impact of grazing on leaching losses have been focussed on grasslands. In high-fertility improved grasslands with high-stocking rates leaching losses from grazed grassland systems can be high (Owens and Bonta, 2004). A number of studies have reported higher losses of N by leaching under grazed grassland swards compared to cut swards, for example Ryden *et al.* (1984) found leaching in cut grasslands was 5.6 times lower than in grazed swards and Eriksen and Vinther (2002) found leaching losses of approximately 5 kg NO_3-N ha^{-1} under cutting compared to 60 kg NO_3-N ha^{-1} under grazing although both of these studies are in intensively managed grasslands. In coastal dunes in North Wales, losses of N in leachate were highest in plots grazed with livestock, increasing from 1 to 2 kg of N ha^{-1} yr^{-1} in ungrazed plots, to 3.9 to 4.7 kg N ha^{-1} yr^{-1} in grazed plots (CEH, unpublished data). It is likely that increased N losses in grazed systems also occur in other habitats. By contrast however, in other grasslands such as upland rough grazing in Snowdonia, leaching losses have been greater in ungrazed areas compared to grazed areas (Chris Evans, unpublished data).

The timing of grazing is also important. If N is released by mineralisation during the vegetation growing season (see section 3.3.2.4), plants will be able to assimilate extra N, whereas winter grazing may lead to an excess of N that is lost through leaching.

Leaching represents a pathway for increased N loss but has a negative impact on water quality.

3.2.2.3 Soil nitrogen processes

The process of grazing affects rates of N turnover via changes in the form of N available to soil microbes due to dunging, via changes in litter quality, and via the impact of grazers on soil microclimate. Effects on N mineralisation and nitrification in relation to rates of N assimilation by plants impact upon the amount of N lost via leaching.

Dunging returns N to the soil in a form more accessible, and more rapidly cycled, than when N is returned through litter. Stock type is important because while the concentration of N in dung can be similar across grazers such as cattle, rabbits and voles (Bakker *et al.* 2004), the size and spatial distribution of dung differs. This has important implications for the accessibility of N for plants, and thus the retention or loss of N from the system. In a floodplain grazing experiment in the Netherlands, grazing with cattle had an effect on net mineralisation of N over the year: net N mineralisation with cattle was 10.1 g per m^2 per year, and was increased without cattle to 17.9 g per m^2 per year (Bakker *et al.* 2004). Similar increases in mineralisation with grazing have been observed in heathland (Bokdam and Gleichman, 2000). However, N mineralisation rates were lower in grazed treatments compared to ungrazed treatments in coastal dune grassland (Ford *et al.* 2012).

Nitrogen mineralisation is also indirectly affected by grazing via the impact on litter quality. Some herbivores selectively feed on legumes, resulting in a decrease in legume abundance, increased litter quality, and N fixation. In birch woodland plots grazed by deer, grazing reduced litter quality in grazed compared to un-grazed litter, which reduces leaf litter decomposition rate and nutrient release (Harrisson and Bardgett 2008). Grazing also affects rates of N mineralisation and nitrification because of the impact on soil microclimate. Grazing increases soil temperature, leading to increased rates of N mineralisation and nitrification in grasslands (Bouman, 2008) and in regenerating birch woodland browsed by deer (Carline and Bardgett, 2005).

Soil compaction resulting from overgrazing can reduce N mineralisation (Breland and Hansen, 1996).

3.2.2.4 Habitat suitability

Grazing affects habitats by increasing the area of bare ground, removing overstorey vegetation, and preventing build-up of litter (Marrs, 1993).These mechanisms act to increase light penetration and alter the microclimate, with implications for seed dispersal, germination and growth. This can lead to a change in vegetation species composition with the potential to increase stress tolerant species lost as a consequence of increased shading from tall competitive species.

Despite the potential for grazing to change the competitive interactions between species and mitigate the impacts of N deposition in heathland Berendse (1985) concluded that once a community had changed reintroduction of grazing may not be effective.

Changes in bare ground and light availability depend on the stock type, because of difference in selectivity and the method of removal. In unimproved grasslands sheep will tend to bite the vegetation grazing close to the ground level. Sheep have thin mobile lips which enable them to select individual items, even from low in the sward preferentially removing the most palatable species and leaving grass stems, litter, and taller or tussocky vegetation untouched (Crofts and Jefferson, 1999). This selectivity means that at low grazing intensity they are less likely to open the canopy to increased light. Cattle use their tongues to pull and tear vegetation as well as biting it. Their thick immobile lips and jaws mean that they cannot effectively manipulate the vegetation to select individual species. Cows will also not avoid taller or tussocky vegetation as sheep will (Crofts and Jefferson, 1999) which makes them more suitable for grazing aiming to open up the canopy but they will maintain a longer sward than sheep so do not allow as much light into the lower levels of the canopy. Like sheep, ponies will cut vegetation with their teeth producing a very short sward. Although they are selective they don't avoid tall or tussocky vegetation (Crofts and Jefferson, 1999). In order to mitigate the effects of N a mixed grazing regime combining sheep or horses and cows would be most effective in maintaining a short sward whilst also removing taller tussocky vegetation. This is in line with current management advice for most habitats.

Grazing will impact upon vegetation species composition directly A number of studies have demonstrated a significant effect of grazing on plant species composition (e.g. Augustine and McNaughton, 1998; Bakker *et al.* 1984; Milchunas *et al.* 1988). Birske (1996) identifies a tradeoff between grazing resistance and competitive ability of plants. This was recently supported by a global synthesis study (Lind *et al.* in press). Defoliation by grazers alters competitive interactions favouring species tolerant of herbivory. Tolerance to herbivory is determined by a range of different factors including relative growth rate, plant architecture, reallocation of resources to different parts of the plant, and resource availability (Del-Val and Crawley, 2005). Crawley (1990) identified species as either 'increasers' (species that respond positively to grazing either by tolerance or avoidance by grazers) or 'decreasers' (species that respond negatively to grazing through sensitivity to defoliation or preferentially grazed). Investigation of eight grassland species showed that all of the 'increaser' species investigated (*Senecio jacobaea, Trifolium repens, Rumex acetosella* and *Holcus lanatus*) were tolerant of defoliation (Del-Val and Crawley, 2005).

Grazing intensity is an important consideration, because at high stocking intensities less palatable species will be browsed. For example, increased grazing intensity decreases the cover of shrub species in dwarf shrub heath (Bullock and Pakeman, 1997; Newton *et al.* 2009) which in some situations is a negative impact on the habitat. Overgrazing can negatively impact upon vegetation diversity with a negative effect on vegetation. For example, in acid grasslands, moss cover declines under high grazing pressure (Emmett *et al.* 2004a), and *Calluna* is unable to outcompete grasses under high N deposition and high grazing density in dwarf shrub heath (Alonso *et al.* 2001). Since both of these groups decline under N addition this could be considered as exacerbating the effect of N deposition. Indeed there is evidence that both high grazing pressure and N deposition can drive UK habitats towards grass dominance with a loss of species richness (Van der Wal *et al*. 2003).

3.2.2.5 Summary

In summary, current recommendations to graze habitats results in negligible removal of N off-site in animal live-weight gain, but may lead to slightly increased N losses as a result of leaching. However these losses are not sufficient to offset the impacts of atmospheric addition. Leaching also has negative implications for water quality with losses likely to be highest in winter although less N is lost from grazed semi-natural habitats than those managed intensively with high fertiliser addition. Management of grazing stock so that they are removed at night has the potential to provide some reduction in N from the site but this has not been quantified. The main benefit of grazing is to open up the canopy and reduce the dominance of competitive species, thus increasing light availability for species which are poorer competitors in the lower canopy. However, increasing the intensity of grazing has the potential to alter species composition reducing species less tolerant of grazing, and excess grazing may also be detrimental to flora and fauna. Grazing with a mix of sheep or ponies and cattle offers the best potential to both reduce sward height and remove areas of tall vegetation although all management needs to consider the conservation objectives for individual sites.

3.3 Cutting

This section outlines the current use of cutting as a management tool for habitat conservation in the selected habitats and describes the impact of cutting on habitat responses to N deposition.

3.3.1 Current cutting advice

Cutting is discussed as a management method for acid grasslands, calcareous grasslands, dwarf shrub heath, bogs and dunes. It is also mentioned for woodlands but only in specific reference to removal of injurious weeds and woodland rides so this will not be discussed separately.

3.3.1.1 Acid grassland

Current management advice for acid grassland concerns the intensity and timing of cutting as a management of the whole grassland as well as the timing and intensity of cutting to control rushes and weeds. For acid grasslands as a whole grazing is more generally the recommended management but cutting can be used where grazing is not practical. In these circumstances it is recommended that the grassland is cut once between mid-July and mid-August to a height between 5 and 10 cm, and again in the autumn or the following spring with all cuttings removed. Advice on timings of cuts varies although generally advice is not to cut early summer (see appendix 2). Where rush control by cutting is needed advice is generally to cut 1/3 of the area or to achieve an open mix of rushes and grass pasture. Recommended dates vary including between 15thMarch and 31stJuly and after 15th July. Cutting to control injurious weeds, invasive species and bracken is also advised (see Table 3.3).

3.3.1.2 Calcareous grassland

Management advice for calcareous grassland is very similar to acid grasslands. Cutting can be used where grazing is not practical and it is recommended that the grassland is cut once between mid-July and mid-August to a height between 5 and 10 cm, and again in the autumn or the following spring with all cuttings removed. Advice on timings of cuts varies although generally advice is not to cut early summer. Cutting to control injurious weeds, invasive species and bracken is also advised (see Table 3.4).

3.3.1.3 Dwarf shrub heath

Cutting forms part of the current management advice for heathland in upland and lowland habitats. Cutting is advised for the formation of fire breaks and for the management of heather. For heather management cutting is advised in small patches with the majority of advice being to remove cuttings. Some guidance recommends chopping material finely and leaving it on the surface or incorporating it into the soil, when it is not practical to remove it. Advice on the timing of cuts generally recommends cutting during autumn and winter. Cutting is also advised for the control of specific species including rushes, bracken and gorse. It is advised that cuts are not undertaken in wet areas or when the ground is saturated (see Table 3.5).

3.3.1.4 Bog

In bogs cutting is recommended for the creation of firebreaks, the control of specific species and on a small scale to create diverse vegetation heights. Cutting of heather is also used at a number of sites in Scotland. For rushes advice is to cut up to 1/3 of the area of rushes between 15 March and 31 July and cut again if necessary. Cutting to control injurious weeds and invasive species is also advised. In all cases removal of cuttings is recommended (see Table 3.6).

3.3.1.5 Coastal dunes and slacks

Cutting is specifically mentioned for rush control where it is recommended that they are cut and removed. Cutting is also occasionally used to open up the vegetation canopy and remove rank vegetation.

3.3.2 Impacts of cutting

Cutting affects habitats through the removal of N stocks in above-ground biomass (if biomass is removed) and improves habitat suitability by increasing light availability to small, low growing species. Little is known about the direct effects of cutting on soil N stocks and N cycling processes (see Table 3.7).

3.3.2.1 Above-ground N loss

Cutting and removing biomass has a potentially large effect on the N cycle by removing large amounts of N in grasslands however, if biomass is not removed this means that N is not removed from the site. Cutting is not the normal management of acid or calcareous grasslands in the UK and advice only recommends cutting where grazing is not possible. Several studies have investigated the potential for N removal by cutting in both acid and calcareous grassland (see sections 2.3 and 2.4). Jacquemyn *et al.* (2003) found mowing once a year was insufficient to maintain high species diversity whilst others have demonstrated the potential for cutting to mitigate the effects of deposition. A seven year UK study investigated the interaction between N deposition and cutting management using mesocosms taken from acid and calcareous grasslands (Jones 2005). The study showed that both high offtake (clipping to 6cm) and low offtake (clipping to 11cm) with 2 cuts per year significantly increased both species richness and Simpsons Evenness index compared to the uncut control in both acid and calcareous grasslands. In calcareous grassland cutting twice per year removed 20 – 60 kg N ha yr^{-1} depending on the cutting height (Table 3.8). In a cutting experiment on chalk grassland Wells and Cox (1993) found that cutting resulted in an N removal of 26 kg N ha^{-1} yr^{-1}. This would be sufficient to start depleting N stocks in the soil across the majority of calcareous grassland locations in the UK. In acid grasslands the removal rate was lower, between 7 and 34 kg N ha^{-1} yr^{-1} depending on the cutting height (Table 3.9). This lower removal rate of N from acid grasslands would only be sufficient to deplete stocks of N with more intensive cutting.

Table 3.8 Nitrogen budget for calcareous mesocosms, by N treatment and showing net accumulation (kg N ha^{-1} yr^{-1}) with high and low clipping offtake. Values in bold are calculated, those not in bold are derived indirectly from a number of sources, including other data in the experiment and the wider literature. Possible losses under true pristine deposition (2 kg N ha^{-1} yr^{-1}) are included for comparison (taken from Jones, 2005).

All pools (kg N ha^{-1})		**N treatment**			
All fluxes (kg N ha^{-1} yr^{-1})	**True pristine**	**2N**	**10N**	**20N**	**55N**
Atmospheric input	2	9.1	17.1	26.9	61.2
Storage					
Above ground vegetation		66	62	61	68
Below ground vegetation		53	66	76	66
Soils		5787	5768	5750	5731
(of which available inorganic N)		-	-	-	-
Losses					
De-nitrification	2	2	2	2	2
Leaching (TIN)	0.49	0.49	3.62	3.61	7.11
Leaching (DON)	0.49	0.49	3.62	3.61	7.11
Clipping offtake - Heavy	52.1	56.9	52.1	53.9	59.3
Clipping offtake - Light	22.9	27.7	22.9	25.0	45.5
Grazing removal	1	1	1	1	1
Net accumulation per year					
Unclipped	-1.0	6.1	7.9	17.7	45.0
Light clipping	-23.9	-21.6	-15.0	-7.3	-0.6
Heavy clipping	-53.0	-50.8	-44.2	-36.2	-14.3
Grazing removal	-2.0	5.1	6.9	16.7	44.0

Table 3.9 Nitrogen budget for acid mesocosms, by N treatment and showing net accumulation (kg N ha^{-1} yr^{-1}) with high and low clipping offtake. Values in bold are calculated, those not in bold are derived indirectly from a number of sources, including other data in the experiment and the wider literature. Possible losses under true pristine deposition (2 kg N ha^{-1} yr^{-1})are included for comparison (taken from Jones, 2005).

All pools (kg N ha^{-1})		**N treatment**			
All fluxes (kg N ha^{-1} yr^{-1})	**True pristine**	**2N**	**10N**	**20N**	**55N**
Atmospheric input	**2**	**9.1**	**17.1**	**26.9**	**61.2**
Storage					
Above ground vegetation		64	73	81	83
Below ground vegetation		42	44	40	26
Soils		5917	6005	6093	6347
(of which available inorganic N)		5.7	6.2	6.6	14.1
Losses					
De-nitrification	1	1	1	1	1
Leaching (TIN)	**0.32**	**0.32**	**0.40**	**0.35**	**0.50**
Leaching (DON)	0.32	0.32	0.40	0.35	0.50
Clipping offtake - Heavy	**21.0**	**21.6**	**21.0**	**25.3**	**33.5**
Clipping offtake - Light	**7.5**	**8.3**	**7.5**	**11.0**	**15.5**
Grazing removal	1	1	1	1	1
Net accumulation per year					
Unclipped	0.4	7.5	15.3	25.2	59.2
Light clipping	-7.1	-0.9	7.8	14.2	43.7
Heavy clipping	-20.7	-14.1	-5.7	-0.1	25.7
Grazing removal	-0.6	6.5	14.3	24.2	58.2

In a lowland heathland Hardtle *et al*. (2006) found mowing resulted in a reduction in above-ground biomass N stocks of 98.6 kg ha^{-1}. This reduction in N stocks was equivalent to approximately five years of N deposition at the site. Stocks of N in the soil organic layer and A horizon were not affected by mowing. Power *et al*. (2001) reported that a high intensity mow (cut to ground level) resulted in significantly increased shoot growth whereas a low intensity mow (cut to 15 cm) did not, this impacts on the future offtake of N if repeated cuttings are used.

For the majority of habitats current advice is to remove biomass. Cutting and removing biomass has the potential to mitigate N deposition impacts because it represents a net export of N. For heathlands there is some advice to finely chop cut material and either spread it on the site or incorporate it into the soil. This is likely to exacerbate impacts of N deposition since N is not removed by cutting but returned to the soil more rapidly than by normal processes and chopped finely to allow faster decomposition.

The timing of cutting can have an important influence on the amount of N removed. A study in neutral grassland in 2010 showed peak N offtake in early July (unpublished data) although this can vary considerably from year to year depending on climatic conditions. Offtake accounts for both the biomass and the N content of the vegetation. Percentage N content of meadow vegetation is highest in autumn and winter (Stevens *et al.* 2012) when vegetation is not using N for growth. Barker *et al*. (2004) also found variation in tissue nutrient content of heathland vegetation with highest values in May (1.99%) and lowest values in August (0.90%) following growth dilution.

3.3.2.2 Below-ground N loss

Relatively few studies have measured the impacts of cutting on below-ground N loss. Ryden *et al*. (1984) found that leaching in cut grasslands was 5.6 times lower than in grazed swards although this study was focused on intensively managed grasslands. Leaching losses in cut acid and calcareous grassland are shown in tables 2.8 and 2.9 (Jones, 2005) and show that N leaching losses in acid grassland were ~ 1 kg N ha^{-1} yr^{-1}, while in calcareous grassland they could be as much as 14 kg N ha^{-1} yr^{-1}at the highest rates of deposition (~61 kg N ha^{-1} yr^{-1}). In heathland Hardtle *et al*. (2006) found that N leaching did not change in response to cutting immediately after the management was carried out.

3.3.2.3 Soil nitrogen processes

As with leaching there have been few studies focussed on the impact of cutting on other soil N processes. Barker *et al*. (2004) reported that low intensity cutting in heathland resulted in twice as much litter production as burning or high intensity cutting although the manuscript does not discuss whether this was a result of increased above-ground production or a greater proportion of above-ground material being lost as litter. Power *et al*. (2001) found a low intensity mow (cut to 15 cm) resulted in the highest rates of decomposition compared to a high intensity mow or an unmown control. This suggests a higher rate of return of N to the soil. If litter is left in situ then litter quality is an important factor in determining whether decomposition is stimulated or retarded. In a meta-analysis Knorr *et al*. (2005) found that at levels of ambient deposition between 5 and 10 kg N ha^{-1} yr^{-1} or when litter quality was low (litter with a high lignin content) then decomposition was inhibited. However, at lower levels of deposition (<5 kg N ha^{-1} yr^{-1}) and for high quality litter decomposition was stimulated. This suggests that in grasslands systems the removal of litter is particularly important.

3.3.2.4 Habitat suitability

One of the most commonly stated reasons for loss of species richness with increased N deposition is a reduction of light in the canopy as a consequence of rapidly growing species growing tall. This results in reduced light resources for small stature species (Hautier *et al*. 2009). Cutting vegetation more intensively allows more light to reach lower levels of vegetation and has the potential to reduce competition allowing small and less competitive species to survive. Because acid and calcareous grasslands are generally managed by grazing no studies have investigated the impact of cutting on competition in these habitats however, Pavlů *et al*. (2011) found they were able to reduce the abundance of dominant grasses with high nutrient demands with four cuts per year but this cutting regime also had negative effect on other species that were not tolerant of cutting. In heathlands cutting can result in large changes in species composition as dominant shrubs are removed.

3.3.2.5 Summary

Cutting clearly removes N in above-ground biomass in all habitats where it is used and, as long as cuttings are removed from sites, has the potential to mitigate against N deposition impacts. In some habitats there is the potential for increased decomposition and reduced leaching to offset some of this benefit but further research is needed to determine the magnitude of these changes. However, replacing current grazing management with cutting presents practical difficulties and may result in changes in species composition. If cuttings are not removed then cutting could potentially exacerbate the impacts of N deposition. If cutting is used as a management tool the timing of the cut could be used to maximise N offtake although care needs to be taken to avoid adverse effects on seed set of species of conservation interest.

3.4 Burning

This section outlines the current use of burning as a management tool for habitat conservation in the UK, describes the impact of burning on habitat responses to N deposition, and then assesses whether current management practice reduces or exacerbates impacts of N deposition on habitats. The implications of specific components of burning, namely timing and intensity, are considered. In habitats where burning is not commonly used, the potential impacts are briefly discussed.

3.4.1 Current burning advice

Burning is currently used for the conservation of dwarf shrub heath habitats. The use of burning is generally not recommended for bogs, acid grassland and calcareous grassland habitats although there are some areas where it occasionally been used as a management tool (Table 3.1). Burning is not used for habitat conservation in woodlands, due to the presence of epiphytic lichen communities and fire-sensitive ground vegetation. In coastal dune habitats burning is not used, but some accidental fires do occur.

3.4.1.1 Broadleaved, mixed and yew woodland & (natural) Coniferous woodland

Fire is not used as a management method for habitat conservation in UK woodlands. Burning can reduce total N stock, but not at all sites (Williams *et al.* 2012). Furthermore, a global review revealed no effect of fire on soil N (Johnson and Curtis, 2001) (see Table 3.2).

3.4.1.2 Acid and calcareous grassland

Current management advice is to avoid burning in both acid and calcareous grassland in lowlands, although formerly it was a historic practice on limestone grasslands in the Cotswolds and has occasionally been used as a conservation management tool in advance of introducing grazing (Crofts & Jefferson 1999). In uplands, grasslands should not be burnt from January to March, and tall dense vegetation should be left unburnt (see Table 2.5). Burning is not recommended in upland areas where *Molinia* coverage is greater than 30% or where *Eriophorum* spp. are dominant (see Tables 3.3 and 3.4).

3.4.1.3 Dwarf shrub heath

An important management aim for dwarf shrub heath habitat is to maintain low N status, essential for their continued existence (Webb 1998). Current practice is to burn old heather in dry areas, while wet areas and old stands should not be burnt. In dry upland heath, areas of bracken, valley mires, flushes and grass-heath mosaics should not be burnt; but in wet upland heath the burning of firebreaks is sometimes suggested (see Table 3.5). Finally, burning is not recommended in upland areas where *Molinia* coverage is greater than 30% or where *Eriophorum* spp. are dominant, and the height of heathland sub-shrubs should be greater than grass height before burning.

The intensity of burning (i.e. rotation length and burn area), the timing of burning, and the management of litter after burning, are discussed in the advice literature. Current advice is to burn dwarf shrub heath with a rotation length of 10 to 15 years. In lowland heath, rotation length may be reduced to 10 to 12 years; while in upland wet heath, rotation length may be extended to 20 years (Table 3.5). Current advice regarding burn area is to burn small areas, and to not burn the entire site. However, due to the congregation of livestock in recently burned areas, current advice is to burn sufficient area of heath so as to avoid poaching (Table 3.5). In lowland heath, burning is carried out 1st November to 31st March, with a slightly longer burning season in uplands from 1st October to 15th April.

3.4.1.4 Bog

In lowland bog, management by burning is not recommended. Similarly in upland bog, advice is to minimise or eliminate burning (see Table 3.6). If burning is used in upland bog, rotation length is increased to 20 to 30 years. In bogs in North America, burning reduced standing biomass, promoted less competitive vegetation species, and reduced soil C stocks (Middleton *et al.* 2006). Given that the preservation of peat is a conservation objective in bogs, burning may not be a suitable technique. To reduce the risk to peat stocks, burning should not be used in dry conditions.

3.4.1.5 Coastal dunes and slacks

In coastal dunes, accidental fires have led to improved structure and composition of vegetation (Rhind and Sandison 1999), but the effect of managed burning is unknown. There is little information on the effect of burning on N stocks and processes in this habitat.

3.4.2 Impacts of burning

Burning affects habitats via the direct effect of heat on vegetation and soils, and the indirect effect on microclimate via the removal of vegetation (Raison 1979). In dwarf shrub heath the direct effect of heat acts upon losses of N from stocks and the rates of N cycling processes, and the removal of vegetation will influence the subsequent growth and composition of vegetation.

3.4.2.1 Above-ground N loss

In lowland dry heath in the south of England, approximately 108 and 75 kg N ha^{-1} is stored in above-ground vegetation and litter, respectively (Chapman, 1967). After experimental burning of harvested vegetation and litter, only 9.1 kg N ha^{-1}remained in ash, thus 95% of the N was volatised. However, a controlled winter burn as is used for conservation may not be of sufficient duration or temperature to burn all of the above-ground vegetation and litter biomass. In a lowland site in North-west Germany with vegetation N stocks of 197 kg N ha^{-1}, 93 kg N ha^{-1} remained unburned after one controlled winter burning event, which implies that only around 50% of the vegetation N stock was affected (Niemeyer *et al.* 2005).

In contrast to accidental burning, prescribed burning does not remove standing litter biomass, due to shorter burn times and lower temperatures(Barker *et al.* 2004; Niemeyer *et al.* 2005). The amount of N stored in the organic layer in the lowland site in North-west Germany was three times that of above-ground biomass at 740 kg N ha^{-1}(Niemeyer *et al.* 2005), thus prescribed burning may not be as effective as high intensity managements, such as litter removal (Terry *et al.* 2004).

Some ash, and thus some N, will be returned to the site. Niemeyer *et al.* (2005) attempted to quantify the amount of N deposited as ash by comparing soil surface (O-horizon) samples before and after a burning event, though this value will incorporate losses of organic matter. They found an increase in N of 5.2 kg ha^{-1}after burning, such that 5% of the N loss from the vegetation stock is returned as ash, and the overall removal of N from above-ground stocks per burn event is 99 kg N ha^{-1}.

At a typical N deposition at a rate of 20 kg N ha^{-1} yr^{-1}, a low temperature winter burning event mitigates against approximately five years of N deposition. Therefore a burn cycle of 10 to 15 years, as is currently practised in the UK, will not entirely mitigate against N inputs, but a shorter burn cycle for additional N removal may be unrealistic with regards to other conservation objectives. The current practice of burning during winter compromises the effectiveness of burning as a method for N removal because less plant N is stored above-ground in winter than in summer. However, the timing of burns is currently constrained by legislation for several reasons, including the protection of breeding birds.

3.4.2.2 Below-ground N loss

In dwarf shrub heath, the majority of N is stored in the soil (Chapman, 1967; Power *et al.* 1998). In a lowland dry heath of the South of England described earlier, 2210 kg of N ha^{-1}is stored in soils to a depth of 20 cm, ten times more than in vegetation and litter. Furthermore, excess N derived from deposition tends to accumulate in soil rather than vegetation, because the relative magnitudes of N stocks among vegetation, litter and soil are maintained (Power *et al.* 1998; Hardtle *et al.* 2009, Mohamed *et al.* 2007). Soil N stocks represented 76% of the total N stock in both control plots and treatment plots receiving N additions at rates of 15.4 kg N ha^{-1}yr^{-1} (Power*et al*. 1998). As such the soil stocks accumulated more of the added N than did the above-ground compartments; stocks increased by 100, 18 and 14 kg of N ha^{-1}in soils, vegetation and litter, respectively.

Due to the large store of N in the soils of dwarf shrub heath, any effects on this component will have a large impact on the overall N budget. However, it is though that the temperatures and duration of fires in a controlled burn event are not sufficient to burn soil. Indeed, Niemeyer *et al*. (2005) report that the total soil store of 1780 kg of N ha^{-1}was not affected by prescribed burning.

In theory, increased soil temperature could increase soil microbial activity or composition, though studies of controlled burning events in dwarf shrub heath are rare. Laboratory studies suggest that nitrifying bacteria are killed at lower temperatures than ammonifiers, and as such an accumulation of ammonium could occur after burning (Raison, 1979). This effect was observed in an upland heath site in North-west Spain, where soils contained significantly higher concentration of ammonium N than control plots after burning (Marcos *et al.* 2009). Similarly in North-west Germany, burning led to a large increase in ammonium concentration in the O-horizon in burnt plots compared to control plots(Mohammed *et al.* 2007), and low plant uptake resulted in a significant increase in N losses in leachates from 2 to 6 kg of N ha^{-1}yr^{-1}in burnt plots (Hardtle *et al.* 2009). Pilkington *et al*. (2007) measured inorganic N in leachates before and after burning in an upland heath in North Wales, and as well as similar increases in N concentrations in leachates with burning, the increases were positively and linearly related to long term N inputs from atmospheric deposition. However, the longevity of such losses is unknown, and water quality will be impacted as unintended consequence of increased N leaching.

3.4.2.3 Soil nitrogen processes

Few studies document the effect of burning on rates of N processes such as mineralisation and immobilisation. Burning results in increased rates of N mineralisation in the lowland dry heath burning experiment in the South-west of England, such that the cycling time of standing stock of litter into the soil organic matter is reduced from 8.6 years in burned plots to 6.1 years in control plots (Power *et al.* 1998). Conversely, in a low alpine heath in Scotland, plots that had been burnt eight years previously showed slower decomposition rates and lower N loss rates than un-burnt plots (Papanikolaou *et al.* 2010).

3.4.2.4 Habitat suitability

Burning removes standing biomass, which creates gaps in the vegetation canopy and decreases shading. This impacts on vegetation composition via rates of seed germination and seedling growth in forests (Malik, 2003) and can create conditions more favourable to *Calluna* in heath habitats (Mohamed *et al.* 2007). However, prescribed burning does not remove litter biomass, and may not alter the soil microclimate to the same extent as accidental burning.

Also, the wetting of ash results in the hydrolysis of basic cations, and the formation of highly alkaline residues with pH greater than 12 (Tryon, 1948; Raison, 1979) but the effect on soil pH, and thus nutrient availability to plants, will depend on the buffering capacity of the soil. For example, in three heather sites in North-west Spain with soil pH of 3.7 to 4.2, ash with a pH value of 9 had no effect on soil pH (Marcos *et al.* 2009).

Finally, in contrast to the losses of N due to volatisation, burning does not effectively remove P, due to the retention of P in ash. Phosphorus retention in the system can further amplify N limitation, which could favour the competitive advantage of *Calluna* over grass species (Hardtle *et al.* 2009; Mohammed *et al.* 2007). However, at high burn intensity, P becomes less available due to increased sorption at increased temperatures (Ketterings *et al.* 2002).

3.4.2.5 Summary

Overall, burning removes N from vegetation, increases N leaching from soil, and increases habitat suitability for heather in some cases. Given these responses, the current management practice of prescribed burning in dwarf shrub heath has the potential to reduce adverse responses to N deposition. However, burning needs to be carefully managed and can have unintended consequences for wildlife and water quality. It is also not suitable in all situations (e.g. close to urban areas) and so careful consideration should be given to the site characteristics and situation before burning.

In both acid and calcareous grasslands, burning removes standing and litter biomass, but is unlikely to reduce the dominance of competitive species (e.g. tor grass *Brachypodium rupestre*) unless immediately followed by grazing since these are often adapted for rapid re-establishment after fire. Current advice, i.e. to consider vegetation composition, is appropriate for the management of habitat responses to N deposition. Given the sensitivity of woodland ground flora to fire, and the inconsistent effects on soil N, the prescription of no burning in forests should be continued.

3.5 Fertilisation

This section outlines the current use of fertilisation as a management tool for habitats of conservation concern in the UK, and describes the impacts of fertilisation on responses to N deposition. The implications of different types of fertiliser are considered.

3.5.1 Current fertilisation advice

The use of fertiliser is currently not advised for conservation management in bogs, woodland, coastal sand dunes, and dwarf shrub heath habitats. In acid and calcareous grassland, fertiliser is generally not permitted grassland managed as pasture, but under some management advice FYM may be applied at low rates of 15 kg N $ha^{-1}yr^{-1}$. This may only be applied early in the growing season, when ground is dry, and where the grassland is cut. Fertiliser use is not permitted in uplands. Advice for fertiliser application in woodlands is mixed; some advice not permitting application but other advice allowing application up to rates of 25 kg N ha^{-1} yr^{-1}(see tables 2.2 to 2.7).

3.5.2 Impacts of fertilisation

In agricultural systems, fertilisers are applied to increase soil fertility and plant productivity. However, increased productivity is one of the main drivers of biodiversity loss in semi-natural habitats, whether it is a result of atmospheric N deposition or agricultural management. In a very few instances, some fertilisation may be necessary, for example, to maintain a certain level of productivity for graziers to have an interest in keeping livestock on the site. This is also a consideration in agri-environment schemes where farmers' livelihoods need to be maintained. However, there is a clear tradeoff between agricultural productivity and biodiversity, and to maintain habitats in good quality, fertiliser use should in general be discouraged. The effects of different fertilisers and nutrient elements are considered in this section.

3.5.2.1 Plant nutrition

The principle that plant productivity is limited by the nutrient element in shortest supply, known as Liebig's law of the minimum, is not absolute, but provides a useful framework for considering the effects of fertilisers. A common example is a site that suffers from chronic N pollution, but which remains unproductive and species-rich because the supply of P is restricted.

When determining fertiliser requirements it is useful to consider the likely demand from plants for nutrient elements, and the content of these elements in the fertiliser applied. In a natural system at equilibrium, nutrient losses are likely to be small, and net demand for nutrient elements will be that required to replace losses through leaching, gas fluxes, and conversion to unavailable forms. Where there is nutrient export, in silage, hay or livestock liveweight-gain, losses may be more substantial, and equivalent amounts are recommended to maintain productivity (Table 3.10). Detailed guidance on nutrient replacement rates is given in (DEFRA, 2010b). Recommended fertiliser application rates are determined according to the inherent nutrient supply class of the soil, the yield or stocking rate, the cover proportion of clover, and other factors that affect nutrient demand such as altitude. It should be borne in mind however that these rates are intended to maximise agronomic efficiency and maintain an economically viable level of production. This may not be compatible with nature conservation goals.

Table 3.10 Recommended nutrient element application rates for selected crops grown on least-fertile soils (P or K index = 0. Adapted from DEFRA(2010b).

Crop	Nitrogen kg N ha^{-1} yr^{-1}	Phosphorus kg P ha^{-1} yr^{-1}	Potassium kg K ha^{-1} yr^{-1}
Extensive sheep grazing (0.2 Livestock Units ha^{-1})	0	35	50
Grass silage (one-cut system producing 10 t ha^{-1})	120	17	66

3.5.2.2 Organic manures

The term 'organic' has at least three distinct meanings. In chemistry, organic compounds are defined as containing C, and so substances such as urea or the complex C compounds in farmyard manure are considered organic. In agronomy, organic manures are those derived from wastes such as animal manures, biosolids (sewage sludge) or municipal compost. Legally, organic farming systems are those accredited by one of a set of approved bodies (DEFRA, 2010a). The fertilisers allowed by these bodies vary somewhat, but none allows the direct use of artificial N fertiliser, and in general solid manures are favoured. Here we will use 'organic' in the agronomic sense, to refer to solid and slurry manures derived from wastes.

Organic manures generally provide several nutrient elements, and are thus more complete fertilisers than single-element artificial fertilisers. Some examples of organic manures are shown with their nutrient element concentrations in Table 3.11. Not all of these elements will be immediately available to plants, which is beneficial in that nutrients are released more gradually than from most artificial manures, although the release is more difficult to predict and manage. Manures with a large content of C, such as straw, can cause a temporary decrease in N availability, due to increased demand from microbes decomposing the material. This is unlikely to present a solution to N enrichment, however, since over time the immobilised N will be released, together with the N added in the straw.

Another drawback of organic relative to artificial manures may be the shading effect when the manure is applied. For liquid manures which are easily washed below the vegetation or injected into the soil (as required for slurry application to conform to agri-environment scheme standards) this is less of an issue, but solid manures spread onto vegetation can exacerbate ground-level shading. This is particularly true of materials that are slower to decompose, such as cereal straws and bark mulches.

Table 3.11 Typical contents of dry matter and major nutrient elements in selected organic manures. Adapted from MAFF (1976).

Type of Manure	Dry matter g 100 g^{-1} manure	Nitrogen g N 100 g^{-1} manure	Phosphorus g P 100 g^{-1} manure	Potassium g K 100 g^{-1} manure
Cattle slurry	10	0.5	0.09	0.4
Farmyard manure: dairy cows on grass in W Scotland	20	0.4	0.05	0.3
Farmyard manure: dairy cows on mixed ley-arable lowland farms in N and C England	25	0.6	0.16	0.7
Farmyard manure – median	23	0.6	0.13	0.6
Digested sewage sludge, air dried	66	1.1	0.4	0.1
Fresh poultry manure	29	1.7	0.6	0.6
Straw	85	0.5	0.09	0.7

3.5.2.3 Nitrogen fertiliser

Artificial fertilisers containing N are likely to worsen effects of N pollution, and their use should be minimised on sites of nature conservation concern.

3.5.2.4 Phosphorus

Fertilisers containing P are mainly derived from naturally occurring mineral deposits, and as such some forms are allowed by some organic accreditation bodies. Phosphorus is unusual among the major plant nutrient elements in that deficiencies are caused not so much by leaching as by conversion to unavailable forms. Whereas soluble forms of N, and to a lesser extent K, are susceptible to leaching, soluble P is strongly retained by soils. Applications of P fertiliser tend to be highly persistent, as demonstrated by the use of elevated soil P contents to identify archaeological sites.

There is discussion as to the degree to which N or P limit plant productivity in terrestrial ecosystems (e.g. Vitousek *et al.* 2010). It is clear however that productivity is stimulated by P application in many systems (Elser *et al.* 2007). High-P as well as high-N soils are associated with lower plant diversity (Ceulemans *et al.* 2013). If N deposition exceeds the absorptive capacity of the ecosystem, N leaching may occur, causing soil acidification and downstream effects. For this reason it has been recommended by some authors that P be applied to stimulate N uptake and reduce N leaching (Blanes Alberola, 2010). If N leaching is a major concern, there may be some justification for this approach, but in general the priority for conservation site managers will be to reduce productivity and minimise N impacts on the biological interest features of the site, and this is likely to take precedence over concerns about N leaching.

Phosphorus limitation is one mechanism which helps avoid many of the adverse effects of N on habitat suitability in habitats which have received a high N load. Therefore, addition of P will remove this limitation and most likely lead to serious consequences for the nature conservation interest. For this reason, and because P persists in the soil for many years, applications of P fertiliser are not recommended if the aim is to maintain a low-productivity, high-diversity habitat.

3.5.2.5 Calcium

Liming provides another essential element, calcium, and some forms such as dolomitic lime or calcified seaweed also provide magnesium and other essential elements. Liming also increases the turnover of soil organic matter and consequent release of plant nutrients, and can make plant nutrients more soluble and available to plants. These processes tend to increase productivity, which is usually not desirable for maintaining plant diversity. While species richness in temperate habitats generally increases with soil pH, and liming could be used to reduce effects of acidification, care needs to be taken to clearly identify the target species of interest for any management objective. In acidic habitats such as bogs and some acid grasslands, it may be those acidophile species which are a focus for management. Liming is discussed more fully in Section 3.6.

3.5.2.6 Trace elements

Supply of any of the essential plant nutrient elements can restrict productivity. For example, rates of sulphur deposition have now declined to an extent where sulphur deficiency is commonly observed in upland arable and silage systems (DEFRA, 2010b). Plants have to maintain supply of all essential elements, and employ a variety of strategies to do so. This diversity of nutrient acquisition strategies may explain how different plant species coexist without a single one becoming dominant. At a landscape and national level, patterns of nutrient element limitation on different soils probably explain the occurrence of certain species. The distinct flora of serpentine soils, where large magnesium concentration restrict calcium uptake, is a famous example. Understanding remains limited of how the acquisition strategies of different plant species for different nutrient elements maintains plant diversity. It is possible that certain plant species of conservation concern would be favoured by application of particular nutrient elements. However, the set of nutrient deficiencies on a particular site, resulting from its geology, soil formation processes and land use history, form part of its identity. Reducing any of these deficiencies through fertiliser application may result in the loss of distinctive species.

3.5.2.7 Summary

In general the addition of fertilisers, and especially N fertilisers, is likely to exacerbate the effects of N deposition.

3.6 Liming

This section outlines the current use of liming as a management tool for habitat conservation in the selected habitats and describes the impact of burning on habitat responses to N deposition.

3.6.1 Current liming advice

Liming is currently used in acid grassland under some advice schemes. The use of liming is also discussed for bog, heath and calcareous grassland, where it is not recommended.

3.6.1.1 Acid grassland

Current advice in acid grasslands is mixed depending on the scheme consulted (see Table 3.3). Sometimes advice is given not to apply lime whilst other advice is to apply lime only with consent or not to apply lime between the 1st April and 1st August.

3.6.1.2 Dwarf Shrub heath

Advice regarding liming in dwarf shrub heath is not to apply lime (see Table 3.5). Lime has been applied as part of restoration experiments, in this case to allow the return of acid-sensitive species after turf cutting (Dorland *et al.* 2005b). However, in general the addition of lime would exclude acid specialist species.

3.6.1.3 Bogs

Advice regarding liming in bogs is not to apply lime (see Table 3.6). The application of lime would increase the soil pH in this highly acidic habitat and could potentially exclude acid specialist species. However, application of lime has been used as part of restoration of cut-over bogs to stimulate the buoyancy of poorly humified peat when hydrology is restored (Tomassen *et al.* 2003b; Smolders *et al.* 2003).

3.6.2 Impacts of liming

Liming impacts on several aspects of the N cycle. Calcium is an essential plant element, but most of the effects of liming are indirect, mediated via changes in soil pH. Indirect effects include: immobilisation of toxic metals, and often increased availability of N, P and other nutrient elements.

3.6.2.1 Soil nitrogen processes

As the soil pH is reduced, a number of nutrients and metals are affected, especially as some of the impacts of acidification on nutrient cycling may be countered by the addition of N in deposition. Nitrification (oxidation of ammonium to nitrate) is inhibited at low soil pH because the nitrosomas bacteria, responsible for nitrification, have optimum pH requirements of 7 to 8. This has been demonstrated in several habitats including woodlands, grasslands and heathlands (e.g. Dorland *et al.* 2005b; Roelofs *et al.* 1985; Ste-Marie and Paré, 1999). If ammonia accumulates in the soil due to low nitrification this could also reduce denitrification activity (Sanchez-Martin *et al.* 2008) although there is no simple relationship with pH (Šimek *et al.* 2002). Mixed results have been seen for N mineralisation (Aciego Pietri and Brookes, 2008), acidification has been shown to both increase and decrease mineralisation (e.g. Persson *et al.*

1989) but addition of N stimulates N mineralisation (Morecroft *et al.* 1994). As a result of the changes in processing the predominant form of N available in the soil changes and some plants have become adapted to using one form or another according to their preferred growing conditions. Plants adapted to acidic soils with low nitrification rates (and so more N available as ammonium rather than nitrate) use ammonium as their preferred N source. They can tolerate high ammonium concentrations without toxic effects and are less efficient at using nitrate (Britto and Kronzucker, 2002). Conversely, plants growing in neutral to high pH soils are generally well adapted to high nitrate availability and preferentially use nitrate as their main N source.

3.6.2.2 Habitat suitability

Soil pH

The addition of lime increases soil pH. The amount of lime added can be used to determine the level of pH attained, taking into consideration the starting pH of the soil. The addition of lime also makes the soil more highly buffered against pH change in the future since it increases availability of calcium which buffers pH change.

Mobilisation of metals

Below a soil pH of around 5.5, aluminium and other toxic metals, including some iron compounds become highly mobile, with implications for soil microbial community composition and impacts on freshwater systems. There is evidence for mobilisation of Al and some other toxic metals along an N deposition gradient in acid grasslands (Stevens *et al.* 2009) and in experimental studies in similar communities (Blake *et al.* 1999; Horswill *et al.* 2008). Grime and Hodgeson (1969) showed a clear relationship between species occurrence on acid soils and resistance of the seedling root to aluminium toxicity. These impacts of acidity reduce the available species pool to only those species tolerant of Al toxicity and other consequences of acidification thus reducing species richness (Schuster and Diekmann, 2003). At low pH nitrate uptake is reduced by free Al^{3+}, this can also have a negative impact on mycorrhizal symbionts (e.g. Lazof *et al.* 1994).

Impacts on other nutrients

Additionally, as the soil pH is reduced the availability of phosphate in the soil changes, although in acid soils phosphate is in its most mobile form ($H_2PO_4^-$) at low pH this readily binds with aluminium, iron and other metals mobilised by the low pH to form insoluble metal-phosphate compounds. Phosphate is also increasingly sorbed onto the surface of iron and aluminium oxides and clays as it becomes more mobile. Maximum availability of P in the soil occurs between pH 5.5 and 7.5 so as the pH is reduced from this, there is less P available (Kooijman *et al.* 1998).

Base cations (including the macro- and micro-nutrients calcium, magnesium and potassium) are readily leached from acidified soils and concentrations along this deposition gradient are significantly related to pH (Stevens *et al.* 2009). Long term investigation of the unfertilized, unlimed plots at the Park Grass experiment at Rothamstead, UK, have shown reductions in concentrations of exchangeable calcium and reductions in cation exchange capacity and base saturation over the 120 years of atmospheric deposition (Blake *et al.* 1999).

The consequence of all these changes in nutrient availability with pH is that N, and other important nutrients, may be less available to plants growing in acidified soils even though N is added. Even if there is additional N available to plants (as this is least affected by pH changes and is added to the system through deposition) other nutrients could become limiting and responses to nutrient enrichment may not become manifest. In other words, low P availability at low pH may help mitigate some of the adverse effects of N deposition on habitat suitability, while at the same time creating additional constraints such as metal toxicity.

3.6.2.3 Summary

Liming mitigates against the acidification effects of N deposition in habitats with acid soils. However, liming should be used with caution since it alters many aspects of soil N cycling, often increases the availability of other nutrients, changes vegetation species composition and can increase leaching of dissolved organic C with water quality impacts, and loss of soil C stocks through increased rates of organic matter decomposition. Liming soils has the potential to increase eutrophication effects. There should be a clear understanding of the desired endpoint if considering liming as a management option, and unintended consequences on species of conservation interest should be considered. Natural England already provides guidance on liming in its Technical Information Note (TIN045).

3.7 Hydrological management

This section outlines the current use of hydrological management as a tool for habitat conservation in the selected habitats and describes the impact of hydrological management on habitat responses to N deposition. Hydrological management may have a number of aims: increase drainage, thereby increasing productivity; decrease drainage, thereby improving conditions for wetland species; or prevent nutrient-rich groundwater from reaching the site / habitat of concern.

3.7.1 Current management practice

Hydrological management can potentially be used for the conservation of woodland, dwarf shrub heath, bog and dune habitats.

3.7.1.1 Broadleaved, mixed and yew woodland

Although the majority advice is to not install new drainage or modify existing drainage in woodland, management may include restoration of site drains, while wetland features should be protected (see Table 3.2).

3.7.1.2 Acid and calcareous grasslands

Current advice for the management of acid and calcareous grassland habitats is to not install new drainage and to not modify existing drainage (see Tables 3.3 and 3.4).

3.7.1.3 Dwarf shrub heath

In naturally waterlogged areas, blocking of drains is permitted. In other areas drainage should be maintained, but ditches should not be cleared in spring and summer (see Table 3.5).

3.7.1.4 Bog

In upland blanket bog, both the maintenance of existing drains and the blocking of drains are permitted. Specifically, recommendations include maintaining the water table at the surface in winter and to a maximum 10 cm below the surface during the summer (but preferably close to the surface). In lowland raised bog it is recommended that ditches are not cleared, and that rainfall is retained on-site in order to maintain a high water table throughout the year (see Table 3.6).

3.7.1.5 Coastal dunes and slacks

The current advice in coastal dunes and slacks is to maintain existing drainage and flood patterns, and new drainage not permitted or desirable. Target water table depths have been specified in some cases, winter maximum is 0 to 50 cm above ground level, while summer maximum is 50 to 100 cm below ground level (see Table 3.7). However, these ecohydrological guidelines are rather outdated and have been superceded by new research (see Curreli *et al.* 2013).

3.7.2 Impacts of hydrological management

This section considers the impacts of hydrological management, mostly the re-wetting of habitats, on N losses and processes and habitat suitability. The majority of current research investigates the effect of re-wetting after historic drainage. However, caution should be taken when interpreting this data and extrapolating to re-wetting, because re-wetting may or may not result in a return to previous conditions and rates of processes. For example, once peat dries out it often becomes hydrophobic, and does not regain previous levels of moisture content (Egglesman *et al.* 1993).

3.7.2.1 Above ground N loss

Above-ground vegetation biomass is not removed as a direct result of hydrological management; however it impacts on vegetation growth and assimilation of N into the vegetation stock. In a NO_3 addition experiment, high soil moisture favoured the rapid uptake of NO_3 in a peat bog in Germany (Glatzel *et al.* 2008). In an experimental manipulation of water table depth in *Sphagnum* spp. peat cores, *Sphagnum* spp. growth rates decreased with increased water table depth, but N assimilation rate was not affected (Williams *et al.* 1999). Bryophytes act as a sponge for atmospheric nutrient deposition, and can be a mechanism by which N deposition is stored in the plant-soil system and released at a later date. At atmospheric N deposition rates of 12 – 18 kg ha^{-1} yr^{-1}, excess N accumulates in *Sphagnum* spp. tissue (Lamers *et al.* 2000), above this level they are no longer able to retain all the deposited N and the additional excess leaks straight to the soil system.

3.7.2.2 N processes

The processes of the N cycle most significantly affected by soil water availability are mineralisation and denitrification. Mineralisation rate increases as soil water content is reduced due to increased soil aeration. Bacterial numbers and oxygen availability both increase with increased soil aeration. Low water tables increase mineralised N in peat by a factor of 1.5 from 0.99 to 1.48 g N m^{-2} (Williams and Wheatley, 1988). Similarly in Canada, leaf litter mass loss was negatively correlated with water table depth among five sites (Szimgalski and Bayley, 1996). However, changes in water table and aeration could have little impact on mineralisation rates if low temperature, low pH and low litter quality still inhibit microbial activity (Holden *et al.* 2004). For example, N mineralisation rates in an acidic bog with pH of 4.0 were not affected by drainage (Humphrey and Plugh, 1996).

Hydrological regime is an important driver of denitrification rates, because denitrification (N_2O production) is more likely to occur in water-logged anaerobic environments (Grootjans *et al.* 2004). Several studies have measured the effect of hydrology on N_2O production in bogs. In general, N_2O production is highest at high soil moisture levels, but not in fully saturated soils under conditions of inundation (Granli and Bockman, 1994). Danevcic *et al.* (2010) found that peaks in N_2O production rates in spring of around 3 mg m^{-2} hr^{-1} coincided with falling water tables, and Von Arnold *et al.* (2005) report a decrease in N_2O emissions from 0.01 to 0.004 mg m^{-1} hr^{-1} with a rise in water tables from 7 cm below ground level to 1cm above ground level in an un-drained bog. These effects of water table depth on denitrification rate are observed when previously drained peat is re-wetted (Urbanova *et al.* 2011; Glatzel *et al.* 2008). In a laboratory experiment using peat cores from a drained bog and fen in the Czech Republic, re-wetting of peat led to a decrease in nitrate concentrations in peat cores compared to controls, probably due to increased rates of denitirifcation (Urbanova *et al.* 2011). In a peatland in North West Germany, Glatzel *et al.* (2008) observed an increase in N_2O production from less than 0.1 to 0.3 mg m^{-2} hr^{-1} from before to after re-wetting. Therefore, the re-wetting of bogs can result in a loss of N in the first years after re-wetting due to increased ammonium concentrations in leachates (Kieckbusch and Schrautzer, 2007), though the longevity of such effects is unknown.

3.7.2.3 Habitat suitability

Changing water levels may have consequences for the relative contribution of water inputs from outside the site. For example, lowering water levels may increase the contribution of seepage from external groundwater or surface water sources. Raising water levels may lead to a different balance of water sources to the site. Hydrological influences for the majority of wetland sites are rather complex. Any change in the hydrological regime, whether raising or lowering water levels, has the potential to alter the status quo of water inputs to the site, and their geochemical and nutrient influence. These external influences need to be considered particularly where input water for the site is likely to be contaminated by high nutrient loads from surrounding farmland, as in lowland fen systems, and dune slacks, and also where the geochemical composition of groundwater is a major influence on community composition. Raising water levels may alter the extent of groundwater influence, leading to changes in vegetation communities. Soil pH may also be affected depending on the source of water to the site. Depending on the pH of the incoming water this could exacerbate or mitigate the effects of N deposition. In a wet meadow on peat soils in Somerset Stevens *et al.* (2012) found that flooding from high pH waters resulted in no impact of N addition on soil pH.

3.7.2.4 Constructed wetlands

While not explicitly mentioned in current guidance, there is increasing interest in the use of constructed wetlands as an on-site or on-boundary measure to reduce nutrient concentrations of N, P and other compounds in surface waters entering a site. This is currently being trialled within the Anglesey Fens LIFE project in North Wales, and could be used in conjunction with other hydrological management methods to minimise adverse impacts of N by reducing the total N load in addition to or where it is not possible to reduce the atmospheric N load.

3.7.2.5 Summary

Drainage of wet habitats is likely to exacerbate impacts of N deposition by increasing rates of mineralisation and reducing losses of N through denitrification. Current recommendations to avoid drainage therefore seem the most suitable management to minimise N impacts. Rewetting of habitats could potentially increase N losses by denitrification but will have considerable, potentially negative, implications for species composition, although often the main aim of such management measures is to reinstate particular favourable hydrological regimes. However, care needs to be taken to consider whether the nutrient status and geochemical composition of waters used to rewet the site are appropriate and do not exacerbate impacts of N deposition on the site.

3.8 Scrub and tree management

This section outlines the current use of scrub removal as a management tool for habitat conservation in the selected habitats and describes the impact of scrub removal on habitat responses to N deposition. Since the unintended consequences of scrub removal were not explored in section 2 they will be described here.

3.8.1 Current scrub and tree management advice

3.8.1.1 Broadleaved, mixed and yew woodland & (natural) Coniferous woodland

Tree and scrub management in woodland is a large part of the management exercises conducted in sites. Consequently recommendations are rather more complex than in other habitats. Management of trees and shrub in woodland can be divided into four main areas: management of trees; management of scrub and shrub vegetation; management of dead trees and management of the woodland more generally. Management of trees includes a range of different advice including the use of rotational coppicing, not cutting living trees without permission and retaining old trees. Scrub and shrub management includes maintaining a level of cover below 50%, trimming no more than one third of shrubby growth per year and not burning brashings. Advice for deadwood is mixed, with some sources recommending the retention of all dead wood including that on living trees, leaving windblown trees, diversifying even-age stands to ensure dead wood supply and felling or ring barking selected trees for dead wood. Other advice says to remove all cut trees. More general advice for the management of woodlands includes allowing the woodland edge to grow out, retaining native woodland and controlling native species (see Table 3.2).

3.8.1.2 Acid grassland

Advice for tree and scrub control in acid grassland is that scrub encroachment should be prevented, encroaching trees and scrub should be controlled but existing areas of scrub can be retained. The removal of bracken and injurious weeds is also recommended. Prescribed methods include grazing, mowing, cutting, topping, herbicide and removal of bracken by cutting or crushing (see Table 3.3).

3.8.1.3 Calcareous grassland

Advice for tree and scrub control in calcareous grassland is very similar to acid grasslands. Tree and scrub encroachment should be prevented, trees and scrub should be controlled but existing areas of scrub can be retained. Prescribed methods include grazing, mowing, cutting, topping, herbicide and removal of bracken by cutting or crushing. The removal of cut material is recommended (see Table 3.4).

3.8.1.4 Dwarf shrub heath

Within heathlands the control and removal of scrub is mentioned. Most advice is that the spread of scrub should be controlled, further encroachment prevented or a maximum cover permitted given. Species particularly identified include gorse, birch and there is also reference to the control of bracken. Prescribed methods for control include grazing with cattle, sheep, goats or ponies, cutting, cutting followed by ammonium phosphate / glycophosphate, burning and control of bracken by mechanical means. Trees should not be planted (see Table 3.5).

3.8.1.5 Bog

In bogs the recommendations are also generally for the removal of scrub and trees. Advice is that trees and shrubs should be removed where they are considered to be threatening the interest of the habitat or where they affect hydrology as well as more general advice to remove scrub and trees and not plant trees. Species specifically mentioned are gorse and bracken. Prescribed methods for control include hand pulling of seedlings, cutting, burning, grazing and control of bracken by mechanical means. Prevention of re-colonisation with herbicide is also recommended (see Table 3.6).

3.8.1.6 Coastal dunes and slacks

Recommendations for control of scrub in coastal dunes generally advise that scrub should be managed and prevented from spreading (see Table 3.7).

3.8.2 Impacts of scrub and tree management

3.8.2.1 Above-ground N loss

One of the main ways that scrub removal and tree management interacts with the N cycle is offtake of N. When a non-woodland site is dominated by successional species such as *Betula* spp., *Pinus sylvestris*, *Pteridium aquilinum*, *Rhododendron ponticum* and *Ulex europaeus* this results in a total N offtake of between 561 and 2661 kg N ha^{-1} if all above-ground biomass and litter are removed and depending on the species (Mitchell *et al.* 2000). These species could come to dominate in acid grassland, heathland or bog however, although this represents a large removal of N from the site, a site would need to be poorly managed for a number of years for these species to come to dominate. In managed sites it is more likely that scrub would be removed at a much earlier stage and consequently the N offtake would be lower. If scrub is cut, moved or topped and all cuttings removed then this would have a positive effect on the removal of N from the site. The use of burning to remove scrub is also likely to result in the removal of N (see section 3.5.2), but removing scrub by grazing redistributes N rather than removing it and converts it to N forms that are readily available for plants (see section 3.5.1). As long as high N content fertilisers are not used as herbicides (e.g. potassium nitrate) and above-ground biomass is removed, then the addition of herbicides should result in N removal from the site due to the removal of dead vegetation.

In woodlands managed for conservation objectives, advice regarding trees is generally not to remove living trees. Commercial harvesting in productive UK forests results in the removal of 2.9 kg N ha^{-1} year^{-1} for coniferous woodland and 5.88 kg N ha^{-1} year^{-1}for broadleaved woodland (Hall *et al.* 2003). Because trees take a long time to grow removing trees provides relatively little benefit in terms of N removal, and could actually be detrimental since canopy gaps can result in elevated N turnover (Prescott, 2002) (see section 3.9.2.2). Rotational coppice is an alternative management strategy that is recommended and widely used. Intensively managed rotational coppicing has a maximum total above-ground N content ranging from 100 kg ha^{-1} for young plantations up to 400 kg ha^{-1} for 20 year-old plantations (Hansen and Baker, 1979). This results in a higher rate of N removal than seen in the harvesting of productive forests (20 kg N ha^{-1} year^{-1}) but since N content of less intensively managed coppice is likely to be lower than the numbers presented here but rates of removal are likely to be high compared with other management strategies and may present a means of mitigating N inputs. Kirby *et al.* (2005) highlight the potential for reductions in the volume of forest outputs (e.g. removal of wood, litter, bracken and brambles and stock grazing) during the last 150 years to contribute to the eutrophication of woodlands suggesting that reduced quantities of N removed may have had a greater impact than additional N inputs. Prietzel and Kaiser (2005) found litter removed reduced litter, soil, groundwater and fresh leaf N pools but Dzwonko and Gawronski (2002) found that litter removal resulted in no change in the N content of soils.

Wood typically has a low N content (e.g. *Pinus* sp. 0.04%, Hungate, 1940) and takes a long time to decompose so although leaving dead wood *in situ* results in the return of N in woody tissues to the soil biodiversity and soil C accumulation benefits of dead wood retention may outweigh the benefits of N removal.

3.8.2.2 Below-ground N loss

Leaching of N from forest soils can cause acidification of surface waters and eutrophication of inland water and coastal marine environments (Vitousek *et al.* 1997) but removes N from the system without acidifying the soil as nitrate leaching would (Vitousek *et al.* 2010). The key mechanisms leading to N leaching in forest ecosystems are: (a) N deposition surplus to the requirements of plant and microbial communities; (b) disturbance to the vegetation community; (iii) enhanced soil N mineralisation (Gundersen *et al.* 2006). Rothwell *et al.* (2008) applied a non-parametric classification and regression tree approach to evaluate the key environmental drivers controlling N leaching at 215 forest sites across Europe. They found the primary driver to be throughfall NO_3-N deposition; in their analysis this was more important than either NH_4-N deposition or cumulative historical N deposition. Acid deposition was also a key driver. The most important ecosystem characteristics were hydrology (mean annual precipitation, runoff), soil type and soil organic C content. They suggest the use of a dichotomous key as a management tool to identify forests at risk of N leaching from soils, and conclude that the most effective strategy for reducing leaching is to reduce the atmospheric inputs of NO_3-N deposition.

Williams *et al.* (2000) studied 19 oak woodland stands in Wales to determine if broadleaved woodlands were more or less prone to nitrate leaching than coniferous plantations, and to investigate what site characteristics determine the rate of nitrate leaching. The inputs of N and nitrate leaching losses were measured at all 19 oak sites and results compared with two coniferous stands already instrumented from other studies. In addition manipulation studies were carried out at two contrasting oak stands, with three replicates of four treatments: (i) control; (ii) monthly additions of 35 kg N ha^{-1} $year^{-1}$ ammonium nitrate; (iii) removal of ground vegetation by herbicide treatment; (iv) a combination treatment. Results showed that soil N content and turnover, and climatic variables (e.g. rainfall, temperature) were more important than stand characteristics and management in determining the rate of nitrate leaching. They were unable to identify any stand management options that would minimise nitrate leaching because:

- No stand characteristics were consistently related to nitrate leaching.
- Removal of ground vegetation (in the manipulation study) did not have any effect on nitrate leakage, unless in combination with N addition treatments. The implications of this were that ground flora may act as a temporary sink for N, but does not appear to reduce the leaching of N in the long term.
- Broadleaved woodlands on similar soils to coniferous plantations were less prone to nitrate leaching than conifers. So conversion of conifer to oak, or new planting with oak, appeared to be the only management option that might reduce the potential for nitrate leaching.

A number of studies have demonstrated the potential for increased losses of N by leaching following clearfelling (e.g. Keenan and Kimmins 1993) and elevated nitrate in drainage waters Bormann and Likens 1979, Vitousek *et al*. 1979, Sollins *et al*. 1981, Hendrickson *et al*. 1989, Fisk and Fahey 1990) as a result of increased uptake, increased decomposition, reduced N assimilation by microbial biomass and decay of tree debris (Prescott, 2002). Canopy gaps have a similar effect (Prescott, 2002) although single tree thinning does not (Parsons *et al.* 1994).

Leaching losses of N from intensive short rotation coppice are generally reported to be low (Goodlass *et al.* 2007). Leaching losses as a consequence of scrub removal have received little research attention although based on findings from forests we may expect elevated leaching where large areas of scrub are removed.

3.8.2.3 Soil nitrogen processes

There is no specific research on the impact of the impact of the removal of scrub on N cycling. However, there may be some similarities to the impacts of removing trees from woodland (see below). Gorse (*Ulex* spp.) and Broom (*Cytisus scoparius*) are both leguminous species so convert unreactiveN_2 gas into reactive forms of N in the soil. N fixation by these species increases soil nitrate concentrations and their litter is usually also N rich (Rotherman, 2007), consequently existing management strategies to remove these species by cutting, burning or herbicide application are likely to be beneficial as long as cut plant material is removed from the site.

In woodlands increased mineralisation, denitrification and nitrification have all been observed following clearfelling (Frazer *et al*. 1990, Smethurst and Nambiar 1990, Dahlgren and Driscoll 1994). Increased decomposition has also been observed following clearfelling (Bormann *et al*.1974). Although clear-felling is not a method used for nature conservation management in semi-natural woodlands, as with leaching, these effects are also seen if canopy gaps are created. Ritter (2005) found elevated mineralisation, nitrification and soil N concentrations in gaps of 17 and 30 m diameter in Danish beech forests, mineralisation showed a two fold increase in gaps compared to non-gap areas during the growing season. Zeller *et al*. (2008) found that tree girdling (also called ring barking), a management practice recommended for the creation of standing dead wood under some guidance, also results in a significant increase in N mineralisation compared with under trees that have not been girdled with rates of between approximately 1.5 and 3 mg N kg^{-1} soil d^{-1}depending on woodland age. However, the mechanism governing this effect and its likely duration are unknown. These results indicate that even with minimal intervention there are likely to be changes in turnover of N, and warrants further research.

3.8.2.4 Habitat suitability

The removal of scrub and trees or the implementation of coppicing in woodlands all result in increasing light reaching ground level. In woodland plants there is commonly a tradeoff between competition for nutrients and light. In an N enriched habitat that has previously been shaded, creating canopy gaps could provide the opportunity for plant species typical of eutrophic conditions to grow rapidly (Aarssen and Schamp, 2002). In woodlands, changes in species composition in relation to light, acidification and nutrient status are commonly correlated (Kirby *et al.* 2005) (see section 2.1.3) and responses may depend on woodland type and pH conditions (Hardtle *et al*. 2003).

3.8.2.5 Nitrogen interception by vegetation

Deposition velocity of dry deposited N is impacted by aerodynamic resistance, laminar resistance and surface properties (Wesely and Hicks, 2000) and consequently the removal of scrub vegetation will impact on the amount of deposition. Reducing the height of vegetation and decreasing surface roughness by converting scrub vegetation to grassland would reduce deposition inputs although the effect will depend on the extent of the vegetation change and may only be small. Nitrogen deposition rate increases gradually with the height and surface roughness of vegetation, but are estimated on the basis of vegetation types (Matejko*et al.* 2009). For an example location (Lancaster University, SD 349947) deposition would be 13.7 kg N ha^{-1} yr^{-1}, for dwarf shrub heath it would also be 13.7 kg N ha^{-1} yr^{-1}, for broadleaved mixed and yew woodland it would be 23.5 kg N ha^{-1} yr^{-1}.This represents an increase in N deposition of around 70% when changing from short vegetation to woodland.

Unintended consequences of scrub removal

- Changes in plant species composition
- Negative impacts on invertebrate diversity and bird populations
- Increased light levels allow fast growing species to thrive
- Water quality may be impacted by increased leaching of N and possibly DOC

3.8.2.6 Summary

Removing scrub by cutting, topping or mowing has the potential to remove large amounts of N from grassland, heathland or bog sites. It also increases light levels reaching the smaller stature stress-tolerant species and has the potential to reduce rate of N deposition. There is the potential that mineralisation and decomposition may be increased but data are not available on how much rates are likely to be impacted.

In conservation woodlands tree management advice is currently generally not to remove living trees. This strategy seems to be the best for minimising impacts on the N cycle because although removing trees would increase N offtake and also increases leaching it is also likely to increase mineralisation and decomposition making more N available as well as causing considerable damage to the habitat. Deadwood management suggests that deadwood should be left *in situ*, since wood has a low N content this is unlikely to cause an exacerbating effect.

3.9 Disturbance

This section considers advice regarding soil disturbance, this includes turf stripping, peat cutting, harrowing and ploughing, and remobilisation activities.

3.9.1 Current management advice

In most habitats, current advice for conservation management is generally to avoid heavy disturbance. Specific advice includes minimising compaction, poaching and erosion, conserving soil carbon stocks, and prohibiting cultivation and chain harrowing.

There are some exceptions to this advice in certain habitats: (1) in dwarf shrub heath where grass may be controlled by turf stripping; (2) in bog where small scale traditional peat cutting may be permitted; (3) in coastal dunes there is considerable interest in re-establishing natural dune dynamics through a variety of techniques including turf stripping, topsoil inversion and large-scale dune and slack re-profiling; (4) in machair systems in Scotland and Ireland, cultivation by shallow ploughing as part of a management rotation cycle constitutes traditional management of the habitat and contributes to their high flora and faunal diversity.

3.9.2 Effects of disturbance

The effects of general disturbance and turf stripping (including peat cutting) on N stock, N processes and habitat suitability are considered below. General disturbance to soil and vegetation has two main actions on soil, namely aeration and compaction, and will affect N processes rather than affect N stocks. In contrast, turf stripping will reduce N stocks as well as influencing N processes.

3.9.2.1 Effects on N stocks

Turf stripping and sod cutting have an immediate impact on the N stocks of the habitat through the removal of vegetation and the organic soil layer. Depending on the depth and profile of the soil organic layer, turf stripping can remove the majority of the soil N pool (Heil and Bobbink 1993; Hardtle *et al*. 2007). In the latter study on a heath in Germany, the entire above-ground and O-horizon N pools, and 32% of the A-horizon were removed, resulting in an N offtake of 122, 935 and 625 kg ha^{-1}respectively (Hardtle *et al.* 2007). Under atmospheric input of 21.9 kg ha^{-1} yr^{-1} , the N retained in a heath in Germany reduced from 83% to 64% over the first year since management by turf cutting. This was associated with an increased in N lost by leaching from 3.7 to 7.8 (Hardtle *et al.* 2007).

Wamelink *et al*. (2009a) developed a plant successional model to predict the response of vegetation to reductions in atmospheric N deposition and changes in management. They used a biomass removal parameter of 0.002 ton ha^{-1} for turf stripping, and found that this had greater effect on N status of habitats than reductions in N inputs from atmospheric deposition.

While turf stripping removes N from the soil N stock, the frequency of application of this management technique determines the long-term rate of N removal. However, it is the most thorough method of removing accumulated N from any habitat, provided soil and vegetation are removed offsite. It should however be noted that turf stripping can have many unintended consequences including loss of the seedbank, and exposing mineral soil which could lead to increased wind and water erosion and increased C emissions (Alonso *et al.* 2012).

Turf stripping cannot prevent the accumulation of subsequent N additions in vegetation biomass and soil organic matter (Berendse 1990).

3.9.2.2 Effects on N processes

Disturbance to soil and vegetation has an effect on N processes mainly via two main actions: aeration and compaction. Aeration may increase rates of N mineralisation (Balesdent *et al.* 2000). On the other hand the mixing of organic layers with mineral soil physically protects organic material from mineralisation. Disturbance can also cause soil compaction, which increases soil bulk density and reduces soil water infiltration (Andrew and Lange 1986; Kahlon *et al.* 2013). For example, water infiltration capacity in agricultural land decreased from 4.6 cm h^{-1} in no till sites to 1.2 cm h^{-1} in plow till sites (Kahlon *et al.* 2013). Changes in soil moisture content will alter rates of N processes, as described in section 3.8.2.2). Current management for conservation recommends avoiding heavy disturbance but several studies highlight the impact of techniques such as cultivation, chain harrowing, and loose tipping on N processes.

Disturbance such as tillage usually increases N mineralisation due to increased aeration and access to mineralisable N as a result of disruption of soil aggregates (Balesdent *et al.* 2000; Beare *et al.* 1994). A meta-analysis by Balesdent *et al*. (2000) found higher N mineralisation rates by 10 to 100% in tillage compared to no tillage soils in the majority of cases. However, in a UK woodland, mixing of the organic topsoil with mineral subsoil by loose-tipping in clay soils protected organic residue and resulted in a reduction of N mineralisation rates from around 15 to 2 ug g^{-1}per month in disturbed soil compared to undisturbed soil. This led to a decrease in cumulative net N min in ten months since disturbance from 109 to 35 ug g^{-1} dry soil. In a six month lab experiment using the same soils, total soil N in the top 0-5cm decreased from 7.1 to 2.2 mg g^{-1}.

After turf cutting, levels of available N in the soil are reduced: net nitrification was reduced from 10 to 5 umol g^{-1} dry weight of soil over six weeks, and coincided with a reduction in soil moisture (Dorland *et al.* 2004). N mineralisation rates remained low several years after turf stripping. In sites in the Netherlands along a gradient of time since turf stripping, N mineralisation rates remained below 5 g m^{-1} yr^{-1} for the first 10 years, but after 10 years doubled to greater than 10 g m^{-1} $yr^{-1}$and were correlated with the amount of organic matter in the soil (Berendse 1990).

3.9.2.3 Effects on habitat suitability

In addition to removal of N during turf stripping, the seed bank can also be removed, which can result in the loss of some species (Van den Berg *et al.* 2003). However, for heathlands, removing litter and up to 3 cm of top soil can release the seed bank and improve germination rates. The depth of turf removed will control the magnitude and identity of seeds removed and so cutting depth should be considered in management prescriptions. Turf stripping may also result in species loss due to reduced seed germination rates. The mechanism for reduced germination is likely the effect of aluminium mobilisation and toxicity following the removal of humic compounds which form complexes with Al^{3+} (van den Berg *et al.* 2003), but this depends on the pH and chemistry of the site in question. Turf stripping is currently practiced in some UK lowland heaths.

In dune systems, turf stripping or topsoil inversion offer a mechanism to revert the habitat to early successional stages which are required for many of the rare coastal specialist species to maintain a foothold. Reinstating natural dynamics by clearing areas of vegetation, allowing natural dune forming processes to proceed is a more sustainable way of creating new habitat. Working with natural processes allows the system to self-regulate, creating new dune slacks and new dunes in equilibrium with current climatic conditions (Davy *et al*., 2010). When applied on large sites where there is room for the slow migration of individual dune landforms, the ideal situation would be a mosaic of older and younger successional stages, maintained by natural processes, and with the potential to support a wider diversity of habitats and species than is currently present on most UK dune systems. In peatlands peat-cutting can have drastic impacts on bog vegetation removing self-regulatory hydrological capacity and encouraging dominance by graminoids, which will have the undesirable effect of to enhancing methane emissions: restoration of such degraded peatlands is expensive, slow and of variable efficacy.

3.9.2.4 Summary

In most habitats major soil disturbance is generally not recommended. Considering the large number of unintended consequences, in the majority of cases, it seems appropriate to continue to avoid disturbance. In a few other habitats, these techniques may be a viable option in some cases. Turf stripping in dwarf shrub heath and peat cutting in bogs represent a major removal of N from the system with the potential to mitigate N deposition impacts, however this is a destructive and expensive technique and the unintended consequences need to be considered and in the case of peatlands any benefit to N impact amelioration is unlikely to justify the drastic damage produced. In coastal dunes however, it represents a relatively cost-effective management option over the longer term, and may be one of the more sustainable methods of recreating the conditions required for early successional habitats to persist on larger sites.

3.10 Conclusion

Management recommendations vary considerably between schemes and handbooks and in a number of cases are contradictory. The potential for management practices to reduce N deposition impacts were considered in terms of above-ground N losses, below-ground N losses, soil N processes and habitat suitability. There is a paucity of information on the extent to which many management practices impact on N cycling meaning it is not possible to create full N budgets for individual management practices. The majority of management practices do not remove significant quantities of N. Furthermore, impacts of management practices also vary considerably between habitats and sites. However, it is clear that managing a site to remove sufficient N to offset N added by atmospheric deposition may require intensive management. At many sites the level of management required to remove sufficient N to fully mitigate N deposition inputs is likely to be too high to maintain good site condition. However by managing both N losses and habitat suitability it may be possible to reduce N deposition impacts.

4 HOW MEASURES MAY BE AFFECTED BY CLIMATE CHANGE, OR BY MANAGEMENT IN RESPONSE TO CLIMATE CHANGE.

4.1 Introduction

This task focuses on three aspects linked to management of habitats in relation to N deposition and climate change:

- Whether management measures in response to N may make habitats/ sites more vulnerable to climate change impacts (e.g. fire, drought or reduced frost/snow cover).
- How changes in climate over the next few decades could affect habitat response to management measures in place for N and influence their effectiveness at mitigating impact.
- How short to medium term management in response to climate change may influence measures for N mitigation.

We address each of these issues in the sections below.

4.2 Whether management measures in response to nitrogen may make habitats/ sites more vulnerable to climate change impacts

Climate change has the potential to alter all components of our natural environment, to varying degrees. This project is primarily concerned with the interactions between management measures to reduce N deposition impacts and climate change and the management required to adapt to its effects. Therefore we do not exhaustively review climate change effects, but extract the main findings from other studies which address these in more detail (e.g. Natural England 2012).

4.2.1 The principal climate change threats for terrestrial and freshwater habitats

The following threats are taken from the Natural England climate change risk assessment (Natural England 2012) and illustrate the main mechanisms by which climate change is likely to impact UK habitats. Only the main impacts relevant to terrestrial and freshwater habitats are shown. Subsequently we discuss for each of the N deposition management options detailed in Chapter 3 whether they will increase or decrease habitat sensitivity to climate change. The threats selected as relevant to this report come under four broad categories:

Threats to conservation and recovery of priority threatened species and habitats

- Species are unable to track changing climate space.
- Increases in soil moisture deficits and episodic droughts.
- Changes in interspecies interactions. A key issue is the change in invasiveness of non-native species.
- Effects of hydrological extremes, particularly droughts on freshwater ecosystems.

Threats to the condition of protected sites (Sites of Special Scientific Interest, NNRs, MPAs)

- Tipping points in the interactions between climate and ecosystem responses.
- Gradual change will reduce our ability to maintain our current SSSI objectives.

- Interactions between different aspects of environmental change combine to degrade protected sites.
- Climate change will interact with all the other pressures on ecosystems, including land use change, air pollution and invasive species.

Threats to the protection of the natural environment through incentive schemes

- Increased incidence of more extreme weather events compromises the ability of land managers to meet agri-environment objectives whilst maintaining farming businesses.
- Warmer, drier summers and increased fire risk, threaten the ability of land management to provide effective management of priority habitats such as peatland.
- Changes to species abundance and distribution, and the composition of communities will make existing programme options and prescriptions less effective.
- Sea level rise affecting inter-tidal and coastal habitats, make existing scheme options and prescriptions unviable.

Threats to our delivery of planning and sustainable land use responsibilities

- Unsustainable abstraction of water due to summer drought in water stressed areas may have a negative effect on designated sites and BAP habitats.
- Unsustainable responses, especially at the coast, which do not use an ecosystem approach.

4.2.2 Impacts of N management measures on sensitivity of habitats to climate change

Many of the climate change impacts identified above operate at the system level, or are outside the control of site managers, e.g. the climate niche space of a species. Here we identify for each of the N management measures, whether implementation of that measure is likely to increase, decrease or have no impact on the system sensitivity to climate change, based on the potential impacts listed above in section 4.2.1.

4.2.2.1 Grazing

Grazing alters habitat suitability primarily by opening up the canopy, reducing dominance of fast-growing species and creating germination niches, thereby increasing sward heterogeneity. Increasing the level of grazing intensity, which could be recommended for N mitigation, may reduce competitive pressure on slow growing species, allowing them to persist longer under climate change. Similarly, the enhanced creation of germination niches due to small scale soil disturbance by grazers provides a mechanism for enhancing the resilience of grasslands to withstand adverse climate change effects caused by competition. Lastly, a shorter canopy will also lead to lower rates of evapotranspiration and therefore may help moderate problems of increasing soil moisture deficit predicted under climate change, particularly in the south and east. In general therefore, increasing the intensity of grazing regimes is likely to help moderate some adverse effects of climate change in grasslands.

4.2.2.2 Cutting

Cutting influences habitat suitability in similar ways to grazing, but with some differences. The reduction in canopy height applies only to the period immediately after cutting, unless combined with aftermath grazing. Therefore changes in competitive advantage and reduced evapotranspiration as a result of cutting will have less effect than grazing. Cutting tends not to create germination niches through soil disturbance, and therefore not as much sward heterogeneity. For these aspects therefore, cutting has less potential than grazing to moderate some adverse climate change impacts in habitats where it is applied, but still provides some benefit compared with no cutting. On the other hand, cutting (with biomass removal) exports much greater quantities of N and P from the system, and this may help reduce soil fertility to the extent that nitrophiles and invasive species are less likely to spread under climate change. Therefore, enhanced cutting regimes have the potential to reduce sensitivity of habitats to climate change, providing caveats about timing of cutting etc., discussed in Chapter 3, are observed.

4.2.2.3 Burning

More frequent burning is suggested as a management tool to remove N from the system and reduce above-ground biomass in heathlands. Concerns raised about fire-risk under climate change apply primarily to accidental burns in heathland and peatlands, or to management burns which get out of control. In general, more frequent controlled burning is likely to reduce the stock of combustible fuel, which should mean that accidental burns will burn at lower temperatures, and will be less likely to spread over large areas as they will encounter other areas burnt at different timescales which will act as firebreaks. From this perspective, more frequent burning is likely to reduce the damage caused by accidental fires.

4.2.2.4 Fertilisation

The recommendation for mitigation of N impacts is currently to avoid fertiliser application wherever possible, due to its adverse impacts on both habitat suitability and on N storage in the system. This advice will also help protect habitats under climate change, since there are suggestions that stored N in soils may re-enter the available N pool via increased rates of mineralisation, which may act as a facilitating mechanism for the spread of undesirable species such as nitrophiles, and non-native or native invasive species.

4.2.2.5 Liming

The recommendation for mitigation of N impacts is currently to avoid liming in most,situations, due to potential adverse impacts on species composition, soil processes and on N availability in the system. This advice will generally help protect habitats under climate change, since liming may increase the availability of N, facilitating the spread of undesirable nitrophiles or invasive species.

4.2.2.6 Hydrological management

Recommendations for hydrological management tend to be site and system-specific. Where those recommendations include raising of water levels, this is likely to help moderate some of the adverse effects of climate change on wetland habitats listed in section 4.2.1, resulting from increased drought or summer soil moisture deficits. Conversely, recommendations to lower water tables may lead to greater sensitivity to drought, depending on the habitat.

4.2.2.7 Scrub and tree management

Scrub removal in non-woodland habitats is likely to help moderate adverse effects of climate change on target species of these habitats, but in the context of the wider landscape composition may act to reduce the ability of some woodland species to move between woodland areas.

Some woodland management options to mitigate N impacts are likely to be beneficial in terms of moderating effects of climate change. Coppicing improves habitat suitability for a wide range of species. Other guidance for N management of woodlands suggests minimal management is required which may not help alleviate climate change impacts.

4.2.2.8 Disturbance

Disturbance as a habitat management measure has limited applicability for most UK habitats, with the exception of some lowland heaths and coastal dunes, where it has potential to remove soil N stocks or to mitigate over-stabilisation of dunes. In heathlands, the interactions with climate change are unknown. For coastal dunes and slacks however, it is a management technique which can strongly increase the resilience of dune systems to cope with adverse effects of climate change. This is because it reinstates natural dune forming processes allowing the system to effectively become self-regulating and to find a new equilibrium to changing climate conditions. This is particularly important for dune slack wetlands which face an uncertain future under climate change (Curreli *et al*. 2013).

4.2.2.9 Summary

In almost all of the management measures discussed above, with the possible exception of some woodland management recommendations, activities to mitigate adverse effects of N on habitat suitability or on N storage in ecosystems will also help moderate some of the adverse effects of climate change. This is primarily because these measures act to improve habitat suitability, which will be of benefit whether the driver is N deposition or climate change, or they act to reduce the amount of available N in the system thereby increasing the resilience of ecosystems to some aspects of climate change.

4.3 How changes in climate over the next few decades could affect habitat response to management measures in place for nitrogen and influence their effectiveness at mitigating impact.

This section tackles the question above in two ways. Firstly it reviews how climate change is likely to affect habitat sensitivity to N deposition – their sensitivity will change and we need to understand how that sensitivity will change if we are to effectively manage habitats to mitigate N effects into the future. We do this by considering impacts on N cycling from a critical loads perspective. Secondly, we summarise how management measures in place for N are likely to need to adapt in the light of changes in natural processes as a result of climate change.

4.3.1 How will climate change affect habitat sensitivity to N deposition

Climate change will affect the underlying N transformation processes which govern N cycling within habitats as well as having impact on distributions of individual species and communities. A useful conceptual approach for structuring responses of N to climate change is the critical loads Simple Mass Balance (SMB) equation. This summarises the loss terms for N in ecosystems, and is parameterised by calculating the losses that would occur in a natural habitat which is not impacted by excess N deposition. The SMB critical load represents the sum of all the loss terms, i.e. the quantity of N that would be processed in an un-impacted habitat without altering the system.

For nutrient N, the SMB critical load (Hall *et al*. 2004) is defined as:

$$CL_{nut\ N} = N_u + N_i + N_{de} + N_{le\text{-}crit}$$

where:

$$N_{le\text{-}crit} = Q_{le} \times [N]_{crit}$$

In the equations above, N refers to nutrient N and the terms are defined as follows:

u - N uptake by plants and its subsequent removal in harvested biomass, where appropriate

i - long term immobilisation as organic N in soil

de - denitrification

le-crit - the acceptable level of N leaching, i.e. the amount of leaching that would be expected due to natural processes in an unimpacted natural system. This in turn is a function of:

$[N]_{crit}$– the acceptable nitrate concentration in soil water below the rooting zone (i.e. after plants and soil microbial processes have met their demand)

Q_{le}- the percolation flux of water leaving the rooting zone, hereafter termed runoff.

Separate SMB equations deal with the acidifying effects of N, in combination with sulphur, which also use the N_u, N_i and N_{de} terms described above.

Changes in rainfall, temperature, evapotranspiration (and CO_2 concentrations) all have the potential to alter the magnitude of these natural N cycling processes, with implications for the critical load. Climate has two main implications for processes, summarised as chronic effects and acute effects. Chronic effects are those resulting from slow changes in temperature, rainfall etc., impacting on average rates of processes. Acute effects are those which occur either through high impact episodic events such as severe drought, frost, flooding, and fire, or those mediated by other biotic processes such as large-scale pest or disease outbreaks. These changes are explored below, using evidence from the literature, drawing substantially on a report on this topic to Defra (Jones *et al*. 2012b). In general, the findings from Jones *et al*. (2012b) suggested that CO_2 effects were much smaller than temperature effects so we do not consider them further here. There is a greater evidence base to support inference on the chronic effects because they are simpler to model and to test experimentally and it is these effects we discuss here, however it may be the acute effects that ultimately have the greatest impact.

4.3.1.1 Plant uptake (N_u)

Climate can alter the uptake term through effects on plant growth, i.e. net primary productivity (NPP). Nitrogen losses from plant uptake and removal are relevant to forest management where N is locked up in wood and removed in harvesting. It also has relevance for hay meadows and other semi-natural systems where biomass is harvested and removed off-site. In all other habitats and in un-managed woodlands, the N in plant biomass is returned to the soil and forms a component of the long-term N immobilisation discussed separately below.

Increased temperatures are generally predicted to cause an increase in plant growth in temperate latitudes, due to increases in N mineralisation and hence available N for plant growth (e.g. Ducharne *et al*. 2007; Emmett *et al*. 2004b; Sardans *et al*. 2008) and due to a lengthening of the growing season (Linderholm, 2006). Some changes are counteracted by increased leaf respiration (Bernacchi *et al*. 2001), by sub-optimal soil moisture – too wet or too dry (Leirós *et al.* 1999), and by acute effects of climatic extremes such as drought, frost etc. which cause temporary reductions in plant growth. Responses may be species specific: Deciduous trees generally benefit from rising temperatures due to a longer growing season, while conifers may lose out due to the net effect of higher winter leaf respiration (Davi *et al*. 2006).Lindner *et al*. (2010) suggest that forest growth in Europe will increase in northern and western areas, but decrease in southern areas, while modelling by Wamelink *et al*. (2009b) showed increases in tree growth rates between 50 and 60 degrees North, but decreases in growth rates above and below those latitudes. Similar estimates come from Reinds *et al*. (2009). In grassland and agricultural systems temperature effects may be mixed (Campbell *et al*. 2000). Annuals tend to accelerate their life cycle rather than increasing uptake (Patil *et al*. 2010). However Rustad *et al*. (2001) reviewed a wide range of experimental warming studies in grasslands and suggest that studies with a mean soil temperature increase of 2.4 °C resulted in an average increase in plant production of around 19%.

In northern and western parts of Europe, rainfall is generally not limiting to growth, in contrast to southern and continental Europe. An increase in rainfall in the north and west may even lead to reduced tree growth and reduced grassland production (Marcolla *et al*. 2011) due to waterlogging. Rainfall effects are generally less important than temperature effects (Solberg *et al*., 2009) for tree growth, particularly for conifers and sclerophyllous evergreens which are well adapted to low rainfall (Davi *et al*. 2006). Solberg *et al*. (2009) showed that tree growth responses across Europe to changing rainfall were both species-specific and varied with latitude, with rainfall effects typically an order of magnitude less than variation in tree growth due to temperature.

Physiological responses to increased CO_2 result in greater water use efficiency of plants (Field *et al*. 1995), as well as greater photosynthetic efficiency, which together enhance growth. In forests, CO_2 is predicted to increase tree growth (Davi *et al*. 2006), while in grasslands, a doubling of ambient CO_2 led to increased production of around 17% (Campbell *et al*. 2000). However, CO_2 effects on growth are generally smaller than those due to climate (Reinds *et al*. 2009; Wamelink *et al*. 2009b) and we do not consider them further in this study.

In summary, we make the assumption that rising temperature will increase plant uptake of N and other nutrients in most UK habitats, applying a value of 10% per degree C for woodland (Rustad *et al*. 2001) which we also apply to heathland, and 7.9% for grassland (Rustad *et al*. 2001). We assume higher rainfall will increase plant tree uptake by 0.25% per mm annual rainfall (Solberg *et al*. 2009), but have insufficient information for other habitat types.

4.3.1.2 Nitrogen immobilisation (N_i)

Immobilisation represents the long-term accumulation of N (and C) in soil organic matter. This is a function of the balance between increased organic matter inputs from plant productivity and mineralisation or decomposition of that organic matter. Because soil N and C are both stored in complex organic compounds we make the assumption that data on changing C contents also reflect changing total N content, i.e. that the C:N ratio remains unchanged. Climate effects on soil organic matter (C) accumulation are both habitat and latitude dependent. In European forests, the net effect of climate change is projected to be an increase in soil C in mid-latitudes relevant to the UK situation, but with decreases at higher and lower latitudes (Wamelink *et al*. 2009b), but the relative influence of temperature and rainfall is not differentiated. In heathlands, the picture is clearer, with increased temperature having a clear negative effect on soil C stocks in the UK, while changes in rainfall have less effect (Sowerby *et al*. 2008). In grasslands, the effect of climate on long-term C budgets remains unclear. In an alpine grassland over short timescales, net ecosystem exchange (NEE) of C varied from positive to negative during seven years measurements in a climate change experiment and showed carry-over effects between years mediated by plant storage (Marcolla *et al*. 2011).

In summary, we assume rising temperature will increase N immobilisation in forests by 23% per degree C (Wamelink *et al*. 2009b), but will reduce N immobilisation in heathlands by -19% per degree C (Sowerby *et al*. 2008). Information from grasslands is unclear.

4.3.1.3 Denitrification (N_{de})

Denitrification in soils is controlled by soil water content once other pre-requisites such as available nitrate and soil pH are met (Heinen, 2006). The conditions governing denitrification are still not well understood, and predictions for the impacts of climate change vary. Temperature did not affect N_2O fluxes in forest, which were generally low and highly variable (Peterjohn 1993, 1994; McHale *et al*. 1998). As a single treatment factor in a heathland manipulation experiment, temperature did not alter N_2O fluxes on its own, but fluxes showed increases or decreases when it was combined with drought and elevated CO_2 respectively, but not with all three treatments combined (Carter *et al*. 2011). Since a major control on denitrification is availability of nitrate, changes in denitrification may well be driven by changes in mineralisation, where the consensus is for increases in mineralisation with rising temperatures (Rustad *et al*., 2001; Sowerby *et al*. 2008).

As described above, denitrification rates are highly soil-moisture specific and the effect of decreasing rainfall, for example, will depend on the soil type and may increase or decrease denitrification depending on its soil moisture content. Rainfall does not appear to affect denitrification consistently in low N, drier habitats (Carter *et al*. 2011).

In summary, we assume a maximum increase in denitrification of 19.2% per degree C (Sowerby *et al*. 2008) in response to rising temperatures in heathlands, which we apply by default to other habitats in the absence of further information.

4.3.1.4 Runoff (Q_{le})

Runoff or rainfall surplus is the balance between rainfall and Actual Evapotranspiration, and controls the degree of flushing of N from below the rooting zone. In the SMB equations the acceptable leaching flux of N is a function of the leached water flux and critical N concentrations. Since evapotranspiration is controlled by vegetation type, predicting changes in runoff is spatially specific and is difficult to generalise (Green *et al*. 2011).

In general, higher temperatures increase evapotranspiration from plants and crops, which will result in reduced annual runoff (Chiew and McMahon, 2002; Patil *et al*. 2010), except where soil moisture deficit limits plant growth. However, the seasonality of these responses is complex. Runoff in North West Europe is greatest in winter, so a reduction in summer runoff due to high evapotranspiration may have proportionately little effect.

Increasing precipitation should directly lead to increasing runoff, although in drier areas depending on the time of year that rain falls, it may first alleviate soil moisture deficit, thereby increasing evapotranspiration until the soil storage capacity and plant demand are exceeded, beyond which it then increases runoff. Lysimeter studies in a controlled experiment manipulating rainfall in Denmark showed that increased rainfall volume and increased rainfall days increased leachate drainage by 46% and 10% respectively, but effects were not additive (Patil *et al*. 2010).

In general in the UK, climate change is projected to increase runoff over the next few decades, but to decrease it thereafter, due to the balance between soil moisture deficit and evapotranspiration linked to rising temperatures (Holman, 2006; Younger *et al.* 2002). There is both a seasonal and a regional dimension to changing runoff in the UK. Winter runoff is projected to increase and summer runoff to decrease overall, with winter runoff enhanced in the north west and decreases in runoff in the drier south east (Pilling and Jones, 1999; UKWIR, 2003). Annual runoff values for the UK, give broad predictions of increases around 10% in the north and west, and decreases of around 5% in the south and east by the 2080s under the SRES A1b emissions scenario (Nohara *et al*. 2006) with similar magnitudes predicted by other studies (Milly *et al*. 2005; Alcamo *et al*. 2007).

In summary, we apply an increase of 10% runoff in the north and west, a decrease of 5% runoff in the south and east, with a zone of no change in runoff between the two. We use current distribution of runoff to apportion these changes, with increases applying where current runoff >800 mm/yr, decreases where current runoff <500 mm/yr, and no change in between these values.

4.3.1.5 Leachate concentrations (N_{crit}) (and fluxes)

Leaching fluxes are a function of both runoff volume and element concentrations in the soil pore water. Runoff is discussed above, here we focus on climate change effects on concentrations of N or DOC in water leaving the rooting zone resulting from the balance between mineralisation or other inputs, and biological uptake by plants and microbes or chemical binding to the soil. Here we assume no change in C:N ratio, meaning that DOC can be a surrogate for DON, the dominant form of leachate N in unimpacted catchments (Willett *et al*. 2004).

N and DOC production: rising temperature generally increases the rate of net mineralisation, provided soil moisture is optimal (Rustad *et al*. 2001; Emmett *et al.* 2004b; Sardans *et al.* 2008; Patil *et al*. 2010), however plant production will also increase. Many studies assume an increase in leaching of N and DOC due to rising temperature, i.e. increases in mineralisation or decomposition outweigh changes in uptake (e.g. Mol-Dijkstra and Kros, 2001). In boreal catchments, increases in river N fluxes have been attributed to increased mineralisation due to rising temperatures (Wright *et al*. 1998). However, these effects are likely to be dependent on latitude, altitude, soil and vegetation type. Indeed, some studies show negative relationships between temperature and N leaching in the UK (Ineson *et al*. 1998; Monteith *et al*. 2000), suggesting that uptake due to increased production may dominate over enhanced decomposition. Nitrate leaching was negatively correlated with latitude in European forests, i.e. increased with temperature (Dise and Wright 1995), but it was not possible to separate effects of temperature from co-correlated increases in N deposition (Dise N, pers comm.). Studies in heathlands suggest that nitrate leaching is only increased by temperature in N saturated systems (Beier *et al*. 2008). There does not appear to be consensus on the effects of temperature on N or DOC leaching.

Overall due to lack of both consensus and quantified studies from which to derive dose response functions, we assume no change in N concentrations, but that changes in fluxes will be driven by changes in runoff volume.

4.3.1.6 Summary

In summary, chronic (i.e. slow and subtle) effects of climate change via changes in temperature and rainfall will affect ecosystem processes, and therefore the rate and mechanisms of N removal from the system. This means their sensitivity to N will change. Rising temperatures will increase nutrient availability and plant growth. Effects on long-term N storage in soils are habitat specific and depend on the balance between enhanced plant growth and increases in organic matter decomposition. In woodlands they will increase N storage in soils, but in heathlands will decrease it. Denitrification will increase in wetland systems.

In general, effects of rainfall are much smaller than effects of temperature, but may moderate temperature effects if soils become too dry. The exceptions are runoff and leaching of N, both of which are largely governed by changes in rainfall, and are predicted to increase in the north and west and decrease in the south and east.

4.3.2 Implications for management

4.3.2.1 N_u – Nitrogen uptake/offtake

In forests, heathlands and grassland the increase in plant productivity with rising temperature means that the uptake term for N becomes larger, more N is removed from the soil system, and therefore rates of N accumulation in the soil will be lower. This is manifest through management in two ways: either management frequency remains the same but more N is removed in each management cycle due to greater plant biomass, or that management frequency increases in response to faster plant growth. In theory this suggests a higher SMB critical load is applicable and that the system is less sensitive to N. This conclusion derives from a N budget perspective. However, from a habitat suitability perspective, other considerations apply.

Greater plant growth in any habitat is likely to exacerbate impacts of N on habitat suitability. Germination niches or gaps in the canopy caused by disturbance will be available for shorter periods and shading effects of competition will be exacerbated. In order to maintain equivalent levels of habitat suitability, the frequency and or intensity of management will have to increase. For example, cutting frequency may have to be increased and/or timings of cuts brought forward, and grazing intensity or duration may have to be increased. There are likely to be unintended consequences associated with these changes in management, which are difficult to predict, particularly for responses of complex species mixtures to changes in cutting regime via effects on timing of seed set etc.

4.3.2.2 N_i – Nitrogen immobilisation

In forests, there is greater long-term N storage in soil due to enhanced plant production as a result of rising temperatures. This implies a higher SMB critical load and lower sensitivity to N. In practice, although the critical load is higher, the pool of total N in the soil pool will be accumulating faster, which may be vulnerable to remobilisation through changes in other soil processes, as is shown for heathlands below. Therefore, increases in soil N pools will result in a decline in the resilience of the system to future perturbations.

Management of forests needs to be aware of the increasing soil N stocks and be wary of measures which might release this N or increase its variability. This is of particular relevance to forests since most management practices cause a degree of soil disturbance or open up the canopy, both of which are likely to result in release or re-mobilisation of soil N and facilitate colonisation of nitrophilic species which can take advantage of that N.

In heathlands, the opposite effect is suggested, with reduced long-term N storage in soil due to greater rates of mineralisation. This implies a lower SMB critical load and increasing sensitivity to N deposition. However, it may increase the resilience of the system after a period of adjustment due to removal of the more labile N compounds and a consequent lowering of the soil N stocks.

Management of heathlands should be aware of the short-to-medium term consequences of increased mineralisation in response to rising temperatures, in that available N is likely to increase during this period of adjustment, with some potential for spread of undesirable species.

In grasslands, the net effect on soil N stocks and therefore the implications for management are not clear.

4.3.2.3 N_{de} - denitrfication

In all habitats, the greater rates of denitrification with increasing temperature mean a larger loss term, suggesting a higher SMB critical load and consequently a reduced sensitivity to N. This is largely beneficial for site management of N budgets, since there are no obvious adverse impacts at local scale and little or no implications for changing management practices. However, the benefits in terms of N budgets are only likely to make much difference in wetland habitats where denitrification rates are highest. For example, the effect of denitrification on N budgets in dune slacks can slow succession and prolong the longevity of early successional habitats (Grootjans *et al*. 2004). On a national to global scale, increased emissions of N_20 will have implications for climate forcing as it is a greenhouse gas.

4.3.2.4 $N_{leaching}$

Since we assume N leaching is driven by changes in runoff, the impacts apply to all habitats but will be location specific. In the north and west, the larger leaching fluxes with increased runoff mean a higher SMB critical load and reduced sensitivity to N. From a site management perspective there are no obvious adverse impacts unless on-site wetland habitats will be affected. Outside of the site, there may be concerns about pollution swapping, and implications for water quality off-site. This is considered unlikely for most natural habitats unless they are approaching N saturation, cover large areas, and lie upstream of other sensitive habitats. However, some sections of the UK uplands which have historically received high levels of air pollution such as the Pennines, may fall into this category.

In the south and east, the converse applies. Smaller leaching fluxes associated with decreased runoff mean a lower SMB critical load and increased sensitivity to N. In principle, available N is likely to remain longer in the soil profile and therefore be available for plant and microbial uptake for longer periods. This could result in enhanced plant growth with consequences for management as discussed under plant uptake terms above. However, this hypothesis is untested as yet.

4.3.3 Summary of implications for management

The implications of changes in each SMB term for management are summarised in Table 4.1 below. The two terms over which managers have the greatest opportunity to either control or to mitigate the effects are N uptake and N immobilisation. Both these terms have a medium to high impact on the SMB critical load, but have high implications for counteracting adverse effects. Managing N uptake has direct implications both for habitat suitability and for long-term N budgets, and consideration of which management options to focus on should consider implications for both. By contrast, N immobilisation has long-term implications for soil N storage and the resilience of the system which need to be borne in mind when selecting management options. Note that N immobilisation is twice as sensitive to temperature as N uptake.

Table 4.1.Summary of implications of climate change for each SMB loss term and management options.

SMB term	Response function with temperature/ leaching for forest (heathlands in brackets)	Sensitivity of contribution to SMB critical load	Importance for management	Management potential to respond to effects
Nu – Uptake	+10 % per ºC rise	Med-High	High, progress can be made over short timescales	High potential, by increasing intensity or frequency of grazing, cutting or burning
Ni – Immobilisation	+23% per ºC rise (-19% per ºC rise)	Med-High	High, but a longer term issue – alters resilience of natural systems	Limited potential, but managers should be aware of management activities which might affect soil N stocks
Nde – Denitrification	+19.2% per ºC rise	Low	Low, denitrification may be beneficial	Low
Nleaching (runoff)	+10% in North West UK -5% in South East UK	High	Low – High, depending on UK location	Low

4.3.4 Implications for critical loads

The net effect of these changes in individual SMB terms for the overall SMB critical load were explored for forest systems under UKCP09 climate change projections to 2080 in Jones *et al*. (2012b). With a view to wider implications for other habitats, the SMB critical loads were re-calculated with and without the uptake term.

In forests, rising temperature caused an increase in critical load, which offset minor changes in the critical load resulting from altered runoff. The combined effect of temperature and runoff led to an increase in critical loads of 35-37 %, depending on location in the UK, and whether uptake was included. The implication for management is that habitats will become less sensitive to N, but the likely management responses depend on which loss terms are affected to the greatest extent, and which loss terms have the greatest implications for site management of N budgets and their long-term effects.

In heathlands, where the immobilisation response function is negative, there is a net decrease in critical loads of 13-23% depending on UK location, with lowest critical loads in the South East. However, if uptake is also considered, some terms cancel out and there is no change in critical loads for the North West, but a 7% reduction in critical load for the South East. The reduction in critical loads means that habitats become more sensitive to N.

However, for both forests and heathlands, it is the impact on individual loss terms which is the most important for site level management of N, and in particular the uptake term over which site managers have the most control. Therefore these factors should be considered when drawing up management options to mitigate N effects.

4.4 Interactions between management for climate change and N deposition

Based on the management recommendations above, and for the main habitat management options discussed in sections 2 and 3, we discuss the implications of managing for the combined drivers of climate change and nitrogen deposition.

4.4.1 Grazing

Increasing grazing pressure, either by raising stocking levels, or altering the duration or timing of grazing has the potential to improve or maintain habitat suitability under both climate change and N deposition. In the North and West UK, both N deposition and climate change are likely to promote faster plant growth due to warmer temperatures and longer growing season, with a need for more active management to prevent adverse impacts on slow-growing species of conservation interest. In the South and East UK however, soil moisture deficits in drier summers under climate change may restrict plant growth so managers need to be aware of implications for overgrazing, stock condition, and damage to sensitive habitats in dry weather. The caveats identified in sections 2 and 3 about the dangers of overgrazing on certain sensitive species or overall species composition also apply.

Climate change is likely to increase slightly the amount of N removed by grazing in both stock live-weight gain and more so by leaching, but this will still fall far short of compensating N inputs from deposition.

4.4.2 Cutting

Increasing the frequency of cutting or advancing the timing of cutting to maximise N removal has the potential to improve or maintain habitat suitability under both climate change and N deposition. As with grazing, this is because both climate change and N deposition will likely promote plant growth in the North and West UK, but note possible soil-moisture deficit controls on plant growth in the South and East. The caveats identified in sections 2 and 3 apply about the implications of changing cutting times on seed set for species of conservation interest. How climate change will affect seed set is a major unknown and is likely to differ depending on whether seed set is controlled by temperature, day-length or is linked to stress-responses. Changes in species composition will also depend on the mix of annual and perennial species.

Cutting, with removal of biomass, is the measure most effective at removing N from the system, short of the more destructive methods such as turf stripping. Faster plant growth under climate change provides the potential to remove more N from habitats. In any case, altering cutting methods is likely to be necessary to maintain current habitat condition under climate change (see section 4.3.2.1 and Table 4.1).

4.4.3 Burning

As with cutting, increasing the frequency and/or intensity of burning provides benefits under both climate change and N deposition. It is likely that altering current burning management practices will be necessary to both maintain current habitat suitability and to maximise N removal from the system. The impacts on habitat suitability need to consider the caveats raised in sections 2 and 3.

Removal of N as a result of burning may increase under climate change, due to potentially hotter burns as a result of drier fuel, and due to greater leaching losses caused by faster mineralisation in the post-burn period. However, the period of bare soil is likely to be shorter post-burn in the North and West due to faster vegetation establishment, leading to a steeper but shorter leaching pulse of N. Conversely in the South and East, vegetation establishment may be slower due to soil-moisture deficits, leading to a longer pulse of N leaching. Although net fluxes of N are controlled by rainfall, the effect of climate change on net N fluxes in drier areas remains uncertain.

4.4.4 Fertilisation and Liming

We do not consider these in detail here, but note that any impacts caused by fertilisation and liming are likely to happen faster under climate change.

4.4.5 Hydrological management

Adapting hydrological management techniques is likely to be a high priority to jointly manage impacts of climate change and N deposition. Lower runoff in the South and East is likely to concentrate nutrients and pollutants in surface water and groundwater, with the potential to exacerbate eutrophication impacts in water-dependent habitats. Conversely higher runoff in the North and West may alleviate some impacts, but note that increased intensity of rainfall may cause different problems by flushing fertilisers or dung into water courses, thus elevating total nutrient loads.

In addition, falling water tables under climate change will have synergistic but strongly deleterious effects on some groundwater-dependent ecosystems. Altered hydrological regimes, and particularly lower water tables will directly affect species composition, but will also indirectly alter soil processes by reducing the chemical buffering effects of groundwater and by increasing mineralisation of stored nutrients in soils which have dried out as a result of lowered water tables. Management to maintain or reinstate natural hydrological regimes is crucial to maintain health of these habitats. Managers should note the caveats in sections 2 and 3 on the geochemical and nutrient composition of any water sources entering wetland sites.

4.4.6 Scrub and tree management

The frequency or intensity of scrub and tree management will need to increase under climate change to maintain current levels of habitat suitability and N removal, although there may be some differences between North West and the South East UK due to soil-moisture deficit in drier summers. Some species may become more invasive as climate change leads to some alleviation of current climatic constraints on species reproduction or spread such as severe winter frosts.

In woodlands, faster tree growth will similarly require more intensive management for both climate change and N impacts. In addition, the increased spread of insect pests or pathogens may also require more active woodland management, with as yet unknown consequences for N cycling.

4.4.7 Disturbance measures

Disturbance activities such as turf stripping are usually considered as one-off rather than routine management measures. Therefore their frequency is unlikely to change in response to either climate change or N deposition. They are currently practiced at small scale in some UK habitats, but may be considered more widely relevant, bearing in mind the considerable caveats attached, and learning from experience applying such techniques on the continent.

In dune systems, holistic disturbance approaches which work with natural processes such as dune remobilisation are increasingly regarded as a viable management technique to deal with the joint threats posed by climate change and N deposition.

4.4.8 The wider landscape

Management options to mitigate N impacts primarily focus on specific-habitats at the site scale. Management for climate change, while considering site scale options also looks at wider landscape composition and the connections between habitats. This may lead to some tensions between competing management objectives at the site-scale, for example retaining tree cover as habitat corridors, versus scrub and tree management to maintain habitat condition.

4.4.9 Summary

Examination of the management options for both climate change and N mitigation leads to a number of conclusions. There is considerable complementarity in the management options required to tackle both issues, due to similar impacts of climate change and N deposition in many habitats. In order to maintain or improve habitat suitability, the frequency or intensity of measures such as grazing, cutting or burning will all need to increase. Increasing the frequency or intensity of management will also lead to greater N removal, but will not substantially change the net N balance of different management measures. Cutting with biomass removal and some disturbance measures remain the only methods which will actively reduce accumulated N stocks. The need for monitoring and possible subsequent hydrological management of wetland systems is likely to increase in importance as N deposition and climate change both have strong negative and synergistic effects. Working with natural processes is likely to make management for climate change and N deposition impacts easier and cheaper in the long-run, particularly in the case of coastal habitats. Regional differences in climate change within the UK may lead to different emphasis of management options in the wetter North and West compared with the drier South and East.

4.5 Summary of climate change impacts and N management

In relation to the three issues discussed in this section:

Management for N will not make habitats more vulnerable to climate change. Most activities will help moderate some of the adverse effects of climate change. This is primarily because these measures act to improve habitat suitability, which will be of benefit whether the driver is N deposition or climate change. They may also reduce the amount of available N in the system thereby increasing the resilience of ecosystems to some aspects of climate change.

Climate change will affect habitat responses to N deposition, via changes in ecosystem processes. The main impacts of temperature will be to increase plant growth, and to increase denitrification in wetlands. Rising temperatures may increase long-term N storage in woodland soils, but decrease it in heathlands. Effects on rainfall vary across the UK, increasing runoff and leaching fluxes in the north and west, but decreasing them in the south and east. Overall, climate change will make woodlands less sensitive to N deposition in terms of accumulating N in the system (the Simple Mass Balance critical load increases by ~35%), but will make heathlands more sensitive to N deposition (the Simple Mass Balance critical load decreases by 0 – 23%).

There is considerable complementarity in the management options required to tackle both N deposition and climate change. In order to maintain or improve habitat suitability, the frequency or intensity of measures such as grazing, cutting or burning will all need to increase to keep pace with natural processes. Regional differences in climate change within the UK may lead to different emphasis of management options in the wetter North and West compared with the drier

South and East.

5 RECOMMENDING REALISTIC AND PRACTICAL MANAGEMENT MEASURES FOR DIFFERENT HABITAT TYPES WHICH COULD BE USED TO REDUCE NITROGEN IMPACTS OR SPEED RECOVERY AND DISCUSSION OF THEIR EFFECTIVENESS.

This section describes the recommendations for management strategies with the potential to mitigate the impacts of N deposition on individual habitats. The management recommendations should be considered general advice and suitability for individual sites will need to consider conservation objectives and circumstances. The conditions at the site prior to management to mitigate N deposition impacts are an important consideration and may impact on the suitability of different management strategies, their likelihood of success and the rate of recovery.

Management recommendations were drafted based on chapters 2 to 4 of this report and were then presented to Habitat Specialists from the Countryside Council for Wales, Natural England, Scottish Natural Heritage and the Northern Ireland Environment Agency. Their opinions were sought on the following questions, and recommendations were revised accordingly:

- Are the recommendations realistic and practical?
- Are there situations when they might not be applicable?
- Are there any differences we should draw out for upland and lowland habitats?
- Is management in these habitats changing in response to climate change anyway and how might this affect our recommendations?
- What would be the best way for us to present this information so it is useful for you and other habitat specialists?

The management recommendations made are all based on measures that can be implemented within a site of conservation interest.

5.1 General recommendations

- To protect habitats from the negative effects of atmospheric N deposition, they should be well managed according to conservation aims.
- Many of the current regulations advise against the addition of fertilisers. However, for some habitats there are some schemes that permit low to moderate levels of fertiliser addition. In order to prevent exacerbating the effects of N addition we would advise that no fertiliser (organic or inorganic) is added in any habitat, if a major concern of management is to reduce effects of N deposition. Adding fertiliser will counteract attempts to reduce N impacts and will slow down recovery.
- Similarly, in grazed habitats a number of schemes permit supplementary feeding. To prevent exacerbating the effects of N addition we would also advise against this in all habitats because supplementary feeding causes further import of nutrients and seed to the site.

5.2 Broadleaved, mixed and yew woodland & (natural) coniferous woodland

5.2.1 Background

- Managing the habitat to maximise habitat suitability is advised. In woodlands it is difficult to strike a balance between encouraging suitable ground flora and increasing light levels which may encourage eutrophic ground flora species.
- Well managed woodland in favourable condition will be more resilient to the negative impacts of N deposition.
- Current recommendations to create new deadwood by felling or ring barking trees may result in unnecessary N returns to soil and may have implications for N cycling. Therefore, the impact of ring barking should be further investigated.
    - The mechanisms and extent of responses of soil N processes to these management options should be further investigated.
    - The management option is sometimes used to remove invasive species and in these cases should be continued.

5.2.2 Recommendations for maintaining current management

- Current recommendations to retain deadwood should continue
    - While retention of deadwood has the potential to increase N accumulation on-site, the N content of wood is relatively low and decomposition rates are slow. Returns are likely to be outweighed by the benefits to invertebrates.

5.2.3 Recommendations for management changes

- Litter removal is a traditional practice in some woodlands, which would remove N stocks and has the potential to reduce N deposition impacts.
    - This technique is unsuitable in upland woodland sites where the litter layer is essential for soil formation and conservation.
    - There has been very little investigation into the impact of this practice on N cycling and unintended consequences on ground flora, litter and soil fauna, but further work should be undertaken to investigate its potential, and to assess the costs of revising this technique.

Table 5.1 Summary table of management recommendations which could be used to reduce nitrogen impacts or speed recovery for woodland habitat. A confidence of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Recommendation	Justification	Confidence
Do not apply fertiliser	Avoids adding N to the site	1
Do not supplementary feed	Avoids adding N to the site	1
Continue to retain deadwood	N remains on site but in low quantities. Conservation benefits of deadwood outweigh damage.	2
Avoid ring barking	Avoids N returns to soil	3
Litter removal (lowland only)	Removes N from the site	3

5.3 Acid grasslands

5.3.1 Background

- Grazing is currently the main management technique, and is the only realistic and feasible method of management in this habitat. Cutting (with removal) removes N from above-ground stocks, but is not practical as a management technique in larger sites and in some terrain. A change from grazing to cutting will also result in changes in species composition, as cutting is less effective at opening up the canopy.

- Grazing removes very little N from the site in live-weight gain, and may alter rates of N cycling due to increased N return through urine and dunging.
- The main mechanism for reducing N deposition impacts is through increased light availability via lower canopy levels so maintaining a short sward is beneficial.
- The need for increased grazing intensity under climate change requires a delicate balance between optimum and excessive grazing levels.
- Finding and maintaining an optimal grazing intensity to reduce N deposition impacts whilst not having negative impacts on species composition is likely to be very difficult.
- There is little or no data currently available to assess the effect of small changes in grazing intensity in semi-natural grasslands so further research is required to assist in recommending suitable grazing levels to reduce N deposition impacts.

5.3.2 Recommendations for maintaining current management

- Grazing has the potential to reduce N impacts through changes in timing of grazing, increased grazing intensity, and selection of grazing animals.
    - Current advice to maintain sward heights to deliver conservation objectives for the habitat provides the best method of ensuring that grazing is adequate to maintain a suitable sward without risk of overgrazing.
    - Caution is needed because grazing can also result in loss of selectively grazed and grazing intolerant species and damage to lichens. Furthermore, if levels of grazing are too high it can lead to a dominance of grasses (also a negative effect of N deposition).
- Winter grazing can increase N losses by leaching (a benefit for site N levels) so the timing of grazing could be extended to include year round grazing, or stocking rates in winter could be increased where it is possible and suitable.
    - However this may present an increased threat to water quality and may increase poaching, soil erosion and soil compaction so caution is advised.
    - Winter grazing is already a common practice and can lead to an increased need for supplementary feeding.
- The use of mixed stock grazing is recommended where possible and provides other benefits for biodiversity conservation.
    - Cattle remove taller tussocky species that can potentially become dominant under high N deposition and have greater poaching effect creating regeneration gaps, whilst sheep and horses provide a shorter sward and maximise light availability.
    - Further evidence is needed to support this recommendation.
- Current advice to remove scrub should continue as scrub removal increases light and represents a removal of N as long as clippings are removed.
    - However, scrub provides an important habitat for birds and invertebrates and its removal should continue to be balanced with other conservation priorities.
- Current advice to not install drainage should continue as there are no benefits from reducing N deposition impacts by increasing drainage in acid grasslands.

- Current advice not to undertake activities resulting in large-scale disturbance of habitats should continue as there are no benefits to reducing N deposition impacts by disturbing soil in acid grasslands.

5.3.3 Recommendations for management changes

- The benefits that could be provided by stock management are worthy further investigation as a measure that could be targeted at restoration of heavily impacted sites. Anecdotal evidence suggests moving stock off land at night could result in an export of N.
    - The quantities of dung and urine produced at night are unknown, and so the trade offs in cost and time cannot be assessed as yet.
- Liming at low levels in acid grasslands could potentially reduce impacts of acidification in areas strongly impacted by acid deposition.
    - Great care would need to be taken to ensure that liming did not increase pH beyond approximately 5 as doing so would likely lead to large changes in vegetation species composition and could result in the mobilisation of other nutrients.
    - Further research is needed to determine how effective this method is, how practical it would be to apply, and the potential for unintended consequences on species, soil processes and soil C stocks.
    - The use of this method would need to be informed by soil testing and applied on a case by case basis considering conservation objectives.

Table 5.2 Summary table of management recommendations which could be used to reduce nitrogen impacts or speed recovery for acid grassland habitat. A confidence of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Recommendation	Justification	Confidence
Graze to sward height guidelines	Increases light availability	1
Mixed stock grazing	Increases light availability	1
Winter grazing	Increases light availability	2
Stock removal at night	Removes N from the site	3
Lime at low levels where suitable	Reduces acidification impacts	3
Continue to avoid installation of new drainage	No benefits by changing advice	1
Continue scrub management	Removes N and increases light availability	1
Continue to avoid disturbance	No benefits by changing advice	1
Do not apply fertiliser	Avoids adding N to the site	1
Do not supplementary feed	Avoids adding N to the site	1

5.4 Calcareous grassland

5.4.1 Background

- Grazing is currently the main management technique, and is the only realistic and feasible method of management in this habitat. Cutting (with removal) removes N from above-ground stocks, but is not practical as a management technique in larger sites and in some terrain. A change from grazing to cutting will also result in changes in species composition, as cutting is less effective at opening up the canopy.
- Grazing removes very little N from the site in live-weight gain, and may alter rates of N cycling due to increased N return through urine and dunging.

- The main mechanism for reducing N deposition impacts is through increased light availability via lower canopy levels so maintaining a short sward is beneficial.
- The need for increased grazing intensity under climate change requires a delicate balance between optimum and excessive grazing levels.
- Cutting creates a homogeneous sward which is not suitable for invertebrates.
- Finding and maintaining an optimal grazing intensity to reduce N deposition impacts whilst not having negative impacts on species composition is likely to be very difficult.
- There is little or no data currently available to assess the effect of small changes in grazing intensity in semi-natural grasslands so further research is required to assist in recommending suitable grazing levels to reduce N deposition impacts.

5.4.2 Recommendations for maintaining current management

- Grazing has the potential to reduce N impacts through changes in timing of grazing, increased grazing intensity, and selection of grazing animals.
    - Current advice to maintain sward heights provides the best method of ensuring that grazing is adequate to maintain a suitable sward without risk of overgrazing.
    - Caution is needed because grazing can also result in loss of selectively grazed and grazing intolerant species and damage to lichens. Furthermore, if levels of grazing are too high it can lead to a dominance of grasses (also a negative effect of N deposition).
    - Cutting (with removal) removes N from above-ground stocks, and may be practical at some smaller sites where restoration is necessary or grazing is not possible, but cutting needs to be sufficiently frequent to maintain a short sward and ensure that sufficient N is removed. All cuttings should be removed from the site.
- Winter grazing can increase N losses by leaching (a benefit for site N levels) so the timing of grazing could be extended to include year round grazing, or stocking rates in winter could be increased where it is possible and suitable.
    - However this may present an increased threat to water quality and may increase poaching, soil erosion and soil compaction so caution is advised.
    - Winter grazing is already a common practice and can lead to an increased need for supplementary feeding and consequent nutrient import.
- The use of mixed stock grazing is recommended where possible and provides other benefits for biodiversity conservation.
    - Cattle remove taller tussocky species that can potentially become dominant under high N deposition and have greater poaching effect creating regeneration gaps, whilst sheep and horses provide a shorter sward and maximise light availability.
- Current advice to remove scrub should continue as scrub removal increases light and represents a removal of N as long as clippings are removed.
    - However, scrub provides an important habitat for birds and invertebrates and its removal should continue to be balanced with other conservation priorities.
- Current advice to not install drainage should continue as there are not benefits to reducing N deposition impacts by increasing drainage in acid grasslands.
- Current advice not to disturb habitats should continue as there are not benefits to reducing N deposition impacts by disturbing soil in acid grasslands.

5.4.3 Recommendations for management changes

- The benefits that could be provided by stock management are worth further investigation as a measure that could be targeted at restoration of heavily impacted sites. Anecdotal evidence suggests moving stock off habitat land at night could result in an export of N.
    - o The quantities of dung and urine produced at night are unknown, and so the trade-offs in cost and time cannot be assessed as yet.

Table 5.3 Summary table of management recommendations which could be used to reduce nitrogen impacts or speed recovery for calcareous grassland habitat. A confidence of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Recommendation	Justification	Confidence
Graze to sward height guidelines	Increases light availability	1
Consider mixed stock grazing	Increases light availability	1
Consider winter grazing	Increases light availability	2
Consider stock removal at night	Removes N from the site	3
Continue to avoid installation of new drainage	No benefits by changing advice	1
Continue scrub management	Removes N and increases light availability	1
Continue to avoid disturbance	No benefits by changing advice	1
Do not apply fertiliser	Avoids adding N to the site	1
Do not supplementary feed	Avoids adding N to the site	1

5.5 Dwarf shrub heath

5.5.1 Background

- Grazing, burning and cutting are all used to manage vegetation in uplands and lowlands, although burning is not recommended for wet heath.
- Grazing is currently used as it is feasible and realistic, and increases light availability. Grazing removes very little N from the site in live-weight gain, and may alter rates of N cycling due to increased N return through urine and dunging.
- Cutting (with removal) removes N from above-ground stocks.
- Burning results in losses of N from stocks, impacts upon the rates of N cycling processes, and influences the subsequent growth and composition of vegetation due to the removal of vegetation.
- The frequency of burning should be defined relative to vegetation growth rates with more frequent burns in areas of rapid vegetation growth. Under climate change this may mean shorter burn rotations are required.

5.5.2 Recommendations for maintaining current management

- Burning is the most effective method of N removal from dwarf shrub heath.
    - o It also has a large number of potential unintended consequences which are ideally minimised by burning small areas at a time.
    - o Burning may be unsuitable in some sites. For example rich bryophyte communities and juniper are damaged by burning.
    - o Burning is currently not extensively used in lowlands, due to proximity to developed areas, and the risks associated with burning in lowland areas should be considered.

  - Consider the effects of burning on C stocks.
- Higher intensity burns would remove more litter and thus more N and should be used to promote heather regeneration.
  - High intensity burns have the potential to remove the seed bank. Using high intensity burns in small areas would minimise the impact of unintended consequences. However higher intensity burns may be harder to control so should only be recommended with caution.
- Grazing may also be used alongside other management methods. While this does not represent a large removal of N, it opens up the canopy.
  - Supplementary feeding may be necessary with winter grazing, and this should be used off site if possible.
- The benefits that could be provided by stock management are worth further investigation as a measure that could be targeted at restoration of heavily impacted sites. Anecdotal evidence suggests moving stock off habitat land at night could result in an export of N.
  - However the quantities of dung and urine produced at night are unknown, and so the trade offs in cost and time cannot be assessed as yet.
- Current advice to remove trees and undesirable species should continue as this management increases light and represents a removal of N as long as clippings are removed.
- Current advice to not install drainage should continue as there are not benefits to reducing N deposition impacts by increasing drainage.

5.5.3 Recommendations for management changes

- In areas where burning is not a suitable management method cutting provides an alternative method for reducing impacts of N deposition.
  - It is important that all clippings are removed from the site or effects of N deposition could potentially be exacerbated.
- In areas of extreme damage from N deposition turf stripping may provide a method to reduce N deposition impacts.
  - This is a very expensive solution and it has a large number of unintended consequences.
  - Although used extensively in The Netherlands it has not been extensively trialled in the UK.

Table 5.4 Summary table of management recommendations which could be used to reduce nitrogen impacts or speed recovery for dwarf shrub heath habitat. A confidence of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Recommendation	Justification	Confidence
Grazing	Increases light availability	2
Stock removal at night	Removes N from the site	3
Use cutting where burning not possible but remove cuttings	Removes N and increases light availability	1
Use burning where appropriate	Removes N and increases light availability	1
Define burn frequency relative to dwarf shrub heath growth	Removes N and increases light availability	1
Use high intensity burns where appropriate	Removes N and increases light availability	1
Avoid installation of new drainage	No benefits by changing advice	1
Continue scrub management	Removes N and increases light availability	
Consider turf stripping in heavily impacted sites	Removes N from the site	2
Do not apply fertiliser	Avoids adding N to the site	1
Do not supplementary feed	Avoids adding N to the site	1

5.6 Bog

5.6.1 Background

- Grazing and burning are both management techniques occasionally recommended in bogs and where undertaken have the potential to reduce N deposition impacts. However, both have a number of unintended consequences in bogs so should only be used where appropriate.

5.6.2 Recommendations for maintaining current management

- Current advice to remove trees and undesirable species should continue as this increases light and represents a removal of N as long as clippings are removed.
    - Removal of clippings can be a damaging operation, and disturbance to bog habitats should be minimised.
- Current practice allows small-scale peat cutting in some regions. This practice represents a localised export of N but there are potentially a large number of unintended negative consequences. Monitoring of recovery following peat cutting may help to develop best practice guidelines to maximise the benefits of the N removal and minimise unforeseen consequences.
- The current recommendation to block drains potentially increases N losses through denitrification. Denitrification rates are highest in areas with a fluctuating water table. Water management could be undertaken to maximise denitrification with the potential to reduce N stocks as long as species or habitat ecohydrological requirements are accounted for.
    - Increased dentrification rate also impacts upon water quality and greenhouse gas emissions.
    - However, water tables are difficult to manage.
    - Ecohydrological requirements for species or habitat should also be considered.

Table 5.5 Summary table of management recommendations which could be used to reduce nitrogen impacts or speed recovery for bog habitat. A confidence of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Recommendation	Justification	Confidence
Graze where appropriate	Increases light availability	1
Burn where already used for conservation	Removes N and increases light availability	1
Enable water table fluctuation	Maximises N loss	3
Continue scrub management	Removes N and increases light availability	1
Do not apply fertiliser	Avoids adding N to the site	1
Do not supplementary feed	Avoids adding N to the site	1

5.7 Coastal dunes and slacks

5.7.1 Background

- Scrub control is particularly important in dune habitats because shrubs increase the organic matter content of the soil and a number of the dominant shrub species (e.g. sea-buckthorn and gorse) are N fixing, providing additional N input. Some species (bird cherry, sea-buckthorn) are particularly invasive and may spread faster in N impacted sites.
- Dune heath sites may respond to N deposition and management similarly to other dune habitats, but there is a lack of research in this habitat.

5.7.2 Recommendations for maintaining current management

- Grazing is currently underutilised as a management tool in dunes and could be used to reduce N deposition impacts by increasing light levels in the lower canopy.
    - Grazing acts as a mechanism for disturbance which is also beneficial in this habitat.
    - High levels of grazing could damage sensitive habitats and have consequences for some invertebrates.
    - Further exploration of its suitability in different vegetation types, and the effects of different stock types and grazing intensities is needed.
- Scrub should be controlled strongly to maintain a low level of cover.
    - Some species (bird cherry, sea buckthorn) are particularly invasive and may spread faster in N impacted sites.
    - The habitat requirements of invertebrates and birds should be considered.
    - Removal of trees may promote further use of grazing.
    - Control of scrub and trees is also important to improve habitat resilience to other drivers such as climate change.

5.7.3 Recommendations for management changes

- Remobilisation of dunes on large sites would reinstate natural processes allowing sites to become self-regulating in terms of habitat responses to climate change and other long-term drivers such as N deposition and changes in hydrological regimes.
    - Although this incurs a high one-off cost it should reduce the need for management input in the future.
    - Remobilisation may also be beneficial for the conservations of species and habitat.

    - Gradients of disturbance (not restricting all sources of disturbance) in a site may be useful, for example by allowing some disturbance associated with recreational activities.

- Cutting removes N from the site as long as cuttings are collected and removed and may provide a suitable management tool on dune slacks in smaller sites or parts of sites where vegetation is tall or dense.
    - Grazing is preferable as it is more practical and cutting requires vehicle access which may be detrimental to site condition.
    - All cuttings should be removed as leaving material on the surface or buried increases N availability
- Hydrological properties of the groundwater (water levels, nutrient levels) are not easily controlled in dune systems, though where they are adversely affected by nearby land uses or management, steps should be taken to restore natural regimes.
    - Ecohydrological advice in guidelines should be updated

Table 5.6 Summary table of management recommendations which could be used to reduce nitrogen impacts or speed recovery for coastal dune and slack habitat. A confidence of 1 means that there is strong evidence to support the recommendation, 2 means there is some evidence to support the recommendation and 3 means more evidence needs to be collected.

Recommendation	Justification	Confidence
Continue or introduce grazing where appropriate	Increases light availability	1
Use cutting where grazing is not possible	Removes N and increases light availability	1
Remove all cuttings	Removes N from the site	1
Restore natural water regimes	Increases site resilience	2
Continue scrub management	Removes N and increases light availability	1
Remobilisation of dune systems	Restores natural dune processes	2
Do not apply fertiliser	Avoids adding N to the site	1
Do not supplementary feed	Avoids adding N to the site	1

5.8 Conclusion

There is some potential for reducing the impacts of N deposition through on-site management although this varies greatly between habitat and management practice. It is likely that small changes in management and adherence to appropriate guidelines could reduce the impacts of N deposition on habitat suitability and N removal and may already be doing so. However, management of a suitable intensity to remove sufficient N to fully offset N added by atmospheric deposition is likely to damage the habitat and result in a number of unintended consequences.

Further research is needed to determine the impacts of individual management practices on the N budget of different management practices in individual habitats. Further research is also needed to explore the potential for novel management techniques to remove N from sites.

All management recommendations that remove N from the site move it elsewhere and have the potential for unintended consequences. Consequently there is no substitute for reducing the amount of N deposited onto a site which can only be achieved through emission controls.

6 GLOSSARY

Acidification. Increase in soil acidity due to loss of base cations, such as calcium.
Brash. Remnants of cut vegetation.
Chain harrow. To drag a frame with a chain net over ploughed land to break sods and remove weeds.
Coppice. To cut back a tree to ground level periodically to stimulate growth.
Critical load. 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.
Ellenberg N score. The position of a species, or the overall mean score for the community, along a productivity/macro-nutrient availability gradient at which a species reaches peak abundance on a scale of nutrient poor (1) to nutrient rich (10).
Eutrophication. Excessive richness of nutrients.
Haylage. Silage made from grass that has been partially dried.
Hemi-parasite. A plant that is parasitic under natural conditions and is also photosynthetic to some degree.
High forest. Forest produced from seed or from planted seedlings, which usually consists of large, tall mature trees with a closed canopy, in contrast to a low or coppice forest.
Immobilisation (of N). Uptake of N into microbial biomass and thus unavailable for uptake by vegetation.
Leaching. Draining of soluble minerals away from the soil by the action of percolating water.
Liming. To treat soil with lime (calcium compounds) to reduce acidity.
Mineralisation. Conversion of organic matter wholly or partly into inorganic (mineral) matter.
N budget. The size of the flows of N into and out of the site, and the size of the stocks of N in the soil, vegetation and animals.
Nitrification. Oxidation of ammonia or ammonium into nitrites or nitrates by nitrosomas bacteria.
Nitrophilous. A plant preferring soils rich in nitrogen.
Oxidised N. Nitrogen oxides and their dissolved forms
Poaching. Land becoming sodden by trampling by animals.
Pollution swapping. Inadvertently increase one pollutant by introducing a measure to reduce another.
Prescribed fire. A fire started deliberately as a management tool, as opposed to a naturally occurring wildfire.
Reactive N. Mineral N available for uptake by into living tissue, mainly in the form of reduced or oxidised N.
Reduced N. Ammonia gas, NH_3, and its dissolved form ammonium, NH_4^+
Ring barking. Cutting through the bark all the way around a tree, typically in order to kill it.
Rotovation. Breaking up soil using rotating blades.
Rubisco. An enzyme present in plant chloroplasts, involved in fixing atmospheric carbon dioxide during photosynthesis and in oxygenation of the resulting compound during photosynthesis.
Sawlog harvesting. Only bole material is removed.
Sheep folding. Moving stock off habitat land and onto arable land overnight.
Silage. Grass or other green fodder compacted and stored in airtight containers, without being dried first, and used as animal feed in winter.
Thinning. Removal of some trees.
Whole-tree harvesting. All aboveground biomass is removed either as whole trees or by removal of residues.

Abbreviations

C	Carbon
FYM	Farmyard manure
K	Potassium
N	Nitrogen
P	Phosphorus
S	Sulphur
SMB	Simple mass balance

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APPENDIX 1: CURRENT MANAGEMENT PRACTICES IN BROADLEAVED, MIXED AND YEW WOODLAND & (NATURAL) CONIFEROUS WOODLAND

References for management tables are given in appendix 6.

Habitat	Detail	Reference
Burning		
Upland	Do not burn woodland, woodland edges and scrub	The Scottish Government, 2011
	Do not burn vegetation	CCW
	Avoid burning brash	Forestry Commission, 2011
Cutting		
Orchard	Manage by cutting and grazing to maintain varies sward height	CCW
Orchard	80% grasses 7 to 20 cm	CCW
	Do not cut or top (except for injurious weeds)	CCW
	Do not cut	CCW
	Cutting is only permitted to maintain the scrub and grass mosaic and for control of weeds	NE
	Do not cut 01 Mar to 31Aug	NE
	Maintain rides and glades within woodland by grazing or cutting	NE
Disturbance		
	Do not roll or chain harrow	CCW
	Do not use for off-road disturbance	CCW
	Restrict unnecessary disturbance to soils	Harmer *et al.* 2010
	Minimise compaction and erosion	Forestry Commission, 2011
	Minimise soil disturbance	Forestry Commission, 2011
	Conserve and enhance carbon stocks	Forestry Commission, 2011
Fertilisation		
Wood pasture	FYM may be applied but not under or within 5m of forest canopy	CCW
Wood pasture	Maximum 100kgs N / ha/yr	CCW
	Do not apply fertiliser	CCW
	Do not apply slurry, inorganic fertilisers, organic fertilisers, farmyard manure, basic slag, calcified seaweed, sewage sludge, waste paper sludge or other off and onfarm wastes	CCW
	Do not apply fertiliser	NE
	Do not apply synthetic nitrogen fertilisers	NE

	Average animal manure N 170 kg/ha/year	NE
	Field maximum animal manure N 250 kg/ha/year	NE
	No fertilisation	DARDNI
	No application of slurry, farmyard manure, lime, basic slag, sewage sludge, poultry litter	DARDNI
	Do not spread fertiliser, lime or farm yard manure within 5m of habitat edge	DARDNI
	Minimise the use of fertilisers	Forestry Commission, 2011
	Minimise the use of inorganic fertiliser	Forestry Commission, 2011
Grazing		
W11 or W17	Cattle 0.07-0.2 LSU/ha	Harmer *et al.* 2010
W11 or W17	Sheep 0.5 - 2.5 LSU/ha	Harmer *et al.* 2010
W11 or W17	Livestock excluded Nov - Feb	Harmer *et al.* 2010
W17 Upland Oakwood	Maximum cattle 0.05 LSU/ha	Harmer *et al.* 2010
W17 Upland Oakwood	Maximum sheep 0.33 LSU/ha year round	Harmer *et al.* 2010
W17 Upland Oakwood	Maximum sheep 0.5 LSU/ha winter	Harmer *et al.* 2010
W8 or W10 Lowland high forest	Maximum cattle 0.07 LSU/ha	Harmer *et al.* 2010
W8 or W10 Lowland high forest	Maximum sheep 0.5 LSU/ha	Harmer *et al.* 2010
Wood pasture	Maintain by grazing	CCW
Wood pasture	20% < 7cm and 20% > 7cm	CCW
	Exclude all livestock	CCW
	Do not graze	CCW
	Stock must be excluded at all times	CCW
	Avoid supplementary feeding	CCW
	Do not supplementary feed	CCW
	To manage mammal damage, place supplementary feed carefully	Harmer *et al.* 2010
	Maintain fences to ensure exclusion of livestock from woodland	NE
	Restore, repair, or construct new fences around woodland	NE
	Exclude all livestock	NE
	New fencing to results in effective exclusion of stock	NE
	Do not supplementary feed in native woodland	NE
	Do not supplementary feed	NE
	Maintain rides and glades within woodland by grazing or cutting	NE

	Grazing not recommended if previously grazed and little natural regeneration	DARDNI
	Grazing recommended if not previously grazed and successful natural regeneration	DARDNI
	Max 0.5 LSU/ha	DARDNI
	Use mature cattle if possible	DARDNI
	Sheep, goats or horses may be used	DARDNI
	No supplementary feeding	DARDNI
	Grazing permitted 01 Jun to 30 Sep	DARDNI
	Grazing not permitted 01 Oct to 31 May	DARDNI
	Protect vulnerable trees from grazing mammals	Forestry Commission, 2011
	Consider using controlled grazing	Forestry Commission, 2011
Hydrological management		
	Do not clear existing ditches	CCW
	Do not install new drainage or modify existing drainage	CCW
	No new drainage	DARDNI
	Keep streams clear of brash	Forestry Commission, 2011
	Restore site drains	Forestry Commission, 2011
	Ensure wetland features are protected	Forestry Commission, 2011
Scrub management		
Wood pasture	Retain scrub patches (but to max 10% of area)	CCW
	The existing fence must be removed and new fence line created 6m in fields	CCW
	To manage mammal damage, remove thick vegetation, remove brash	Harmer *et al.* 2010
	To control bramble, pull using a harrow during spring time	Harmer *et al.* 2010
	To control bramble, use grazing but high stocking rates can have adverse effects	Harmer *et al.* 2010
	To control bramble, cutting or cultivation is ineffective	Harmer *et al.* 2010
	To control bracken, cut over several years	Harmer *et al.* 2010
	To control bracken, hand pulling is ineffective	Harmer *et al.* 2010
	To control bracken, cultivation by ploughing is effective	Harmer *et al.* 2010
	To control bracken, pigs can be used to scarify the ground and eat rhizomes	Harmer *et al.* 2010
	To control bracken, mulches are likely to be ineffective	Harmer *et al.* 2010
	To control bracken, cattle grazing can be effective	Harmer *et al.* 2010
	To control wood small-reed, repeated cutting is useful	Harmer *et al.* 2010

	To control wood small-reed, hand weeding is ineffective	Harmer *et al.* 2010
	To control wood small-reed, cultivation is not recommended	Harmer *et al.* 2010
	To control wood small-reed, grazing cattle may reduce abundance, but sheep will have little effect	Harmer *et al.* 2010
	To control rhododendron, cutting may be necessary but brash can supress ground flora	Harmer *et al.* 2010
	To control rhododendron, grazing by pigs has been trialled but is not always successful	Harmer *et al.* 2010
	Do not cultivate within 6m of woodland edge, allow woodland edge to grow out	NE
	Scrub growth cover must not exceed 50% of area	NE
	Trim no more than 1/3rd of shrubby growth per year	NE
	Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
Tree management		
Orchard	5 to 10% of area uncut each year	CCW
Orchard	Do not fell any trees	CCW
Wood pasture	Retain fallen deadwood	CCW
	Protect older woodland	Boye and Dietz, 2005
	Protect hollow trees	Boye and Dietz, 2005
	Increase the density of deadwood	Boye and Dietz, 2005
	Maintain good overstory and understory canopy cover to create shading	Harmer *et al.* 2010
	Re-establish tree cover quickly after felling	Harmer *et al.* 2010
	Retain and protect native woodland	NE
	Maintain high forest management	NE
	Use rotational coppicing	NE
	Retain all deadwood	DARDNI
	Leave windblown trees	DARDNI
	Living trees must not be cut down without prior permission	DARDNI
	Do not burn brashings	DARDNI
	Control spread of non-native species	DARDNI
	Do not manage trees 01 Mar to 31 Aug	DARDNI
	Retain existing old and large trees	SNH
	Retain accumulations of dead wood	SNH
	Ensure a continuous supply of dead wood by diversifying even-age stands	SNH

	Do not remove standing or fallen dead or dying trees	SNH
	Avoid removing dead wood from living trees	SNH
	Add dead wood by ring barking selected trees	SNH
	Fell selected trees and leave fallen wood	SNH
	Once felled the cut trees must be cleared from the site	SNH
	The trees must be left on site to decompose	SNH
	Ensure the removal of forest products does not deplete site fertility or soil carbon over the long term	Forestry Commission, 2011
	Leave a proportion of standing and fallen deadwood	Forestry Commission, 2011
	Retain and manage existing veteran trees	Forestry Commission, 2011
	Limit felling to 10% of area in any five year period	Forestry Commission, 2011
	Manage for a minimum of 10% open space	Forestry Commission, 2011
	Remove non-native species	Forestry Commission, 2011
	Avoid removing stumps	Forestry Commission, 2011

APPENDIX 2: CURRENT MANAGEMENT PRACTICES IN ACID AND CALCAREOUS GRASSLANDS

References for management tables are given in appendix 6.

Habitat	**Upland/ Lowland**	**Detail**	**Reference**
Burning			
Acid		Do not burn vegetation or other materials	CCW
Acid (wet)		Burning is not recommended	Treweek *et al*. 1997
Acid (wet)		May be justifies in extreme situations	Treweek *et al*. 1997
Acid (wet)		Burning Jan to Feb is least damaging to conservation	Treweek *et al*. 1997
	Upland	Do not burn 01 Apr to 31 Aug	NE
	Upland	Do not burn where Molinia is present as part of a mixed plant community	Rebane *et al*. 2001
	Upland	Do burn small portions of the site on rotation	Rebane *et al*. 2001
	Upland	Leave areas of tall, dense or tussocky vegetation	Rebane *et al*. 2001
	Upland	Do not burn an entire site	Rebane *et al*. 2001
	Upland	Do not burn the same area every year	Rebane *et al*. 2001
	Upland	Do burn in January, February or March	Rebane *et al*. 2001
Cutting			
Acid		Rushes may be controlled by cutting and the cuttings removed	CCW
Acid		Maintain by cutting and aftermath grazing	DARDNI
Acid		Cut rushes when greater than 1/3rd area	DARDNI
Acid		Cut rushes should be removed by bailing, raking or burning, or by grazing	DARDNI
Acid		Cut after 15 Jul	DARDNI
Acid		Cut 15 Jul to 15 Mar	DARDNI
Acid		Rolling is not permitted in April, May and Jun	DARDNI
Acid		Do not cut before 01 Jul	DARDNI
Acid		Cut after 01 Aug	DARDNI
Acid		Rolling is not permitted in April, May and Jun	DARDNI
Acid		Cutting is an acceptable method of weed control in small areas.	CCW
Acid		The spread of rush may be controlled by topping after 15 July where required. At least 10% of the rush should be left uncut each year.	CCW
Calcareous		Must not be cut until after 15 Jul	DARDNI
Calcareous		Rolling is not permitted in April, May and Jun	DARDNI
	Upland	Cut up to 1/3 of the area of rushes between 15 March and 31 July, aftermath graze with cattle, if doesn't control rushes cut again	NE

	Upland	Cut up to 1/3 of the area of rushes between 15 March and 31 July, aftermath graze with cattle, if doesn't control rushes cut again	NE
	Upland	Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
	Upland	Do not cut 01 Apr to 31 Aug	NE
	Upland	Selective mechanical control of weeds is permitted	NE
		Cut up to 1/3 of the area of rushes between 15 March and 31 July, aftermath graze with cattle, if doesn't control rushes cut again,	NE
		Management must include grazing and/or cutting for hay	NE
		Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
		Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
		Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
		After cutting you may graze or heavy roll the area	SNH
		Manage areas of dense rushes (i.e. where over 50% of the vegetation is rushes) by cutting and/or grazing each year	SNH
		Between 1 August and 31 March inclusive, you must achieve an open mix of rushes and grass pasture, by cutting between a third and two thirds of your rushes in a random pattern, and/or by grazing to remove and thin between a third and two thirds of your rushes.	SNH
		Cut close to the ground and certainly under half-stem height	SNH
		Where grazing is not practical, cut once between mid-July and mid-August to a height between 5 and 10 cm, and once again in the autumn or the following spring. A single cut is usually not sufficient to harvest the year's growth, so a second cut is required to mimic the effect of aftermath grazing on a hay meadow. The cuttings must be turned in the field in order to allow their seed to drop and they must then be removed or they will smother the underlying vegetation	SNH
		In areas where Corn Buntings breed, the site must not be grazed or mown from 16 April until 15 August inclusive The guidance on sward heights given above for spring and summer does not apply to these sites but the guidance on sward heights in winter does apply.	SNH
Disturbance			
Acid		Cultivation and chain harrowing not permitted	DARDNI
Acid		Cultivation and chain harrowing not permitted	DARDNI
Acid		Do not plough, cultivate or re-seed.	CCW
Acid		Do not roll or chain-harrow without prior approval	CCW
Acid (wet)		Digging of water bodies is not recommended	Treweek *et al.* 1997
Acid (wet)		Rolling should be avoided during bird nesting season	Treweek *et al.* 1997
Acid (wet)		Chain harrowing can provide regeneration niches	Treweek *et al.* 1997
Acid (wet)		Avoid harrowing in spring and summer	Treweek *et al.* 1997
Acid (wet)		Leave some areas unmanaged	Treweek *et al.* 1997
Calcareous		Cultivation and chain harrowing not permitted	DARDNI

	Upland	Between 1 April and 30 June do not harrow or roll	NE
		Do not plough, cultivate or reseed	CCW
		Do not roll or chain-harrow between 15 March and 15 July	CCW
		Do not roll or chain-harrow. Do not carry out any earth moving activities	CCW
		Do not roll or harrow between 1 April and 30 June	NE
		No ploughing or re-seeding	NE
		Avoid poaching or creating wheel ruts	SNH
Fertilisation			
Acid		Fertiliser not permitted	DARDNI
Acid		Application of slurry, chemical fertiliser, lime, basic slag, sewage sludge, poultry litter not permitted	DARDNI
Acid		Maximum 15 kg N/ha FYM	DARDNI
Acid		Fertiliser not permitted	DARDNI
Acid		Application of slurry, chemical fertiliser, lime, basic slag, sewage sludge, poultry litter not permitted	DARDNI
Acid		Maximum 15 kg N/ha FYM	DARDNI
Acid		Do not apply any inorganic or organic fertilisers such as farmyard manure, slurry, sewage sludge, chicken manure or fish meal within 10 metres of marshy grassland.	CCW
Acid		Do not apply any lime, basic slag calcified seaweed, waste paper sludge or off farm wastes within 10 metres of marshy grassland.	CCW
Calcareous		Fertiliser not permitted	DARDNI
Calcareous		Maximum 15 kg N/ha FYM	DARDNI
	Upland	Do not apply fertilisers, manures, lime or slag	NE
	Upland	Do not apply fertiliser, manure or slag	NE
	Upland	Do not apply fertiliser within 6m of top bank of a watercourse	NE
		Do not apply fertiliser	CCW
		Do not apply more than 50Kg/Hectare nitrogen per year as inorganic fertiliser. Where FYM is applied, either alone or in addition to inorganic fertilisers, the total rate of nitrogen must not exceed 100Kgs/Hectare nitrogen per calendar year	CCW
		Do not apply more than 50kg N or 100kg N including manure	NE
		Add only early in growing season	NE
		12.5 Tonnes of manure but only where grassland is regularly cut	NE
		FYM 12.5 tonnes per hectare	NE
		Do not apply fertilisers, manures, lime or slag	NE
		Maximum FYM 2.5 tonnes/ha/yr and only where grassland is cut	NE
		Apply FYM during growing season	NE
		Apply FYM when ground is dry to prevent compaction	NE
		No other type of fertiliser (besides FYM) may be applied	NE

		Do not increase current FYM applications	NE
		Average animal manure N 170 kg/ha/year	NE
		Field maximum animal manure N 250 kg/ha/year	NE
		Do not apply synthetic nitrogen fertilisers	NE
		Do not apply fertilisers, slurry, farmyard manure or lime	SNH
		Grasslands that are unenclosed should not receive fertilisers	Rebane *et al.* 2001
		The only situation where any type of nutrient application would be allowed on species-rich (semi-natural) grassland is in relation to species-rich meadows where periodic dressings of FYM are allowed albeit at low rates < 6t/ha/year	NE
Grazing			
Acid		5-10 cm sward	Crofts and Jefferson, 1999
Acid		Any combination of 2 or more of sheep, cattle and horse (and rabbit) does occur (not common but does occur)	CCW
Acid		Do not cut or top (except to control injurious weeds)	CCW
Acid		Maintain a varied sward height where at least 75% of grasses and herbs are less than 10 cm between 15 May and 15 September (If drought prone)	CCW
Acid		Ensure that at least 60% of the sward is between 2 cm and 10 cm from 1 October until 31 March	CCW
Acid		Maintain a varied sward height where at least 75% of grasses and herbs are between 3 cm and 20 cm between 15 May and 15 September	CCW
Acid		Different bird species require different management e.g. lapwing need an open habitat which has had relatively heavy grazing during the spring so that there is a uniformly short sward over the whole site by late February or early March, and then grazed lightly to the end of June.	CCW
Acid		Grassland fungi benefit from a shorter sward. The presence of localised ranker areas benefits over-wintering invertebrates.	CCW
Acid		1-5 cm sward	Crofts and Jefferson, 1999
Acid		15% or more bare ground	Crofts and Jefferson, 1999
Acid		0.2 LSU/ha per year	Crofts and Jefferson, 1999
Acid		Sheep, cattle, horses and rabbit	Crofts and Jefferson, 1999
Acid		Land must be maintained by grazing	DARDNI
Acid		No poaching is permitted	DARDNI
Acid		No poaching is permitted	DARDNI
Acid		Grazing permitted 01 May to 31 Dec 1.0 LSU/ha	DARDNI
Acid		No supplementary feeding	DARDNI
Acid		No supplementary feeding	DARDNI
Acid		No grazing 01 Jan to 30 Apr	DARDNI
Acid		Grazing permitted Apr to 15 May	DARDNI
Acid		No grazing 01 Nov to 31 Mar	DARDNI

Acid		Spring (April to May): Allow sward to grow to a height between 5 and 20 cm.	SNH
Acid		Summer (June to August): Graze to maintain a sward height between 5 and 20 cm.	SNH
Acid		Winter (September to March): Graze to reduce the sward height to between 5 and 15 cm.	SNH
Acid		0.5-0.75 LUs/ha all year, or equivalent during the summer only on Unimproved upland grassland with more than 50% Agrostis-Festuca grassland	Rebane *et al.* 2001
Acid		0.37 LUs/ha all year, or equivalent during the summer only on Unimproved upland grassland with less than 50% Agrostis-Festuca grassland	Rebane *et al.* 2001
Acid		Stocking should not normally exceed 0.25-0.6 LUs/ha on upland rough grazing pastures	Rebane *et al.* 2001
Acid		Obtain prior approval from Project Officer before using sheep.	CCW
Acid		Do not supplementary feed without prior approval from the Project Officer.	CCW
Calcareous		Some cattle grazing in Wales (3%)	CCW
Calcareous		Maintain a varied sward height where at least 75% of grasses and herbs are less than 10 cm through the year	CCW
Calcareous		Maintain a varied sward height where at least 75% of grasses and herbs are between 3 and 50 cm between 15 May and 15 September	CCW
Calcareous		Maintain a varied sward height in autumn, but ensure that at least 50% of the sward is between 2 and 10cm from 1 October until 31 March	CCW
Calcareous		Low grazing levels or no summer grazing, with occasional scrub clearance. No upper sward height range.	CCW
Calcareous		up to 10% bare ground	Crofts and Jefferson, 1999
Calcareous		2-10 cm sward	Crofts and Jefferson, 1999
Calcareous		2-15 cm sward	Crofts and Jefferson, 1999
Calcareous		1-5 cm sward	Crofts and Jefferson, 1999
Calcareous		5 % or more bare ground	Crofts and Jefferson, 1999
Calcareous		0.25 LSU/ha per year	Crofts and Jefferson, 1999
Calcareous		sheep and rabbit	Crofts and Jefferson, 1999
Calcareous		sheep, cattle, horses and rabbit	Crofts and Jefferson, 1999
Calcareous		Must be grazed	DARDNI
Calcareous		No poaching is permitted	DARDNI
Calcareous		Year round 0.5 LSU/ha	DARDNI
Calcareous		01 Aug to 30 Apr 0.75 LSU/ha	DARDNI
Calcareous		No supplementary feeding	DARDNI
Calcareous		Spring (April to May): Allow sward to grow to a height between 2 and 15 cm.	SNH
Calcareous		Summer (June to August): Graze to maintain a sward height between 2 and 15 cm.	SNH
Calcareous		Winter (September to March): Graze to reduce the sward height to between 2 and 10 cm.	SNH
Calcareous		Encourage diversity of the habitat by having some areas only grazed in autumn and others un-grazed	Rebane *et al.* 2001
Calcareous		Graze stock at no more than 1 sheep/ha or 0.15 LUs/ha for any continuous period of eight weeks between 1 May and 31 August	Rebane *et al.* 2001

Calcareous		At any other time graze stock at no more than 2 sheep/ha or 0.3 LUs/ha.	Rebane *et al.* 2001
	Upland	Manage by grazing only	NE
	Upland	20% of sward <7cm	NE
	Upland	Between 1 April and 30 June maximum 0.4 LU	NE
	Upland	01 April to 30 June maximum 0.6 LSU	NE
	Upland	A minimum 30% of LUs must be grazing cattle (over 2 year period)	NE
	Upland	There must be no supplementary feeding of any kind except where access to forage restricted	NE
	Upland	Feeders and troughs must not be used at any time	NE
	Upland	Supplementary feeding allowed but move feeders often	NE
	Upland	Do not supplementary feed using silage but haylage is permitted	NE
	Upland	Supplementary feeding is permitted	NE
	Upland	Do not supplementary feed within 6 m of the top bank of a watercourse	NE
	Upland	Do not supplementary feed in native woodland	NE
		Do not supplementary feed	CCW
		Tighter grazing in early autumn (to mostly 2 to 10 cm) is desirable to prevent spread of rank grasses and accumulation of too much leaf litter, although the presence of localised ranker areas benefits over-wintering invertebrates	CCW
		Areas of lowland unimproved grassland and agriculturally improved grassland should ideally be grazed as separate farm units. Where this is not possible, to avoid transfer of nutrients movement of stock between the habitat and improved grassland should be limited	CCW
		20% of sward <7cm	NE
		Do not increase current stocking level	NE
		30% of LSU cattle 15% of LSU sheep	NE
		Do not supplementary feed	NE
		Move feeders often	NE
		Management must include grazing and/or cutting for hay	NE
		No heavy poaching	NE
		Manage areas of dense rushes (i.e. where over 50% of the vegetation is rushes) by cutting and/or grazing each year	SNH
		Between 1 August and 31 March inclusive, you must achieve an open mix of rushes and grass pasture, by cutting between a third and two thirds of your rushes in a random pattern, and/or by grazing to remove and thin between a third and two thirds of your rushes.	SNH
		You must graze cattle at a level of at least one bovine per 25 hectares	SNH
		You must turn cattle out onto unenclosed or hill land (i.e. rough grazing) on or before 1 June, and keep them there for at least three months.	SNH
		Make sure that grazing is evenly distributed	SNH

		Include both sheep and cattle. To avoid over-grazing, you may need to reduce the number of sheep in proportion to the number of cattle introduced.	SNH
		Do not use the site for supplementary feeding.	SNH
		Pay special attention to avoiding over-grazing, trampling or supplementary feeding on any areas of wetter ground or woodlands.	SNH
		In areas where Corn Buntings breed, the site must not be grazed or mown from 16 April until 15 August inclusive The guidance on sward heights given above for spring and summer does not apply to these sites but the guidance on sward heights in winter does apply.	SNH
		Graze the aftermath of burning	Rebane *et al.* 2001
Hydrological management			
Acid		Do not install any new drainage	CCW
Acid (wet)		Maintain drainage channels with light maintenance every year, or half on a two year cycle, or less frequent with targeted control	Treweek *et al.* 1997
		Do not install new land drainage	NE
Acid		New drainage not permitted	DARDNI
Acid		Existing drainage can be maintained but not widened, deepened or extended	DARDNI
Acid		New drainage not permitted	DARDNI
Acid		Existing drainage can be maintained but not widened, deepened or extended	DARDNI
Calcareous		New drainage not permitted	DARDNI
Calcareous		Existing drainage can be maintained but not widened, deepened or extended	DARDNI
		Do not install new drainage or modify existing drainage	CCW
		Do not clear out existing ditches	CCW
		No installation of new drainage	NE
Liming			
Acid		Do not apply lime or any other substance to alter the soil acidity	CCW
	Upland	Continue adding lime if you already do so	NE
	Upland	Only apply lime with consent	NE
	Upland	Do not apply lime 01 Apr to 01 Aug	NE
	Upland	Only apply lime with consent	NE
	Upland	Do not apply lime 01 Apr to 01 Aug	NE
		Continue adding lime if you already do so	NE
		Only apply lime with consent	NE
Tree/scrub management			
Acid		Trees, scrub, bracken and injurious weeds may be cut	CCW
Acid		Scrub/trees must be controlled	DARDNI
Acid		Scrub must be prevented from spreading	DARDNI

Acid		Scrub/trees must be controlled	DARDNI
Calcareous		Scrub may be cut (the cut material must be stored away from the habitat)	CCW
Calcareous		Scrub/trees must be controlled	DARDNI
	Upland	Cutting and burning of common gorse is permitted	NE
	Upland	Control bracken by mechanical means	NE
	Upland	Control common gorse by cutting or burning	NE
	Upland	Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
	Upland	Retain areas of existing scrub	NE
	Upland	Control encroachment of scrub by cutting or herbicide	NE
	Upland	Prevent spread of bracken by cutting and/or crushing	NE
		Fallen deadwood must be retained	CCW
		Prevent scrub encroachment by grazing, mowing or topping	NE
		Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE

APPENDIX 3: CURRENT MANAGEMENT PRACTICES IN DWARF SHRUB HEATH

References for management tables are given in appendix 6.

Wet/Dry	Upland/ Lowland	Detail	Reference
Burning			
Dry	Upland	Avoid areas of bracken, and dwarf shrubs into areas of bracken	Rebane *et al.* 2001
Dry	Upland	Avoid areas where stock tend to congregate	Rebane *et al.* 2001
Dry	Upland	Avoid areas where the grazing pressure exceeds 1.5 ewes per hectare (or equivalents for other animals)	Rebane *et al.* 2001
Dry	Upland	Avoid flushes and valley mires	Rebane *et al.* 2001
Dry	Upland	Avoid grass-heath mosaics	Rebane *et al.* 2001
Dry	Upland	Do not burn dwarf shrub stands which have not been burnt for long periods (more than 40 years) and have well developed layering.	Rebane *et al.* 2001
Dry	Upland	Allow heather to grow taller than 20-30 cm before burning	Rebane *et al.* 2001
Dry	Upland	Rotation 20 years in the south west of England and 15 years in the Pennines, at least in some areas, and have other areas which are never burnt.	Rebane *et al.* 2001
Dry	Upland	Rotation lengthened where heather is the dominant species but grows in mixtures with grasses, until the plants are at least taller than the grasses (excluding flowering stems of grasses).	Rebane *et al.* 2001
Dry	Upland	Rotation long on slopes, above gullies and cloughs, and at the moorland edge	Rebane *et al.* 2001
Dry	Upland	Rotation of 12-20 years may be preferable	Rebane *et al.* 2001
Dry	Upland	Rotation short on some flat or gently sloping (<15oC) ground	Rebane *et al.* 2001
Dry	Upland	Rotation variety across a moor may be desirable.	Rebane *et al.* 2001
Dry	Upland	Rotations can be from 6-10 years on Exmoor in southern England to 10-15 years in Scotland	Rebane *et al.* 2001
Wet	Upland	Burn fire breaks where accidental fires are likely and extensive areas of old, woody heather exist	Rebane *et al.* 2001
Wet	Upland	Do not burn areas where Molinia is present at more than 20-30% cover	Rebane *et al.* 2001
Wet	Upland	Do not burn if in doubt	Rebane *et al.* 2001
Wet	Upland	Do not burn if in favourable condition	Rebane *et al.* 2001
Wet	Upland	Do not burn large areas dominated by cotton-grass Eriophorum spp	Rebane *et al.* 2001
Wet	Upland	Do not burn large areas of old, tall heather on wet substrates	Rebane *et al.* 2001
Wet	Upland	Do not burn some areas (wetter, steeper, higher altitude locations)	Rebane *et al.* 2001
Wet	Upland	Rotation minimum 20 years, 20-30 years may be preferable.	Rebane *et al.* 2001
	Lowland	Do not burn vegetation	CCW
	Lowland	Burn no more than a quarter of the heathland in 5 years	CCW

	Lowland	Burn 1 Nov to 15 Mar	Welsh Assembly Government, 2008
	Lowland	Burn gorse on 10-12 year rotation	Michael,1996
	Lowland	Burn 1 Nov to 31 Mar	Defra, 2007 (Heather and Grass Burning Code)
	Lowland	Burn, and/or cut and remove, small patches of heathland each year	NE
	Upland	Burn 1 Oct to 31 Mar	Welsh Assembly Government, 2008
	Upland	Do not burn heather already regenerating vegetatively by layering	Rebane *et al.* 2001
	Upland	Burn a sufficient total area at any one time to prevent concentration of livestock on recently burnt patches	Rebane *et al.* 2001
	Upland	Burn on a regular rotation basis	Rebane *et al.* 2001
	Upland	Burn some heathland areas and margins less intensively	Rebane *et al.* 2001
	Upland	Burn using variety of cycles and patch sizes across an area, to improve habitat complexity Aim for patches as small as possible but occasional larger fires may suit some species.	Rebane *et al.* 2001
	Upland	Burn 1 Oct to 15 Apr	Rebane *et al.* 2001
	Upland	Burn to be carried out in strips no more than 20m wide	SNH
	Upland	Do not burn 16 Apr to 30 Sep	SNH
	Upland	Permitted 1st Oct to 15th Apr (<450m a.s.l.)	The Scottish Government, 2011
	Upland	Permitted 1st Oct to 30th Apr (>450m a.s.l.)	The Scottish Government, 2011
	Upland	Do not burn when heather > 20cm tall	The Scottish Government, 2011
	Upland	Do not burn on deep peat (>0.5m)	The Scottish Government, 2011
		Do not burn vegetation on rocky areas	CCW
		Burn 1 Oct to 31 Mar	CCW
		Do not burn stands of old rank (mature and degenerate) heather	Welsh Assembly Government, 2008
		Allow some patches of heather and/or other heath to grow to about40 cm (16 in) or more to increase structural diversity.	Welsh Assembly Government, 2008
		Burn dry heath with heather and/or other dwarf shrubs (outside no-burn areas) when between 20 cm (8 in) and 30 cm (12 in) tall.	Welsh Assembly Government, 2008
		Do not burn 15 Apr to 31 Aug	DARDNI
		Do not burn	DARDNI
		Do not burn (without prior written agreement)	SNH
		Avoid burning heather in wet, shaded or humid situations	SNH
		Burn stands of dense, tall heather on dry substrates	SNH
		Burn where heather forms dense, continuous, evenly-structured stands	SNH

		Do not burn any stands which occur in conditions which are likely to be conducive to well developed heather layering	SNH
		Do not burn stands which have not been burnt for long periods (more than 40 years) and which have well developed heather layering	SNH
		Do not burn some stands	SNH
		Rotation 10-15 yrs dry heather dominated areas	SNH
		Burn old heather	SEARS, 2008
		SNH Current Muirburn season in Scotland is 1st October to 15th April with extension to 30th April, without altitudinal distinction.	SNH
		Burn common gorse in manageable blocks	NE
Cutting			
Dry	Upland	Cut a strip of 5 m from the bracken edge, or burn narrow strips '30 m wide' at right angles to the bracken edge	Rebane *et al.* 2001
	Lowland	Do not cut or top (except for injurious weeds)	CCW
	Lowland	Burn, and/or cut and remove, small patches of heathland each year	NE
	Lowland	Maintain fire breaks	NE
	Lowland	Install firebreaks, 10m wide, cutting at 2.5 cm and/or rotovation	Michael,1996
	Lowland	Remove heather cuttings	Michael,1996
	Lowland	Avoid cutting between March and October	Michael,1996
	Upland	Cut up to 1/3 of the area of rushes between 15 March and 31 July, aftermath graze with cattle, if doesn't control rushes cut again	NE
	Upland	Short cuts should be no more than 1 ha in size	Rebane *et al.* 2001
	Upland	The cut should not exceed 30 m in width.	Rebane *et al.* 2001
	Upland	Leave a 10 cm heather stem above the ground.	Rebane *et al.* 2001
	Upland	Do not leave material on the cut area	Rebane *et al.* 2001
	Upland	However, brash will break down more rapidly in western locations	Rebane *et al.* 2001
	Upland	Alternatively, a double-chop forage harvester can be used, which chops the material finely and allows it to be incorporated into the soil quite rapidly.	Rebane *et al.* 2001
	Upland	Do not store bales or heaps of cut heather on the moorland	Rebane *et al.* 2001
	Upland	Avoid cutting from mid-April to the end of July.	Rebane *et al.* 2001
	Upland	If possible, cut during the burning season, from 1 October to 15 April.	Rebane *et al.* 2001
	Upland	Avoid cutting when the ground is saturated	Rebane *et al.* 2001
	Upland	Cut every 10-20 years for heather growing alone or in mixtures with grass	Rebane *et al.* 2001
	Upland	Avoid wet areas and bogs	Rebane *et al.* 2001

	Upland	Avoid cutting large areas of old heather	Rebane *et al.* 2001
	Upland	Retain some areas of old heather	Rebane *et al.* 2001
	Upland	Avoid archaeological sites	Rebane *et al.* 2001
	Upland	Avoid steep and rocky ground	Rebane *et al.* 2001
	Upland	Leave a bank of old heather adjacent to roads	Rebane *et al.* 2001
		Cut no more than 1/15th of your manageable vegetation each year	CCW
		Burning can only take place between October 1st and March 31st, it is highly recommended for cutting to follow the same dates	CCW
		It is best to use a tractor mounted flail, cutting the vegetation twice to break it up and stop it forming a mat and stifling future growth.	CCW
		Do not cut 15 April to 31 August	DARDNI
		Cut Firebreaks at least 6 m and preferably 10 m wide.	DARDNI
		If trash removal is impractical, produce finely chopped material	SNH
Disturbance			
	Lowland	Do not roll or chain harrow	CCW
	Lowland	Do not use for off-road vehicles	CCW
	Lowland	Create bare ground patches 1m square.	Michael,1996
	Lowland	Create sandy patches – 2-5 m long by 1-2 m wide , 1-5 % of heathland area. min of 5 per hectare, 20 per hectare ideal. Create sandy traces 2-3 m wide. Scraping and turf stripping mid April to mid May.	Michael,1996
	Upland	Do not plough, cultivate, re-seed or harrow	NE
	Upland	use only low ground pressure vehicles	SNH
		Plough/tillage by late autumn	SEARS, 2008
		Do not plough or cultivate any land within 2 metres of a watercourse or a wetland habitat	CCW
		Do not damage habitat land	CCW
		Damage is defined as causing a loss of the vegetation type typical of that habitat	CCW
		Do not plough, cultivate or re-seed the habitat land	CCW
		Do not roll or chain harrow on habitat land between 15 March and 15 July	CCW
		not cultivate or surface seed	DARDNI
		No Cultivation, chain harrowing	DARDNI
		No dumping is allowed on heathlands	DARDNI
		No damaging activities	DARDNI
		Do not plough, cultivate or reseed	NE

Fertilisation			
	Lowland	Do not apply lime	CCW
	Lowland	Do not apply fertiliser, slurry or farmyard manure	SNH
	Upland	Do not apply fertiliser, manure or slag	NE
	Upland	Continue adding lime if you already do so	NE
	Upland	Do not apply fertiliser or manures	NE
		Do not apply slurry, inorganic fertilisers, organic fertilisers, farmyard manure, basic slag, calcified seaweed, sewage sludge, waste paper sludge or other off and onfarm wastes	CCW
		not apply lime	DARDNI
		No fertilisation	DARDNI
		No application of slurry, farmyard manure, lime, herbicides, pesticides, insecticides, sheep dip, fungicides, basic slag, sewage sludge, poultry litter	DARDNI
		No spreading of any organic or inorganic fertilizers.	DARDNI
		Do not apply fertilisers, manures, lime, slag	NE
		Do not apply synthetic nitrogen fertilisers	NE
		Average animal manure N 170 kg/ha/year	NE
		Field maximum animal manure N 250 kg/ha/year	NE
		Do not apply fertiliser, lime, slurry or farmyard manure	SNH
Grazing			
Dry	Lowland	Canopies with less than 50% western gorse: April-June 0.2 - 0.6 LSU/ha	CCW
Dry	Lowland	Canopies with less than 50% western gorse: July-September 0.1 - 0.3 LSU/ha	CCW
Dry	Lowland	Canopies with less than 50% western gorse: October-March 0 - 0.05 LSU/ha	CCW
Dry	Lowland	Canopies with more than 50% western gorse: April-June 0.4 - 0.6 LSU/ha	CCW
Dry	Lowland	Canopies with more than 50% western gorse: July-September 0.2 - 0.3 LSU/ha	CCW
Dry	Lowland	Canopies with more than 50% western gorse: October-March 0 - 0.05 LSU/ha	CCW
Dry	Upland	April-June 0.2 - 0.4 LSU/ha	CCW
Dry	Upland	July-September 0.1 - 0.2 LSU/ha	CCW
Dry	Upland	October-March 0 - 0.1 LSU/ha	CCW
Dry	Upland	Year-round: maximum 0.5-1.5 sheep/ha or 0.075-0.225 LSUs/ha	Rebane *et al.* 2001
Dry	Upland	Winter: stocking rates should be reduced by 25%, with all hoggs, cattle and horses removed, and stocking should not exceed 1 sheep/ha or 0.15 LUs/ha	Rebane *et al.* 2001
Dry	Upland	Increasing altitude and wetness: yea- round maximum 1.0 sheep/ha or less than 0.15 LUs/ha.	Rebane *et al.* 2001

Dry		Cattle and/or sheep 0.3 LSU/ha	DARDNI
Dry		Cattle and/or sheep 1 Mar to 31 Oct	DARDNI
Wet	Lowland	Canopies with less than 60% purple moor-grass: April-June 0.2 - 0.3 LSU/ha	CCW
Wet	Lowland	Canopies with less than 60% purple moor-grass: July-September 0.1 - 0.2 LSU/ha	CCW
Wet	Lowland	Canopies with less than 60% purple moor-grass: October-March 0 - 0.05 LSU/ha	CCW
Wet	Lowland	Canopies with more than 60% purple moor-grass: April-June 0.2 - 0.4 LSU/ha	CCW
Wet	Lowland	Canopies with more than 60% purple moor-grass: July-September 0.1 - 0.2 LSU/ha	CCW
Wet	Lowland	Canopies with more than 60% purple moor-grass: October-March 0 - 0.05 LSU/ha	CCW
Wet	Upland	Canopies with less than 50% purple moor-grass: April-June 0.1 - 0.2 LSU/ha	CCW
Wet	Upland	Canopies with less than 50% purple moor-grass: July-September 0.05 - 0.1 LSU/ha	CCW
Wet	Upland	Canopies with less than 50% purple moor-grass: October-March 0 - 0.05 LSU/ha	CCW
Wet	Upland	Canopies with more than 50% purple moor-grass: April-June 0.1 - 0.3 LSU/ha	CCW
Wet	Upland	Canopies with more than 50% purple moor-grass: July-September 0.05 - 0.2 LSU/ha	CCW
Wet	Upland	Canopies with more than 50% purple moor-grass: October-March 0 - 0.05 LSU/ha	CCW
Wet	Upland	Year-round: maximum 0.25-0.5 ewes/ha or 0.037-0.075 LUs/ha	Rebane *et al.* 2001
Wet	Upland	Winter: reduced by at least 25%, with all hogs, cattle and horses removed and preferably all stock should be removed in winter	Rebane *et al.* 2001
Wet	Upland	No grazing in the autumn or winter, with at most very light grazing in the summer	Rebane *et al.* 2001
Wet	Upland	Undisturbed wet heaths and blanket mires require little management and should be left completely alone as far as possible	Rebane *et al.* 2001
Wet		Sheep 0.25 LSU/ha	DARDNI
Wet		Cattle 0.2 LSU / ha	DARDNI
Wet		Cattle and/ or sheep 0.2 LSU / ha	DARDNI
Wet		Sheep 1 Mar to 31 Oct	DARDNI
Wet		Cattle 1 Jun - 31 Aug	DARDNI
Wet		Cattle and/ or sheep 1 Jun 31 Aug	DARDNI
	Lowland	Do not supplementary feed	CCW
	Lowland	On lowland heath at least half (50%) of the heathland should be dwarf-shrub species such as heathers and bilberry	CCW
	Lowland	Both woody mature plants and young regenerating plants of heather species must be present	CCW
	Lowland	Grazing maximum 1 April – 30 June 0.4 Livestock Units / Hectare	CCW
	Lowland	Grazing maximum 1 July – 30 September 0.2 Livestock Units / Hectare	CCW

	Lowland	Grazing maximum 1 October – 31 March 0.1 Livestock Units / Hectare	CCW
	Lowland	Do not supplementary feed	CCW
	Lowland	Prevent scrub and gorse encroachment by grazing with cattle, sheep, goats or ponies	CCW
	Lowland	A minimum of 30% of the livestock units (LUs) must be grazing cattle in each calendar year	CCW
	Lowland	A minimum of 15% of the livestock units (LUs) must be grazing sheep in each calendar year	CCW
	Lowland	No supplementary feeding is allowed	NE
	Lowland	Light grazing by sheep cattle and ponies.	Michael,1996
	Lowland	Avoid overgrazing	Michael,1996
	Lowland	Sheep grazing max 2.5 ewes per hectare, or as low as possible.	Michael,1996
	Lowland	Cattle grazing 2 - 5 cows per hectare	Michael,1996
	Lowland	Ponies (may lead to dunging in same place) One per 5-12 hectares.	Michael,1996
	Lowland	To control grass – turf stripping or light grazing by cattle	Michael,1996
	Lowland	Light grazing by sheep cattle and ponies.	Michael,1996
	Lowland	Gorse – rotational cutting or burning on 10-12 year rotation. Strip litter. Graze by ponies.	Michael,1996
	Lowland	Supplementary feeding off-site	Michael,1996
	Lowland	Sheep grazing March to September	Michael,1996
	Lowland	Cattle grazing can be all year.	Michael,1996
	Lowland	To control birch - light grazing by sheep or cattle or cut down trees, remove cut scrub	Michael,1996
	Lowland	Maximum 0.3 LU/hectare	SNH
	Lowland	Low level of grazing from 1 May to 1 September	SNH
	Lowland	Exclude farm livestock 1 November to the end of February	SNH
	Lowland	Extend the grazing into March/April in the spring and September/October in the autumn	SNH
	Upland	Manage by grazing only	NE
	Upland	20% of sward <7cm	NE
	Upland	01 April to 30 June maximum 0.6 LSU	NE
	Upland	Minimum stocking rate of 0.05 LSU/ha	NE
	Upland	A minimum 30% of LUs must be grazing cattle (over 2 year period)	NE
	Upland	Livestock can include cattle, sheep and ponies	NE
	Upland	There must be no supplementary feeding of any kind except where access to forage restricted	NE
	Upland	Feeders and troughs must not be used at any time	NE
	Upland	Supplementary feeding allowed but move feeders often	NE

	Upland	Supplementary feeding is permitted	NE
	Upland	Do not supplementary feed using silage	NE
	Upland	Feeding of hay is permitted	NE
	Upland	Move feeding sites regularly	NE
	Upland	The minimum level of grazing must be maintained 1 June to 30 September	NE
	Upland	(Above the moorland line) grazing with 0.4 and 1.0 Livestock Units/ha	NE
	Upland	(Above the moorland line) grazing with cattle and/or sheep	NE
	Upland	(Above the moorland line) grazing between 31 March and 20 June.	NE
	Upland	Shepherd sheep to ensure the area is grazed evenly, or as desired	Rebane *et al.* 2001
	Upland	Do not feed stock on land with wildlife interest such as heaths and blanket mires.	Rebane *et al.* 2001
	Upland	Where winter feeding is unavoidable, any feed, mineral supplements and blocks should not be on or ideally within 100 m of dwarf shrub heath, blanket mire or wet, flushed areas.	Rebane *et al.* 2001
	Upland	Do not feed stock on habitats of nature conservation interest	Rebane *et al.* 2001
	Upland	Many farmers remove their stock from unenclosed land for the winter, usually taking them off in October-November and returning them between March-June. Dwarf shrubs are most susceptible to grazing damage in the spring and most vulnerable to grazing in the autumn and benefit from this reduced grazing.	Rebane *et al.* 2001
	Upland	Shepherding is required for good grazing management of a hill sheep flock. For example, moving stock away from the 'bottom edge' of the heather at least twice a week could be beneficial.	Rebane *et al.* 2001
	Upland	Maintain current grazing practice, provided grazing practice has not recently altered and is not causing a deterioration of the habitat.	Rebane *et al.* 2001
	Upland	Favourable condition may also result from a complete absence of stock grazing.	Rebane *et al.* 2001
		Cattle and fewer sheep	SEARS, 2008
		High stocking density over winter	SEARS, 2008
		Supplementary feed on bracken areas	SEARS, 2008
		Pigs will eat rhizomes but cause extreme ground disturbance	SEARS, 2008
		No supplementary feeding	DARDNI
		No grazing 1 November to 28/29 February	DARDNI
		No supplementary feeding	DARDNI
		As well as shepherding, other methods of manipulating stock grazing over a site to ensure even coverage may include use of blocks or licks, or targeted burning of heath.	SNH
		Do not supplementary feed	NE
		Move feeders often	NE
		Take account of the combined impacts of livestock and other grazing animals present on the land.	SNH

		You must use the moorland for agricultural livestock production	SNH
		Maximum 1.2 Livestock Units (LU) per hectare	SNH
		Exclude farm livestock from 1 April until 31 August	SNH
		Graze 1 September until 30 November	SNH
		Manage grazing levels to enable plants to flower and set seed in the summer to maintain a balance between the cover and vigour of the dwarf shrubs and fine grasses with broad-leaved herbs. The area must be sufficiently grazed over the autumn to remove rank growth and lightly dwarf shrubs.	SNH
		Manage grazing levels in accordance with published guidance to ensure the sward is at its longest in the summer to allow plants to flower and set seed, and is shorter in the spring and autumn to allow grassland species to germinate and to remove rank growth.	SNH
		Ensure that red deer densities in woodland, or the equivalent densities for domestic livestock, do not exceed 15 km−2 (and preferably are kept below 10 km−2)	SNH
		Ensure that large herbivore densities on the open hill do not exceed three times these critical densities.	SNH
		Ensure that a significant proportion of the shoot tips of heather and blaeberry remain un-browsed by deer or livestock.	SNH
Hydrological management			
	Lowland	Do not clear existing ditches	CCW
	Upland	Do not install or modify drainage that increases runoff	NE
	Upland	Drain blocking is permitted	NE
	Upland	Maintain wetlands including peat bogs, mire, hillside flushes	NE
	Upland	Maintenance of existing drains is permitted except in areas of deep peat	NE
	Upland	No new drainage should be undertaken on any upland mires or heaths, especially around bog pools and wet flushed areas.	Rebane *et al.* 2001
	Upland	Prevent further physical disturbance to upland heaths and mires as far as possible.	Rebane *et al.* 2001
	Upland	Avoid nutrient enrichment via water courses on upland heaths and mires.	Rebane *et al.* 2001
	Upland	Any water inputs should be acidic and nutrient poor.	Rebane *et al.* 2001
	Upland	Block existing drains and seal any cracks in the peat to prevent further drainage.	Rebane *et al.* 2001
		Do not install new drainage or modify existing drainage	CCW
		Do not clear ditches between 1 March and 31 August	CCW
		not install new or improved drainage	DARDNI
		No new drainage	DARDNI
		Existing drainage systems can be maintained, but not widened, deepened or extended	DARDNI
		No peat extraction, reclamation or new drainage to be created	DARDNI
		Do not install new drainage or modify existing drainage	NE

		Protect waterlogged wetlands	NE
Tree/scrub removal			
	Lowland	Rhododendron – cut and remove	Michael,1996
	Lowland	Bracken – control in early stages of invasion, buy cutting, rolling or crushing, cut as low as possible in mid June and again in late July. a 3rd cut may be made in August. Remove cut material. Initial winter burn to remove litter. Or rotovate. or disced or chisel-plough in winter. Some chemical control also possible	Michael,1996
	Lowland	Gorse – rotational cutting or burning on 10-12 year rotation. Strip litter. Graze by ponies.	Michael,1996
	Lowland	Pine – cut in the winter months	Michael,1996
	Lowland	Keep narrow shelterbelts of trees.	Michael,1996
	Lowland	Maintain areas of permanent open water and remove encroaching trees.	Michael,1996
	Lowland	Remove pines over two metres	Michael,1996
	Lowland	To control birch - light grazing by sheep or cattle or cut down trees, remove cut scrub	Michael,1996
	Upland	Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
	Upland	Remove trees and shrubs from mires where they are considered to be threatening the interest of the habitat	Rebane *et al.* 2001
	Upland	Several years of follow-up work such as hand-pulling of seedlings to control trees and shrubs may be necessary where removal is considered appropriate.	Rebane *et al.* 2001
		Cut/ roll/flail in May/Jun and Jul/Aug	SEARS, 2008
		Repeat once a year for 5 years	SEARS, 2008
		Burn bracken litter	SEARS, 2008
		Remove bracken litter	SEARS, 2008
		Bruising and cutting, if done regularly, are an effective way of controlling bracken	CCW
		Ideally, bracken will need to be cut or rolled 3 times at year in spring and summer	CCW
		Grazing areas will help break up the mat of dead bracken	CCW
		Spraying any returning bracken can often be undertaken on a much smaller scale	CCW
		Protect and retain all in-field and veteran trees	CCW
		Use Asulam for the control of bracken	DARDNI
		The spread of scrub/trees must be controlled	DARDNI
		Trees must not be planted on heather moorland	DARDNI
		Removal of western gorse on dry heath is not permitted	DARDNI
		Control scrub by cutting followed by ammonium phosphate / glyphosphate, do not remove stumps	DARDNI
		Do not control scrub 1 Mar to 31 Aug	DARDNI
		pines – (max 15% cover of trees and scrub)	NE

		Rhododendron – cut and remove	NE
		Control bracken by cutting or herbicide	NE
		Control common gorse by cutting or burning	NE
			NE

APPENDIX 4: CURRENT MANAGEMENT PRACTICES IN BOGS

References for management tables are given in appendix 6.

Habitat	Details	Reference
Burning		
	Burning is not recommended	Treweek *et al.* 1997
	May be justifies in extreme situations	Treweek *et al.* 1997
	If in doubt, do not burn	Stoneman and Brooks, 1997
	Not generally recommended	McBride *et al.* 2011
	Avoid burning brash on bog surface	Stoneman and Brooks, 1997
	Ash must be removed from the bog	Stoneman and Brooks, 1997
	Burning Jan to Feb is least damaging to conservation	Treweek *et al.* 1997
	Do not burn after 31st March	McBride *et al.* 2011
	Do undertake burning in winter when peat is waterlogged and slow to ignite	McBride *et al.* 2011
Blanket bog	Do not burn exposed peat	The Scottish Government, 2011
Blanket bog	Do not burn on deap peat (>0.5m)	The Scottish Government, 2011
Blanket bog	Minimise or eliminate burning	Rebane *et al.* 2001
Blanket bog	Areas where Molinia is present at more than 20-30% cover, are best not burnt	Rebane *et al.* 2001
Blanket bog	Avoid burning areas dominated by cotton-grass Eriophorum spp	Rebane *et al.* 2001
Blanket bog	20 year burning regime is the recommended minimum rotation	Rebane *et al.* 2001
Blanket bog	burning rotation of 20-30 years may be preferable	Rebane *et al.* 2001
Blanket bog	No burning from 15 April to 31 Aug	DARDNI
Blanket bog	Do not burn 01 Apr to 31 Aug	NE
Blanket bog	Permitted 1st Oct to 15th Apr (<450m a.s.l.)	The Scottish Government, 2011
Blanket bog	Permitted 1st Oct to 30th Apr (>450m a.s.l.)	The Scottish Government, 2011
Lowland raised bog	Do not burn vegetation	CCW
Lowland raised bog	Do not Muirburn	SNH
Cutting		
	Topping is generally discouraged	Treweek *et al.* 1997
	Small scale to provide diverse vegetation heights	McBride *et al.* 2011
	Mechanical mowing to cut to uniform height	McBride *et al.* 2011
	Do not plough, cultivate or reseed	CCW
	Do not roll or chain-harrow between 15 March and 15 July	CCW
	Do not remove peat	CCW
Blanket bog	Where accidental fires are likely and extensive areas of old, woody heather exist, burn or cut firebreaks	Rebane *et al.* 2001
Blanket bog	Cut up to 1/3 of the area of rushes between 15 March and 31 July, aftermath graze with cattle, if doesn't control rushes cut again	NE

Blanket bog	Do not cut 01 Apr to 31 Aug	NE
Blanket bog	No cultivation, chain harrowing	DARDNI
Blanket bog	Peat cutting maximum 0.1 ha for domestic use only	DARDNI
Blanket bog	Within designated sites peat cutting is prohibited	DARDNI
Blanket bog	Between 1 April and 30 June do not harrow or roll	NE
Blanket bog	Avoid driving over wet habitats	SNH
Blanket bog	Peat banks may be cut, carefully replace turfs with vegetation side uppermost	SNH
Blanket bog	Prevent physical disturbance	Rebane *et al.* 2001
Disturbance		
Lowland raised bog	Do not cut or top (except for injurious weeds)	CCW
Lowland raised bog	Do not roll or chain harrow	CCW
Lowland raised bog	Do not use for off-road disturbance	CCW
Lowland raised bog	No cultivation, chain harrowing	DARDNI
Lowland raised bog	Trees must not be planted	DARDNI
Lowland raised bog	Peat cutting on existing cut bog maximum 0.1 ha for domestic use only	DARDNI
Lowland raised bog	Within designated sites peat cutting is prohibited	DARDNI
Lowland raised bog	Mechanised peat cutting not permitted	DARDNI
Lowland raised bog	Do not use all terrain vehicles	DARDNI
Lowland raised bog	Peat cutting not permitted on intact uncut areas	DARDNI
Lowland raised bog	No digging or turning over peat	NE
Lowland raised bog	Keep the peat and vegetation surface intact, undisturbed, and wet as possible	SNH
Lowland raised bog	Do not extract peat	SNH
Lowland raised bog	No cultivation	SNH
Lowland raised bog	No track creation	SNH
Lowland raised bog	No tree planting	SNH
Fertilisation		
	Do not apply fertiliser	CCW
	Do not apply fertilisers, manures, lime or slag	NE
Blanket bog	No fertilisation	DARDNI
Blanket bog	No application of slurry, farmyard manure, lime, basic slag, sewage sludge, poultry litter	DARDNI
Blanket bog	Do not apply fertilisers, manures, lime or slag	NE
Blanket bog	Do not add fertiliser	Rebane *et al.* 2001
Blanket bog	Avoid nutrient enrichment via water courses	Rebane *et al.* 2001
Lowland raised bog	No fertilisation	DARDNI
Lowland raised bog	No application of slurry, farmyard manure, lime, basic slag, sewage sludge, poultry litter	DARDNI
Lowland raised bog	No fertiliser	NE
Lowland raised bog	No fertiliser including manure	SNH
Grazing		

	Light grazing may have positive effect, overgrazing may lead to problems	Stoneman and Brooks, 1997
	Where grazed in the past	McBride *et al.* 2011
	Where possible	McBride *et al.* 2011
	Suggested medium rates mid May - Nov 100-250 LSU days/ha/yr	Treweek *et al.* 1997
	Suggested medium rates Mid Jul to Oct 120-370 LSU days/ha/yr	Treweek *et al.* 1997
	Suggested medium rates aftermath grazing 50-80 LSU days/ha/yr	Treweek *et al.* 1997
	0.6 sheep / ha	Stoneman and Brooks, 1997
	0.25 sheep / ha on wet bog	Stoneman and Brooks, 1997
	Do not increase current stocking level	NE
	Cattle, or cattle and sheep can be used to control purple moor grass	Stoneman and Brooks, 1997
	Minimum 30% LSU cattle per year, minimum 15% LSU sheep per year	CCW
	Exclude stock during prolonged or extreme wet weather	McBride *et al.* 2011
	Avoid intensive grazing	McBride *et al.* 2011
	Remove stock when 10% of bare soil is visible	McBride *et al.* 2011
	Cattle, water buffalo, sheep, horses and ponies , goats	McBride *et al.* 2011
	0.5 to 1 cattle per ha or 6 ewes per ha	McBride *et al.* 2011
	Supplementary feeding may be required in winter	Stoneman and Brooks, 1997
	Avoid supplementary feeding	CCW
	Off -site	McBride *et al.* 2011
	Move stock regularly off to transfer N in dung and urine	McBride *et al.* 2011
	Intensively March, April and May	McBride *et al.* 2011
	Do not install new drainage or modify existing drainage	CCW
	Do not install new land drainage	NE
Blanket bog	check trampling by deer and manage population accordingly	SNH
Blanket bog	Maintain current grazing practices provided grazing practice has not recently altered and is not causing a deterioration of the habitat	Rebane *et al.* 2001
Blanket bog	Favourable condition may also result from a complete absence of stock grazing	Rebane *et al.* 2001
Blanket bog	Stock density 0.075 LSU/ha	DARDNI
Blanket bog	Between 1 April and 30 June maximum 0.4 LU	NE
Blanket bog	Minimum stocking rate of 0.05 LSU/ha	NE
Blanket bog	Mid-May to Mid-Sep 1.0 cow/ha	Rebane *et al.* 2001
Blanket bog	Year-round 0.33 cows/ha	Rebane *et al.* 2001
Blanket bog	Mid-May to Mid-Sep 0.3 cows/ha	Rebane *et al.* 2001
Blanket bog	Year-round 0.1 cow/ha	Rebane *et al.* 2001
Blanket bog	year round stocking rates should not exceed 0.25-0.5 ewes/ha or 0.037-0.075 LUs/ha;	Rebane *et al.* 2001
Blanket bog	winter stocking rates should be reduced by at least 25%, with all hoggs, cattle and horses removed and preferably all stock should be removed in winter	Rebane *et al.* 2001
Blanket bog	Shepherd sheep to ensure the area is grazed evenly, or as desired	Rebane *et al.* 2001
Blanket bog	Sheep only	DARDNI

Blanket bog	Livestock can include cattle, sheep and ponies	NE
Blanket bog	No supplementary feeding	DARDNI
Blanket bog	Do not supplementary feed using silage but haylage is permitted	NE
Blanket bog	Feeding of hay is permitted	NE
Blanket bog	Move feeding sites regularly	NE
Blanket bog	Do not feed stock on habitats of nature conservation interest	Rebane *et al.* 2001
Blanket bog	No grazing 1 November to 28/29 February	DARDNI
Blanket bog	Grazing permitted 01 Mar to 31 Oct	DARDNI
Blanket bog	The minimum level of grazing must be maintained 1 June to 30 September	NE
Blanket bog	Remove an agreed number of livestock from moorland to in-bye land for at least 22 weeks during winter	SNH
Blanket bog	no grazing in the autumn or winter, with at most very light grazing in the summer	Rebane *et al.* 2001
Blanket bog	Light spring/summer grazing and higher cattle grazing in late summer/autumn	Rebane *et al.* 2001
Blanket bog	No new drainage	DARDNI
Blanket bog	Existing drainage systems can be maintained, but not widened, deepened or extended	DARDNI
Blanket bog	Drain blocking is permitted	NE
Blanket bog	Maintain wetlands including peat bogs, mire, hillside flushes	NE
Blanket bog	Maintenance of existing drains is permitted except in areas of deep peat	NE
Blanket bog	Do not drain	Rebane *et al.* 2001
Blanket bog	Maintain water table at surface in winter, maximum 10 cm below the surface during the summer and preferably close to the surface.	Rebane *et al.* 2001
Blanket bog	Block existing drains and seal any cracks in the peat	Rebane *et al.* 2001
Hydrological management		
Lowland raised bog	no overgrazing	SNH
Lowland raised bog	Remove grazing if poaching is evident	SNH
Lowland raised bog	1st Aril to 30th Sep 0.05-0.10 LSU/ha	CCW
Lowland raised bog	1st Oct to 31 Mar 0.00-0.01 LSU/ha	CCW
Lowland raised bog	1st Aril to 30th Sep 0.2-0.3 LSU/ha	CCW
Lowland raised bog	1st Oct to 31 Mar 0.0-0.1 LSU/ha	CCW
Lowland raised bog	Stock density on fen 1.0 LSU/ha	DARDNI
Lowland raised bog	Stock density on swamp or reedbed 0.075 LSU/ha	DARDNI
Lowland raised bog	Stock density on wet heath 0.25 LSU/ha	DARDNI
Lowland raised bog	Stock density on semi-natural grassland 1.0 LSU/ha	DARDNI
Lowland raised bog	Stock density on woodland > 0.1ha 0.2 LSU/ha	DARDNI
Lowland raised bog	Stock density on woodland < 0.1ha 0 LSU/ha	DARDNI
Lowland raised bog	Do not supplementary feed	CCW
Lowland raised bog	No supplementary feeding	DARDNI
Lowland raised bog	On cutover bogs, grazing not permitted 01 Nov to 31 May	DARDNI
Lowland raised bog	Grazing permitted 01 Jun to 31 Oct for sheep	DARDNI

Lowland raised bog	Grazing permitted 01 Jun to 31 Aug for cattle	DARDNI
Lowland raised bog	Open all year but graze in drier spells	SNH
Lowland raised bog	Do not clear existing ditches	CCW
Lowland raised bog	No new drainage	DARDNI
Lowland raised bog	Retaining rainfall to maintain high water table throughout the year	NE
Lowland raised bog	Maintain water control structures in good working order	NE
Lowland raised bog	Block ditches to raise the water table to bog surface or 15cm of surface	SNH
Lowland raised bog	no digging or clearing out ditches	SNH
Liming		
Lowland raised bog	Do not apply lime	CCW
Tree/Scrub management		
	Minimise disturbance, prevent sphagnum hammocks being pulled up	Stoneman and Brooks, 1997
	Pull when ground less susceptible to damage (in summer when water is low, or in winter with mild frosts)	Stoneman and Brooks, 1997
	Scrub can be killed by raising water levels, flooding for the entire year is most effective	Stoneman and Brooks, 1997
	Control injurious weeds, invasive non-native species or bracken by selective trimming or manual removal	NE
	Seedlings can be left onsite or removes	Stoneman and Brooks, 1997
	Leaving brash onsite can lead to localised enrichment and shading out	Stoneman and Brooks, 1997
	Brash can be disposed of onsite in blocked drainage or man-made pool system	Stoneman and Brooks, 1997
	Remove brash	Stoneman and Brooks, 1997
	Grazing late spring to control birch	Stoneman and Brooks, 1997
Blanket bog	The spread of scrub/trees must be controlled	DARDNI
Blanket bog	Cutting and burning of common gorse is permitted	NE
Blanket bog	Control injurious weeds, invative non-native species or bracken by slective trimming or manual removal	NE
Blanket bog	Control braken by mechanical means	NE
Blanket bog	Control common gorse by cutting or burning	NE
Blanket bog	Control common gorse by cutting or burning	NE
Blanket bog	Remove trees and shrubs from mires where they are considered to be threatening the interest of the habitat	Rebane *et al.* 2001
Lowland raised bog	The spread of scrub/trees must be controlled	DARDNI
Lowland raised bog	Clear woodland when affecting hydrology	SNH
Lowland raised bog	remove seedling trees where affecting hydrology	SNH
Lowland raised bog	Introduce grazing to control heather and scrub	SNH
Lowland raised bog	Remove scrub	SNH
Lowland raised bog	Prevent scrub re-colonisation with herbicide or grazing	SNH

APPENDIX 5: CURRENT MANAGEMENT PRACTICES IN COASTAL DUNES AND SLACKS

References for management tables are given in appendix 6.

Details	**Reference**
Cutting	
Cut rushes when greater than 1/3rd area	DARDNI
Cut 15 Jul to 15 Mar	DARDNI
Must not be cut until after 15 Jul	DARDNI
Rolling is not permitted in April, May and Jun	DARDNI
Disturbance	
Do not plough, cultivate or reseed	CCW
Do not remove peat	CCW
Do not roll or chain-harrow between 15 March and 15 July	CCW
Do not damage habitat land	CCW
Do not plough or cultivate any land within 2 metres of a watercourse or a wetland habitat	CCW
Retain accumulation of seaweed and wood debris	NE
Cultivation and chain harrowing not permitted	DARDNI
Rolling is not permitted in April, May and Jun	DARDNI
Cultivation and chain harrowing not permitted	DARDNI
Fertilisation	
Do not apply fertiliser	CCW
Do not apply slurry, inorganic fertilisers, organic fertilisers, farmyard manure, basic slag, calcified seaweed, sewage sludge, waste paper sludge or other off and onfarm wastes	CCW
No fertiliser	NE
Application of slurry, chemical fertiliser, lime, basic slag, sewage sludge, poultry litter not permitted	DARDNI
Maximum N application 25kg/ha/yr	DARDNI
Fertiliser not permitted	DARDNI
Maximum 15 kg N/ha FYM	DARDNI
Grazing	
Manage by light grazing	CCW
Maintain a range of sward heights (20% less than 5cm, 40% less than 10cm)	CCW
Maintain less than 70% cover of grasses in wet hollows	CCW

Grazing levels should not exceed 0.6 LSU/ha between 01 Mar to 15 Jul	CCW
Graze with cattle, sheep, goats or ponies	CCW
Minimum 30% of LSUs must be cattle and 15% of LSUs must be sheep in each year	CCW
Do not supplementary feed	CCW
Avoid supplementary feeding	CCW
Extensive grazing or mowing regime	NE
No supplementary feeding	NE
Must be grazed	DARDNI
Year round 0.5 LSU/ha	DARDNI
01 Aug to 30 Apr 0.75 LSU/ha	DARDNI
No poaching is permitted	DARDNI
No supplementary feeding	DARDNI
Hydrological management	
Lowering of the water table is not desirable	Davy *et al.* 2006
Ideal winter water table maximum 0 to 50cm above ground level	Davy *et al.* 2010
Ideal summer water table maximum 50 to 100cm below ground level	Davy *et al.* 2010
Do not install new drainage or modify existing drainage	CCW
Maintain existing drainage and flood pattern	NE
New drainage not permitted	DARDNI
Existing drainage can be maintained but not widened, deepened or extended	DARDNI
Tree/scrub management	
Include scrub management	NE
Scrub/trees must be controlled	DARDNI
Scrub/trees must be controlled	DARDNI

APPENDIX 6: MANAGEMENT REFERENCES

Handbooks used to collate current management prescriptions.

Reference author, year	Reference Title
Boye and Dietz, 2005	Development of good practice guidelines for woodland management for bats, English Nature Research Reports Number 661.
Crofts and Jefferson, 1999	Lowland grassland management handbook.
Davy *et al.* 2006	Development of eco-hydrological guidelines for dune habitats, English Nature Research Reports No 696.
Davy *et al.* 2010	Protecting the plant communities and rare species of dune wetland systems: Ecohydrological guidelines for wet dune habitats, Environment Agency.
Defra, 2007	Heather and Grass Burning Code
Forestry Commission, 2011	The UK Forestry Standard.
Harmer *et al.* 2010	Managing Native Broadleaved Woodland.
McBride *et al.* 2011	The Fen Management Handbook.
Michael,1996	The lowland heathland management handbook version 2.0.
Rebane *et al.* 2001	The upland management handbook.
SEARS, 2008	Bracken control: A guide to best practice.
Stoneman and Brooks, 1997	Conserving Bogs: The Management Handbook
The Scottish Government, 2011	The Muirburn Code.
Treweek *et al.* 1997	The Wet Grassland Guide.
Welsh Assembly Government, 2008	Heather and grass burning code for Wales.

Agri-environment schemes and advisory notes used to collate current management prescriptions.

Agency	Agri- environment schemes and elements
CCW	Glastir Entry, Glastir Targeted Element, Glastir Whole Farm Code, Glastir All Wales Element, Advice for controlling bracken, Guidelines for undertaking burning, Guidelines for undertaking cutting, Tir Gofal.
DARDNI	Northern Ireland Countryside Management Scheme.
NE	Entry Level Stewardship Environmental Stewardship, Higher Level Stewardship Environmental Stewardship, Organic Entry Level Stewardship.
SNH	Scotland Rural Development Programme, SNH Information and Advisory Note number 78: Heather moorland management for Lepidoptera, SNH Information and Advisory Note number 58: Cutting of heather as an alternative to muirburn, SNH Information and Advisory Note number 35: Heather layering and its management implications.

Review of the effectiveness of on-site habitat management to reduce atmospheric nitrogen deposition impacts on terrestrial habitats: Suggestions for field trails

C. Stevens, L. Jones, R. Payne

CCW Science Report No. 1037 (B)

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9 INTRODUCTION

Globally the deposition of reactive nitrogen (N) has more than doubled over the last one hundred years and in the UK only small declines in N deposition are predicted in the next ten years. The potential loss of biodiversity as a result of N deposition has important implications for both environmental and agricultural policy. Given the widespread impacts on habitats in the UK it is essential to understand how habitat management measures could reduce N deposition impacts and promote recovery. This report builds on the report 'Review of the effectiveness of on-site habitat management to reduce atmospheric nitrogen deposition impacts on terrestrial habitats' to make recommendations for how the effectiveness of management practices to reduce N deposition impacts can be discussed. The report begins with a description of current experimental trials being conducted in the UK to investigate interactions between N deposition and management (section 1.1) and then goes on to discuss the value of new management trials for both conventional and more novel management practices (section 1.2). Section 2 describes potential new experimental trials for investigating novel management techniques, section 3 discusses the potential for utilizing management trials conducted for other purposes to investigate interactions with nitrogen deposition and section 4 provides advice for land managers who wish to conduct management trials.

All options presented in this report represent worthwhile methods of adding to the current knowledge base on habitat management and interactions with N deposition.

9.1 Existing experimental trials investigating interactions between N deposition and management

There are a number of existing experiments investigating the interaction between N deposition and management. These are outlined in section 2.11.1.4 of the main report and are described briefly here.

Park Grass Experiment

The Park Grass Experiment is the longest running experiment on grassland in the world. The experiment is on a neutral grassland in Hertfordshire and was established in 1856. Experimental additions of N, P, K, and organic fertilisers are made, singly and in combination with liming. Management is by cutting with biomass removal; there are also control plots which have been managed but not received nutrient or lime additions.

Defra UKREATE experiments

Five experiments in the Defra UKREATE consortium have N x management treatments (Table 1.1), and have been variously running from seven to twenty five years. The experiments span acid and dune grasslands, lowland and upland *Calluna* heath and alpine heath. Management treatments are grazing for the grassland communities and burning for the heaths. In the grassland experiments, grazing has been continuous. In the heathland experiments burning (experimentally-controlled or accidental) has been a one-off event, with N additions and monitoring continuing afterwards. These experiments offer a unique opportunity to examine how management may alter responses to N. While individual experiments have published many papers, there has been no co-ordinated attempt to synthesise N and management responses across multiple experiments.

BEGIN experiment

The BEGIN experiment is located in an acid grassland in North Wales and is replicated in differing climatic zones (Fusa municipality, Norway; Bordeaux, France). These experiments have been running for six years and investigate N and management treatments focusing on cutting and removal of biomass.

	Site name (Abbreviated code)	Vegetation type: NVC classification	N treatment rates (kg N ha^{-1} yr^{-1})	N form (as solution)	Management treatments
Heath	Ruabon (RUH)	Upland heath: H12 *Calluna –Vaccinium*	0,40,80,120 0,10,20,40, 120	NH_4NO_3	Controlled burn
	Thursley (TLH)	Lowland heath: H2 *Calluna - Ulex minor*	0, 7.7, 15.4 0, 30	$(NH_4)_2SO_4$	Uncontrolled burn, Controlled burn
	Culardoch (CAH)	Low Alpine Heath: H13 *Calluna-Cladonia*	0, 10, 20, 50	NH_4NO_3	Clipping, Burning
Acid Grassland	Pwllperian (PAG)	Upland acid grassland	0, 10, 20	$NaNO_3$ $(NH_4)_2SO_4$	Sheep grazing: Light, Heavy
Sand dune grassland	Newborough (NDG)	Fixed sand dune grassland: SD8 *Festuca – Galium*	0, 7.5, 15	NH_4NO_3	Ungrazed; Rabbit grazed; Large Stock (ponies, cattle)

Table 1.1. Experimental sites from the Defra UKREATE nitrogen research network, in which management and N deposition have been manipulated. Adapted from Phoenix *et al*. (2012). A fuller version of this table giving more details of the sites can be found in section 2.11.1.4 of the main report.

9.2 The value of new management trials

The value of new management trials is considered for both conventional management practices and novel techniques (those not currently in widespread use within a habitat) which may be of value for N impact mitigation. For novel management practices (table 1.2) there is clear benefit to conducting new management trials as we do not currently have sufficient information on their impact on the stocks and turnover of N to assess whether they will be effective at removing N and increasing habitat suitability. Suggested trials for some of these management techniques are outlined in section 2 of this report.

Table 1.2. Novel management techniques identified in section 4 of section A of the report.

Habitat	***Management technique***
Woodland	Litter removal
Acid and calcareous grasslands	Stock removal at night
Acid grassland	Liming
Heathland	High intensity burns
Bogs	Water table management
Sand dunes	Large scale remobilisation

For conventional management practices (i.e. those in current use within a given habitat) there are already some existing experimental trials as outlined above (section 1.1). Where a management practice has already been investigated in a given habitat, continuation of existing management trials should be a priority as opposed to starting new ones as it can take many years for treatment effects to be apparent. However, there are a number of knowledge gaps which can be identified such as where the interactions between a common management practice and N deposition in a given habitat have not been investigated or where there is insufficient information on N stocks or processes to reach an informed decision on effectiveness. Table 1.3 provides a summary of existing experiments investigating interactions between management and N addition.

Furthermore there are some habitats, such as some coastal habitats, where there have been no experimental trials investigating N addition or interactions between N deposition and management. There is value to investigating interactions between conventional management practices and N deposition in these situations. This may be possible by making additional measurements of nitrogen stocks and turnover in existing management trials where N is not manipulated or measured currently (see section 3).

Table 1.3. Summary of existing field experiments exploring management interactions with N addition. Cells shaded grey indicate that the management technique is not relevant to the habitat.

	Grazing	Cutting	Liming	Burning	Litter removal	Ringbarking	Remobilisation
Acid grassland	Pwllpeiran	BEGIN,					
Calcareous grassland							
Neutral grassland		Park Grass					
Dune grassland	Newborough						
Other coastal habitats							
Upland heath				Ruabon			
Lowland heath				Thursley,			
Montane heath		Culardoch		Culardoch			
Fens							
Woodland							

10 NEW EXPERIMENTAL TRIALS FOR NOVEL NITROGEN REDUCTION TECHNIQUES

Possible new experimental trials will be described for the following novel management practices: litter removal in woodland, liming in acid grassland, and sheep removal at night in grassland. These management techniques were selected because they are not part of normal management practice, there is insufficient information to determine their effectiveness and experimental trials are necessary to identify their impact on habitats. This cannot be determined by assessment of nitrogen budgets alone. Based on the findings of section A of this report we believe that these management practices have the potential to reduce the impacts of N deposition.

10.1 Litter removal in woodland

An experimental trial investigating litter removal in woodland might have three management treatments: 1. Control (no litter removal), 2. Low level litter removal (50% of litter removed), High level litter removal (100% of litter removed); and four nitrogen treatments:

- Control (no nitrogen)
- Low nitrogen (10 kg N ha^{-1} yr^{-1})
- Medium nitrogen (20 kg N ha^{-1} yr^{-1})
- High (40 kg N ha^{-1} yr^{-1}).

Nitrogen treatments could be applied monthly throughout the year, as ammonium nitrate in solution. The solute concentration should not be too concentrated as this may lead to chemical burn effects rather than N dose effects. The simplest application method is using a backpack sprayer or watering can with bar extension, although automated methods and canopy level application methods have also been used. Background and through-fall N deposition could be determined by monitoring or interpolated values could be taken from the APIS website. Replicate 5 x 5 m plots could be set out in areas below tree canopies. Canopy cover could be assessed to find areas with similar canopy cover and a canopy consisting of the same component tree species. Ideally, five replicates of each of the 12 treatment combinations (i.e. litter removal x N treatment) would be set up, either randomly located, or within a blocked design if necessary to account for variability within a site, where one complete replicate set of the 12 treatments would be located in one block, and so on. The need for consistent canopy cover and tree species may mean that plots or blocks cannot be located in ideal positions. Given the scale of woodlands, and the fact that processes are mediated through growth of the trees themselves, there should be adequate buffer areas between experimental treatments, and (depending on the scope of the experiment) it may not be appropriate to nest one treatment within another. If the study aims to look at effects of litter removal and N deposition on tree growth and nutrient cycling as well as on understory vegetation and litter invertebrate fauna, the scale of the processes means that nesting experimental treatments will not be feasible. The experiment would be conducted in a mature deciduous woodland and should be maintained for a minimum of five years, ideally longer, because woodland processes are strongly seasonal and effects may take a long time to develop.

Litter removal over a specified area should take place annually in late autumn, once the majority of leaves have dropped. Nets could be used to prevent litter blowing into plots from other areas. The (oven dried) mass of litter removed from plots should be recorded and measurements of the N and carbon content of the litter should be made, in order to calculate gross fluxes of N removal from the plot. The experiment should collect baseline data on soil chemistry and biology, ground flora, and soil and litter invertebrate species composition prior to treatments. These measurements should then be collected annually immediately prior to litter removal the following year. Recommended measurements include: plant-available soil nitrogen (nitrate and ammonium), soil total carbon (C) and N, soil total organic C and N, soil organic matter content, soil microbial biomass C and N, soil invertebrate sampling, soil microbial composition, vegetation ground flora, decomposition rates, mineralisation rates, and leaching losses of N.

Estimated total set up costs: 15 days staff time, £1000 consumables (includes costs of fencing and plot markers)

Estimated annual treatment maintenance cost:

-Litter removal (removing, drying and weighing litter, once per year): 10 days, £100 consumables.

-Nitrogen treatments (monthly): 30 days, £300 consumables (includes all chemicals, sampling and sample storage materials)

(based on 60 plots: 5 replicates of 12 treatment combinations, all at one site)

Measurement costs including baseline measurements are not included: see below for indicative costs. Also note that these costs do not include travel and subsistence, or incorporate significant travel time which will vary depending on the experiment location.

10.2 Liming in acid grassland

To investigate the potential for liming in acid grasslands, a site severely impacted by acidification could be selected. This would be an acid grassland site with highly acidic soils in an area of historically high pollutant inputs. There would be three experimental treatments, a control (no lime) and lime applied at a sufficient level to increase the soil pH to 5, or pH 6.5. The amount of lime applied will depend on the starting pH of the soil. Treatments should be replicated five times using a randomised block design and plots should be maintained under normal management regimes. Plots should be 2 x 2 m, with at least 1 m buffer zone between them, more if the site is sloping. We are primarily concerned with habitat suitability and N processes in this experiment rather than N removal so a very simple experiment can be used which does not need to be crossed with N addition. Because this results in a simple, low cost experiment replicating it at several sites would be very valuable. The experiment should be maintained for a minimum of five years, ideally longer, because vegetation species composition changes, and changes in key soil processes, are one of the main interests of this experiment.

Sampling should be conducted before experimental treatments are applied and annually in the summer. Vegetation species composition should be assessed annually together with soils sampled to determine pH, plant-available soil nitrogen (nitrate and ammonium), soil total C and N, soil microbial biomass C and N, decomposition rates, mineralisation rates, and leaching losses of N. Since the focus is on soil processes which are highly variable at small scale, we recommend a minimum of two measurements per replicate plot rather than one to better account for this variability.

Estimated total set up costs: 9 days staff time, £300 consumables (includes lime and costs of marking out plots)

Estimated annual treatment maintenance cost: 2 days, £100 consumables (includes all chemicals, sampling and sample storage materials)

(based on fifteen plots, at one site)

Measurement costs including baseline measurements are not included: see below for indicative costs. Also note that these costs do not include travel and subsistence, or incorporate significant travel time which will vary depending on the experiment location.

10.3 Removing sheep from grassland at night

An experimental trial investigating the potential for sheep removal at night (sheep folding) to mitigate the impacts of N addition is likely to be costly. This is because large scale plots are needed to ensure animal welfare in a long-term experimental trial. Experimental replication would also result in the movement of a large number of animals each day. Because this method is primarily concerned with nitrogen removal an alternative method would be the calculation of nitrogen budgets. This method would not show the impact of sheep folding on, for example, species composition, but it would allow calculation of the amount of nitrogen removed from the site. The amount of additional nitrogen removed from the site through sheep folding (as opposed to traditional grazing) could be relatively easily calculated by monitoring the amount of nitrogen in defecation and urination overnight. Nitrogen removal is likely to vary seasonally so should be calculated at regular intervals throughout the grazing period. For example, if grazing is year round monthly measurements of volume and N content over a 24 hour period would be appropriate.

Estimated set up costs: Requires use of a facility where animal waste can be easily collected whilst maintaining animal welfare.

Estimated annual treatment maintenance cost: Difficult to estimate, as this has not been done before.

Assuming the simplest set of measurements involving collection and sampling of animal urine and dung, see times and costs for soil C:N (section 3.4.1) – the same methods would be applied for analysing dung. Costs for analysing N content of urine and dung are likely to be similar to those for measuring available N in soils.

11 UTILISING MANAGEMENT TRIALS AND PROGRAMMES TO ASSESS NITROGEN DEPOSITION IMPACTS

This section explores how existing management trials, or strategically designed surveys to incorporate widely practiced management techniques might be used to provide scientifically robust information on how management can be used to mitigate N deposition impacts. It first describes the options for design of a series of targeted measurements, then discusses the measurement options in detail, and how they might be put together for different habitats.

11.1 Experimental designs for additional measurements

The ideal situation would be a well-designed management trial set up at a site with a control (non-managed) treatment as well as a management treatment (e.g. ungrazed areas if the trial is for grazing). The trail would also have replication of both control and management treatments (as an absolute minimum, two examples each of the control and the management treatments, preferably three or more). These areas should be randomly allocated to ensure there are no consistent underlying differences between e.g. grazed and ungrazed areas, which might result if the most productive areas have been chosen for grazing plots and the ungrazed plots located in marginal grazing areas – see Section 4 for more detailed advice on initiating new management trials.

If the management trial is unreplicated, then it may be possible to obtain useful information by surveying more than one site with such trials, or where such treatments are being implemented. Each site would still need to have control areas of similar underlying character but where the management option has not been implemented. Each site would then comprise a paired set of treatments: control and management treatment.

A broader survey approach might also allow comparison of management options across a range of sites, but would need to be carefully designed. The survey would incorporate a range of sites where the management option has, or has not, been implemented, aiming to avoid potentially co-correlated factors which might give spurious results such as temperature, rainfall, size of site, etc. For instance, if most grazed sites occur in the north-west and most ungrazed sites occur in the south east, this introduces bias due to climatic differences between the two sets of sites, and leads to a risk of incorrect conclusions being drawn based on a simple comparison between the two datasets. This study design would be a useful approach to the problem of finding suitable controls and treatment within a single site by studying other sites (ideally nearby) where management has not been implemented. Taking this approach requires awareness of different management histories and background levels of N deposition.

11.2 Which scientific measurements might be useful

Suggested measurements focus on two aspects of mitigation of N impacts: comparisons of effectiveness focused on measures of conservation interest (e.g. species richness) and measures of underlying processes which ultimately determine the effectiveness of a management technique such as nitrogen processing or nitrogen storage in the soil-plant system. All measurements should be taken in all treatments (control treatments and management treatments), ideally with multiple measurements within each plot, depending on the variability of the results e.g. soil character may be substantially different in locations only 20 cm apart, therefore it is important to collect enough samples to overcome this small-scale variability within plots in order to better explain differences that might occur between management treatments.

11.2.1 Outcome measures (e.g. botanical diversity)

These are simple measures of outcome which help interpret whether the management trial is being effective at achieving conservation objectives. They might include monitoring of vegetation community type or plant species occurrence or abundance, or abundance of other organisms such as insects, birds or microorganisms. Each of these variables have established monitoring strategies, but note that these may need to be adapted or added to in order to provide scientific evidence to support interpretation of whether the management trial is successful. For example, the Common Standards Monitoring methodology focuses on certain positive and negative indicator species and is conducted at a relatively coarse scale over a large area. It is designed for a specific purpose: a relatively quick methodology for reporting on habitat condition. More detailed full species inventories of defined (and sufficiently replicated) quadrats may be necessary to assess relatively subtle changes in species composition or abundance between different treatments. See Section 4 for specific advice on experimental design.

11.3 Measures of ecological processes or conditions, including N storage.

A wide range of processes may be measured which can help explain why a management trial may or may not be achieving desired outcomes.

Plant biomass: A measure of above-ground plant biomass can help explain how productive a site is, and how much nitrogen it contains. A fixed area (and shape) should be harvested in each location. The area to be cut depends on the scale of the vegetation. In a close-cropped sward with a very even distribution of species it may be sufficient to cut a small square area of e.g. 25 x 25 cm. In a taller, tussocky plant community such as a tall-fen at the other extreme, it may be necessary to cut 100 x 100 cm. The area of the cut vegetation should be recorded for scaling up any subsequent measurements. In perennial or shrubby vegetation, there may be lots of accumulated woody plant material. If the focus is productivity, then a dual cut system should be made, with a preliminary cut to clear vegetation in mid-winter and a subsequent cut at peak biomass in late summer. In grazed systems, exclusion cages need to be set up to exclude grazers to allow regrowth to be sampled. For cutting or mowing treatments, experimental cutting should match the timing of that used in the treatment and be done just before the main cut is applied to ensure that the typical biomass is sampled. For multiple mowing/cutting treatments in a year, the same principle applies, biomass weight from each cut can be added to give an annual off-take. Plant material should be oven-dried at a temperature of 60ºC and 80°C then weighed and scaled up to give a dry weight biomass per m^2.

Plant tissue chemistry: The nitrogen, phosphorus and carbon contents of plant tissue can be measured, which may provide a range of useful information. The total N content (%N in a plant sample) can be used, in combination with the weight of biomass removed from a plot by cutting, to calculate the total amount of N removed from a habitat by cutting and removal of biomass off-site. Tissue N:P ratios provide useful information on whether the site is N-limited, P-limited or N-P co-limited. In the latter two cases, P limitation may mean that the vegetation is unlikely to be increasing growth in response to N, although N will still be accumulating in the soil. Tissue N can be measured relatively cheaply by combustion methods in a C:N analyser, if tissue P is required, then both tissue N and tissue P can be measured by acid digestion.

Basic soil measures: pH, moisture content, organic matter content, bulk density: A lot of explanatory information can be gained from some fairly basic soil measures. These include soil pH which has a bearing on the fertility of the site, its sensitivity to acidification and its phosphorus status. Soil moisture content and organic matter content, measured as %Loss On Ignition, combined with pH give some indication of fertility. Organic matter content is likely to be affected by techniques such as burning, but is unlikely to be affected by cutting or grazing except over long timescales. pH may be affected by management treatments over shorter timescales if they result in large-scale removal of plant material, and therefore base cations such as calcium and magnesium, from the site. Bulk density is typically used for upscaling of other measurements but also indicates the degree of soil compaction.

Available N and P in soils: Measures of plant-available N and P in soils tell you approximately how much nutrients there are in the soil which are available for plant uptake at any one time. They are measured using a range of extraction techniques in the laboratory. Methods for available P are more complicated and differ depending on the soil type, but may provide additional information as to whether the site is P limited, and therefore less able to respond to N.

Mineralisation of N and P: The above measures of available N and P only provide information on how much of these nutrients is in the soil at the time of sampling. The site may be productive, but the plants and microbes take up the nutrients as soon as they are produced. The rate of turnover of nutrients is provided by measures of N and P mineralisation. There are a range of measurement techniques, which are typically at least twice the cost of measures of available nutrients.

Total N and C stocks: The total amount of N or C stored in the soil. Although by far the majority, typically >98%, of this N is bound up in organic matter and is not available for direct uptake by plants or microbes, this nonetheless represents the store of N which is potentially available in the future following mineralisation of the organic matter. Mineralisation rates may alter due to climate change. Soil N and C content is typically measured by combustion of prepared soil samples in a C:N analyser, or total N content by acid digest of prepared soils. Soil C:N ratios have been used as an indication of N saturation, and can define thresholds at which nitrate leaching occurs in forests and heathlands. A lower C:N ratio generally implies more N in the system and therefore more N saturated, although ratios are habitat specific.

N leaching: Leaching of N may help understand knock-on effects of management on neighbouring ecosystems (e.g. N in freshwaters) or if trying to complete a N budget for a site. While grazing impacts on leaching of N are relatively low in semi-natural systems, they may be substantial after burning, although this has not been quantified. Leaching measurements involve installation of suction lysimeters below the main rooting zone and require substantial commitment in terms of time and laboratory resources. Lysimeters need 1-3 months after installation to let flushes of N caused by the installation process to dissipate, then a full 12+ months of measurements and water chemistry analysis of the collected leachates, typically at monthly intervals, to get an annual estimate (leaching varies seasonally). In order to calculate the flux (i.e. total quantity) of N leached, it is necessary to estimate the gross water fluxes of leachate, for which a measure of monthly rainfall volume is the basic requirement to estimate evapotranspirative losses.

Gaseous N losses: Gaseous losses of nitrous oxide may be important from wetlands (methane emissions may also be of interest for greenhouse gas budgets). These are complex to measure and estimate annual fluxes, but there is a specialist literature on this subject.

11.4 Recommended environmental measurements for different management types

Table 3.1. Recommended measures for a selection of management techniques. ✓ Identifies recommended measures.

Management measure	Plant biomass	Plant tissue N, P	pH, moisture, Loss On Ignition, bulk density	Available N; available P	Mineralisation of N and/or P	Soil N (and C) stocks	Leaching of N	Gaseous N losses
Grazing	✓	✓	✓	✓	✓		✓	✓
Cutting	✓	✓	✓	✓	✓	✓	✓	✓
Burning	✓	✓	✓	✓	✓	✓	✓	✓
Hydrological management	✓	✓	✓	✓	✓			✓

Most measures are relevant for most management techniques, depending on the question of interest. A few measures such as soil N stocks are unlikely to change substantially under some measures e.g. under grazing or hydrological management over the timescales of project monitoring.

11.4.1 Indicative costs for a range of measurement techniques.

These costs are presented as staff days and recurrent costs in table 3.2. They are based on conducting the analysis in accredited laboratories with established Quality Assurance protocols and which run inter-laboratory comparisons to ensure high quality data. All methods should use the most appropriate method for the measure in question, and use analytical machines with the appropriate detection limits to cope with samples from low nutrient habitats. Many commercial organisations are geared towards analysis of e.g. water samples from polluted habitats and, while they are accredited, the analytical equipment does not have the required sensitivity to analyse samples from semi-natural, nutrient poor systems. We do not provide costs for botanical or invertebrate surveying, as these are routinely costed and commissioned by site managers, and can often be done in-house with existing expertise. Costs include set up time, sample collection & preparation time, analysis time including materials and staff time. Costs are based on conducting measurements for an experiment involving around 50 samples at one site, except for leachate analysis, based on 25 samples. Costs will be higher for experiments conducted across multiple sites due to travel time and accommodation costs. Note, these costs do not include travel and subsistence, or incorporate significant travel time which will vary depending on the experiment location.

Table 3.2. Indicative costs for a range of measurement and sampling techniques.

Activity	Activity details	Staff time (days)	Consumables cost
Setting up and sample collection			
Selecting and marking ~ 25 plots	Selecting and marking ~ 25 plots	5-10 depending on size, nature and location of experiment	£300 – 500 for posts, markers, etc.
Plant biomass	Sample collection in the field (per cut) for 50 samples	6-10 depending on experiment	£100
Soil samples	Collection in the field and preparation in the lab prior to analysis, for 50 samples	4-5 days	
Laboratory analysis			
Tissue chemistry analysis	Biomass preparation for 50 samples: Coarse cutting/grinding, sub-sampling, grinding samples	5-10 depending on size of samples and type of vegetation	
%C, %N by combustion	Weighing and preparation of 50 samples for combustion	1	£600
%N, %P by acid digest	Acid digest of 50 samples	10	£100
pH, moisture, %LOI	50 samples	2	£50
Bulk density	50 samples	1	
Available N	50 samples	6	£100
Available P	50 samples	6	£100
N mineralization	50 samples	8	£200
P mineralization	50 samples	8	£200
Soil N and C stocks	Including preparation of samples, ball milling etc. Note this method is not appropriate for calcareous soils.	5	£600 on C:N analyser
Leaching of N	Set up and installation of 25 lysimeters and rain-gauge	10	£50 per lysimeter
	Routine monthly collection of 25 lysimeter samples for 15 months (minimum recommended time period), includes filtering and basic pH measurements on non-filtered samples	40	£600
	Chemical analysis for NO_3, NH_4, of 25 samples per month for 15 months	15	£300

12 ADVICE FOR MANAGERS INITIATING MANAGEMENT TRIALS

If land managers are conducting experimental management trials the utility of the data collected for identifying the impact of different management practices can be maximized by following the guidelines detailed below. We recognise that in practice many outside factors will constrain what is practicable, with availability of funding likely to be paramount among these limitations. However, we believe that the considerations below are important and should be considered early in the process of designing any management trial. This is because without a proper experimental design, it is not possible to say whether the management trial has achieved its goals. The observed changes, however dramatic, might actually be due to other factors that have not been taken into account.

12.1 Replication

A key feature of the scientific method is the concept of reproducibility; that the same result can be produced independently. In experimental ecology this is often equated to a need to have replicated treatments. The number of replicates necessary is a subjective decision and often involves a trade-off against the scale of those replicates. As a general rule three replicates is usually considered the absolute minimum but five or more may be desirable where possible. A feature of many experimental studies is psuedoreplication (Hurlbert 1984); typically where the treatments are not truly replicated but samples are. For instance if two fields have different management regimes and multiple vegetation quadrats are conducted within those fields there is no true replication as there is only one field receiving each management regime. The individual quadrats are pseudoreplicates and are not truly independent. At an early stage consideration should be given to how data will be statistically analysed and the level of statistical power desired; generally the more complex the experimental design the more sophisticated an analysis will be required.

12.2 Controls

Another fundamental feature of the scientific method is the use of controls: samples which are not subject to the experimental treatment but are as similar as possible in all other ways. In the context of ecological experiments there may be many other factors and interactions which influence the variable of interest. It is important that control plots are as similar as possible to treatment plots in terms of, for instance, past management regime, topography, hydrology, initial community composition, etc. Treatments should be randomly assigned to plots to help avoid systematic differences.

12.3 Permanent monitoring plots

Again, due to the high variability across habitats, it is easier to detect change by going back to the exact same location when making repeat measurements over time. This is easiest by setting up permanent plots, at an appropriate scale for the habitat, usually a minimum of 2 x 2 m in grassland, 5 x 5 m in heathland, 50 x 50 m in woodland. Permanent plots can be marked using stakes, metal poles, or buried metal plates which can be re-found using a metal detector. If using tall markers on sites with stock, they should be located at least 2 m away from the permanent plot to prevent stock damage when rubbing on the marker. Plots should ideally be set up consistently, e.g. all oriented North-South with a key identifying marker at the south-west corner. In addition, the location of all plots should be located with a GPS at the greatest accuracy possible (e.g. NY12345678), as a failsafe for when markers disappear or cannot be re-located.

12.4 Time-scale

One of the most widely discussed issues with all ecological experiments is that of time-scale with a widespread recognition that the duration of many experiments is too brief (Silvertown et al. 2010). The duration of a typical ecological experiment is less than three years, driven by the duration of a typical ecological research grant. While this may be sufficient for certain systems, for many more it is inadequate. Two issues are critical here: 1) the time-scale of the environmental question and 2) the time-scale for ecological change. In the case of nitrogen deposition, semi-natural ecosystems in the UK have been exposed to elevated N deposition since at least the late 18th Century, accelerating with anthropogenic N fixation in the post-war period (Fowler et al. 2004). Against this long-term context even the oldest experiments (>25 years) are relatively short-term but three-year experiments extremely so. The speed at which ecosystems respond to environmental change varies by ecosystem: in a deciduous forest the life-span of an individual canopy tree will be many decades and community adaptation to environmental change is therefore likely to be even longer; communities dominated by annual plants however will respond much quicker and microbial communities quicker still. Optimum experimental duration will need to balance expected time-scales for change and response with practical considerations particularly of cost.

12.5 Treatment regime

Studies which include the direct application of nitrogen, as opposed to simply the removal of previous accumulated nitrogen, will need to consider questions of application regime. In the real world ecosystems receive nitrogen in a variety of chemical forms (reduced and oxidised, organic and inorganic) through a range of pathways (dry and wet). The quantity and form of this deposition varies spatially and temporally. Deposition often occurs near-continuously, but such treatment regimes are difficult to simulate experimentally. The majority of experimental studies have opted to apply ammonium nitrate in solution at intervals which rarely exceed once a month. Doses are often unrealistically high to account for the unrealistically-short duration of the experiments (c.f. Phoenix et al. 2012). Such trade-offs are generally viewed as acceptable, or at least inevitable, but interpretation of results needs to be aware of the simplifications involved, and the potential for unintended effects of the treatment method. For instance there are good reasons to believe that the ecological impacts of N depend on deposition path and chemical form (Cape et al. 2009; Sheppard et al. 2011), and certainly are affected by the solute concentration and the frequency of treatment application. A single annual dose of N in pellet fertilizer form will have very different effects from the same dose applied fortnightly as a spray. Generally a monthly application in a low solute concentration is considered to be the minimum acceptable frequency. Similar considerations also apply to possible management interventions which should be as close as possible in experimental situations to what could realistically be implemented in routine management.

12.6 Scale

Decisions need to be made on the scale of an experiment which is appropriate and achievable. Plot size should be dictated by the hypotheses of the experiment. Larger plots are less affected by edge affects and are likely to encompass more internal heterogeneity. Treatment regimes may dictate minimum sizes for plots; for instance if the treatment involves stocking then the minimum number of animals in a plot is one and a minimum plot-size must be sufficient for at least that one animal.

12.7 Baseline data

Interpretation of experimental results will be helped if data is collected before the experimental treatments. A popular experimental design in ecological studies is before/after, control/treatment in which data are collected before and after treatments from both treated and control plots. This design allows two kinds of comparisons: both spatially between treatments and control, and temporally between sampling occasions. The design thereby allows improved confidence that other, nuisance variables have been adequately accounted for, giving more confidence in the results. Many sites of conservation interest have long-term monitoring data, particularly those which are designated such as NNRs and especially those which are part of networks such as Environmental Change Biodiversity Network/Long Term Monitoring Network. The choice of sites with such data for experimental studies offers the advantage of comparing short-term with long-term records to address the extent to which these fall within, or exceed, natural variability.

12.8 Data management

It is advisable to give consideration to how data will be managed, stored and analysed prior to commencing the project. Data should checked for errors and be stored electronically in a place where backed up regularly. Data analysis needs to be appropriate to the experimental design and the type of data collected.

12.9 Practicalities

Ecological experiments are never ideal - there are always trade-offs with what is practically achievable. Key issues are likely to include cost, man-power, space, access to suitable sites, site security and trade-offs against the conservation of protected sites. These factors need to be balanced against the aim to carry out high-quality science which is robust and representative of the real-world situation.

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