Final report for LM0202:
Scoping study to develop a methodology that can be used to assess the value of agri-environment scheme options in the creation and maintenance of small-scale habitat mosaics to benefit priority species

Executive summary

Priority habitats and conservation sites need to be improved to contribute to resilient ecological networks. Increasing small-scale habitat heterogeneity may be one approach to enhance the quality of priority habitats and sites. This scoping study addressed the question: What current evidence is available that small-scale habitat heterogeneity can benefit priority species conservation, and how can this be tested using a field-based study and potentially delivered through Agri-Environment Scheme (AES) options? The study focussed on conservation priority invertebrate species, chosen because a recent meta-analysis found that invertebrates are more responsive to the combination of localized management intensity at the within-farm scale and landscape complexity than either plants or vertebrates (Gonthier et al. 2014). Lowland grassland mosaic habitats were chosen as a focal habitat, as grassland forms a substantial proportion (38%) of English agricultural land, large areas of grassland are under AES, and grassland has a large number of associated species of conservation priority. 116 priority invertebrate species were selected for the study, based on known associations with grassland (86 species) including hedgerows (12 additional species) in lowland farmland, or veteran trees (18 species).

Two systematic reviews of the literature were conducted: one focussed on the ecology, conservation and management of small-scale heterogeneity in grassland mosaic habitats; and the second on the autecology and habitat requirements of the 116 priority invertebrate species. The first literature review consisted of full-text appraisal of 343 references, the majority (252) of which were original research studies. The species review resulted in 607 references containing 1092 pieces of information across the 116 species. Surveys of expert opinion were sent to 30 participants from 17 organisations; 22 responses were received. The surveys collated information on grassland mosaic management at high value nature conservation sites (National Nature Reserves), and detailed ecological information for those priority species with scant published information.

The literature reviews yielded substantial evidence to demonstrate that management of habitat elements within grassland mosaics can affect the diversity and abundance of a range of invertebrate taxa, and that the diversity and/or abundance of invertebrate taxa correlate with the presence or extent of grassland mosaic habitat elements at a range of spatial scales. Management effects on aspects of grassland structure and characteristics are often quantified in these studies, for example in terms of sward height, sward heterogeneity, plant diversity or host plant availability. However, many studies mention grassland heterogeneity as a desired characteristic without directly quantifying it, or only measure one attribute of grasslands. No
study manipulated the management or extent of multiple elements to address the optimal size or layout of elements in a grassland mosaic.

Very few studies quantitatively link the management or attributes of grassland mosaics with the abundance or presence of the conservation priority invertebrate species addressed by this study. This may be due to the small population sizes and scarcity of many priority species, which make them difficult subjects for experimental studies or surveys at multiple sites. Limited evidence suggests that grassland specialists from the same taxa might be used as proxies for the response of some conservation priority invertebrate species to mosaic habitat management in grasslands.

The autecological data collected showed 73% of the priority invertebrate species assessed require more than one habitat element within a grassland mosaic during their life cycle. Information was gathered from National Nature Reserve managers relating to the scale at which mosaic elements are currently managed in grasslands of high nature conservation value. Limited evidence relating to foraging distances for a few priority invertebrate species suggests that multiple elements need to be present at small spatial scales (< 50 – 100m) within a grassland mosaic, though immobile life stages (e.g. larvae, eggs) may move much shorter distances, while some more mobile species require resources at a landscape scale (e.g. bumblebees forage over distances of several kms).

The autecological information on priority species life cycles and broader evidence relating to invertebrate responses to grassland management were used in a provisional assessment of prescriptions and prescription guidance for species-rich grassland management within the Higher Level Stewardship AES. The new Countryside Stewardship AES, starting in 2016, has a similar set of grassland options and option prescriptions as HLS. Current HLS prescriptions and guidance in relation to the management of individual habitat elements are broadly likely to benefit invertebrate assemblages and the conservation of several priority invertebrate species. There may be potential to alter some fine-scale aspects of management guidance, for example the size and distribution of scrub parcels following scrub clearance, and the potential for rotational grazing to increase floral and seed resources. These areas require further research. However, the value of AES for creating a grassland mosaic with multiple elements will depend on the use of multiple options and prescriptions at appropriate spatial scales within individual AES agreements.

Research to quantify the links between grassland mosaics and the conservation of priority invertebrate species could be conducted using a structured, targeted survey or a field experiment manipulating management of one or more habitat elements. A survey of grassland sites at which priority species are present would provide correlative evidence for links between priority species and the presence of habitat elements and heterogeneity within elements, at a range of spatial scales. An experiment would test whether small-scale grassland management can be altered to affect mosaic elements and small-scale heterogeneity within elements to benefit invertebrate communities, and so is more likely to lead to management recommendations relevant to AES. Either a survey or an experimental approach
would run the risk of gathering priority species data that are not robust enough to tease apart
the effects of multiple habitat parameters, due to the potential low abundance of many
priority invertebrate species. The monitoring of a wider range of invertebrates in addition to
priority conservation species is recommended as discussed above.
1. Introduction

There is a need to improve the quality of priority habitats and protected conservation sites in the UK if they are to contribute to “coherent and resilient ecological networks” that are able to maintain ecosystem services under future challenges such as climate change (Lawton et al. 2010; Defra 2011, 2013; Woodcock et al. 2015). Agri-environment schemes (AES) may be one way to create and improve the quality of ecological networks, through their coverage of large areas of farmland. There is evidence that habitat heterogeneity can improve habitat quality to increase the diversity of some groups of species (Benton et al. 2003; van Klink et al. 2015), though the majority of this comes from large-scale landscape studies, primarily on bird communities (Bennett et al. 2006; Baldi 2008). Conversely, habitat fragmentation can increase the chance of population extinctions and contribute to a decline in the abundance and diversity of species, so trade-offs may exist between increased heterogeneity and fragmentation (Batary et al. 2007; Batary et al. 2011; Allouche et al. 2012; Suggitt et al. 2014).

Many taxa move and utilise resources at smaller spatial scales than across entire landscapes. A recent meta-analysis showed that invertebrate species richness and abundance were affected both by localized (within farm) management intensity and by landscape complexity, while plant species richness responded only to local management. In contrast, vertebrate species richness responded only to landscape complexity (Gonthier et al. 2014). Webb et al. (2010) reviewed the requirements of priority species (those defined as being “of principle importance” in section 41 of the Natural Environment and Rural Communities Act 2006), and concluded that many priority species may benefit from habitat heterogeneity in the form of mosaics composed of small patches of habitats that differ in structure or composition. Many plant and invertebrate species are thus likely to respond to habitat mosaics at a small spatial scale instead of, or in addition to, landscape factors (Webb et al. 2010).

The Mosaic Approach has been developed by Natural England (2013b) to communicate the potential benefits of small-scale structural habitat heterogeneity for priority species. However, there is very limited published evidence linking priority species conservation to small-scale habitat heterogeneity, or to the creation and management of small-scale mosaics. Even in relation to common invertebrate species, few studies quantitatively link small scale heterogeneity with species diversity or abundance, and this has been identified as a key research gap (van Klink et al. 2015). This scoping study addressed the question: What current evidence is available that small scale habitat heterogeneity can benefit priority species conservation, and how can this be tested using a field-based study and potentially delivered through AES options?

1.1 Focus of scoping study

The time-scale and resources for this scoping study necessitated a focus on one type of mosaic habitat and a subset of priority species. The study focussed on mosaics within
grassland habitats, including bare ground, scrub and scattered trees within lowland farmland. Grasslands form a large proportion of English agricultural land (estimated at 38%; Tallowin et al. 2005) and of the 308 priority species associated with lowland farmland, the largest number (206 species) are associated with grassland habitats (Webb et al. 2010). Nearly 800,000 ha of grassland in England are covered by AES agreements, approximately 20% of the areas of permanent grass (Natural England 2009). The majority of the eligible area of grassland BAP priority habitats are covered by AES agreements; for example coverage of lowland calcareous grassland is 85% (Natural England 2009). Grasslands are also suitable habitats for the creation of mosaics at the scale of metres, including elements of bare ground and scrub.

Priority terrestrial invertebrates that are found in lowland grasslands formed the focus of the species element of the scoping study. Many invertebrate species operate over relatively small spatial scales, so as a group invertebrates are likely to be responsive to small-scale habitat changes (Gonthier et al. 2014). Other taxa such as birds or mammals are likely to operate over larger scales, and to be more strongly affected by habitat structure and heterogeneity at the landscape scale as discussed above (Webb et al. 2010; Gonthier et al. 2014). Terrestrial invertebrates form the largest group (86 species) within the 206 conservation priority species associated with lowland farmland (Webb et al. 2010).

1.2 Definition of terms

The following terms are used throughout this report to describe mosaic habitats. They are defined below, and the definitions provided are broadly consistent with usage in Webb et al. (2010) and Natural England (2013b).

Mosaic - a habitat made up of patches that differ in structure and composition. For example, a mosaic habitat in grassland might consist of patches of grassland (possibly of variable sward heights, structure and species composition) together with some or all of scrub, bare ground, hedgerows and veteran trees.

Mosaic element – one part or feature of a mosaic. For example, scrub or bare ground.

Heterogeneity – variation within a mosaic element. For example, sward structural heterogeneity relates to a variable sward height or variation in sward structural complexity.

Scale of mosaics - for the purpose of this study mosaic elements are defined as being measured at the scale of several metres rather than kilometres, while recognising that landscape characteristics may interact with small-scale mosaics to affect priority invertebrate species as discussed below (section 4.4). The literature reviews reported below include a consideration of relevant scales for different mosaic elements (section 4.2.5).
1.3 Objectives and research questions

The general aims of this scoping study were i) to summarise current evidence to determine whether management for habitat mosaics is likely to improve priority species conservation and ii) to specify a methodology to test how this can best be delivered through AES options. To achieve these aims, the study had the following broad objectives:

1) Review the literature on the ecology and management of habitat mosaics and small-scale heterogeneity, focused on mosaics within lowland grasslands and management interventions that would be practical under current and future AES options.

2) Review the available literature on the ecological characteristics and requirements of priority invertebrate species in habitat mosaics in lowland grasslands, with focal priority species identified using the work of Webb et al. (2010). Where available, to collate information for each species on factors such as resource and habitat requirements, and on traits that may affect the type and scale of species’ responses to habitat mosaics, for example trophic grouping, dispersal ability or range size, and extent of trophic specialisation.

3) Undertake a survey of expert opinion on how AES options could be relevant to habitat mosaics and small-scale spatial heterogeneity in lowland grasslands, and where possible to provide additional information for the literature review of priority species ecology.

4) Use the knowledge gathered in objectives 1-3 to design a large-scale field experiment and/or systematic survey to examine the effectiveness of management interventions in providing mosaics to benefit invertebrates in lowland grassland habitats.

In order to address objectives 1) and 2) above, the literature reviews focussed on the following research questions:

1) How can small-scale habitat heterogeneity and/or mosaic habitats be created and maintained in lowland grasslands?

2) What evidence is available regarding the characteristics (e.g. composition, structure, shape, size, configuration) of the elements that make up grassland mosaics that benefit invertebrates?

3) How effective are current AES options in promoting small-scale heterogeneity and habitat mosaics in lowland grasslands?

4) What are the ecological characteristics and requirements that may determine the response of priority invertebrate species to habitat heterogeneity and elements of habitat mosaics in lowland grasslands?
2. Methodology

2.1 Literature reviews

The literature reviews were based on a systematic methodology outlined in Pullin & Stewart (2006), and used widely in scientific reviews (e.g. van Klink et al. 2015). The literature review consisted of two parts, each consisting of a systematic review.

2.1.1 Review 1: The ecology, conservation and management of small-scale habitat heterogeneity

The first section of the literature review identified evidence relating to the ecology, conservation and management of grassland mosaics, and information about small-scale habitat heterogeneity, to address research questions 1-3 above. Information regarding the potential processes of mosaic creation and management was assembled. Potential trade-offs with increasing habitat fragmentation were also considered, as the chance of populations going extinct due to stochastic demographic processes may increase when patch sizes decrease (Allouche et al. 2012). Evidence regarding species or taxa characteristics that make them more likely to benefit from small-scale heterogeneity (e.g. niche width; Allouche et al. 2012), or more likely to be vulnerable to fragmentation (e.g. specialists; Batary et al. 2007, 2011) was also collated, together with information about habitats and potential key invertebrate groups that have been shown to respond to small-scale heterogeneity.

2.1.1.1 Literature search terms and databases

Literature searches for this first review were carried out using 22 keyword search terms in each of six online databases (Table 1). Wild cards are not accepted in the search function of Defra research reports, so for this database additional search terms were used to ensure each possible combination of a wild card search term was searched (e.g. for ‘grassland heterogeneity OR mosaic’; three search terms were used instead in Defra research reports: ‘grassland and heterogeneity’; ‘grassland and mosaic’; ‘grassland and mosaics’).
Table 1. Search terms used in each of six databases to identify literature (journal articles, theses, reports) relating to the ecology, conservation and management of grassland mosaics and heterogeneity.

<table>
<thead>
<tr>
<th>Databases</th>
<th>Search terms</th>
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<tbody>
<tr>
<td>ISI Web of Science</td>
<td>small scale heterogeneity, grassland heterogeneity OR mosaic*, habitat heterogeneity AND invertebrate*, habitat heterogeneity AND manage*, habitat heterogeneity AND creation</td>
</tr>
<tr>
<td>Google scholar</td>
<td></td>
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<tr>
<td>ConservationEvidence.com</td>
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<tr>
<td>Defra research reports</td>
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<tr>
<td>Natural England publications and reports</td>
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<td>British Wildlife</td>
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2.1.1.2 Literature screening criteria

Results of each literature search were sorted by relevance where the database allowed. Where large numbers of hits were returned, the first 200 hits were assessed. The title and if necessary the abstract of each reference were assessed for relevance to the study, using defined inclusion and exclusion criteria. A second reviewer independently checked a database using the same search terms for a subsection of literature searches to determine if the
screening inclusion and exclusion criteria were being applied in a consistent manner.
Agreement between the two reviewers was tested using a Kappa test (Viera & Garrett 2005).

*Criteria for inclusion* – studies which met any of the following:
1) Addressed methods for the creation or management of small scale heterogeneity or grassland mosaics in lowland farmland, e.g. (but not exclusively) grazing.
2) Assessed the characteristics of mosaic elements (e.g. size, configuration etc) in terms of the creation and management of a grassland mosaic, or in relation to impacts on invertebrate populations or communities.
3) Addressed the effects of small-scale fragmentation of grassland habitats on plant and / or invertebrate populations and communities.
4) Examined the effects of isolated trees (in hedgerows or fields) or bare ground in lowland farmland on invertebrate populations or communities.
5) Assessed the effectiveness of AES options in creating heterogeneity and/or mosaics in lowland grasslands.

*Criteria for exclusion* – the following were outside the scope of the review:
1) Studies that addressed the effects of heterogeneity on other taxa (e.g. microbial communities).
2) Studies that assessed heterogeneity in habitats other than grassland (e.g. forest).
3) Studies that addressed grassland systems that are not present in the UK (e.g. desert grasslands). However, studies conducted outside the UK using grassland systems that are present or very similar to those in the UK were included.
4) Studies that assessed heterogeneity in habitats at the landscape scale, or manipulated assemblages of plants in greenhouse / pot experiments, or presented a theoretical model.

Full text copies of each reference that met the screening criteria were downloaded or accessed from books and reports. The full text of each reference was then assessed to determine if the reference met the study objectives using the same inclusion and exclusion criteria above. In addition, reference lists of review papers that were identified (e.g. Tscharntke, T., Brandl, R., 2004. Plant-insect interactions in fragmented landscapes. Annual Review of Entomology 49, 405-430) were checked for relevant references.

2.1.1.3 Data extraction and collation

All references that passed the initial screening criteria were entered into an Endnote database. The full text of each reference was read, and information and entered in an excel spreadsheet, which consisted of 98 variables containing details on study design, experimental treatments (where applicable), timescale, taxa, detailed methodology and results for research studies and detailed findings of review papers. Variables and extracted data are stored in a spreadsheet (Mosaic_Approach_Scoping_Study.xlsx, MethodsConcepts tab).
2.1.2 Review 2: The ecology and habitat requirements of priority invertebrates associated with lowland grassland, hedgerows and veteran trees

The second literature review was conducted to gather information on the ecological characteristics and habitat requirements of priority invertebrate species associated with lowland grassland and related habitats, to address research question 4 above. The species list consisted of 116 priority terrestrial invertebrate species identified by Webb et al. (2010) as associated with grassland (86 species) and hedgerows (a further 12 species) in lowland farmland and with veteran trees (18 additional species), see Appendix A for list.

2.1.2.1 Literature searches and screening

A literature search for this second review was carried out using each priority species name in Google Scholar. Hits for each search were sorted by relevance, and the title and abstract of the first 100 hits were assessed for relevance to the study using an inclusion criteria: references were included if they contained information on the ecological characteristics and habitat requirements of priority invertebrate species associated with grassland or hedgerows in lowland farmland or veteran trees.

A search using each species name was also conducted in the Species Resources Database (Edwards 2014). Searches in additional databases, websites and reference manuals were made for specific taxa: e.g. Bees, Wasps and Ants Recording Scheme website; Butterfly Conservation website (for moths and butterflies); The Moths and Butterflies of Great Britain and Ireland (Emmet & Heath 1991).

2.1.2.2 Data extraction and collation

Full text versions of all relevant references were downloaded or accessed from books and reports. Details of each reference were entered into an Endnote database. Information on ecological attributes for each species was entered into a database, including detailed habitat information, host plant or animal, micro-climate requirements, degree of dietary specialisation, dispersal / range size information, body size, feeding category, generation time and recommended management. Variables and extracted data are in a spreadsheet (Mosaic_Approach_Scoping_Study.xlsx, PrioritySpecies tab).

Following these initial literature searches the information collated for each species was reviewed, and species were categorised as having a good, fair or poor amount of information. This was used to prioritise species with a fair or poor amount of information available from the literature, for inclusion in a survey of experts working in ecology and conservation.

2.2 Expert opinion survey

A survey of expert opinion was conducted, to gather information and ideas on the creation and maintenance of habitat mosaics and heterogeneity in grasslands, and to collect additional
information on those priority invertebrate species for which little information was found in the literature review (species classified as having ‘poor’ and in some cases ‘fair’ information above in section 2.1.2.2). A multiple survey approach was chosen to target participants with expertise in specific taxa, while minimising the amount of information requested from any one participant. Four surveys were designed, one to gather practical expertise and experience on the management of small-scale habitat heterogeneity within grasslands and the conservation of grassland habitats for invertebrates in the UK, and three requesting information on specific invertebrate taxa (beetles, moths and other invertebrates). Bee and butterfly priority species were not included as large amounts of information were available from the literature review for these taxa.

The grassland habitat management survey consisted of 18 detailed questions covering priority invertebrate species conservation, habitat mosaics and heterogeneity in grasslands and grassland AES options (Appendix B for full details). The priority taxa surveys contained multiple choice questions on the degree of mobility and specialisation of each species, and on their detailed habitat requirements (Appendix C for taxa survey questions; Appendices D-F for priority species include in each survey). Surveys were constructed using Survey Monkey, an online survey website. One to four surveys were sent to each of 30 experts from 17 organisations, including National Nature Reserve managers and taxon experts within Natural England, universities, conservation charities and recording schemes. Responses to the surveys were entered into the Methods and Concepts (habitat survey) and Priority Species (three taxon surveys) spreadsheets.

2.3 Short-listing of priority invertebrate species and link to mosaic elements

Once information from the literature searches and expert opinion surveys on the 116 priority invertebrate species had been collated, species were shortlisted for inclusion in a summary of the use of potential elements within a mosaic habitat (‘mosaic elements’). Species were excluded from the short-list if they had been allocated by Natural England for bespoke habitat management (as opposed to more general mosaic management) within the new Countryside Stewardship AES, or if they were present at five or fewer sites across England. Species present at five or fewer sites were considered likely to be the focus of specific habitat management, and less likely to benefit from generalised mosaic approach management of grassland supported by AES. The short-list of 45 priority invertebrate species is in Appendix G, and the summarised information in a spreadsheet (Mosaic_Approach_Scoping_Study.xlsx, MosaicElements tab).

The literature and expert opinion survey information was reviewed for each of the 45 short-listed species and summarised according to which mosaic elements they required, to create an overview of their habitat requirements. Summary information included the requirements of each species for specific mosaic elements, the time of year at which they might require each mosaic element and any information on their mobility (Mosaic_Approach_Scoping_Study.xlsx, MosaicElements tab).
3. Results

3.1 Literature review 1: The ecology, conservation and management of small-scale habitat heterogeneity in grasslands

Titles, and in some cases abstracts, of over 10800 hits from searches of the six databases were screened during literature review 1 as detailed above, of which 396 papers and reports were shortlisted for full text appraisal. Application of the screening inclusion and exclusion criteria were shown to be objective by substantial agreement between two independent reviewers (Kappa test statistic = 0.91; substantial agreement where statistic >0.6; Viera & Garrett 2005). Following full text appraisal, the details of 343 paper and report details were entered in the ‘methods and concepts’ spreadsheet.

Of the 343 references selected for inclusion in this study, 252 described original research studies (that presented new data), 71 were reviews and / or meta-analyses, and the remainder were opinion articles (e.g. editorials) and handbooks. The original research studies fell into two methodological categories, with 89 studies presenting results from experiments where grassland management was manipulated in a controlled, replicated manner for the purpose of the study, and 160 studies describing surveys of grasslands that differed in management before the start of the study, sometimes over long timescales (though the timescale over which management had been applied often wasn’t specified in studies reporting on surveys).

Figure 1: The number of experimental and survey studies reviewed by the length of data collection.

The timescale over which data were collected varied between studies, with 41% of experimental studies presenting data from just 1 year, and 86% from 3 or less years (Figure 1). Survey studies followed a similar pattern, with the majority (62%) presenting data from 1
year, and 88% presenting data from 3 or fewer years. Less than 6% of studies in either
category contained data gathered over 10 or more years (3.3% for experiments, 5.2% for
surveys).

A large proportion of the original research studies reviewed assessed the response of
grassland or scrub plant communities (132 of 252 studies), either alone or in conjunction with
invertebrate taxa. The majority of studies (56%) that assessed the response of invertebrate
taxa sampled just one taxon (Figure 2A), while 25% of studies compared two taxa, and a
minority of studies assessed multiple taxa. The most frequently studied invertebrate taxon
was butterflies, with beetles the second (split into ground beetles and other beetles, Figure
2B). Orthoptera, bees, spiders and moths were also common invertebrate taxa for study, as
each was included in 10 or more studies.

Only 13 of the original research studies addressed UK priority invertebrate species and 8 of
these were on butterflies. The vast majority of research studies used a measure of invertebrate
species richness, diversity and/or taxon abundance in their assessment of invertebrate
responses to grassland management. A small minority of studies assessed functional
groupings to assess the response of invertebrates to grassland management, for example using
beetles categorised by mobility and size classes (Cole et al. 2010) or by trophic grouping and
degree of herbivore specialisation (monophagous vs. oligophagous vs. polyphagous
herbivores vs. predators; Woodcock et al. 2009).

![Figure 2: The number of studies reviewed in relation to (A) number of invertebrate taxa and
(B) coverage of specific taxa. The “Others” category in (B) includes leaf miners, woodlice,
harvestmen, millipedes and earthworms.](image-url)

"Invertebrate taxa"
3.2 Literature review 2: The ecology and habitat requirements of priority invertebrates associated with lowland grassland, hedgerows and veteran trees

Searches of Google scholar and specialist databases and resources resulted in 11,140 hits. After screening for relevance, 1092 pieces of information were entered into the priority species database across all 116 species, from 607 reference sources. The number of data records per species from the literature searches varied from 26 and 25 for Bombus sylvarum (shril carder bee) and Maculinea arion (large blue butterfly) respectively to two for Dorycera graminum (phoenix fly). The priority invertebrate literature review built on the work of Webb et al. (2010), while including additional categories of information on management recommendations, lifecycle timing (to link to timing of mosaic element resource use, for example nesting and foraging periods), mobility (quantitative information was only available for a minority of species), degree of specialisation and trophic level (both for larvae and adults). For many of the priority species more detailed habitat information was collated than was available in Webb et al. (2010). For example, the cuckoo bee Nomada armata is parasitic in the larval stage and so dependent on populations of its host (Andrena hattorfiana), which is an additional piece of information in the Priority Species spreadsheet. Reference sources are attributed for each piece of information in the Priority Species spreadsheet, making it possible to distinguish between published scientific references and expert opinion.

The majority of priority invertebrate species were categorised as specialist (70%) with a number of species unspecified or with conflicting information (8%; Table 2A). Categorisation of specialist vs. generalist was drawn from the studies reviewed, and so followed the definitions used within these studies. The conflicting information for some species may have been due to degree of specialism being related largely to host plant species and plant part (e.g. flowers, seeds) specificity in some studies (Cowley et al. 2001) and more broadly to distribution breadth and habitat specificity in others (Botham et al. 2015). The largest number of priority invertebrate species were categorised as having limited or some mobility (47%), with roughly equal numbers in the sedentary (17%) and mobile (22%) categories (Table 2B). As with degree of specialism, categorisations of mobile vs. limited mobility vs. sedentary were taken from the studies reviewed, so there may be some variation between studies in how mobility was classified. Quantitative data relating to mobility (e.g. foraging distance or dispersal distance) were only available for a small minority of the priority invertebrate species reviewed.
Table 2: Number of priority invertebrate species in categories relating to (A) specialist / generalist and (B) degree of mobility

<table>
<thead>
<tr>
<th>(A)</th>
<th>Number of species</th>
<th>(B)</th>
<th>Number of species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalist</td>
<td>6</td>
<td>1 (not mobile, sedentary)</td>
<td>20</td>
</tr>
<tr>
<td>Specialist</td>
<td>80</td>
<td>2 (limited or some mobility)</td>
<td>54</td>
</tr>
<tr>
<td>Conflicting information</td>
<td>9</td>
<td>3 (mobile)</td>
<td>25</td>
</tr>
<tr>
<td>Not specified</td>
<td>21</td>
<td>Conflicting information</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not specified</td>
<td>16</td>
</tr>
</tbody>
</table>

A large majority of priority invertebrate species are herbivores, both in the larval (79%) and adult (84%) stages (Table 3). Some species have herbivorous adult stages and predatory or parasitic larval stages. For example, adults of the cuckoo bee *Nomada armata* feed on nectar from *Knautia* and *Scabiosa* spp., while their larvae are parasitic on another bee species (*Andrena hattorfiana*; Horsley et al. 2013).

Table 3: Number of priority invertebrate species in each trophic group in adult and larval stages of life cycle. Species that are both herbivores and obligate predators (in different larval instars) are classified as predatory.

<table>
<thead>
<tr>
<th></th>
<th>Adult trophic level (number of species)</th>
<th>Larval trophic level (number of species)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbivore</td>
<td>97</td>
<td>92</td>
</tr>
<tr>
<td>Predator</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Parasitic</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Unknown</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

3.2.1 Contradictory information for a few priority invertebrate species

Information from different sources provided complementary or similar information regarding habitat requirements, life-cycle and traits for almost all of the priority invertebrate species reviewed. One exception related to the way in which degree of specialism was defined, leading to a few Lepidoptera species being classified as specialist by one reference source and generalist by another, as discussed above (section 3.2). These species are noted as having conflicting information in Table 2A above, and information from both reference sources are included in the priority species database. One other occurrence of conflicting information relates to *Aricia artaxerxes* (northern brown argus butterfly), for which a requirement for scrub for shelter was specified by Webb *et al.* (2010), while three other reference sources recommend grazing management to prevent the development of scrub (Ravenscroft & Warren 1996; Ellis 2003; Pecsenye *et al.* 2007). Information from all the references is included in the priority species spreadsheet, but *A. artaxerxes* is not listed as having a requirement for scrub in the Mosaic Elements spreadsheet.
3.3 Expert opinion surveys

Twenty-two responses were returned across the four surveys, with the greatest response (11) for the habitat management survey (full responses in Appendices H - K). Many of the habitat survey responses contained detailed information about practical management of grassland to increase heterogeneity (Table 4A for examples), which was largely missing from the literature reviews. Similarly, responses to the priority taxa surveys (Table 4B for examples) contained detailed ecological, habitat and management information for many species that were not well represented from the literature reviews, including for *Dorycera graminum* (phoenix fly) discussed above (section 3.2).

The expert opinion survey built on evidence from the priority invertebrate literature review (section 3.2) and Webb *et al.* (2010) to collate more detailed habitat and lifecycle information for many of the more rare species. For example, the expert opinion survey on beetles provided information on adult feeding preferences and recommended management for the Red-horned cardinal beetle (*Ampedus rufipennis*), and detailed information on the structure of host plants (mosses) used by scarce brown streak moth (*Aplota palpella*) larvae.
Table 4: Example responses to (A) habitat management and (B) priority invertebrate taxa expert opinion surveys. Full responses to all surveys in Appendices H-K.

| (A) Habitat management survey: What methods were used to create the small-scale heterogeneity - e.g. grazing regimes, disturbance to create bare ground, scrub management? | Example response: Edge Common: Low intensity grazing – approx. 15 cattle (including around 7 cows with calves at foot and a bull for part of the grazing period) on 15 hectares of grassland from 1st August to 30th March with a 6 week break in Oct/Nov. Cutting and stump treatment of scrub with glyphosate each winter. Usually a small area each winter with volunteers but also some removal of larger scrub and mature trees to reduce seed proliferation. As a typical example this winter we have done one day with volunteers and cleared perhaps 1/4 hectare and also spent 3 days with 3 reserve staff clearing mature scrub and trees from approx. 1/2 hectare. We have also in the past cut and removed dense tor grass from approx. 1/2 hectare using an allen scythe and planted cowslips in the cut area. When clearing scrub we generally aim for about 15% retention of a range of species with particular emphasis on thorns. Juniper Hill: Grazing with up to 4 Dexter cattle on a 9 hectare site (probably about 5 hectares of grassland) from early August to early December. Scrub management similar to above. Bulls Cross: Grazing in paddocks from 1-3 hectares with up to 4 Dexter cattle from early August through to October/November. Scrub management similar to above. |
| Habitat management survey: What types of habitat were present, and at what scale were the different patches of habitat - e.g. metres, tens of metres, hundreds of metres? | Example response: All sites comprise a mixture of unimproved species-rich limestone grassland, ungrazed limestone grassland with a dominance of tor grass, dense and scattered scrub, mature secondary woodland, scattered mature trees and areas of short grazed rabbit turf. On all of the sites we aim for, and generally achieve, habitat diversity at the very small scale i.e. short turf mixed with longer tussocks and/or scrub in the space of a few metres. This diversity also occurs across the site i.e. across hundreds of metres. |
| (B) Priority moth survey: Coleophora vibicella – large gold case-bearer | Example response: Associated with Dyer's greenweed, the larva feeding from within a black case on the leaves, probably from before winter, becoming full-fed in late June. The adult flies in July and August. Now confined to less than 10 sites, these in Sussex, Hampshire and Dorset. Likely to require light cattle grazing to sustain populations of the plant in the longer term; two sites (on MoD holdings) are occasionally mown and seem to be in decline. Sites where it is found tend to have a plentiful supply of Dyer's greenweed. |
Priority invertebrate survey: *Dorycera graminum* – phoenix fly

| Example response: | More widespread than thought, southern England especially Thames gateway, Birmingham probably the most northern site. At edge of climatic range in UK. Associated with hogweed and possibly other large umbellifers in very rank neglected grassland, larvae develop in decaying stems and roots, coastal districts and brownfield sites. No association with linear features. Adults do not feed. Needs warmth. Not as mobile as some of the other hoverfly species. Management for cycle of grassland neglect |

### 3.4 Summary of mosaic element requirements for priority invertebrate species

Twelve grassland habitat elements were identified as necessary for the short-listed priority invertebrate species, including bare ground, scrub, hedgerows and grassland swards at a range of heights and with floral resources at different times of year (Table 5; mosaic elements spreadsheet). Thirty-three of the short-listed 45 species used more than one mosaic element, with 19 species using two elements, 8 species using three elements and 6 species using four or more elements.

Table 5: Number of priority invertebrate species associated with each grassland habitat element, out of a total of 45 short-listed species.

<table>
<thead>
<tr>
<th>Mosaic habitat element</th>
<th>No. of priority invertebrate spp. using element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare ground</td>
<td>25</td>
</tr>
<tr>
<td>Dung</td>
<td>1</td>
</tr>
<tr>
<td>Litter</td>
<td>2</td>
</tr>
<tr>
<td>Short grassland sward &lt;15cm</td>
<td>13</td>
</tr>
<tr>
<td>Flower rich sward, medium-tall height, spring</td>
<td>7</td>
</tr>
<tr>
<td>Flower rich sward, medium-tall height, summer</td>
<td>13</td>
</tr>
<tr>
<td>Grassy tussocks</td>
<td>4</td>
</tr>
<tr>
<td>Grassland unspecified in terms of sward height or structure</td>
<td>1</td>
</tr>
<tr>
<td>Scrub-grass edges</td>
<td>2</td>
</tr>
<tr>
<td>Scrub or topographic shelter</td>
<td>19</td>
</tr>
<tr>
<td>Hedgerows</td>
<td>10</td>
</tr>
<tr>
<td>Scattered trees</td>
<td>11</td>
</tr>
</tbody>
</table>
4. Discussion

4.1 Priority invertebrate species responses to small-scale habitat heterogeneity in grasslands

4.1.1 What evidence demonstrates that grassland mosaic habitats and heterogeneity within mosaic elements may benefit priority invertebrates?

There is limited published quantitative data showing that conservation priority invertebrate species associated with lowland grassland habitats respond positively to small-scale heterogeneity or grassland mosaics. Less than 5% of the studies in the methods and concepts review assessed species of high conservation priority (section 3.1), while a recently published review found little evidence that arthropod diversity is greatest in heterogenous grasslands (van Klink et al. 2015). Several of the 13 studies that addressed priority invertebrate species focussed on their response to grassland management at large spatial scales (Brereton et al. 2008) or to plant assemblages or nectar resources (Guido & Gianelle 2001, Carvell 2002). Thomas et al. (2001), Botham et al. (2011), Smee et al. (2011), Cizek et al. (2012) and Klapwijk and Lewis (2014) found priority invertebrate species abundance or presence to be linked to the height of larval host plant or sward and/or larval host plant abundance (as indicators of habitat quality), but did not assess multiple mosaic elements. These 13 studies thus provide evidence for the importance of the structure or composition of individual mosaic elements for priority invertebrates, but not for a range of diverse habitat structures and elements.

The vast majority of studies quantifying the effects of grassland management or grassland habitat structure on invertebrates assess the response of the diversity or species richness of one or more invertebrate taxa (section 3.1). Most of these studies assess the response of broad invertebrate assemblages, dominated by common species, rather than conservation priority species. Some of these studies show links between habitat heterogeneity or the presence of multiple mosaic elements at various spatial scales and invertebrate diversity or species richness, though many studies discuss habitat heterogeneity without directly quantifying it (Adler et al. 2001). For example, Marini et al. (2009a) demonstrated that Orthoptera diversity relates negatively to sward height and butterfly species richness correlates positively to plant species richness, and the diversity of both groups responds positively to the proportion of nearby forest at small spatial scales, while Woodcock et al. (2015) identify local site quality, measured in terms of floral community and sward structure (height), as the most important factor in ensuring high levels of invertebrate diversity. In a large-scale manipulative experiment across four European countries, Wallis De Vries et al. (2007) found that butterfly and grasshopper species richness and abundance were increased by low grazing intensities but not affected by livestock breed, while ground-dwelling invertebrate taxa had a varied and site specific response to grazing intensity. Reduced grazing intensity increased the abundance of butterfly species characteristic of tall and short vegetation (WallisDeVries et al. 2005), so sward height heterogeneity may have contributed to the improved habitat for butterfly assemblages.
Five studies assessed whether the response of invertebrate assemblages to grassland management or habitat structure represents the response of invertebrates of high conservation priority. Oertli et al. (2005) surveyed assemblages of bees, grasshoppers and aculeate wasps in grasslands varying in management and landscape context. Species richness of red-listed invertebrates across grassland sites was not correlated with species richness of the total taxa for either bees or grasshoppers (Oertli et al. 2005). Similarly, the diversity of threatened butterflies, grasshoppers, ground beetles and gastropods were found to correlate poorly with each other, resulting in a recommendation to assess a range of invertebrate taxa in conservation studies (Niemela & Baur 1998). In contrast, Spitzer et al. (2009) found that butterfly species richness across grassland sites varying in management, plant composition and presence of shelter (woody structures) correlated positively with the abundance of the Large blue butterfly (*Maculinea arion*), a conservation priority species. Butterfly species with similar habitat preferences as the large blue (warm, semi-natural, mesic grasslands with scrub) tended to co-occur at the same grassland sites, while widespread, ubiquitous butterfly species had negative associations with sites occupied by the large blue butterfly (Spitzer et al. 2009). In a survey of Orthoptera at 16 grassland sites under AES management in Germany Weiss et al. (2013) showed that the occurrence of red-listed Orthoptera species overlapped strongly with high Orthoptera species richness, and a survey of butterflies on grasslands along a temporal gradient of abandonment in Sweden found species richness of red-listed butterflies was positively related to total butterfly species richness (Ockinger et al. 2006). This limited evidence from five studies suggests that the responses of priority invertebrates to grassland management and type may be predicted from the response of other invertebrates within the same taxa that share their habitat requirements, but may not relate more broadly to the diversity or species richness of invertebrate species within their taxa, or to priority invertebrates in other invertebrate taxa.

Despite the limited evidence from published studies quantifying a direct link between priority invertebrate species and structural heterogeneity in grasslands, there is a case for managing grassland habitats to increase structural diversity from analyses of the lifecycles and requirements of priority species (Webb et al. 2010 and priority species spreadsheet), and from the first-hand experience of grassland managers and taxon experts. Over 70% of the short-listed priority invertebrate species reviewed here had a requirement for two or more mosaic elements within lowland grassland habitats in order to complete their lifecycles (section 3.4), often a combination of bare ground and/or a woody habitat element (scrub or hedgerows) with a particular height or structure of grass sward (Table 5). Populations of priority invertebrates such as *Decticus verrucivorus* (wart-biter cricket), and the duke of burgundy butterfly have increased on National Nature Reserves following management for bare ground/short sward and grassland/scrub mosaics respectively (Appendix H). In addition, across these 45 priority species resources such as pollen and nectar were required at different times of year, indicating a need for temporal as well as spatial heterogeneity in grassland mosaics if they are to cater for a range of priority species.
4.1.2 What grassland mosaic elements are important for priority invertebrate species lifecycles?

Over half of the short-listed priority invertebrate species have a requirement for bare ground for part of their life cycle. Bare ground is required for nesting for several bee (e.g. *Eucera longicornis* and *Anthophora retusa*; Horsley et al. 2013), wasp (e.g. *Odynerus melanocephalus*; Edwards 2002) and beetle (e.g. black oil beetle; Lückmann & Assmann 2006) species; to provide a warm microclimate for larval development for moths and butterflies (e.g. northern brown argus butterfly *Aricia artaxerxes*; Ellis 2003); and for adult basking and roosting (e.g. chalk carpet moth *Scotopteryx bipunctaria*; Hearle 2009) and hunting (e.g. hornet robberfly *Asilus crabroniformis*; Key 2000b). Over half of the short-listed species have a requirement for scrub and/or hedgerows. Some species use scrub or hedgerows as a larval (e.g. argent and sable moth *Rheumaptera hastata*; Parsons et al. 2011) or adult (e.g. white letter hairstreak butterfly *Satyrium w-album*; Emmet & Heath 1991) feeding resource, while others use scrub or hedgerows primarily for shelter (e.g. black oil beetle *Meloe proscarabaeus*; Lückmann & Assmann 2006) or adult roosting (e.g. dingy skipper butterfly *Erynnis tages*; Bourn et al. 2000).

Grassland sward requirements differ among priority invertebrate species in terms of sward height (short < 15cm vs. medium-tall), requirement for floral resources at different times of year (spring vs. summer), and a need for grassy tussocks. The majority of short-listed priority species have a requirement for at least one type of grassland sward, in combination with bare ground, scrub or both in order to complete their life cycle. For example, the long-horn bee *Eucera longicornis* needs bare or re-vegetating ground for aggregated nests, adults feed on Fabaceae pollen from herb- and legume-rich, open, medium height swards (15-60cm) and require a warm, sunny microclimate (e.g. south facing slopes; Horsley et al. 2013, Edwards 2014). The dingy skipper butterfly (*Erynnis tages*) also needs bare ground for oviposition, as females require 15% bare ground around the leguminous host plants in order to lay eggs, in an open, short sward around 3-8 cm tall (Oates 1995; Jaschke & Kolligs 2009). In addition, the dingy skipper needs tall vegetation or scrub for shelter and to roost (Bourn et al. 2000).

Scattered trees are a requirement for just under a quarter of the short-listed priority species. Some of these species use scattered trees as one among several grassland mosaic habitat elements. For example, the wall mason bee (*Osmia parietina*) nests in dead wood or dry stone walls while adults feed on birds-foot trefoil in grasslands (Fowles 1996) and the red-horned cardinal click beetle (*Ampedus rufipennis*)’s larvae feed on red rot in veteran and scattered trees (Horák & Rébl 2012) while adults feed on hawthorn flower nectar in scrub and hedgerows (expert opinion beetle survey respondent 3; Appendix I). Several of the priority invertebrate species associated with scattered trees are not known to use other grassland resources, for example larvae of the goat moth (*Cossus cossus*) feed under the bark of scattered and hedgerow trees growing in open situations in a range of damp habitats (Butterfly Conservation 2015b) and larvae of the dingy mocha moth (*Cyclophora pendularia*) feed on small (1-3 m tall), isolated willow trees growing in open, damp habitats (Butterfly Conservation 2015a). These species require the micro-climate or resources such as animal
nests which are found more frequently in trees or bushes growing in open rather than woodland habitats (Ranius & Jansson 2000), rather than requiring additional grassland habitat elements to complete their lifecycle.

Three of the 45 short-listed priority species require specialised habitat elements such as dung in addition to other grassland mosaic elements. The hornet robberfly (*Asilus crabroniformis*) oviposits in dung, where their larvae feed on nematodes and dung beetle larvae (Larsen & Meier 2004), and adults require bare ground for hunting their invertebrate prey while on the wing (Key 2000b). The moss and red-shanked carder bees (*Bombus muscorum* and *B. ruderarius*) both have an association with leaf litter for nesting sites (Edwards 2014), in addition to needing tall grassland with an abundance of floral resources in spring and summer (Benton 2008).

In addition to the elements of small-scale habitat heterogeneity discussed above, several of the more mobile priority invertebrate species need large-scale resources or habitat heterogeneity at the landscape scale. For example, *B. muscorum* is estimated to need 1km$^2$ of floral resources to support each nest (Saunders 2008) while some butterfly species such as small blue (*Cupido minimus*) exist as meta-populations across grassland habitats (Piessens *et al.* 2009).

### 4.2 Creation and management of grassland mosaic elements

The creation and management of small-scale habitat heterogeneity within grasslands has been interpreted as resulting from dynamic, natural processes, rather than a static goal for grassland management (Natural England 2013b). The Intermediate Disturbance Hypothesis proposes that biodiversity may be maximised in habitats subjected to an intermediate frequency and intensity of disturbance, creating mid-successional communities that also contain early and late successional species (Hobbs & Huenneke 1992). The Intermediate Disturbance Hypothesis has been shown to be valid under some circumstances (e.g. moderate populations growth rates or high productivity; Odman *et al.* 2012), and Warren *et al.* (2007) build on it to propose the Heterogenous Disturbance Hypothesis, suggesting that biodiversity is maximised where disturbance occurs at a range of spatial and temporal scales and intensities. Military training grounds may epitomise habitats subjected to heterogenous disturbance, with small areas subject to intense disturbance that vary in frequency, and large areas of habitat that are undisturbed over long periods of time (Warren *et al.* 2007). In addition to supporting high levels of biodiversity (Hirst *et al.* 2003), military training grounds such as Salisbury Plain may be important for the conservation of priority invertebrate species (Carvell 2002; Edwards 2002).

#### 4.2.1. Bare ground

Bare ground provides a warm microclimate for incubating eggs and basking invertebrates as it can be up to 10 °C warmer than surrounding vegetation (Key 2000a), in addition to being used as a nesting substrate and hunting ground by several priority invertebrate species.
Bare ground is created by a range of natural processes including rabbit burrows and scrapes, anthills (Veen et al. 2012), paths and high intensity grazing (Key 2000a). In a study on grazing herbivore species, Rosa-Garcia et al. (2011) found that the area of bare ground created was greatest under cattle grazing and least under sheep, while grazing either species in mixed flocks with goats created intermediate amounts of bare ground. Extensive sheep grazing in summer and autumn (April to November) resulted in more bare ground than extensive autumn (August to early November) sheep grazing treatments (Watt & Gibson 1988). Bare ground can cover up to 25% of the area following scrub clearance through the clear-felling and removal of woody vegetation (Rushton et al. 1990), and may persist for two or more years after scrub clearance (Barbaro et al. 2001). In addition to natural processes and as a side effect of ongoing management, areas of bare ground can be actively created through turf cutting or scraping the surface litter and vegetation (Key 2000a; Cameron & Leather 2012).

Smaller patches of bare ground may benefit invertebrate species more than large areas (Key 2000a). For example, Weiss et al. (2013) found that bare ground was a key resource for Orthoptera at covers of < 10%. However, Cameron & Leather (2012) found that the best size for bare ground patches may depend on surrounding habitat. Carabid beetle abundance, species richness and diversity was maximised on small bare ground patches (5 m) a year after their creation, except when purple moor grass (Molinia caerulea) was present at the patch edge, when all three parameters were greatest on the largest patches of bare ground. The patch size which maximised carabid abundance and diversity changed over time following the creation of bare ground (Cameron & Leather 2012). A year after 3-9 cm diameter gaps in a grassland sward were formed, tiller density was 70% of the original density (Bullock et al. 1995). Both invertebrate and plant communities will thus vary in their response to gaps depending on the length of time since they were formed, and gap formation needs to be an ongoing part of grassland mosaic management.

4.2.2 Grassland swards

The effects of grassland management on plant and invertebrate communities has been the subject of numerous research and review papers, covering grassland restoration (Mortimer et al. 1998; Bakker & Berendse 1999), mowing (Tscharntke & Greiler 1995; Mladkova et al. 2015), and grazing regime parameters including grazing animal species (Oates 1995), breed (Tallowin 2005) and behaviour (Bailey et al. 1998; Dumont et al. 2007b), grazing intensity (van Klink et al. 2015), timing (Cole et al. 2010), and rotational grazing (Morris 2000). A full summary of research into grazing is outside the scope of this review and has been covered elsewhere, so the focus here is on a summary of grassland management which may increase the heterogeneity of grasslands and benefit conservation priority species by providing a variety of grassland sward types and resources. In a recent quantitative review of grassland management research, van Klink et al. (2015) found that more than half of 141 studies assessed the response of just one arthropod taxa to grazing management, which corroborates our finding that 56% of the studies addressed one arthropod taxa in the current review.
There is strong evidence that the composition and structure of grassland plant communities can be affected by management regime. Cutting or mowing grasslands may result in lower herbaceous plant diversity (Isselstein et al. 2005), sward heterogeneity (Bakker et al. 1984) and a tighter grass sward compared with grazing (Oates 1995; Rook et al. 2004). This may depend on the duration of management, the number of cuts per year and the plant community, as Jacquemyn et al. (2003) found no difference in plant species richness between swards mown in late June and those that were grazed by cattle in a three year experiment. However, some meadows are grazed either before cutting in July, or both before and after cutting (e.g. upland hay meadows in Great Britain; Crofts & Jefferson 1999), so a direct comparison between grazing and mowing may not be relevant for all grasslands. Some traditionally mown grassland systems such as Swiss alpine meadows have reduced plant species richness if grazing is introduced (Plantureux et al. 2005). A seven-year experiment on species rich grasslands in the Carpathian Mountains found that neither mowing nor grazing affected total vegetation biomass, but mowing resulted in plant communities dominated by non-leguminous forbs with low potassium availability, while grazing resulted in grass dominated communities with low availability of phosphorus in the soil (Mladkova et al. 2015). Woody species establishment may be greater in grasslands managed by mowing or trimming compared with those that are grazed (Schuch et al. 2011), though this varies with the intensity, timing and species of grazing livestock.

The type and productivity of a grassland can also affect the speed and extent to which it responds to management such as grazing, mowing or disturbance. For example, the resilience of grasslands following disturbance by military vehicles was found to differ between calcareous and mesotrophic grasslands. Mesotrophic plant assemblages had 35% similarity to undisturbed mesotrophic grasslands 3 years after disturbance and 80 – 90% similarity 35 years after disturbance, whereas calcareous grasslands recovered at a slower rate to just 80% similarity after 50 years (Hirst et al. 2005). Optimal stocking rates for grazing vary with region, which has led to the suggestion that they should be zoned across the country (CEAS Consultants 1993). The effects of management can thus vary with type of grassland, region and aspect, so managers of high conservation value grassland sites may need to monitor the effects of grassland management and adapt their management regimes accordingly.

4.2.2.1 Effects of grazing regimes on plant communities and structural heterogeneity

Several studies have shown that grazing with livestock can increase plant diversity (Gibson et al. 1987; Pykala 2003; Rosen & Bakker 2005) and sward heterogeneity (Marion et al. 2010) compared to other forms of grassland management or no management. In a review of 11 studies testing the link between grazing and heterogeneity, the majority of studies found that grazers preferentially fed in previously grazed patches thereby increasing spatial heterogeneity (Adler et al. 2001), which may also be promoted by trampling and local fertilisation through deposition of dung and urine (Littlewood et al. 2012b). Selective defoliation can alter competition between plant species through biomass removal and changes in light and microclimate to increase plant diversity, while treading also opens up regeneration niches for gap-colonising species (Rook et al. 2004). Livestock grazing may
create gaps in low productivity grasslands, but this may be less likely in productive grasslands (Pywell et al. 2007). Grassland responses to grazing can be slow, as Ward & Jennings (1990) found a calcareous grassland subject to several types of disturbance responded to grazing after 8 years, after which plant diversity was increased at a small spatial scale (1 m²) through species being more closely packed.

Many individual studies have shown that plant diversity is maximised at a low or moderate grazing intensity (e.g. Soder et al. 2007; Plantureux et al. 2005; Rook et al. 2004), while intensive grazing can reduce species richness by eliminating species that are not grazing tolerant (Soder et al. 2007). Rook et al. (2004) suggest this may be partly due to livestock behaviour, as under moderate grazing pressure animals are more likely to demonstrate dietary preference than under severe grazing pressure. A stocking rate of less than 1.5 livestock units per ha per year has been suggested to promote plant diversity (Plantureux et al. 2005). However, two recent meta-analyses of studies manipulating grazing intensity demonstrated that plant diversity and species richness do not show a consistent response to grazing intensity (Scohier & Dumont 2012; van Klink et al. 2015), possibly due to variation in the productivity of grassland systems which may affect whether plants compete for light in the absence of herbivores (Olff & Ritchie 1998). Many European grassland systems have a long history of extensive grazing under which plant species richness is often maximised by a continuation of historic grazing regimes, and reduced following abandonment or a move to intensive grazing (van Klink et al. 2015).

Sward structural heterogeneity may be maximised at an intermediate grazing intensity, though there is insufficient research to test the spatial and temporal scales at which this occurs (van Klink et al. 2015). For example, using a three year experimental study Dumont et al. (2007a) found that an intermediate cattle stocking density (1 livestock unit per ha per year) resulted in greater heterogeneity of sward height across the growing season than low stocking (at which heifers retained their preference for short sward patches and much of the sward remained tall). In addition, intermediate stocking resulted in reproductive grass patches across 15% of the grassland area, providing greater structural components for invertebrates than under a high stocking density. In contrast, RSPB et al. (2011) found that sward heterogeneity, measured as the number of transitions between tall and short sward patches, was greater under lenient grazing (target sward height 12-16 cm) than under a moderate cattle grazing intensity (target sward height 8-9 cm), but that plant species richness was not affected. Another four year manipulative grazing experiment found that the density of flower heads in summer was greater under lenient (target sward height 12-16 cm) than moderate (target sward height 6-9 cm) cattle stocking densities (RSPB 2009). In addition to sward structure and plant diversity, grazing intensity can affect the cover of plant litter, one of the grassland habitat elements identified as necessary for priority invertebrate species (section 4.1.2 above), as litter cover is reduced under intensive grazing relative to low or moderate grazing (Morris 1969; Sjodin et al. 2008; Eschen et al. 2012).

The timing of grazing can affect plant community composition. A long term sheep grazing experiment resulted in greater plant diversity and more species typical of permanent
grassland under spring grazing than autumn grazing, but no change in the rate of colonisation of plots by new plant species (Gibson et al. 1987). In contrast, Lenoir & Lennartsson (2010) found that late summer grazing gave a taller sward, deeper litter layer and greater sward heterogeneity than grazing from May-September. As with many aspects of grassland management, the timing of grazing may have varying effects on different types of grassland. Kirby (1992) suggests that winter grazing is suited to light, well-drained soils, as it is traditionally used on calcareous grasslands, while summer grazing may be needed on fertile soils to reduce plant growth. Rotational grazing, whereby grasslands are grazed in sections with some ungrazed areas present at all times, may establish structural, floristic and temporal plant diversity (Tscharntke & Greiler 1995).

Grazing animal impacts on plant community composition and structure can vary with the species and age of livestock. Bigger animals can eat less digestible plant species as they have longer, larger guts, so they are often less selective than smaller animals. For example, sheep are generally more selective than cattle and are better at selecting high quality plant parts such as flowers, pods and young shoots (Rook et al. 2004). Grazing with sheep can lead to a dominance of grasses in temperate plant communities because of their high selectivity for legumes and forbs (Scohier & Dumont 2012), and a reduction in plant species richness compared to grazing with cattle (Ockinger et al. 2006). Cattle grazing may be more effective than sheep at gap creation in the sward (Pywell et al. 2007) thereby allowing germination and seedling establishment. Livestock feeding decisions are affected by their digestive systems as well as size; horses are less efficient than cattle so they graze for longer periods, bite closer to the ground (Rook & Tallowin 2003) and have higher trampling pressure which can result in a greater cover of rosette plant species (Marion et al. 2010). Cattle are more tolerant of plant secondary metabolites than horses and so graze a higher proportion of dicotyledonous plants (Marion et al. 2010). Rabbit grazing reduces plant tussocks to create a short sward (Hassall 1996). Differences in foraging preferences and decisions may mean that multi-species grazing flocks at intermediate stocking rates may maximize sward heterogeneity (Marion et al. 2010). The effect of grazing animal breed on plant diversity is largely anecdotal (Rook & Tallowin 2003), and is less important than the effects of grazing intensity and the species of livestock.

4.2.2.2 Effects of grazing regimes on invertebrates

Several reviews have suggested that the grazing intensity at which invertebrate species richness is maximised might be lower than that at which plant species richness is highest especially among invertebrate species which depend on flowers, seed heads, specific plant species or have long-lasting larval development (Morris 1969; Gibson et al. 1992; Steffan-Dewenter & Tscharntke 2002; Littlewood et al. 2012a). This may lead to management conflicts between the optimal grazing conditions for plant and invertebrate diversity (Bakker & Berendse 1999). A meta-analysis of 24 studies manipulating grazing intensity showed that arthropod diversity responded negatively to grazing intensity, with more than 80% of the data showing a decrease in arthropod species richness in response to increased intensity of grazing (van Klink et al. 2015). The study duration, productivity of the ecosystem being studied, type
of experiment, and difference in grazing intensity applied did not significantly affect the response of arthropod or plant diversity to grazing intensity (van Klink et al. 2015). Several factors may contribute to the negative effect of intensive grazing on arthropod diversity, including direct effects (arthropod mortality through trampling and ingestion of immobile stages present on plant hosts), reduction of resource availability (plant biomass), and changes in plant diversity, structure and microclimate (van Klink et al. 2015). Invertebrates are more sensitive to trampling disturbance than plants, as many plant species can recover from trampling (Hobbs & Huenneke 1992). van Klink et al. (2015) also found little empirical evidence to demonstrate that arthropod diversity is greatest in structurally heterogenous grasslands, though conceptually there is a potential link between greater sward heterogeneity and increased diversity of habitat niches for invertebrates. Grazing may potentially increase arthropod diversity if it increases structural heterogeneity to the extent where this compensates for the direct mortality caused by grazing, which is most likely under low grazing intensities (van Klink et al. 2015).

The response of invertebrate taxa and species to intensity of grazing will depend on their specific lifecycle and habitat requirements. In a comparison of carabid beetle responses to intensive and extensive sheep grazing regimes, large relatively immobile beetles (e.g. from the Carabus genus) were found to be more abundant under extensive grazing, while Carabidae species specialising on Collembola were more abundant under intensive grazing which provided an open sward to facilitate hunting (Cole et al. 2006). This varying response among different functional groups of Carabidae led to the overall Carabidae species richness, diversity and evenness not being affected by sheep grazing intensity (Cole et al. 2006). Both grasshopper and butterfly species richness were reduced under a moderate (6 cm sward height) cattle stocking density compared with lenient (12 cm) or very lenient (18 cm) densities at a 10 year manipulative experiment, but the two invertebrate groups responded to different plant parameters (Jerrentrup et al. 2014). Grasshopper species richness was positively related to plant species richness, while butterfly abundance related positively to the availability of nectar sources (Jerrentrup et al. 2014), a response also shown by other pollinator groups such as bumblebees which have increased abundance (Tallowin 2005) and species richness (Soderstrom et al. 2001) under reduced grazing intensities. Grazing intensity was shown to more strongly affect abundance and species richness of butterfly (WallisDeVries et al. 2005) and grasshopper (Wallis De Vries et al. 2007) taxa than the breed of grazing livestock in a 3 year experiment in four European countries, though ground dwelling invertebrates did not respond to either grazing intensity or breed (Wallis De Vries et al. 2007). An experiment manipulating grazing intensity in the USA has shown that the response of bees varies with genus. The abundance of Bombus spp. decreased as grazing intensity increased possibly due to the removal of floral resources, while Lasioglossum spp. abundance was unaffected (Kimoto et al. 2012).

The timing of grazing has the potential to affect small-scale heterogeneity in grasslands, and the diversity of associated invertebrates. The response of invertebrates to the timing of grazing also varies depending on their lifecycle and resource requirements (Scohier & Dumont 2012). For example, the effects of the timing of sheep grazing on invertebrates
depended on their mobility and size class, which also affected the spatial scale at which they responded to habitat variables (Cole et al. 2010). Eschen et al. (2012) found that timing of grazing had a stronger effect on plant community and sward heterogeneity than the intensity of grazing in a manipulative experiment at 13 sites. In contrast, the abundance of several invertebrate taxa (Collembola, Auchenorrhyncha, Staphylinidae, Heteroptera and Araneae) was increased under lenient compared with intensive grazing and did not respond to grazing timing (Eschen et al. 2012), though the response of invertebrates using reproductive plant parts was not assessed. Other studies which have assessed the response of pollinating invertebrates have shown bumblebee and butterfly abundance to be increased on plots that are not grazed in spring and summer to increase floral resources as part of a rotational grazing regime (Farruggia et al. 2012; Scohier et al. 2013). Late grazing by cattle (mid-July to September) was found to increase the species richness as well as abundance of pollinating insects visiting flowers, compared with continuous grazing from mid-May to September, in an experiment in Sweden (Sjodin 2007). However, the abundance of individual species can differ in response to timing of grazing, as Bombus lapidarius had higher abundance under continuous grazing probably due to the increase in Trifolium repens cover, while four other Bombus species were more abundant under late grazing (Sjodin 2007). Sheep have been shown to negatively impact nectar-dependent insect groups as a result of their preferential use of flowering plants; the species richness of bumblebees and butterflies is lower in sheep-grazed pastures than in similar grasslands used by cattle (Scohier & Dumont 2012).

Rotational grazing (for example grazing small paddocks for 7 days in rotation) may establish structural, floristic and temporal diversity within a sward (Morris 1969; Tscharntke & Greiler 1995). This can benefit plant and invertebrate diversity (Plantureux et al. 2005) by ensuring that plants can set seed, and so flowers and seed heads are available for pollinators and specialist invertebrate herbivores (Gibson et al. 1992; Scohier et al. 2013), and has also been shown to increase Coleoptera species richness and abundance (Gibson et al. 1992). Conversely, rotational grazing may result in sudden changes in sward structure which could be detrimental to some less mobile invertebrate species (Crofts & Jefferson 1999).

Few studies have quantified the effects of grazing regimes on priority invertebrate species, which are often too rare to form part of replicated experiments or surveys. Exceptions include a study which found the marsh fritillary (Euphydryas aurinia) butterfly’s host plant Succisa pratensis (devil’s bit scabious) is less abundant at sites where grazing has recently been started or ungrazed sites compared with those under extensive grazing (Smee et al. 2011). A survey of bumblebees on Salisbury plain found abundance of the priority species Bombus humilis was maximised on disturbed edge habitats, as well as on habitats that were grazed by sheep or had recently been cultivated for arable crops, on which abundance of the nectar plants Odontites verna and Echium vulgare were maximised (Carvell 2002).

Even fewer studies have quantified the effects of grazing regimes on interactions between invertebrates from different trophic levels, though trophic interactions may be key in maintaining stable populations and communities of invertebrates (Tscharntke et al. 2002b). Grazed woodlands were found to have greater vascular plant species richness than woodlands
that had not been grazed by cattle for at least 10 years in a single study (Vanbergen et al. 2006). Grazing also increased the abundance and rate of parasitism of a tephritid fly species, possibly due to more abundant nectar sources for the adult flies and parasitoids (Vanbergen et al. 2006).

4.2.3 Scrub and hedgerows

Scrub forms part of an ecotone between grasslands and woodlands, increasing microclimate heterogeneity through shading, shelter and reduced soil moisture (Kollmann & Poschlod 1997). Scrub also increases the diversity of microhabitats available to invertebrates, with more microhabitats in larger, more structurally complex scrub (Mortimer et al. 2000). Open, patchy scrub may be of greater benefit to priority invertebrate species than large stands of dense scrub, and some invertebrates have specific requirements for the edge between grassland and scrub (Kirby 1992). For example, the red-shanked carder bee (Bombus ruderarius) nests in scrub edge as well as tussocks of grass (Webb et al. 2010), and the Sloe carpet moth (Aleucis distinctata) lays eggs on the leading edge of blackthorn scrub where it suckers into grassland (Butterfly Conservation 2015c). The proximity of scrub to nectar sources is an important factor in the conservation of scrub (Mortimer et al. 2000).

Seed dispersal and proximity of seed sources are critical to the development of scrub (Mortimer et al. 2000), and the majority of seed dispersal of scrub species is by birds (Kollmann 1995). Following establishment, the average rate of scrub increase into calcareous grassland at Salisbury plain was found to be 1096 m² per ha per decade (10.96% per decade; Redhead et al. 2012). Some form of scrub management or clearance is therefore needed to maintain a mosaic of grassland elements, and prevent succession of grasslands to dense scrub followed by woodland.

Cattle may be better at opening up scrub during grazing than sheep through trampling and mechanical damage (Crofts & Jefferson 1999), while goats are the best grazing livestock for reducing woody species (Oates 1995). Grazing management of grasslands has historically often been targeted at eradicating scrub, but the sward may need to be overgrazed by sheep or cattle before scrub is grazed, leading to a uniform short turf (Oates 1995). In addition, winter grazing may not control scrub, which becomes less palatable from mid-summer onwards due to an increase in lignin (Crofts & Jefferson 1999). If scrub removal is necessary mechanical or chemical methods may work better than grazing, though sheep grazing can prevent the establishment of scrub seedlings (Good et al. 1990). In a comparison of scrub removal methods spraying with herbicide was the least effective at reducing the area of scrub, while multiple cutting and spraying was the most effective (Redhead et al. 2012). If only a single scrub clearance option is available then cutting was found to be best, as shoots from cut stems were more palatable to grazers than adult scrub (Redhead et al. 2012). Mechanical scrub clearance may also create substantial areas of bare ground (section 4.2.1 above). Saproxylic species can form a substantial component of invertebrate communities on scrub, for which the proximity of dead wood to nectar sources is important (Mortimer et al. 2000), so
maintaining scrub in the vicinity of veteran trees or trees with wood decay may benefit invertebrate diversity.

Recolonization of cleared scrub by grassland species depends on the seed bank and seed dispersal (Kollmann & Poschlod 1997; Davies & Waite 1998), which are often limiting factors in grassland restoration (Edwards et al. 2007). Grassland community development after scrub clearance of large areas can be poor (Mortimer et al. 1998), and may depend partly on how long the scrub has been present. The seed bank under young scrub (<15 years) was found to be similar to that of calcareous grassland, but under mature scrub (40+ years) the seed bank no longer resembled that of grassland (Bossuyt et al. 2006). In addition, soil nutrient status under long-established scrub is usually enhanced, so clearance of scrub may result in colonisation by nitriphilous species which inhibit colonisation by plant species of semi-natural grassland through competition. Maintaining scrub in a mosaic of small, young patches would increase the chance of grassland colonization following clearance, as well as providing the optimal structure of scrub for priority invertebrates and transitional patches of bare ground.

Some priority invertebrates that require scrub can use hedgerows as an alternative or additional woody habitat. For example, the sloe carpet moth (Aleucis distinctata) will lay eggs on blackthorn in overgrown hedges as well as scrub (Butterfly Conservation 2015c), while other species have a requirement for specific structures or a warm microclimate within scrub. A survey of butterfly and grasshopper species in grasslands across a disturbance gradient in Greece found the abundance of four butterfly species was positively associated with the presence of hedgerows or tree lines (Kati et al. 2012), while the shelter provided by hedgerows was found to increase the abundance and species richness of bumblebees and butterflies as well as floral abundance in a survey of field margins in the UK (McCracken & Tallowin 2004).

The majority of hedgerows are managed through cutting with mechanised flails on a short rotation (every 1 or 2 years; Sparks & Croxton 2007; Staley et al. 2012) and a minority through infrequent hedge-laying or coppicing (Staley et al. 2015), both of which can change hedgerow structure and the abundance of flowers (nectar sources) to affect invertebrate populations (Facey et al. 2014; Amy et al. 2015). Frequent hedgerow cutting may cause direct mortality to priority invert species, for example through removing brown hairstreak butterfly (Thecla betulae) eggs (Merckx & Berwaerts 2010). However, some form of management is required to stimulate the new growth of blackthorn on which brown hairstreak butterfly lay eggs, either through cutting sections of hedges on a long rotation, hedge-laying or coppicing (Bourn & Warren 1998). An infrequent cutting regime (>3 years) is also recommended for the sloe carpet moth (Butterfly Conservation 2015c) which needs large, wide hedges. Hedgerows may therefore contribute to the conservation of priority invertebrate species within a mosaic of grassland elements, and their management should be adjusted to encourage new woody growth while maximising floral abundance.
4.2.4 Scattered trees

Trees that are scattered in open situations throughout grasslands have been advocated as potential keystone structures, which have the potential to increase the diversity of a range of taxa by providing additional habitat niches (Tews et al. 2004), a warmer microclimate than trees growing in shaded, woodland conditions (Ranius & Jansson 2000) and more resources for invertebrates such as squirrel’s dreys and birds’ nests than woodland trees (Ranius & Jansson 2000; Bee 2007). These differences in microclimate and resources result in scattered trees being associated with different invertebrate assemblages than woodland edge trees (Kirby 1992). In addition, the continuity represented by scattered trees in very long established wood pastures (such as Windsor Forest and the New Forest) is key to the presence of threatened invertebrate communities (Manning et al. 2006), for example ancient beetle species that are indicators of old growth forests (Alexander 2004).

Several invertebrate taxa are associated with or benefit from scattered trees. Spiders use spatial structures on ancient and other trees (Bee 2007). For example, the conservation priority money spider Midia midas priority is confined to ancient parkland trees as its microhabitat requirements include squirrel dreys, bird nests and possibly leaf litter in hollow trunks of veteran trees (Bee 2007). Spider species richness and abundance increased with the number of habitat types per farm in Hungary, including trees and linear features, while different habitat factors were more important for other invertebrate taxa, such as floral resources and grazing intensity for bumblebees (Kovacs-Hostyanszki et al. 2013). Habitat diversity, which was strongly linked to the cover of trees and shrubs, had a positive effect on Orthoptera species richness from a survey of semi-natural grassland fragments in an arable matrix in Italy (though habitat area had a larger effect; Marini et al. 2010). Butterflies, bumblebees and dung beetles were found to be positively related to the amount of tree cover within pastures, though negatively related to woodland area at a landscape scale (Soderstrom et al. 2001).

Invertebrate traits may determine their response to the presence of scattered trees. For example, trees and shrubs were found to be detrimental to thermophilous Orthoptera species of the sub-order Caelifera due to a cooler microclimate, but not to species in the sub-order Ensifera (Marini et al. 2009b). The presence of scattered trees within hedgerows can increase the abundance of macro-moth species with shrub or tree-feeding larvae, though the abundance of moth species with grass or forb-feeding larvae were not affected by the presence of trees (Merckx et al. 2010b). Moth species with low mobility were especially benefitted by the presence of scattered trees, as less mobile species are more prone to convective cooling in exposed agricultural landscapes and benefit most from shelter (Merckx et al. 2010b). The species richness of macro-moths was also increased by the presence of hedgerow trees, though this was greater for moth species that feed further from the ground than low-feeding species (Merckx et al. 2012). The conservation priority species pale shining brown moth (Polia bombycina) was more abundant at sites with hedgerow trees compared with sites without trees (Merckx et al. 2010a).
Management recommendations for scattered trees include retaining fallen branches and leaf litter around the tree, and keeping the area under the crown free of ploughing and grazing (Bee 2007; Boatman et al. 2013). The main challenge in management of scattered trees is their declining numbers, due to a lack of regeneration (Manning et al. 2006) and high rates of mortality (Gibbons et al. 2008). A survey of hawthorn in Wales found few seedlings and trees less than 20 years old, due to high intensities of sheep grazing (Good et al. 1990). Mortality of scattered trees may be increased by land clearing, herbicide spray drift, nutrient enrichment, fire, salinity, vertebrate and invertebrate browsing, though the relative importance of these factors has not been quantified (Gibbons et al. 2008). An analysis of the stock of scattered trees in four countries (not including the UK) predict that they will be gone from agricultural landscapes in 90 – 180 years, with the fastest predicted decline in Europe (Spain) (Gibbons et al. 2008). To avoid this more trees need to be planted and protected from grazing in open grassland and established within hedges. This is incentivised in England under AES which include options for tagging and establishing buffer strips for hedgerow trees, and reducing cultivation around trees in fields (Natural England 2013a).

4.2.5 Size, shape and configuration of grassland mosaic elements

Although a mosaic of different successional stages is widely recommended for grassland management, there is almost no information in the literature on the optimal scale, spatial structure or configuration of mosaic elements or heterogeneity within an element which are likely to benefit invertebrates (Steffan-Dewenter & Tscharntke 2002; Mortimer et al. 2006; van Klink et al. 2015). One exception at the landscape scale is a survey of butterflies at 33 calcareous grassland sites in Germany, which found that 10 ha of calcareous grassland is predicted to support 98% of the butterfly species sampled during the survey if it is composed of many (around 30) small fragments, but only 50-60 % of the species if it is composed of 1 or 2 large grasslands (grassland sizes ranged from 300 – 76,000 m²; Steffan-Dewenter & Tscharntke 2000). A survey of restored species rich grassland sites found that invertebrate diversity was not related to site size, though size may have been confounded with the type of management applied as smaller sites were more often owned by conservation organisations (Woodcock et al. 2015). Woodcock et al. (2015) suggest that local site quality, assessed as floral community and mean sward height, may be the most important driver of invertebrate diversity (especially the diversity of grassland specialist invertebrates) rather than site size. However, neither study assessed the size or configuration of different habitat elements within a site. van Klink et al. (2015) suggest that grazing may decrease vegetation structure at small scales while increasing it at large scales, and identify the spatial and temporal scales at which grazing affects vegetation heterogeneity to alter resource availability and microclimate for arthropods as a priority research area.

The habitat management expert opinion survey provided some anecdotal evidence on management of grassland to increase heterogeneity for priority invertebrates. For example, some English National Nature Reserves are managed using low intensity cattle grazing (1 livestock unit per ha) in August – March with a break in October and November along with
removal of scrub and mature trees through cutting and herbicide treatments, and dense tor grass with scything (Appendix H). The scale of mosaic management applied varies with the target invertebrate for conservation, with bare ground being created at the scale of cms or metres, scrub managed at the scale of metres or 10s metres and larger scale mosaics for more mobile bumblebees at 10s or 100s metres (Appendix H).

Some evidence is available on the mobility of conservation priority invertebrates and invertebrate taxa more broadly, which gives an indication of the spatial scale at which different grassland habitat elements would need to be available in order to be accessible to invertebrates. While some invertebrate species are highly mobile, a distinction is necessary between daily foraging movements and less frequent dispersal events, as the latter tend to occur over much greater distances than daily foraging. The northern brown argus (*Aricia artaxerxes*) butterfly makes 98% of its movements across less than 100 m though it will move up to 200 m to find new nectar sources (Ravenscroft & Warren 1996), while most adult small blue (*Cupido minimus*) butterflies move less than 40 m (Krauss et al. 2004). Three grassland butterfly species, including two conservation priority species (lulworth skipper *Thymelicus acteon* and glanville fritillary *Melitaea cinxia*), were found to form discrete populations when they were separated from conspecifics by unsuitable habitat at distances of 75 – 100 m (Thomas et al. 2001). In contrast, the highly mobile hornet robberfly (*Asilus crabroniformis*) moves more than 400 m a day (Holloway et al. 2003), while many bee species need mosaics of resources across landscape scales (Connop et al. 2011), for example large garden bumblebee (*Bombus ruderatus*) workers have a maximum flight distance of 1.9 km from their nests (Hagen et al. 2011). Within a species, mobility may vary with the age (Dover & Settele 2009) or sex of an individual invertebrate, for example female stag beetles (*Lucanus cervus*) move over shorter distances than males (Rink & Sinsch 2007).

A few studies have assessed invertebrate communities in relation to habitat and landscape variables at a range of spatial scales. A survey of restored grasslands found that land snails and Orthoptera communities on sites that were more than 100 m from the nearest source grassland had lower species richness and a reduced assemblage compared with restored grasslands that shared a boundary with permanent grasslands (Knop et al. 2011), showing that over comparatively short distances invertebrate movement can be limited. The proportion of woody vegetation present within 95 m of grasslands related positively to species richness of butterflies and Orthoptera in a survey of 44 grassland-forest mosaic sites in Italy, while the proportion of woody vegetation at larger spatial scales did not affect either invertebrate group (Marini et al. 2009a). Invertebrates were found to range 117 – 185 m from Swiss meadows under AES management into non-preferred habitat, depending on the taxa, with ground beetles moving the greatest distances and true bugs the least (Albrecht et al. 2010).

**4.2.6 Summary of creation and management of grassland mosaic elements**

The establishment and management of grassland mosaics has its origins in natural processes (Natural England 2013b) as discussed above (4.2), including the effects of grazing animals on plant diversity and sward structure, creation of bare ground and effects on the spread of
Nonetheless, management techniques and decisions determine how these natural processes will affect grassland mosaics, from grazing intensity, timing and choice of livestock breed to active planting and management of scattered trees. Creation of mosaics at small spatial scales may require micro-management of natural processes, for example rotational grazing of small areas of grassland (Scohier et al. 2013; van Klink et al. 2015). Table 6 provides a summary of the management and natural processes discussed in sections 4.2.1 – 4.2.5 above.
Table 6: Summary of types of management and characteristics of grassland mosaic elements that may be affected by management

<table>
<thead>
<tr>
<th>Management or natural process</th>
<th>Mosaic element parameters affected by management / natural process</th>
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<tr>
<td>Grazing by livestock</td>
<td>Plant diversity and plant community composition</td>
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<td>Ratio of forbs to grasses</td>
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<td>Presence / abundance of conservation priority plant species</td>
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<td>Sward height</td>
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<td>Sward structural heterogeneity</td>
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<td></td>
<td>Availability of plant reproductive structures (flowers, seedheads)</td>
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<td>Scrub growth</td>
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<td>Establishment of woody species</td>
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<td></td>
<td>Area of bare ground</td>
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<td></td>
<td>Provision of warm microsites</td>
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<td></td>
<td>Seedling germination and establishment sites</td>
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<td></td>
<td>Plant litter cover</td>
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<td>Dung (type, amount, spatial distribution)</td>
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<td>Mowing</td>
<td>Plant diversity</td>
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<td>Sward heterogeneity</td>
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<td></td>
<td>Availability of plant reproductive structures (flowers, seedheads)</td>
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<td></td>
<td>Establishment of woody species</td>
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<td>Anthills</td>
<td>Area of bare ground</td>
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<td></td>
<td>Provision of patches of warm microclimate</td>
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<td>Sites for seedling germination and establishment</td>
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<td>Rabbit grazing and scrapes</td>
<td>Area of bare ground</td>
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<td>Provision of patches of warm microclimate</td>
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<td>Sites for seedling germination and establishment</td>
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<td>Sward height</td>
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<td>Paths</td>
<td>Area of bare ground</td>
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<td>Provision of patches of warm microclimate</td>
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<td></td>
<td>Sites for seedling germination and establishment</td>
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<tr>
<td>Bare ground creation</td>
<td>Area of bare ground (influenced by bare ground creation method)</td>
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<td>Provision of patches of warm microclimate</td>
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<td>Sites for seedling germination and establishment</td>
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<td>Scrub management and clearance</td>
<td>Area of scrub</td>
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<td>Size of scrub patches</td>
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<td>Configuration of scrub patches</td>
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<td>Scrub age profile</td>
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<td></td>
<td>Diversity of microclimates within scrub</td>
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<td>Area of bare ground</td>
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4.3 What ecological characteristics and traits determine the response of invertebrates to habitat management and structure in lowland grassland mosaics?

Trophic position can have a strong effect on the response of invertebrates to habitat structure and management (Niemela & Baur 1998). Using an experiment manipulating a range of grassland management regimes Woodcock et al. (2009) found that sward architecture most strongly affected predatory species richness, which was also positively related to grass species richness and negatively to forb species richness. Carnivorous Heteroptera abundance can be reduced by grazing, while omnivores are reduced under heavy grazing but not affected by rotational grazing (Gibson et al. 1992). A meta-analysis of invertebrate responses to habitat structure showed that increased habitat structural complexity can increase abundance of both predators and parasitoids, while herbivores did not show a consistent response to habitat structure, possibly because they are more affected by resource availability (Langellotto & Denno 2004). A survey of calcareous grasslands in Germany found parasitoids are more sensitive to habitat loss and isolation than herbivorous invertebrates (Kruess & Tscharntke 2000). The majority of the priority invertebrate species reviewed here are herbivores (section 3.2), though sward structural complexity may be important for the four spider species. In addition, interactions between different trophic levels may be disrupted during grassland management, for example percentage parasitism of solitary bees and wasps was lower on grasslands that were grazed compared with ungrazed grasslands, regardless of the intensity of grazing (Kruess & Tscharntke 2002).

The degree of specialism and mobility also affect the response of invertebrate species to habitat management and the surrounding landscape. Habitat specialists often have limited dispersal abilities, and respond to habitats and landscape at a smaller spatial scale than generalist species (Steffan-Dewenter & Tscharntke 2002; Tscharntke et al. 2002a; Bruckmann et al. 2010). Generalist butterfly species have been shown to have a closer relationship to diversity of the surrounding landscape than specialist species, which are more closely linked to the grassland patch area (Tscharntke et al. 2002b; Krauss et al. 2003a, b).
Specialist butterfly species richness and density relate to larval host plant abundance, while generalist butterfly species richness and abundance are more closely linked to total nectar source abundance in a more recent survey of calcareous grasslands in Germany (Kramer et al. 2012). Some invertebrate taxa that are less mobile than butterflies also show differences in the response of specialist and generalist species to habitat. Species richness of specialist leafhoppers responds to grassland cover, while that of generalist species does not (Korosi et al. 2012).

In one of the few studies to address small-scale habitat variability as opposed to landscape fragmentation, the assemblage of mobile arthropods (Araneae, Carabidae adults, Opiliones and predatory beetle larvae) was found to relate most strongly to habitat variables at spatial scales of 3 m or less, while immobile arthropod assemblages (Arionidae slugs, Limacidae slugs, Lepidoptera larvae, Symphyta larvae, and Lepidoptera larvae) were related to habitat variables at scales of 0.25 m (Cole et al. 2010). The diversity of less mobile Carabidae species was linked closely to habitat heterogeneity and reduced in landscapes characterized by small, isolated habitat patches, while diversity of generalist species did not relate to either factor (Hendrickx et al. 2009). Similarly, the abundance of flightless Orthoptera species is much more closely related to habitat area than that of flying mobile species (Marini et al. 2010). Sedentary Orthoptera species have been shown to have greater turnover in plots in meadows than mobile species, and degree of mobility determines the beta diversity of Orthoptera species more strongly than grassland management intensity (Marini et al. 2012).

4.4 The effect of landscape factors on invertebrates within grassland mosaics

The surrounding landscape has the potential to alter the response of invertebrate species and communities to smaller scale habitat variables. The presence of larvae of the priority invertebrate marsh fritillary butterfly (Euphydryas aurinia) is related to abundance of its host plant Succisa pratensis (Devil’s bit scabious) and sward height, but optimal sward height varies with landscape context. In fragmented landscapes optimal sward height was found to be 15 cm, while in unfragmented landscapes larval presence was greatest in taller swards (20 cm; Botham et al. 2011). Botham et al. (2011) suggest that habitat requirements of E. aurinia on sites in a large unfragmented landscape may be less specific and thus require less extensive management than that required to create optimal conditions necessary at smaller, more isolated sites in fragmented landscapes. Landscape factors may also affect invertebrates differently at varying scales (Woodcock et al. 2015). For example, the abundance of wider countryside butterflies was linked to habitat diversity at the scale of 500 m from the grassland site being surveyed, but not at the scale of 2 km (Botham et al. 2015).

The response of invertebrates to landscape fragmentation may depend on their degree of specialism and trophic position, as discussed above in relation to response to habitat variables (section 4.4). Specialist grassland butterflies often have reduced abundance or species richness in more fragmented grasslands (Tscharntke et al. 2002b) as they are more dependent on the size of individual habitat patches and availability of specific resources (Steffan-
Dewenter & Tscharntke 2002; Krauss et al. 2003a; Sang et al. 2010), while generalist butterfly species are more able to use resources across the landscape matrix (Tscharntke et al. 2002a; Woodcock et al. 2015). Invertebrates at higher trophic levels may be more prone to extinction due to habitat fragmentation and isolation than those at lower levels (Littlewood et al. 2012b), while landscape complexity may also alter the effects of habitat on trophic interactions (Tscharntke & Brandl 2004). Parasitism of herbivores feeding on Red clover (Trifolium pratense) and Bush vetch (Vicia sepium) was three-fold greater on large compared to small grassland fragments (size range 300 - 76000 m²) in a survey of calcareous grasslands in Germany (Tscharntke et al. 2002b). Landscape factors should therefore be quantified and included in any assessment of habitat quality including small-scale heterogeneity.

Theoretical studies on landscape fragmentation have focussed on the spatial arrangement of habitat patches and dispersal between them, but empirical studies show that fragmentation effects often relate strongly to the loss of habitat quality through an increase in edge habitat (Harrison & Bruna 1999). As landscape fragmentation can alter invertebrate communities through changes to habitat quality as well as habitat area and isolation, there could be potential for small-scale structural heterogeneity to have negative effects on invertebrate populations through an increase in micro-fragmentation, though this has not been tested in the context of grassland mosaics. A meta-analysis of studies testing the link between habitat heterogeneity and species diversity found that a negative relationship was more common at small than large spatial scales (Tamme et al. 2010). However, definitions of large and small-scale heterogeneity differ between studies, and at the scale of mosaic elements discussed here (metres) the relationship between heterogeneity and diversity was predominantly positive (Tamme et al. 2010). A reduction in invertebrate populations due to an increase in small-scale heterogeneity thus seems unlikely for the majority of priority invertebrate species, with the possible exception of a few very immobile taxa and less mobile stages such as larvae (Cole et al. 2010).

4.5 What role do grassland AES currently play in promoting small-scale heterogeneity for conservation of invertebrate species?

Several published studies have assessed the role of AES in enhancing invertebrate species richness and abundance, but none have specifically tested whether AES have increased small-scale structural heterogeneity or created mosaic habitats to affect invertebrates. In a review of studies on AES across Europe, Kleijn & Sutherland (2003) conclude that common arthropod species are more likely to be benefitted by AES than rarer species that are more likely to be a priority for conservation. In addition to uncertainty about which types of invertebrates may be benefitted by AES, landscape factors may interact with local management to determine whether invertebrates respond to AES. A meta-analysis of the effects of AES on species richness found that farms managed under AES had greater arthropod species richness than those not under AES management in landscapes dominated by grassland (Batary et al. 2011). In contrast, in arable landscapes the effects of AES on arthropod species richness and the species richness of pollinators varied with landscape complexity, as both were enhanced by AES in simple but not in complex landscapes (Batary et al. 2011).
Bee and hoverfly species richness was greater on grasslands managed under AES options that included delaying the start of grazing or first mowing to later in the season (Kleijn et al. 2001; Kleijn et al. 2004). A survey of hay meadows in Switzerland showed that grasshopper and bee species richness was increased under AES management that included reduced fertiliser input and less frequent mowing, but spider species richness was not affected by AES management (Knop et al. 2006). Macro-moth abundance and species richness was found to be greater on farms managed under AES, though this effect was stronger on arable than mixed farms (Fuentes-Montemayor et al. 2011). Chalkhill blue butterfly (Polyommatus coridon) populations increased between 1991 – 2000 on grassland sites managed under AES, mirroring an earlier population increase on protected sites and nature reserves (Brereton et al. 2008). The silver spotted skipper butterfly (Hesperia comma) also increased more rapidly (22% per year) on calcareous grasslands under AES which were managed under traditional grazing regimes compared with sites not in AES (increase of 9% per year; Davies et al. 2005).

Despite the paucity of published data directly relating grassland AES management to the abundance or diversity of priority invertebrate species, evidence collated above regarding which grassland mosaic elements are important for priority invertebrates (section 4.1.2) and the creation and management of grassland mosaic elements (section 4.2) can be combined to provide a provisional assessment of the potential benefits of some English grassland AES prescriptions to managing mosaic habitats (Table 7). 61,000 ha of species-rich grassland were in Higher Level Stewardship (HLS) maintenance and restoration options in England in 2009 (Natural England 2009). The option for maintenance of species-rich, semi-natural grassland (HK6) was present in 29% of HLS AES agreements, while restoration of species-rich, semi-natural grassland option (HK7) was in 44% HLS agreements in 2009. HK15 (maintenance of grassland for target features, including priority species) and HK16 (restoration of grassland for target features) provided targeted options for HLS agreements where priority invertebrate species were known to be present. The new Countryside Stewardship AES (starting in 2016) has a suite of similar grassland options to those under HLS. Selected prescriptions and prescription guidance from the HK6 and HK7 options (many of which are common to both options) were assessed using the information collated in the literature reviews and expert opinion survey above (Table 7). Not all prescriptions and prescription guidance within these options have been covered, as some are outside the scope of this study.
Table 7: Summary assessment of potential contribution to grassland mosaic management of prescriptions and prescription guidelines that form part of HLS AES species-rich grassland options. Prescriptions are optional for HK6 or HK7 agreements unless stated otherwise. Priority invertebrate species considered are drawn from the 45 species identified as likely to benefit from general mosaic management of grasslands (as opposed to bespoke management, section 3.4 above). Prescriptions were chosen where relevant information from this study was available to comment on them; not all HK option prescriptions are included. Text in { } in the HK options column does not form part of the prescription. Numbers in [ ] refer to reference numbers in Priority Species spreadsheet.

<table>
<thead>
<tr>
<th>HK options Prescription / Prescription guidance</th>
<th>Potential contribution to creating or maintaining a grassland mosaic habitat which may benefit invertebrates, or specific information on priority species where the species is included in prescription guidance. Based on evidence gathered in literature reviews (section 2.1 above) and summarised in sections 4.1 and 4.2 above.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graze lightly with [cattle and/or hardy ponies] in years [1 to 10, in particular during late winter/early spring and summer] to maintain the bracken and grassland mosaic and achieve the indicators. Avoid heavy poaching by managing stock carefully when ground conditions are wet.</td>
<td>Use of cattle for grazing advantageous for creation of small patches of bare ground and for maintaining forb diversity. Low intensity grazing likely to benefit overall arthropod diversity, though if applied uniformly this may be to the detriment of the 13 priority invertebrate species identified as requiring a short (&lt;15 cm) grassland sward. Early spring and summer grazing can remove floral resources to reduce pollinator (butterfly and bumblebee) abundance. No specific evidence was gathered during this scoping study relating mosaics of bracken and grassland.</td>
</tr>
<tr>
<td>In year [1 to 5], follow a programme (agreed in writing with your NE adviser) of rotational scrub management. Never manage more than [xth ] of the site in any one year and never completely eradicate scrub from the site.</td>
<td>Rotational scrub management is likely to benefit invertebrates through a creation of mixed age stands of scrub. Some evidence that many, smaller patches of scrub may benefit invertebrates (including some priority species) more than a few large stands of scrub, partly due to an increase in scrub-edge habitat. This requires further research.</td>
</tr>
<tr>
<td>Prescription 3450 [From year X], manage the sward by [grazing and/or cutting] to achieve a sward height of [between 2cm and 10cm in October / November]. [Mandatory, specified sward heights vary]</td>
<td>At the lower end of the sward height range (2 cm) by late autumn there are unlikely to be many seed heads present, which may disadvantage seed feeders and their predators and parasitoids. In addition, some priority invertebrate species have associations with</td>
</tr>
</tbody>
</table>
specific host plant species, for which management recommendations include increasing population size through allowing seed set (e.g. *Cupido minimus* – small blue butterfly). This 2cm sward may only be appropriate at sites where the priority is conservation of species with a requirement for a short sward for larval development (e.g. *Plebejus argus* - silver-studded blue butterfly). Specifying a variable sward height or rotational grazing might be advantageous to create a heterogenous sward and benefit a wider range of priority and other invertebrates.

<table>
<thead>
<tr>
<th>Guidance for prescriptions 3450 above and 3365 below, specific to presence of priority invertebrates:</th>
<th><em>Brown-banded carder bee</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Brown-banded carder bee</em></td>
<td>Management recommendations include a taller grassland with sward height of 15 – 60cm [399, 1003] and avoiding grazing or cutting management during bee foraging season in late May to September [735, 749].</td>
</tr>
<tr>
<td><strong>Timing</strong>: [From year one], manage the sward by [grazing] to achieve a sward height of between [10 cm to 15 cm from mid-May to mid-September as a minimum].</td>
<td>Rotational grazing may be advantageous for this species [748]; the prescription guidance reflects this with the recommendation for 25% longer grass and tussocks.</td>
</tr>
<tr>
<td><strong>Species in text</strong>: &quot;Indicators of success&quot; should specify species to be frequent such as vetches, clovers, dead-nettles and red bartsia.</td>
<td>Specialises heavily on pollen from Fabaceae [461], <em>Trifolium pratense</em> and <em>Lotus corniculatus</em> are key forage [749]</td>
</tr>
<tr>
<td><strong>Frequency/Density/Cover</strong>: Cover of wildflowers should exceed 30% in the summer</td>
<td></td>
</tr>
<tr>
<td><strong>Agriculture</strong>: [From year one], manage the sward by [grazing only lightly from Spring to Late-summer preferably with cattle].</td>
<td></td>
</tr>
<tr>
<td>Do not top, roll or harrow [any] of the total grassland area in any one year and always leave a minimum of [25% tussocks / longer grass].</td>
<td></td>
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</tbody>
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<thead>
<tr>
<th>Guidance for prescription 3450 above</th>
<th><em>Chalk carpet moth</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chalk carpet: Lowland calcareous grassland – maintenance of sward</strong></td>
<td>This species needs a very short sward [449,711] and sites with rocks or bare ground present are preferred [399], so the recommendation for cattle grazing is likely to be beneficial.</td>
</tr>
<tr>
<td><strong>Timing</strong>: [late June to early September] - adult flight period.</td>
<td>Larval host plants include <em>Lotus corniculatus</em>, <em>Trifolium pratense</em>, <em>Trifolium repens</em>, <em>Medicago lupulina</em> and <em>Hippocrepis comosa</em> [700].</td>
</tr>
<tr>
<td><strong>Frequency/Density/Cover</strong>: [2-5 cm including areas of bare ground where bird's foot trefoil and other vetches occur] - to create the right conditions for larval food plant.</td>
<td></td>
</tr>
<tr>
<td><strong>Agriculture</strong>: [Grazing (cattle preferred)] - cattle preferred as they create areas of poaching and areas of bare ground required by larval host plant.</td>
<td></td>
</tr>
</tbody>
</table>
### Guidance for prescription 3450 above

#### Duke of Burgundy: Lowland calcareous grassland – maintenance/restoration of sward

**Timing:** [End April - end June] - heavy periods of grazing can be sustained in winter months however lighter stocking is required over this (above) period to create the correct sward/allow cowslips/primroses develop.

**Frequency/Density/Cover:** [10–20cm where cowslips occur] - do not allow sward to get much shorter than this, c10% of eggs are laid in areas <10cm.

**Agriculture:** [Grazing (cattle preferred)] - cattle are preferred as they produce poached areas of bare ground which can encourage cowslips. Sheep are not favoured as they tend to produce a tighter sward with shorter food plants.

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#### Grizzled skipper: Lowland calcareous grassland – maintenance/restoration of sward

**Timing:** [March to July] - this species is single brooded which may occur at any time throughout this period. Therefore maintaining correct sward height during this period is crucial to ensure successful egg-laying.

**Frequency/Density/Cover:** [2–10cm where agrimony, creeping Cinquefoil or wild strawberry occur] - this is to allow for growth of larval food plants. Areas of ranker vegetation (10-50cm) should also be present and patches of scrub (<30% of the area) should be retained.

**Agriculture:** [Grazing (cattle preferred)] - this is to create the bare ground and short vegetation needed for the larval food plant. Sheep grazing is only likely to be successful if bare ground can be created simultaneously through other activities e.g. scrub clearance, rabbits. As a last resort, mow annually in September (to c 5 cm).

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#### Narrow bordered bee hawk moth: Lowland calcareous grassland – maintenance/restoration of sward

**A mosaic of turf heights is recommended, partly because other priority conservation**
<p>| Frequency/Density/Cover: [5-15cm where devil's-bit scabious occurs] on damp pasture/ [5-10cm where devil's-bit scabious occurs] on chalk grassland - the requirements of this species are slightly different to marsh fritillary as this species requires a slightly shorter sward. Agriculture: [cattle/pony grazing]- cutting inappropriate/ burning suitable on rhus pasture where helps manage litter/scrub build-up caused by a less intensive regime. On chalk grassland winter sheep grazing is acceptable and may be useful to control ragwort. Extensive summer grazing is recommended. | invertebrate species with differing requirements such as Marsh fritillary may occur on same type of damp meadows [923]. Larvae are typically found in short turf (&lt; 12cm) [923], as reflected in the prescription guidance. Adults fly and oviposit from mid-May to mid-June, and larvae develop from late June to August [923]. |
| Guidance for prescription 3450 above Northern brown argus: Species-rich grassland - sward height Timing: [May to July] Frequency/Density/ Cover Aim for a general sward height of 5-20cm. This benefits the food plant. Variable sward is important for this species. Adults like taller areas for roosting. Agriculture: [grazing/cutting] - Light all year round grazing is preferred or autumn/winter grazing with sheep or cattle (Hebridian sheep in the summer are suitable for bramble control). A single rotational cut every September leaving some areas uncut is also acceptable. | Northern brown argus The adult flight period is June – August. Larvae feed almost exclusively on common rock rose [422]. Larvae feed from September to April, hibernating over winter in 2nd or early 3rd instar in detritus or moss [420]. Overwintering larvae may be vulnerable to autumn and winter management [420]; if cutting is necessary the recommendation for rotational cutting is likely to be beneficial. Light grazing is recommended [420] |
| Guidance for prescription 3450 above Pearl bordered &amp; high brown fritillaries: Upland calcareous grassland/lowland dry acid grassland - sward management Timing: [late April - Mid June] - this time is critical as it covers the flight period of Pearl-bordered Fritillary and the emergence period of high brown fritillary. Frequency/Density/ Cover: [5-15cm this should be targeted at areas where there is a mosaic of grassland and bracken litter and the food plant nectar sources occur. Agriculture: [grazing (cattle preferred) and or cutting]- there should also be no sheep grazing in the spring as this will remove nectar sources. Cutting should be performed in February. For restoration purposes a | Pearl bordered &amp; high brown fritillaries The adult flight period is May – June (July for small pearl-bordered fritillary) [968,472,473]. The larval food plants are Viola riviniana, Viola palustris [474,968,976] Summer grazing had a negative effect on small pearl-bordered fritillary populations [598] |</p>
<table>
<thead>
<tr>
<th>Period of heavier grazing and intensive bracken management may need to be agreed with the site manager in order to produce an appropriate bracken/grassland/food plant matrix.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guidance for prescription 3450 above Silver-studded blue: Lowland calcareous grassland - sward management</td>
</tr>
<tr>
<td><strong>Timing</strong></td>
</tr>
<tr>
<td><strong>Frequency/Density/Cover</strong></td>
</tr>
<tr>
<td><strong>Agriculture</strong></td>
</tr>
<tr>
<td><strong>Silver-studded blue</strong></td>
</tr>
<tr>
<td>This species has a symbiotic relationship with ants [398,399].</td>
</tr>
<tr>
<td>Medium intensity grazing is recommended, with a 2-7 cm sward height [652] as stated in the prescription guidance.</td>
</tr>
<tr>
<td>Guidance for prescription 3450 above Small blue: Lowland calcareous grassland - maintenance of sward</td>
</tr>
<tr>
<td><strong>Timing</strong></td>
</tr>
<tr>
<td><strong>Frequency/Density/Cover</strong></td>
</tr>
<tr>
<td><strong>Agriculture</strong></td>
</tr>
<tr>
<td><strong>Small blue</strong></td>
</tr>
<tr>
<td>The larval feeding resource is kidney vetch flower heads [498].</td>
</tr>
<tr>
<td>Management recommendations are centred around increasing host-plant populations [499] which occurs more frequently on cattle grazed sites [501], and require bare and revegetating ground [399]. Mowing should be avoided [502].</td>
</tr>
<tr>
<td><strong>Scrub clearance may be needed [449].</strong></td>
</tr>
<tr>
<td><strong>Prescription 3365</strong></td>
</tr>
<tr>
<td>Manage the grassland to achieve the indicators by [grazing with cattle for at least</td>
</tr>
<tr>
<td><strong>Use of cattle for grazing may be advantageous for creation of small patches of bare ground and for maintaining forb</strong></td>
</tr>
</tbody>
</table>

44
<table>
<thead>
<tr>
<th><strong>6 weeks between May and September / cutting and removing field-dried hay after 15 July. / In years when hay is taken graze the aftermath / in autumn. / Where spring grazing takes place exclude livestock at least 7 weeks before cutting for hay.</strong></th>
<th><strong>diversity.</strong> Early spring and summer grazing may remove floral resources to reduce pollinator (butterfly and bumblebee) abundance.</th>
</tr>
</thead>
</table>
| **General guidance for prescription 3365**  
**Timing:** Whilst it can be helpful to specify minimum and/or maximum grazing periods, remember that short periods of grazing by relatively large numbers of stock can be very effective e.g. for removing rank herbage in late summer, or avoiding selective grazing of flowers in spring/summer. And this may be the most practical option for larger farmers. |  |
| **Guidance for prescription 3365 above, specific to presence of priority invertebrates:**  
*Marsh fritillary - HK06 Indicators of success*  
Species in Text: devil’s-bit scabious should be specified to be at least frequent or widespread and locally abundant in the sward.  
Agriculture: Management options used on marsh fritillary sites should be determined by the type and condition of the grassland present. [extensive grazing with cattle/ponies for at least 6 weeks between May and September] should provide suitable conditions. However, on chalk grassland [grazing with sheep in winter] is also acceptable and may be useful to control ragwort.  
In all cases cutting is inappropriate.  
For Rhos Pasture aim to produce a varied sward between 8 cm and 25 cm. There may be taller patches of rush, but generally no more than 25% taller than 45 cm, and taller emergent species such as wild angelica and marsh thistle. Where sphagnum bog mosses form carpets the sward is likely to be thin. | **Marsh fritillary**  
The larval foodplant is devil’s-bit scabious [398,560].  
Management should include both cut/grazed parts for nectar and uncut / abandoned areas for larval development [557]; the prescription guidance recommendation for a varied sward is likely to be beneficial.  
Extensive cattle grazing is recommended [561,563].  
Devil’s-bit scabious does not form a persistent seed bank, so may require restoration through seedlings or transplants [566].  
The landscape context affects optimal management: smaller, isolated sites in fragmented landscapes require more extensive management than larger sites in unfragmented landscapes [565]. |
| **Prescription 3229**  
Do not [top, roll or harrow more than 30%] of the total grassland area in any one year and always leave a minimum of [5% tussocks / longer grass]. | **Limiting the proportion of grassland that can be rolled or harrowed will reduce direct mortality of invertebrates. Maintaining refuge areas was found to increase invertebrate abundance following mowing for hay.** |
**Prescription 3510**
Rabbits must be controlled to achieve the indicators. Where this is impractical due to the nature of the land, the numbers of grazing livestock must be adjusted to take account of this change to grazing pressure.

Taking rabbit grazing into account to avoid over-grazing is likely to benefit overall invertebrate diversity and the many priority invertebrate species that require medium and tall grassland swards.

**Prescription 3308**
Field operations and stocking must not damage the soil structure or cause heavy poaching. [Small areas of bare ground on up to [5%] of the field are acceptable.] Take particular care when the land is waterlogged. [Mandatory]

Bare ground likely to benefit over half of the 45 priority invertebrate species.

Active management to increase bare ground may be advantageous.

Retain all standing and fallen dead wood unless it presents a genuine safety hazard.

Likely to be of benefit to invertebrates, especially if retained dead wood is under or near scattered trees.

Do not remove or disturb rock and scree

Likely to benefit priority invertebrate species that nest in rock cavities, and/or require host plants surrounded by rock for warm microclimate (e.g. *Osmia parietina* wall mason bee).

[Well-rotted farmyard manure may be applied at a maximum rate of 12 tonnes/ha every other year to grassland managed as hay meadow, but not within 10 metres of a watercourse] There must be no [other] application of nutrients such as fertilisers, [other] organic manures or waste materials including sewage sludge. [On neutral grassland you may apply lime, subject to a soil test, to raise pH to 6.0.] [Mandatory]

Restriction of fertilisers likely to benefit plant diversity (especially forbs) and invertebrate diversity (e.g. Auchenorrhyncha).

The evidence gathered in the literature reviews and expert opinion survey support the majority of the HK6 and HK7 prescriptions and guidance for specific invertebrate species in Table 7 above, as being likely to contribute to management that is beneficial for individual elements within grassland habitat mosaics. In a few instances additions or slight changes to the options might benefit priority invertebrate species as highlighted in Table 7. For example, specification of a variable sward height rather than a single sward height (prescription 3450); structuring scrub management to create many, small patches of scrub and increase grass-scrub edge; and rotational grazing (recommended for brown-banded carder bee and generally to retain floral resources for pollinators, prescriptions 3450 and 3365). The use of rotational grazing and management of scrub to maximise grass-scrub edge require further research as discussed in sections 5 and 6 below. While the majority of prescription guidance above is supported by the evidence gathered in this study in relation to the management of individual
habitat elements, their overall value in creating a grassland mosaic containing multiple habitat elements cannot be assessed from the individual prescriptions and guidance. This will be determined by the deployment of multiple prescriptions at appropriate spatial scales within each individual HLS agreement.

4.6 What most limits priority invertebrate conservation in grasslands?

The habitat management survey began with a wide-ranging question: What most limits the conservation of priority invertebrate species in lowland grassland, in your experience / opinion? Answers fall into four categories: 1) poor understanding of the ecology of target invertebrates (e.g. “a lack of knowledge re: the autecology of target invertebrates”, “poor baseline knowledge of site managers of species requirements”); 2) difficulties applying appropriate management (e.g. “the opportunity or ability to control grazing and provide the variety of conditions at the right time of year across a range of species”, “the inability of most land managers to ‘fine tune’ the grassland management sufficiently to take in to account the necessary vegetation structure(s) for the different stages in the species life cycle”, “loss of micro-structure. Excessive grazing and/or mowing to deliver uniform short sward.”); 3) lack of monitoring (e.g. “Lack of knowledge about what is there. Never any budget to employ experienced specialists to survey invertebrates...”, “Lack of adequate data to make judgements.”, “Even when the appropriate grazing has been agreed often the ability to monitor and ensure/enforce that grazing is a significant problem.”); and 4) other factors (e.g. “The relative connectivity of sites and extinction debt may well emerge to be as equally significant as site condition”), full responses in Appendix H. This shows that the practical experience of conservationists and managers echoes the gaps identified by the literature review and discussed above, with only limited quantitative information on how priority invertebrate species in particular respond to grazing regime, and no quantitative evidence to link small-scale heterogeneity or mosaic habitats to increasing priority invertebrate populations.

In addition to the gaps in available evidence, some respondents to the habitat management survey stressed that site management may sometimes have a limited role in the conservation of priority invertebrate species, as other factors such as site location and climate contribute to determine species conservation success. An example of the importance of site location in determining invertebrate diversity is given by a survey of grasslands managed under AES in Germany, which found that site aspect was a stronger determinant of Orthoptera species richness than whether the management applied was extensive (within an AES) or intensive (Weiss et al. 2013).
5. Summary and research priorities

The literature reviews discussed above have identified a wealth of information on links between grassland management and invertebrate diversity (across a range of taxa); on the response of invertebrate taxa to grassland fragmentation, habitat loss and isolation at the landscape scale; and on the lifecycles, autecology and habitat requirements of many (but not all) of the 116 priority invertebrate species addressed. The majority of the priority species addressed require more than one grassland habitat element to complete their lifecycle, providing a case for management of grasslands as mosaic habitats and enhancing heterogeneity. However, no study directly tests the effects of management interventions in grassland mosaics on the abundance of priority invertebrate species, although numerous studies discuss or recommend small-scale grassland heterogeneity for invertebrate conservation without directly quantifying structural heterogeneity. Responses to the expert opinion surveys show that conservation managers have an abundance of detailed, practical experience of grassland management regimes aimed at creating small-scale habitat heterogeneity, but that the effects of these regimes on invertebrates are often not monitored, partly due to funding constraints.

The following priority research areas are recommended:

5.1 Quantification of mosaic elements and structural heterogeneity at a range of spatial scales linked to invertebrate populations and communities

Only a very few studies have correlated habitat features at several spatial scales with invertebrate populations and species richness (e.g. Marini et al. 2009a), and none have quantified grassland habitat across a range of spatial scales from sward structural heterogeneity, to size and number of mosaic elements (such as patches of bare ground and scrub), through to complexity of the surrounding landscape. Ideally these habitat data would be linked to the density or abundance of priority invertebrate species, though this may prove impractical for some priority species due to small population sizes.

5.2 A quantified comparison of methods to create and manage grasslands mosaics to increase small-scale structural heterogeneity and benefit invertebrates

One approach to create mosaic habitats and structural heterogeneity in grasslands may be through dynamic natural processes such as disturbance and grazing as discussed above. More active interventions are also likely to be needed, such as creation of bare ground, scrub clearance and planting of scattered trees, and small-scale management of grazing. These experimental interventions are likely to build on the HLS AES option prescriptions discussed above (Table 7), thus forming tests of potential improvements to AES prescriptions.

The literature reviews above have been used to identify areas in which there is currently only limited evidence for the effects of management on one or a few invertebrate taxa:

1) active creation of bare ground (section 4.2.1)
2) management of scrub to create more, smaller patches in order to increase the length of grass-scrub interface (section 4.2.3)
3) creation of ungrazed areas within a grassland to provide small patches of taller sward with floral and reproductive plant parts, through rotational grazing (section 4.2.2.2).

5.3 The effects of heterogeneity on interactions between invertebrate trophic groups

Invertebrate trophic levels (herbivores vs. predators and parasitoids) and plants are likely to be differentially affected by changes to small-scale heterogeneity as well as landscape factors, potentially altering interactions such as predation, parasitism and pollination which underpin key ecosystem services (pest control, pollination). In addition, the application of management such as grazing can disrupt interactions between invertebrates, resulting in populations of higher trophic groups being reduced (section 4.3). Only a handful of studies have tested the effects of grassland management on trophic interactions between invertebrates, and none on interactions involving conservation priority invertebrate species. However, as few higher trophic level invertebrate species are listed on the as current section 41 priority species, this research area is a lower priority than the two discussed above.

6. Field study recommendations

6.1 Field study options

The field study could consist of a structured, targeted survey, and/or a manipulative field experiment. The two approaches test different elements of the link between invertebrates and grassland habitat mosaics. A structured survey would link current priority species locations (and where possible abundance) with the presence and proximity of mosaic elements and surrounding landscape habitat at a range of spatial scales, using a correlative approach. A manipulative experiment would be used to test how management interventions could alter the structure of grassland mosaics to potentially increase the abundance of priority invertebrate species. Ideally, both a survey and experiment would be conducted as results from the survey would inform the final design of the field experiment, in terms of selection of mosaic elements for manipulation and the spatial scale of experimental manipulations. Further discussion of the pros and cons of the two approaches is below (section 6.5).

6.2.1 Targeted structured survey

6.2.1.1 Objectives

To provide information on:
1) correlations between the presence and extent of different grassland mosaic elements and the location (and where possible abundance) of priority invertebrate species
2) the spatial scales at which grassland mosaic elements affect the presence (and where possible abundance) of priority invertebrate species
3) the effect of landscape attributes (e.g. complexity, proportion of grassland) on the relationship between grassland mosaic elements and invertebrate presence / abundance.

6.2.1.2 Site selection and surveying techniques for priority invertebrate species

A targeted survey would be conducted at locations where priority species are known to occur. Prior to the survey, detailed distribution analyses of the 45 short-listed priority species (section 3.4) would be used to identify grassland sites where distributions of two or more priority invertebrate species overlap. A short-list of priority invertebrate species and grassland sites for survey would be prioritised using the results of the distribution analyses.

Surveys would be conducted over two years to establish priority invertebrate locations (and where possible their abundance) using intensive field surveys on the ground, combined with remote sensing and landscape data (section 6.4). Field surveys will use well established sampling techniques, depending on the priority invertebrate species and taxa that are chosen from the analysis of distributions above. For example, if chosen for inclusion in the survey, moths would be surveyed using light traps and bees and butterflies using linear transects. Where possible the behaviour of invertebrates that are recorded would be categorised to identify the way in which a habitat resource is used, in order to link resources within habitat elements to life cycle stages. For example, use of bare ground for nesting or floral resources for foraging by priority bee species.

6.2.1.3 Quantification of habitat and landscape parameters

Grassland mosaic elements and characteristics would be mapped and quantified including plant species diversity and priority plant species, sward structure and heterogeneity and the location and size of patches of bare ground and small areas of scrub. High resolution remote sensing could be used to map the position and extent of larger mosaic elements such as linear features (hedgerows), scrub, scattered trees and larger areas of bare ground. Landscape heterogeneity at a range of scales would be assessed from land use categories in the land cover map, and the aspect using a digital elevation model (see section 6.4, table 8 for potential of remote sensing to quantify habitat parameters).

6.2.2 Manipulative field experiment to test effects of grassland management to enhance small-scale habitat heterogeneity on invertebrates

6.2.2.1 Objectives

To test:
1) whether management interventions designed to increase the number of mosaic elements present and/or their heterogeneity increase the abundance of priority invertebrate species
2) how the management interventions in 1) affect the diversity and abundance of broader invertebrate assemblages
3) the potential cost of implementing management interventions designed to increase small-scale grassland heterogeneity
4) the effects of landscape attributes (e.g. complexity, proportion of grassland) on the relationship between the management interventions applied and invertebrate diversity and abundance (the potential to address this will be determined by the number of experimental sites).

6.2.2.2 Site selection and experimental design

Distribution analyses of the 45 priority species would be used as described for the survey (section 6.2.1.2) to select 3 – 5 sites for the manipulative experiment and a short-list of target priority species. Potential sites include National Nature Reserves, which are likely to include one or more priority invertebrate species.

Replicated management interventions would be applied to create grassland mosaics at a few lowland grassland sites over a 5+ year timescale. Results from the literature reviews and habitat management survey discussed above indicate that current National Nature Reserve management is often focussed on creating grassland mosaics and increasing heterogeneity, but there is little evidence regarding the effectiveness of this for priority species conservation within the scientific literature. To capitalise further on the experience of conservation managers in grassland management, a workshop should be held to gather ideas and assess the practicality of manipulative management treatments before the experimental design is finalised. Based on the evidence reviewed in this study, current priorities for experimental management interventions include: creation of bare ground; scrub removal to create small parcels of scrub interspersed with grassland; and rotational grazing to increase sward heterogeneity and retain ungrazed areas each year to increase abundance of floral and seed resources. A brief example experimental design for rotational grazing is given below, but we strongly recommend that conservation practitioners are consulted further before experimental treatments are prioritised and treatment design is finalised.

Example experimental design: Rotational grazing

Small-scale treatments will be applied to manipulate summer grazing on a rotational basis to increase sward structural heterogeneity, and also to create ungrazed areas to maximise flower and seed provision. Five experimental blocks of species-rich grassland plots will be located at each field site. Within each block two plots, 100m × 100m, will be fenced. Additional fencing will be used to apply a rotational grazing treatment to one plot within each block, whereby 25% of the plot will be left ungrazed from early spring to late autumn, and the remaining 75% will be split into three sections, each of which would be grazed for approximately 2 weeks in rotation. A pilot study may be needed to test the optimal length of grazing given the type of grassland and grazing livestock at each site. The second plot within each block will be grazed using the normal grazing regime at the site, to provide a control
where standard management is applied. Grazers will be the normal stock used at each experimental site, at an extensive stocking rate (<1 livestock unit per hectare). The experiment will run for 5 years. Any priority invertebrate species, the broader invertebrate community, the plant community and habitat parameters will be monitored on each plot, and landscape parameters on a wider scale (section 5.4). For data collection see section 6.2.2.3 see below, and for focal invertebrate taxa see section 6.3.

6.2.2.3 Data collection for manipulative experiment

The response of a range of invertebrate taxa including any priority species present will be monitored following application of the management interventions. Monitoring will use well established sampling techniques such as suction sampling or linear transects, depending on the priority invertebrate species and taxa that are chosen from the analysis of distributions above (see section 6.2.1.2 above). Small-scale attributes of habitat elements (plant diversity and conservation priority plant species, sward structure and heterogeneity, the extent and location of small scrub patches and small patches of bare ground) would be mapped on the ground in response to the treatments. Larger habitat elements, including elements such as scrub that may be altered by the experimental treatments, and habitat features that are likely to be present but may not be manipulated during the experiment (scattered trees, hedgerows), will be mapped using remote sensing technology. The heterogeneity of the surrounding landscape would be quantified using the land cover map as described for the survey above (section 6.4, Table 8).

The cost of management applied would be quantified. For example, if rotational grazing were tested, the costs of fencing and cattle performance (in terms of weight gain and condition; RSPB 2009) could be assessed relative to the costs of a control treatment where standard management at the site was applied.

6.3 Invertebrate taxa for potential inclusion in field study, in addition to priority invertebrate species

The field study will ideally focus on priority invertebrate species, using a subset of the short-listed 45 species based on overlap in distributions (see 6.2.1.2 and 6.2.2.2 for selection of sites and species). It is recognised that collecting robust abundance data across a number of priority invertebrate species may prove unpredictable in practice, due to low population sizes and a lack of information about population size for some or many priority invertebrate species (e.g. Carvell, 2002). The literature reviews provided limited evidence (five studies) to suggest that across taxa there may be little consistency in the response of invertebrates to grassland management, but that within taxa priority invertebrate species may respond in a similar way to other invertebrate species that share their habitat requirements (section 4.1.1). In addition, the response of the wider invertebrate assemblage to grassland mosaic elements and heterogeneity should be assessed in addition to the response of priority invertebrate species, to determine whether potential management interventions have positive or negative effects more broadly on the diversity of invertebrate communities.
A number of invertebrate taxa should be included in the field study to cover a range of mosaic element habitat requirements and a variety of traits including mobility and trophic position. Within taxa, data would be split according to whether species are generalists or grassland specialists where possible, as the habitat requirements of the latter are more likely to overlap with the requirements of priority species. Invertebrate taxa to be monitored could include:

1) Bees and wasps, which require bare ground as well as a range of floral resources, and represent both herbivorous and predatory trophic groups.

2) Butterflies, which require bare ground, shelter including scrub for some species, a range of floral resources and sward heights, and include species that vary in their mobility and degree of specialism. While butterflies have been the subject of numerous studies on grassland management, butterfly species require a broader range of mosaic elements than many other taxa and so may be good indicators for mosaic habitats.

3) Moths, the taxa with the most species on the list of 116 grassland priority invertebrate species and a large proportion (2/3) of rapidly declining common and widespread macromoth species. Moth species vary in their mobility and degree of specialisation, and include some species with requirements for scrub, hedgerows and scattered trees in addition to specific larval host plant species.

4) Beetles, which include species with a requirement for bare ground for hunting as well as range of sward heights and structure, have low mobility compared with many bee and butterfly species, and occupy a range of trophic positions (e.g. predatory, phytophagous, saproxylic).

6.4 Small scale habitat and landscape parameters to be quantified in the field study, and the potential use of remote sensing

New and developing remote sensing technologies may provide opportunities to quantify some of the habitat variables for the proposed field study more repeatedly and efficiently than is possible with field surveys. Two types of remote sensing platforms are relevant in this context:- aircraft and unmanned aerial vehicles (UAV). Airborne remote sensing has been used to monitor habitat and landscape variables successfully, so established calibration methods are available. The finest resolution that can be achieved by airborne sensors is determined by the speed at which an airplane is flying and the minimum height at which an airplane is capable and allowed to fly. Generally sensors such as multi-spectral or hyperspectral scanners and LiDAR scanners will achieve at best 1m and frequently coarser than 1m (Gerard et al. 2015), making it less useful for quantifying small scale mosaic elements and heterogeneity within elements. Colour and near infrared (NIR) aerial photography (i.e. cameras) can achieve cm resolutions, but has been limited to providing spectral data in 4 spectral bands (blue, green, red and near-infrared). Thermal sensors which capture the emission in the shortwave infra-red (SWIR) require longer integration times to reach an appropriate signal to noise ratio which inherently leads to reduced resolutions of > 2m. Airborne active radar (X-band) can achieve 0.25 m. All optical sensors (aerial photography, multi-and hyperspectral, LiDAR and thermal) will be affected by cloud, so the probabilities
of successfully collecting cloud free data for a chosen date or time window will vary substantially across the country.

Unmanned aerial vehicles (UAVs) have the advantage of being able to fly much lower than an aircraft. As a consequence an UAV can fly below clouds and so increases the opportunities to capture data at appropriate times of the year and frequencies. UAVs, although limited with respect to the areal coverage they can achieve, are also cheaper to run. The use of UAVs has the potential to deliver the same type of data at finer spatial resolutions than the resolution achieved from an aircraft, provided that the weight and size of the sensor used to collect the data is substantially reduced. Recent technological developments have made this possible for multi- and hyperspectral observations through cameras, and also LiDAR observations, although the latter require very large UAVs which at the moment cannot be flown in British airspace. It is only a matter of time for the thermal imaging and possibly even active radar to follow suit. However this miniaturisation has led to instruments that differ from those used on aircraft. Research is needed to calibrate remote sensing data from UAVs in relation to habitat variables, for example by using permanent sampling plots for ground-truthing (Gerard et al. 2015). There is strong potential to use UAVs in habitat assessments, and while the technology is currently not proven in this context, it is an expanding research area that is developing rapidly and is likely to provide fine scale habitat data in the near future.

There may be potential to use LiDAR or radar for accurate sward height assessments, but this needs further research to verify its accuracy, as LiDAR biases in height can be up to 10cm for grasses and forbs (Gerard et al. 2015). Field survey methods such as sward sticks and drop discs may be more appropriate for the fine resolution required for sward height. The extent of forb dominance in grasslands has been quantified using a spectral gradient obtained from earth observation (Gerard et al. 2015). The majority of vegetation parameters such as species richness, presence of indicator species, community composition and probably sward height will need to be quantified using traditional field survey methods (Table 8). The extent of bare ground in grasslands could be quantified using high resolution earth observation such as radar data, though this may require calibration with field survey data (Gerard et al. 2015).

Earth observation approaches may be more appropriate for the quantification of woody vegetation parameters than grassland parameters. There is potential to assess hedgerow height and width using a digital surface model, though this may need additional field data (Gerard et al. 2015). Redhead et al. (2012) showed that the total scrub cover, number of scrub patches and size of scrub patches in an calcareous grassland could be classified using aerial photographs that were classified into basic land cover classes at a resolution of 0.25 × 0.25m. Additional field surveys were needed to differentiate between types of scrub, for example Juniper scrub (Redhead et al. 2012). The number and location of scattered trees could be determined using existing LiDAR data (e.g. available from the Environment Agency), though the amount of processing effort needed might restrict this to trees within 100s of metres of the survey or experimental site rather than across the larger landscape scale. The accuracy of tree
height and crown size estimates using LiDAR data may be limited by the 2 × 2m resolution. A national map of all trees over 3m in height could also be used.

Thermal imaging could be used to quantify surface temperature, potentially at quite fine scales if UAVs were used. Surface temperature changes rapidly with time, so repeat data would need to be collected both over a day and across days and weeks to account for seasonal variation (Gerard et al. 2015). Additional ground-truthing data would need to be collected in order to calibrate thermal imaging with surface temperature.

Table 8. Habitat and landscape parameters relevant to a field study on grassland mosaics, and potential approaches to quantify the parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spatial scale(s)</th>
<th>Potential approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassland sward height</td>
<td>Centimetres</td>
<td>Sward stick, drop disc, Field survey (possibly remote sensing, see above)</td>
</tr>
<tr>
<td>Vegetation composition, species richness and % cover</td>
<td>Metres, 10s of metres</td>
<td>Quadrats, field survey (remote sensing can determine forb-dominance in grasslands but not species richness)</td>
</tr>
<tr>
<td>Presence and % cover of conservation priority plant species</td>
<td>Metres, 10s of metres</td>
<td>Quadrats, Field survey</td>
</tr>
<tr>
<td>Floral resources</td>
<td>10s of metres</td>
<td>Linear quadrats linked to pollinator (butterfly and bee) surveys, field survey</td>
</tr>
<tr>
<td>Bare ground – extent and number of patches</td>
<td>Cms, metres (scale depends on remote sensing platform)</td>
<td>Quadrats, field survey, Remote sensing</td>
</tr>
<tr>
<td>Woody vegetation height (scrub, hedgerows, veteran trees)</td>
<td>Metres, 10s of metres</td>
<td>Remote sensing, may also require field data</td>
</tr>
<tr>
<td>Scrub – extent and number of patches</td>
<td>10s-100s of metres</td>
<td>Remote sensing</td>
</tr>
<tr>
<td>Hedgerows – length, height, width, number</td>
<td>10s-100s of metres</td>
<td>Remote sensing, digital surface model</td>
</tr>
<tr>
<td>Scattered trees – individual canopy areas, number of trees</td>
<td>10s-100s of metres</td>
<td>Remote sensing</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>Cms, metres (scale depends on remote sensing platform)</td>
<td>Thermal imaging, remote sensing</td>
</tr>
<tr>
<td>Area of semi-natural grassland</td>
<td>200m, 500m, 1km, 2km</td>
<td>Land Cover Map</td>
</tr>
<tr>
<td>Area of grassland</td>
<td>200m, 500m, 1km, 2km</td>
<td>Land Cover Map</td>
</tr>
<tr>
<td>Area of woodland</td>
<td>200m, 500m, 1km, 2km</td>
<td>Land Cover Map</td>
</tr>
<tr>
<td>Landscape diversity</td>
<td>200m, 500m, 1km, 2km</td>
<td>Land Cover Map</td>
</tr>
<tr>
<td>Aspect</td>
<td>5m, 50m</td>
<td>Digital Elevation Model</td>
</tr>
</tbody>
</table>
6.5 Statistical analyses of targeted structured survey and manipulative field experiment data

Potential statistical approaches include mixed effects models to account for habitat factors at the site-level, as well as the habitat factors at broader scales for both approaches to a field study. In addition, mixed effects models can be used to test for the effects of management manipulations in the field experiment. Within mixed effects models, random effects should be considered at the site-level (and include replicates within sites) where possible, though this may not be necessary if only a few years of data is available, as there may not be enough data to estimate group-level variation (Gelman & Hill 2007). For data from a manipulative experiment, treatment would be the main effect and the analysis could adjust for baseline data on abundance/diversity. Data may need to be offset by sampling effort, for example when examining transect data the length of a transect can be used as a proxy for sampling effort.

For analyses of abundance data, the model residuals should be assessed for fit to a poisson distributed, though these may be over-dispersed in which case the negative binomial distribution may offer a better fit to the data. Excessive zeroes in a response can cause over-dispersion (Zuur et al. 2009), so models that take account of zero-inflation may also need to be considered. Although methods exist to take into account zero-inflation, a large proportion of zeros or very low values for abundance would reduce the power of models to discriminate between different experimental treatments and habitat variables. For example (RSPB 2009) and RSPB et al. (2011) found that the effects of grazing intensity and fertiliser treatments were only apparent in years of high invertebrate abundance, and that trends in the abundance of taxa were driven by the response of a few very abundant species. This is highly likely to be an issue with data on priority invertebrate species. Odman et al. (2011) assessed the abundance of six red-listed beetle species under a disturbance treatment (perturbation and undisturbed control). Four of the six species were present on one of the two treatment levels, and the beetles were too scarce to show a statistically significant response to disturbance (Odman et al. 2011).

We anticipate that the vegetation and habitat covariates may be highly correlated, so methods for dealing with potential collinear variables should also be assessed. For example, the application of the variance inflation factor to fitted models to ascertain the collinearity between the covariates may be applicable (Zuur et al. 2010). In relation to the selection of covariates in the fitted models, subjective thresholds for the p-values for the covariates in a stepwise regression procedure may be considered, though methods that use Akaike’s Information Criterion (AIC) and its derivations are also recommended (Burnham & Anderson 2002). Multi-model inference approaches could be used to account for model selection uncertainty in parameter estimation (e.g. McCracken et al. 2015). In the case of mixed effects models, conditional AIC may be more appropriate (Vaida & Blanchard 2005; Liang et al. 2008; Greven & Kneib 2010). An alternative method to consider the autocorrelation structure in addition to the hierarchical structure within the data would be generalised estimating equations (GEEs).
6.6 Pros and cons of a survey vs. experimental approach

A structured survey has the potential to provide information about more priority invertebrate species than a designed experiment, as it would be targeted at a larger number of grassland sites where priority invertebrates are known to be present than would be practical for a manipulative experiment. A survey inevitably takes a correlative approach to quantifying the link between habitat structure and invertebrates, so it may not be possible to differentiate between the effects of habitat parameters, especially those that co-vary closely. This is illustrated by a recent survey of restored species-rich grassland sites, at which site size and management objectives co-varied, since smaller sites were more frequently owned by conservation organisations such as wildlife trusts. This made it impossible to determine the effects of site size on restoration success for invertebrates, and led to the conclusion that “to directly demonstrate the importance of any given explanatory factor would require manipulative experiments” (Woodcock et al. 2015). A survey approach also would have limited ability to control for or detect the effects of a site’s past management history.

Some of the priority invertebrate species are likely to have small populations (Odman et al. 2011), so there is a risk that for some species the presence and abundance data may not be robust enough to test relationships between abundance and a range of habitat and landscape parameters. This potential problem with confounded variables and zero-inflated data is a risk for both a survey and a manipulative experiment, if the focus of the field study is solely on priority invertebrate species (see section 6.5).

The remote sensing technology potentially available on UAVs requires work to calibrate the data with ground-based measurements, as discussed above (section 6.4). A survey could provide the chance to undertake some of this calibration and ground-truthing in relation to field-based assessments, to determine the potential of UAVs as remote sensing platforms in this context (Gerard et al. 2015).

A manipulative experiment is likely to be more expensive to set up than the survey, and would require time and resources for ongoing management of the experiment in addition to the monitoring of invertebrates that would be needed under both approaches. It may be possible to reduce the cost of treatment applications by linking in to ongoing management at National Nature Reserves (section 6.2.2.2). The cost of either approach to a field study will depend on the number of priority species to be addressed under each approach, which will be one factor in determining the number of study sites needed.

A manipulative experiment would have the advantage of testing whether grassland management can affect mosaic elements and small-scale heterogeneity within elements to alter invertebrate communities, which a survey would not. Thus the results of a manipulative experiment are more likely to lead to concrete management recommendations for AES. However, a manipulative experiment would address fewer priority invertebrate species than a survey as it would be conducted at fewer sites. As a manipulative experiment would be run at
fewer study sites than a targeted survey it would be less likely to detect whether landscape complexity interacts with smaller-scale habitat parameters to affect site quality for invertebrates, though landscape complexity will be assessed in both cases.

Table 9. Summary of the purpose, pros and cons of a structured targeted survey and a manipulative experiment approach to the field study, discussed in more detail above

<table>
<thead>
<tr>
<th>Feature of field study</th>
<th>Survey</th>
<th>Designed experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose</td>
<td>Test the link between priority species abundance and locations, and the presence and proximity of grassland mosaic elements, using a correlative approach. Could inform which mosaic elements should be manipulated under a field experiment.</td>
<td>Test experimentally how management relevant to AES options could alter the structure of grassland mosaics to increase the abundance and potentially species richness of priority invertebrates.</td>
</tr>
<tr>
<td>Number of priority invertebrate species covered</td>
<td>More</td>
<td>Fewer</td>
</tr>
<tr>
<td>Ability to determine link between priority invertebrate species abundance and grassland mosaic habitat variables</td>
<td>Weak for those priority species with low population size</td>
<td>Weak for those priority species with low population size</td>
</tr>
<tr>
<td>Ability to differentiate between grassland mosaic habitat variables in terms of their effects on priority invertebrate</td>
<td>Takes a correlative approach to analysis of species abundance and habitat variables, so cannot differentiate between habitat variables that co-vary to a large extent</td>
<td>Will differentiate between mosaic habitat variables that are manipulated under the management treatments. Little ability to differentiate between habitat variables that are not manipulated due to low number of sites.</td>
</tr>
<tr>
<td>Ability to determine a link between landscape scale variables (e.g. complexity) and small-scale grassland mosaic variables</td>
<td>Medium, depending on number of sites and the degree of contrast within each landscape variable between the sites.</td>
<td>Weak, due to low number of sites</td>
</tr>
<tr>
<td>Potential to contribute to development of remote sensing technology in assessment of grassland mosaic elements and heterogeneity</td>
<td>Strong</td>
<td>Weak, due to low number of sites</td>
</tr>
<tr>
<td>Cost</td>
<td>Cheaper, but depends on coverage of priority species and number of sites</td>
<td>More expensive, but depends on number of sites</td>
</tr>
<tr>
<td>Relevance to improving AES options management prescriptions</td>
<td>Unlikely to provide evidence for benefits of management changes</td>
<td>Experimental treatments can be tailored to be highly relevant to AES management</td>
</tr>
</tbody>
</table>
7. Conclusions

1) There is substantial published evidence showing that management of individual elements within grassland mosaics can affect the diversity and abundance of invertebrates across a range of taxa. For example, a recent meta-analysis found that across 24 studies on grazing pressure, arthropod diversity significantly decreases in response to increased grazing intensity (van Klink et al. 2015). There are also many published surveys of grasslands which link the diversity and/or abundance of one or more invertebrate taxa with the presence or extent of grassland mosaic habitat elements at a range of spatial scales, and often also with historic grassland management, using a correlative approach. Management effects on grassland structure and attributes are often quantified, for example in terms of sward height, sward heterogeneity, plant diversity or host plant availability. However, many studies mention grassland heterogeneity as a desired characteristic without directly quantifying it, or only measure one attribute of grasslands. No study manipulated the management or extent of multiple elements to address the optimal size or layout of multiple habitat elements within a grassland mosaic.

2) Very few published studies quantitatively link the management or attributes of grassland mosaics with the presence or abundance of the priority invertebrate species addressed in this study. Exceptions to this are a limited number of surveys of priority butterfly and bee species, for example a survey of Marsh fritillary butterfly larvae which were affected by the abundance of their host plant and the height of the surrounding sward (Botham et al. 2011). This lack of evidence may partly be due to the small populations sizes and scarcity of many priority species, which make them difficult subjects for experimental studies or surveys across multiple grassland sites.

3) Information collated from the literature review on priority species and expert opinion surveys show the majority (73%) of the 45 priority invertebrate species addressed require more than one habitat element within a grassland mosaic to complete their life cycle. Across these 45 priority species resources were required at different times, indicating a need for temporal as well as spatial heterogeneity in grassland mosaics if they are to cater for a range of priority species. No published evidence was found regarding the optimal configuration, shape or size of habitat elements within a grassland mosaic, but information was gathered from National Nature Reserve managers relating to the scale at which mosaic elements are currently managed in grasslands of high nature conservation value. Limited evidence relating to foraging distances for a few priority invertebrate species suggests that multiple elements need to be present at small spatial scales (< 50 – 100m), though immobile life stages (e.g. larvae, eggs) may move much shorter distances, while some more mobile species require resources at a landscape scale (across several kms).

4) The autecological information on priority species and broader evidence relating to invertebrate responses to grassland management were used in a provisional assessment of prescriptions and prescription guidance for species-rich grassland management within the Higher Level Stewardship AES. Current prescriptions and guidance in relation to the management of individual mosaic elements are broadly likely to benefit invertebrate
assemblages and the conservation of several priority invertebrate species. There may be potential to alter some fine-scale aspects of management guidance, for example the size and distribution of scrub parcels following scrub clearance, and the potential for rotational grazing to increase floral and seed resources. These areas require further research. However, the value of AES for creating a grassland mosaic with multiple elements will depend on the use of multiple options and prescriptions at appropriate spatial scales within individual AES agreements, so cannot be assessed from generic prescription guidance.

5) There is an inherent difficulty in quantitatively linking habitat parameters or management and the presence or abundance of many priority species, due to their low population sizes. Limited evidence suggests that grassland specialists from the same taxa might be used as proxies for the response of some conservation priority invertebrate species to mosaic habitat management in grasslands.

6) Gaps in knowledge identified in the points above (1-3) indicate a clear need for further focussed empirical research. Research into the links between grassland mosaics and the conservation of priority invertebrate species could be conducted using a structured, targeted survey and / or field experiment manipulating management of one or more habitat elements. A survey of grassland sites at which priority species are present would provide correlative evidence for links between priority species and the presence of habitat elements and heterogeneity within elements, at a range of spatial scales. A survey could also be used to test and calibrate remote sensing technology mounted on unassisted aerial vehicles, a new area of remote sensing that has the potential to deliver fine scale habitat data. An experiment would test whether small scale grassland management can be altered to affect mosaic elements and small-scale heterogeneity within elements to benefit invertebrate communities, and so is more likely to lead to management recommendations relevant to AES. Either a survey or an experimental approach would run the risk of gathering priority species data that are not robust enough to tease apart the effects of multiple habitat parameters, due to the potential low abundance of some priority invertebrate species. The monitoring of a wider range of invertebrates in addition to priority conservation species is recommended as discussed above.
Acknowledgements

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