Landscape-scale species monitoring of agri-environment schemes (LandSpAES project)

Final project report, 2022

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Bombus terrestris queen
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Curlew
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Long-eared bat
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Dark green fritillaries
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Executive summary

Background

Agri-environment schemes (AES) are the most significant mechanism to deliver environmental policy within England, and include the Countryside Stewardship (CS) AES which started in 2016, ongoing Higher Level Stewardship (HLS) agreements, and a new Environmental Land Management Scheme that is currently being developed and piloted. Previous studies of AES have found mixed evidence for effects on biodiversity, and have largely focussed on responses of wildlife taxa within individual AES options or agreements, with fewer assessments of effects at the landscape-scale.

Aim

This project aimed to address the question of whether key mobile taxa are affected by the quantity of AES management, measured at local and landscape scales, specifically considering impacts beyond option and farm or AES agreement boundaries, and across multiple taxa. To meet this aim, we used data on the uptake of AES options, weighted by the benefit each option gives to target taxa, to calculate AES gradient scores for 1km squares. We applied a novel, pseudo-experimental design to collect a survey dataset of the responses of mobile taxa to local and landscape AES gradients over four years, from 54 survey squares across six regions (National Character Areas, hereafter NCAs) in England. We monitored the responses of multiple mobile taxa to these generalised AES gradients, which were applied within arable, grassland and upland agricultural systems.

This dataset both allows an assessment of contemporary spatial responses and forms a baseline against which to measure change in the future. The results also underpin further work to evaluate AES impact, by extrapolation from target landscapes to the national level, using input into larger-scale modelling (e.g. Jarvis et al., 2021).

Broad approach

Survey sites were selected along orthogonal AES gradients at local and landscape scales, following a survey design and site selection process that had been developed previously (project LM0465, Staley et al., 2016, 2021).

Mobile taxa were surveyed in nine 1km squares in each of six NCAs, over four (four lowland NCAs) or three (two upland NCAs) years, during 2017 – 2021. The mobile taxa surveyed were pollinating insects (bees and hoverflies), butterflies, moths, bats and birds. Mobile taxa were identified to species level for the vast majority of records, and included data on abundance (for insects and birds) or activity (for bats) per species. The mobile taxa monitoring followed established methods used by national recording schemes, with adaptations for the specific context, but retaining comparability with existing data collection. Data were also collected on the plant communities present in the 1km survey squares and the floral resources available at the time of each insect survey. Broad habitat types, agricultural land-use (cropping and livestock) and AES options were mapped within each 1km survey square. AES option implementation was also assessed for a sample of each type of option.

The spatial responses of mobile taxa across each 1km surveyed square were analysed in relation to the local and landscape AES gradients at the 1km square scale. The broad habitat, plant and floral data were used to assess relationships of the taxon responses with other key influences within the 1km survey squares. The field data also support field- or AES-patch-level analyses, but only preliminary analyses of within-square responses for limited insect taxa have been undertaken at this stage.

Key findings

Study design, AES gradient verification and AES option implementation

- The accuracy of generalised AES gradients that were calculated initially from spatial option uptake data to enable site selection, along with their relevance across multiple taxa, were assessed in several ways.
- Verified local (1km square) AES gradient scores were calculated from options mapped in the field, and found to relate strongly to the predicted gradient scores which had been calculated from spatial uptake data. This strong relationship validates the use of spatial uptake data to calculate the landscape AES gradients in the surrounding 3 × 3km square, where mapped option data were not available.
- The average score for the AES gradients correlated very strongly with taxon-specific AES gradients, which were calculated separately for butterflies, pollinating insects, in-field birds and boundary birds. These strong relationships support both the co-location of taxa monitoring at survey squares selected across the range of average AES gradient scores, and the use of average gradient scores in analyses of taxon responses.
- Data from option implementation surveys were used to attribute implementation scores to clusters of AES options. The aggregated implementation scores were used to calculate implementation-weighted versions of the AES gradients for each survey square. These implementation-weighted gradients had a strong, positive relationship with the unweighted gradients, thus the unweighted AES gradients were used in analyses of taxa responses.
- While AES implementation did not differ substantially when combined at the square-level, at the level of option types and individual option-patches there was substantial variation, as found in previous studies.

Taxa responses to the local and landscape AES gradients

- This survey was designed to detect effects of local and landscape AES gradients at the scale of 1km survey squares, and most analyses focussed on this primary objective across the taxa.
- Responses were calculated at the survey square level, aggregating over transect sections, traps or detectors, and also aggregated over multiple visits within each year, to reflect total species richness, abundance or diversity across the year. Thus, the focus is on the total

community present, capturing any turnover in species that may occur across the survey season. For birds, maximum rather than total counts were used, and for bats, activity and presence were captured instead of abundance.

- The strongest evidence for relationships with the AES gradients, within the taxa surveyed, was found for Lepidoptera (butterflies and moths) and for two bat species. There was little or no evidence of AES gradient relationships found for either bees or hoverflies and weak evidence for associations with bird metrics.
- Positive relationships with AES gradients were found with almost all those response variables for which strong evidence of an AES effect was shown, whereby an increase in gradient score was associated with greater species richness or diversity, or with higher abundance.
- Where there was strong evidence for a relationship with the AES gradients, the majority of effect sizes were found to be moderate to substantial (see butterflies and moths below).
- Evidence for an interaction between the local and landscape AES gradients, whereby the score of one gradient modifies the effects of the second gradient on a taxon’s response, was also found for one or more responses for moths, birds and bats.

Butterflies

- The abundance of all butterfly species surveyed showed a strong, positive relationship with the landscape (3 × 3km) AES gradient, which suggests that the presence of AES options within the landscape is having a positive effect on butterfly abundance. Survey squares at the high end of the landscape AES gradient had on average 117 more butterflies (a 53% increase), compared to the average for squares at the low end of the gradient.
- There was weaker evidence for similar relationships for the abundance of several trait groupings of butterfly species: species with red list status, larger species of high or medium mobility, multivoltine species, wider countryside generalist species and species with a high larval host breadth (i.e. larvae feed on three or more core host plant species). These last three trait groups are all indicative of the more generalist butterfly species. Butterfly species in these more generalist groups seem to be responding more to the landscape AES gradient, similar to the abundance of all butterflies. The response of red list butterfly abundance is likely to have been driven by Small Heath (*Coenonympha pamphilus*), which made up 91% of the total red list butterfly abundance.
- Two butterfly trait groupings responded differently to the AES gradients. Total abundance of the smaller, less mobile butterfly species showed strong evidence for a positive relationship with the local, 1km^2 AES gradient when data were analysed from lowland NCAs, but no relationship with the landscape gradient, as might be expected given their mobility and likely flight distances. Total abundance of the butterfly species with more specialist larvae (those that feed on just one or two core host plant species) also showed weak evidence for a positive relationship with the local AES gradient.
- The species richness and diversity of butterflies were not related to AES gradients, and appear to be driven more by plant diversity and habitat. Both these sets of covariates were largely independent of the AES gradients.
- Butterfly species richness had a strong positive relationship with the diversity of higher plants, as did the total butterfly abundance. Butterfly diversity was not related to the plant variables tested. This suggests that additional, rarer butterfly species were recorded in

squares with higher plant diversity, but that butterfly abundance was still dominated by more common species.

- Relationships between butterfly response variables and habitat variables were more complex, partly as the stronger effects were seen in analyses of lowland only data, where the effects of different habitat variables are harder to separate. There is fairly strong evidence of a positive effect of habitat diversity on both butterfly species richness and diversity, with relationships found from the lowland-only analyses, and a trend towards similar relationships when all data were analysed. In lowland NCAs habitat diversity was strongly positively correlated with the length of hedgerows (woody linear features), area of semi-natural habitat and area of woodland.

Bees

- There was no strong evidence that either the local or the landscape AES gradients affected the abundance, species richness or diversity of bumblebees or solitary bees.
- For transect counts of bumblebee species that first fly in May or later (‘summer bumblebees’), strong evidence was found for an interaction between the two AES gradients, which suggests that the effect of the local AES gradient on abundance was stronger where the landscape AES gradient score was lower. This should be interpreted with some caution, as there was only weak evidence of main effects of the two AES gradients. It has been suggested that bumblebee species which first fly earlier in spring may face a shortage of resources, which could potentially be filled by tailored AES options (Carvell et al., 2017). Along the generalized AES gradients used here, there is a weak indication that it is the bumblebee species which first fly in May or later that may be benefitted by AES options currently.
- There was weak evidence of negative relationships between the landscape AES gradient and abundance of parasitic (cuckoo) bumblebee species on transects, and the local AES gradient and parasitic bee abundance from pan traps. Previous studies have shown that parasitic bees may not respond to farming practices in the same way as their host bumblebees (Howard et al., 2019), and they may be more closely linked to the density of their host bee’s nests than abundance of the host bee.
- Total abundance, species richness and diversity of bumblebees on transects were found to relate more strongly to the plant and habitat covariates than to the AES gradients. The strongest relationships for bumblebee abundance on transects were with both floral abundance and botanical diversity, similar to previous studies. No relationship was found between the total abundance of floral resources within the survey square and the local AES gradient, which suggests that at the scale of 1km squares AES interventions are not delivering increased floral resources.
- For total bees surveyed with pan traps, no strong relationships were found with botanical or floral variables, in contrast to bumblebees on transects. There was weak indication of a positive relationship between botanical diversity and both total bee abundance and species richness.
- Weak evidence was found of a positive relationship between the total abundance of bees in pan traps and the area of mass-flowering crops. There was strong evidence of a negative relationship between bee diversity and area of mass-flowering crops, and no relationship with bee species richness. This suggests that common bee species may be more abundant where there is more mass-flowering crop present. The solitary bees also showed evidence

for positive relationships with habitat diversity, with strong evidence for diversity and weaker evidence for species richness.

Hoverflies

- No evidence was found that the AES gradients affected the total abundance, species richness or diversity of hoverflies.
- Just one of the hoverfly trait groups, larger species that were more mobile, had strong evidence of a positive relationship between species richness and the landscape AES gradient, and weaker evidence of a relationship between abundance and the landscape gradient.
- There was weak evidence of relationships with the AES gradients for two hoverfly trait groups. Abundance of the larger, more mobile butterfly species had a positive relationship with the landscape AES gradient. Hoverfly species with detritivorous larvae had a positive relationship with the landscape AES gradient.
- The total abundance of hoverflies related more strongly to the habitat variables than the AES gradients, with a strong positive relationship with the area of arable land. This may be driven a few dominant hoverfly species with predatory larvae that feed on aphids that are prevalent on cereal crops.

Moths

- Moths showed more evidence of strong responses to the AES gradients than the other insect taxa surveyed, in relation to species richness as well as abundance.
- The species richness of all moths and micro-moths both showed a strong positive relationship with the local AES gradient in the lowland NCAs, and there was weak evidence of a similar relationship for macro-moth species richness. An increase in species richness of 14% (12 species) for all moths, and 20% for micro-moths, was found on average for 1km squares at the higher end of the local AES gradient, compared to the average for squares at the low end. These average estimates give an indication of effect size, but do have substantial uncertainty.
- When data were analysed across all NCAs there was only weak evidence of a relationship between the local AES gradient and micro-moth richness, but strong evidence of an interaction between the two AES gradients.
- Moth abundance and micro-moth abundance also showed strong evidence of interaction effects between the two AES gradients, which suggest a stronger effect of local AES on abundance in a low AES landscape.
- The moth trait groups that showed a positive relationship with the local AES gradient, or a strong interaction between the two AES gradients, were broadly those associated with greater specialism, for example requiring more specialist habitat or food plant requirements. Univoltine species also showed stronger effects of the AES gradients than multivoltine species.
- Moth mobility groups differed in their responses to the AES gradients. The low and medium mobility species showed some relationships either with the local AES gradients or with the interaction between the two AES gradients, which differed between the analyses of all data vs. lowland only data. No strong relationship was found for the high mobility moths with either AES gradient, but there was a weak indication of a positive effect of landscape AES gradient.

- Moths also showed strong relationships with some of the habitat and botanical variables. Habitat diversity had a positive relationship with both moth species richness and diversity, while the length of woody linear features had a positive relationship with macro-moth diversity and a negative relationship with abundance. This suggests that for macro-moths, hedgerows may support some of the less abundant macro-moth species.
- Botanical diversity had a strong, positive relationship with the species richness of all moths, macro- and micro-moths. The majority of moth caterpillars feed on plants, and a greater botanical diversity provides a greater range of host plant species and is also likely to help create greater structural diversity (e.g. varied sward heights), resulting in greater moth species richness.

Mobility trait across insect taxa

- The one trait group that showed a consistent response across several insect taxa was the larger, more mobile species. For butterflies, moths and hoverflies, evidence was found that either the abundance or species richness of the more mobile groups respond to AES management at larger, landscape spatial scales.
- For butterflies and moths, there was also strong evidence that the smaller, less mobile species had a positive relationship with the local AES gradient, as might be expected given their more limited ability to forage and disperse at the landscape scale. This relationship was only found in analyses of the lowland-NCA dataset.

Birds

- No individual bird community measures were strongly related to the AES gradients. There was no evidence for effects of the landscape-scale gradient on bird community metrics. This may reflect the use of community-level variables for standardisation with the other taxa, whereas most other evidence for AES effects on birds involves species-level patterns and temporal change, as opposed to spatial distributions.
- There were weak, positive associations with local-scale AES for abundance in the winter, species richness in the winter and Red-List species abundance in winter. There was also weak evidence for positive associations with the spring abundance of breeding season invertebrate feeders and winter seed-eaters, with weak evidence that the seed-eater relationship was also found in winter.
- The local AES score effects could indicate the combination of various species-level population effects or a tendency for birds to select AES habitats (or areas adjacent to them) for feeding or nesting. However, the evidence here was not strong, statistically.
- There was little evidence for any real AES effect on individual bird species. The only strong relationship involved Yellow Wagtail and the landscape-level gradient, and is unlikely to reflect a real AES influence. Otherwise, there was a mixture of weak, positive (for Whitethroat and Reed Bunting) and negative (for Goldfinch, Greenfinch and Stock Dove) associations, in the breeding season and/or in winter, as well as two, weak, interactions in the data for each season. Given the number of tests conducted at the species level and the lack of ecological cohesiveness in these results (such as a shared pattern among seed-eaters), there can be little confidence that these patterns do not show spurious, chance results.
- Bird responses showed stronger relationships with habitat diversity than with the AES gradients.

Bats

- No evidence was found for relationships between bat richness or diversity and the AES gradients. In contrast, strong relationships were found between these bat community variables and background habitats.
- There is strong evidence for positive relationships between the AES landscape gradient and the presence of two bat species. However, the effect sizes were small for both species (1% increase in the chance of the bat species being present in a survey square).

Table i. Summary of AES local and landscape gradient effects across taxa.

		Butterflies	**Moths****	**Bees (transects)**	**Bees (pan traps)**	**Hoverflies**	**Birds*****	**Bats**
Whole taxa	**Local AES gradient**		+ Variable (SR, div, abund)				+ Weak (SR, abund, lowl only, B &W)	
	Landscape AES gradient	+ Strong (abund)	+ Weak (SR, div)					
More detailed responses*	**Local AES gradient**	+ Strong (one trait group: low mobility spp.)	+ Variable (several trait groups inc. low mobility, oligophagous)	+ Weak (summer species, lowl only)	- Weak (parasitic species only)		+ Variable (invertebrate feeders & seed feeders for B, Reed bunting for W)	
	Landscape AES gradient	+ Weak (several trait groups inc. red list spp.)	+ Weak (medium and high mobility spp., multivoltine)	+/- Weak (summer spp. and cuckoo spp., lowl only)		+ Variable (SR and abund, more mobile spp., detritivore larvae)	- Variable (Goldfinch & Yellow Wagtail for B, Greenfinch for W)	+ Strong (Barbastelle, Daubenton's bat)

Strong / weak relates to strength of evidence (strong, $P < 0.01$; weak $0.01 < P < 0.05$), not strength of relationship with AES. Variable = strength of evidence varies between detailed responses (functional group or species abundance). * More detailed responses are analyses of trait group abundance for insects; trait groups and species for birds; and species for bats. ** Macro- and micro-moth results included along with all moth results (Section 5.5 for more details). *** Breeding (B) and winter (W) bird survey results included together (Sections 5.1 and 5.6 below).

Butterfly and bumblebee responses to AES option patches within survey squares

- In addition to the analyses of local and landscape AES gradients across taxa (above), a limited number of within-square assessments of insect responses to AES were conducted. While the design of the study was focused on AES management at the 1km square scale, the data collected also provide a contrast between occurrence and abundance of the monitored taxa at the option patch scale.
- For butterflies and bumblebees surveyed on transects, total abundance, species richness and diversity were analysed in relation to whether each transect section was on an AES option-patch vs. off option.
- The abundance, species richness and diversity of both butterflies and bumblebees were all increased substantially on AES options compared to off-option patches, in these within-square analyses.
- The effect size for butterfly abundance was substantial, with an estimated average difference of 11.13 butterflies between off and on option transect sections per year. The average number of butterflies seen on any transect section in a year was 34.
- For bumblebees, on average there were 6.30 more individuals when transect sections were on an option-patch, compared to those that were off option, in the context of an average number of bumblebees seen per transect section of 20.4. This effect was even higher in lowlands, where there were an estimated additional 10.7 bumblebees on transect sections with AES.
- On average across all NCAs the difference in butterfly richness between transect sections on and off AES option was 0.86 species, with an average of 6.25 butterfly species recorded across all sections.
- Although all the community metrics analysed for butterfly and bumblebees showed an effect of AES at the option-patch scale, only butterfly abundance was affected by the AES gradients (the landscape gradient) in analyses at the whole square scale. These results suggest that, in common with other large-scale AES studies (Carvell et al., 2007, Pywell et al., 2011), effects observed when comparing options vs. non-option parcels within the same square do not necessarily scale up.

Summary

In this project, we applied a novel, pseudo-experimental design in order to collect a baseline survey dataset of the responses of mobile taxa to local and landscape AES gradients over four years, from 54 survey squares across six regions (NCAs) in England. This is the first project to monitor the responses of multiple mobile taxa to generalised AES gradients across large spatial extents, which were applied to arable, grassland and upland agricultural systems, in order specifically to address impacts beyond AES option or agreement boundaries.

This baseline dataset supported a spatial assessment of relationships between the AES gradients and taxon abundance (or activity), species richness and diversity. Strong evidence for relationships with local and / or landscape AES gradients were found for one or more response variable for butterflies, moths and bats. Little or no evidence of AES gradient relationships found for either bees or hoverflies and weak evidence for associations with bird metrics.

A future resurvey would allow analyses of the longer-term changes in target taxa in response to AES management, against this baseline. The identification of various spatial relationships is encouraging in terms of the likely power to detect AES effects on biodiversity change in the future.

1 Introduction

Agri-environment schemes (AES) are the most significant mechanism to deliver environmental policy within England. Current AES include Countryside Stewardship (CS), launched in 2016, and remaining Higher Level Stewardship (HLS) agreements started under the previous Environmental Stewardship scheme, many of which are ongoing. In addition, a new Environmental Land Management Scheme is currently being tested and piloted, including many of the same management measures that have been used in previous schemes. Within these existing and developing AES, conservation of biodiversity has been and remains a key goal. There is an urgent need to understand whether AES are delivering for biodiversity, to inform current and future policy.

1.1 Why monitor biodiversity responses to agri-environment schemes at the landscape scale?

The majority of research into the effects of AES interventions on wildlife taxa has been focussed on monitoring of individual AES options, or AES agreements (e.g. Mountford et al., 2013), over short timescales, and has shown varying results (Kleijn et al., 2011; Scheper et al., 2013; Froidevaux et al., 2019). This scale of research is necessary to test and improve AES management prescriptions, and to assess whether AES interventions benefit target taxa on land directly under AES management (Carvell et al., 2007; Staley et al., 2016). For mobile taxa, there is the potential for individuals to move onto land under AES management when resources increase, without this necessarily having a sustained effect on populations over time or across the surrounding countryside. Recognition of this possible ‘honeypot’ effect has led to some assessments of whether responses to AES interventions are also detectable at the population level and from local to landscape scales, for some taxa (butterflies, Brereton et al., 2008; birds, Baker et al., 2012; Redhead et al., 2018; pollinating insects, Kleijn et al., 2018; Wood et al., 2015). Alternatively, if provision of resources under AES is effective, abundance of target taxa may increase to the extent that populations spill over from habitats managed under AES into the surrounding countryside. However, this is hard to detect as it requires identifying and monitoring sites with contrasting levels of local and landscape AES uptake. Consequently, only a few studies have made tests of spill-over for pollinating insects (Carvell et al., 2015; Jönsson et al., 2015; Scheper et al., 2015), and none directly for other taxa.

Studies using data from long-term national monitoring schemes to test whether populations change in response to the amount of specific AES habitat (both locally in the site surveyed and in the surrounding landscape) have focused on bird (Baker et al., 2012; Daskalova et al., 2019) and butterfly (Brereton et al., 2007; Oliver, 2014) species, reflecting the availability of well-established monitoring scheme data in the UK (O’Connor et al., 2019). These studies have had mixed success in demonstrating population change resulting from AES interventions. This may be partly because monitoring sites within such schemes are not targeted to sample sufficient contrast in the extent of AES management (Oliver, 2014), and potentially also because of inter-correlations between AES uptake across spatial scales, and with other landscape variables.

To determine whether AES management effects extend beyond the short-term redistribution of individuals in response to increased resources, the following questions need to be assessed across multiple taxa, given that AES patch-level effects occur:

1) Can spatial associations be detected between AES and the abundance, species richness or diversity of mobile taxa at larger spatial scales than that of AES options?
2) Are these effects stronger for AES gradients at the local scale (1km square) or across the surrounding landscape (3 × 3km), and are there interactions between the effects of these two spatial scales?
3) Do different mobile taxa respond in the same way to AES management effects at these two spatial scales, when monitored in a focal 1km square?
4) Does taxon richness, abundance or diversity change over time in response to AES management, indicating population growth (or reduced rates of decrease)?

Note that (4) requires repeat sampling in the future to demonstrate change over time.

1.2 Project aim

This project aims to address the question of whether key mobile taxa are affected by local and landscape AES gradients, specifically considering impacts beyond option and farm or AES agreement boundaries and across multiple taxa. Population responses are long-term, by definition, so monitoring needs to allow sufficient time for change to occur and to be detectable in the context of background variation. To begin to meet this aim, data were collected for a multi-year baseline that would underpin future repeat surveys to measure change. Multiple years were important given that mobile species populations are subject to annual fluctuations. Within the baseline dataset, the effects of gradients in AES management quantity at the local and landscape scales on the spatial responses of mobile taxa at the field and farm scales were assessed. Within each taxon, abundance, species richness and diversity were analysed in relation to the AES gradients, along with the responses of a number of policy-relevant and conservation priority species, as well as functional trait groups.

This project (the LandSpAES project hereafter) provides a robust, multi-year baseline, against which future population change can be quantified though a resurvey 8-10 years (or more) after the baseline. The results also underpin further work to evaluate AES impact, by extrapolation from target landscapes to the national level, using input into larger-scale modelling (Jarvis et al., 2021).

2 Methods

2.1 Survey design, calculation of AES gradients and square selection

2.1.1 Survey design

A survey design was developed to monitor the response of mobile species to AES interventions at large spatial scales, specifically considering impacts beyond option and farm or AES agreement boundaries and across multiple taxa. In order to answer the questions outlined above (Section 1.2), we developed a method whereby survey sites could be selected along two orthogonal AES gradients at local and landscape scales (Figure 2.1.1). The use of orthogonal gradients allows the effects of AES interventions to be tested independently at local and larger (landscape) scales, in order to determine whether taxa differ in the scale at which they respond to AES management. Replication of survey squares was modest, thus the survey was carefully designed to maximise contrast in taxon-relevant AES options across the full extent of two AES gradients, to increase the power to detect AES effects (Pasher et al. 2013). Gradients were designed to include all option types that are relevant to the taxa considered and hence to be measurable and transferable across all regions within England.

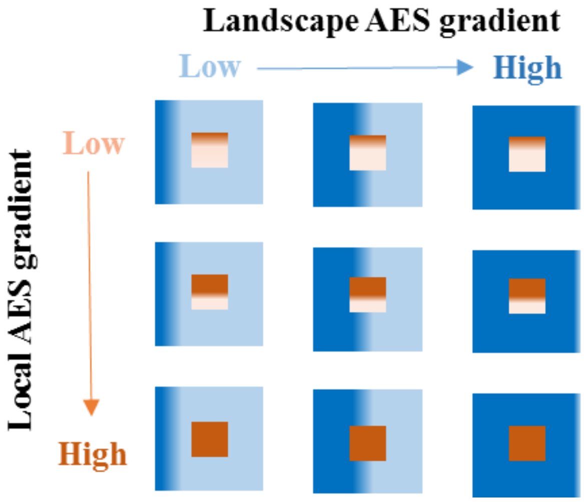

Figure 2.1.1 Contrasting gradients of taxon-relevant AES intervention at local and landscape scales, split into three levels of intervention. The local gradient is represented by shading from cream (low AES intervention) to brown (high intervention) in the focal 1 km squares in which mobile taxa will be monitored, and the landscape AES gradient by pale blue (low intervention) to dark blue (high intervention) in the surrounding landscape (3 × 3 km) units. Reproduced from Staley et al. (2021) under a Creative Commons CC-BY licence.

The following steps were used to calculate predicted AES gradients and select 1km squares for survey:

1) an evidence review was conducted, in order to identify AES management options likely to benefit the target mobile taxa;
2) AES management options identified through the evidence review were scored according to the type of evidence and the impact on target taxa;
3) AES gradients were calculated using the evidence scores from the previous steps, and the spatial uptake data of AES options;
4) a weighted random process was used to select survey squares, in order to determine whether squares could be selected to fill the matrix of contrasting AES gradients in Figure 2.1.1, within homogenous regional blocks (National Character Areas).

The process used to calculate AES gradients, survey square selection and the verification of the gradients were specified in a previous project (LM0457). Table 2.1.1 gives an overview of the key issues considered in the design of the survey. A summary of the survey design process is in Sections 2.1.2 and 2.1.3 below, with further details in Staley et al. (2016, 2021). Some of the text and figures have been published previously (Staley et al., 2016, 2021), material from the latter is reproduced under a Creative Commons CC-BY licence.

While the design of the study was focused on AES gradients at the 1km square scale, the data collected also provide a contrast between the occurrence and abundance of the monitored taxa at the option patch scale vs. patches not under AES management. Subject to the degree of contrast that is present in practice between option and counterfactual habitat (which was not the focus of the study design), analyses of the data at this within-square scale could provide additional inference about small-scale AES effects (Section 6).

Table 2.1.1 Overview of the key issues and potential biases considered during design of survey, and how these were accounted for in the design process. Brief details of the survey design processes are in the sections below, for further detail see the LM0457 final report (Staley et al. 2016) or Staley et al. (2021).

Potential issues / biases considered in design of large-scale, multi-taxa AES monitoring	**Mechanism by which the potential issue / bias is controlled for in LandSpAES survey design**	**Further details - section of current report / previous publication.**
1. What AES management is likely to benefit the key taxa to be surveyed?	AES gradient scores were calculated from the uptake of management options shown to benefit key taxa, shortlisted through an evidence review. Higher weighting was given to AES management shown to provide stronger benefits to key taxa, and / or to benefit at landscape scales or in relation to temporal change, in line with LandSpAES objectives.	Staley et al. 2016, Section 2. Staley et al. 2021, Section 2.2 & supplementary information.
2. Is the AES management temporally stable, or likely to change substantially?	1km squares were excluded if there were substantial changes in AES management before or during the LandSpAES survey. Squares were excluded from the survey if: 1) they had changed AES gradient category (low, medium, high) in the three years prior to the survey starting, or 2) > 50% of the AES gradient score was contributed by options due to end during the survey.	Staley et al. 2016, Appendix D Current report, Section 2.2
3. Is AES management specific to one taxon or relevant to several taxa? Is it appropriate to co-locate surveys?	AES gradient scores were calculated separately for four taxa / functional groups. Taxon-specific gradient scores were shown to relate strongly to average AES gradient scores, providing support for co-location of surveys.	Current report, Section 3.2. Staley et al. 2021
4. What scales of AES management and survey locations are relevant for the taxa surveyed?	The evidence review included collation of data on the scales at which key taxa responded to AES. This was combined with published information on foraging distances to define ‘local’ (1 × 1 km square) and ‘landscape’ (3 × 3 km annular landscape unit) scales for LandSpAES AES gradient calculations, and for field surveys. While mobile organisms will move outside the landscape units, especially when dispersing or migrating, the majority of foraging journeys for any given population are within 3 km (Carvell et al., 2012; Knight et al., 2005; Siriwardena, 2010; Siriwardena et al., 2006), and so populations are likely to be affected most by factors within these local and landscape scales.	Staley et al. 2016, Section 3.1 Staley et al. 2021, Section 2.3
5. Are survey sites broadly	1km squares without high coverage of agricultural land (or with high covers of	Staley et al. 2016, Section 2

Potential issues / biases considered in design of large-scale, multi-taxa AES monitoring	**Mechanism by which the potential issue / bias is controlled for in LandSpAES survey design**	**Further details - section of current report / previous publication.**
representative of farmland in England?	other land uses such as woodland or built-up land) were filtered out. Survey squares were randomly selected within each combination of the local and landscape AES gradient categories (low, medium, high). Six survey regions (National Character Areas) were chosen to cover major types of agricultural land use: arable, pastoral, mixed and upland.	Staley et al. 2021, Section 2 Staley et al. 2021, Table 3.
6. Were survey sites independent from one another?	Survey squares were selected to ensure at least 1km separation between 'landscapes' (i.e. the 8 surrounding cells), giving at least 3km separation between surveyed squares (average distance to nearest other survey cell was 7.98km).	Staley et al. 2021, Section 2.4. Staley et al. 2016, Section 2.
7. Are AES gradient scores / management independent of other habitat variables? Can AES effects be separated from potential confounding factors?	Survey squares along each of local and landscape AES gradients were grouped within regions with homogenous background habitat characteristics (National Character Areas). AES gradient score was shown to be independent from other key habitat variables, both within and across NCAs.	Current report, Section 3.3, Table 3.2. Staley et al. 2021, Table 4.
8. Are AES gradient scores calculated from spatial option uptake data an accurate representation of AES management on the ground?	Field mapped AES options were used to calculate validated AES gradient scores, and compared with the predicted AES gradients (calculated from option spatial uptake data) used in survey square selection. Validated AES gradient scores strongly correlated with predicted AES gradient scores.	Current report, Section 3.1 Staley et al. 2021, Section 3.3.
9. Does variation in the implementation of AES management affect AES gradient scores at 1km square scale?	AES option implementation was surveyed in field, and implementation scores calculated from field data for each option patch. AES gradient scores were recalculated to include weighting for option implementation, for each 1km survey square. Although implementation varied widely at the level of individual AES options, at the scale of 1km survey squares implementation-weighted gradient scores were not substantially different to unweighted AES gradient scores.	Current report, Section 4.3

2.1.2 Agri-environment gradient calculations

To determine which AES management options were likely to affect key mobile taxa, we conducted structured searches of peer-reviewed papers and grey literature. The methods used for searching the literature, shortlisting papers and reports and extracting data are detailed in the LM0457 report (Staley et al., 2016). There was sufficient empirical evidence to score AES management effects for three taxa: birds, butterflies and pollinating insects. Birds were the taxon with most evidence, allowing separate scores to be attributed to two bird functional groups, reflecting how different species use the farmed environment. Birds that both nest and feed in in-field habitats typically respond negatively to the presence of field boundary structures (e.g. Schläpfer, 1988), whereas species that nest in hedgerows may respond positively to AES management of either or both in-field and boundary habitats.

AES options were grouped by type of management and habitat for scoring (e.g. grass buffer strip options), as individual AES options were rarely identified in the literature. A single evidence score was allocated per AES option group for each taxon / functional group with sufficient evidence, from the combination of scoring of the evidence type and impact (scoring details in Staley et al., 2016). Combined evidence scores were used alongside national datasets of AES option uptake to calculate evidence-based AES gradients, so that options designed to meet other objectives, such as protection of water quality, were excluded (unless shown to benefit the target taxa). Combined evidence scores were attributed to 53 groups of AES options for the four taxa scored (further details in Staley et al., 2016).

The evidence review showed that in assessments of AES efficacy, ‘local’ is frequently interpreted either as land directly under an AES management option, or whole farms under AES agreement, and ‘landscape’ as areas around a local site ranging from 1 km – 10 km in radius. To construct contrasting local and landscape gradients in AES intervention, the local scale was defined here as a 1 × 1 km square, and landscape scale as the surrounding eight 1 km squares, i.e. a 3 × 3 km annular landscape unit. While mobile organisms will move outside the landscape units, especially when dispersing or migrating, the majority of foraging journeys for any given population are within 3 km (Carvell et al., 2012; Knight et al., 2005; Siriwardena, 2010; Siriwardena et al., 2006), and so populations are likely to be affected most by factors within these local and landscape scales.

The UKCEH Land Cover Map 2015 data (LCM 2015; Rowland et al., 2017) were used to exclude 1 km squares that did not have high coverage of agricultural land, using the criteria: > 30% of combined urban, suburban, saltwater and freshwater coverage, or > 50% woodland coverage. These criteria excluded about 15% of 1 km squares in England. Predicted scores of AES intervention gradients were calculated separately for each taxon / functional group, for each remaining 1 km square in England.

Gradient scores for each AES option type were calculated as the spatial extent of option uptake per parcel, multiplied by the combined evidence score, and multiplied by the payment given to each spatial unit of each AES option. AES options that involve the creation of habitats to provide resources for biodiversity, such as pollen and nectar or wild bird food strips, are applied to small areas of land with high associated payments. The relative contributions of these options are expected to be higher per unit areas than more generalized habitat management options. This was accounted for by weighting the gradient scores by option payment. Where options had high likelihood of overlapping 1 km square boundaries (i.e. being associated with a land parcel that occupied only part of the square), the score was weighted by the proportion of the land parcel that fell inside the 1 km square.

Gradient scores were summed across the option types to give a total predicted gradient score per taxon and 1 km square. Option uptake data for the Environmental Stewardship AES were downloaded from the Natural England Open Data Geoportal (https://naturalengland-defra.opendata.arcgis.com/datasets/ 20b24e747bc34a9fa4ffb2ef827efda7_0; last accessed February 2019) and for the Countryside Stewardship AES were provided directly by Natural England and updated in 2021 (Countryside Stewardship Scheme 2016 Management Options (England). Payments for each option were compiled from AES handbooks (Natural England, 2013a, b, 2015). Spatial data handling was performed in ArcGIS 10.3 (© ESRI 2016, Redlands, CA) and R (version 3.2.2-3.6.3; R Core Development Team, 2016).

Gradient scores were also calculated for each 3 × 3 km annular landscape unit in England, using the same process. The landscape gradient scores were calculated as average scores across the eight squares surrounding each focal 1 km square (the landscape unit), to represent the two gradients on similar scales.

National Character Areas (NCAs) were chosen as relatively homogenous landscape units in order to avoid confounding AES gradients with variation in habitat composition. NCAs are regions with cohesive landscape characteristics, and were used as blocks in which to group survey squares. 159 NCAs have been identified within England, using a combination of landscape, habitat, biodiversity, and geology variables (https://data.gov.uk/dataset/21104eeb-4a53-4e41-8ada-d2d442e416e0/national-character-areas-england). Relationships between AES gradients calculated for each of the four taxa within each NCA and the average gradients across the taxa were tested using Kendall’s correlation test. Strong evidence was found that gradients between all four taxa were correlated in the vast majority of NCAs (Staley et al., 2016, 2021 and see Section 3.2 below), thus an average predicted AES gradient across taxa was calculated for each 1 km square and landscape unit.

2.1.3 Survey square selection

The gradient scores (average scores across the taxa) were used to define a matrix of contrasting local and landscape AES gradients (Figure 2.1.1). Correlations between the scores for individual taxa and the average gradients were high (see Section 3.2). AES gradients were divided into three categories (low with scores up to 500, medium 501 - 5000, and high 5001 - 50,000), which covered the majority of the distribution of gradient scores. There were approximately equal numbers of 1 km squares in each category. Squares with a score of over 50,000 were excluded, as they contributed to a long ‘tail’ of anomalously high scoring cells, and probably resulting from limitations in the spatial accuracy of the input data.

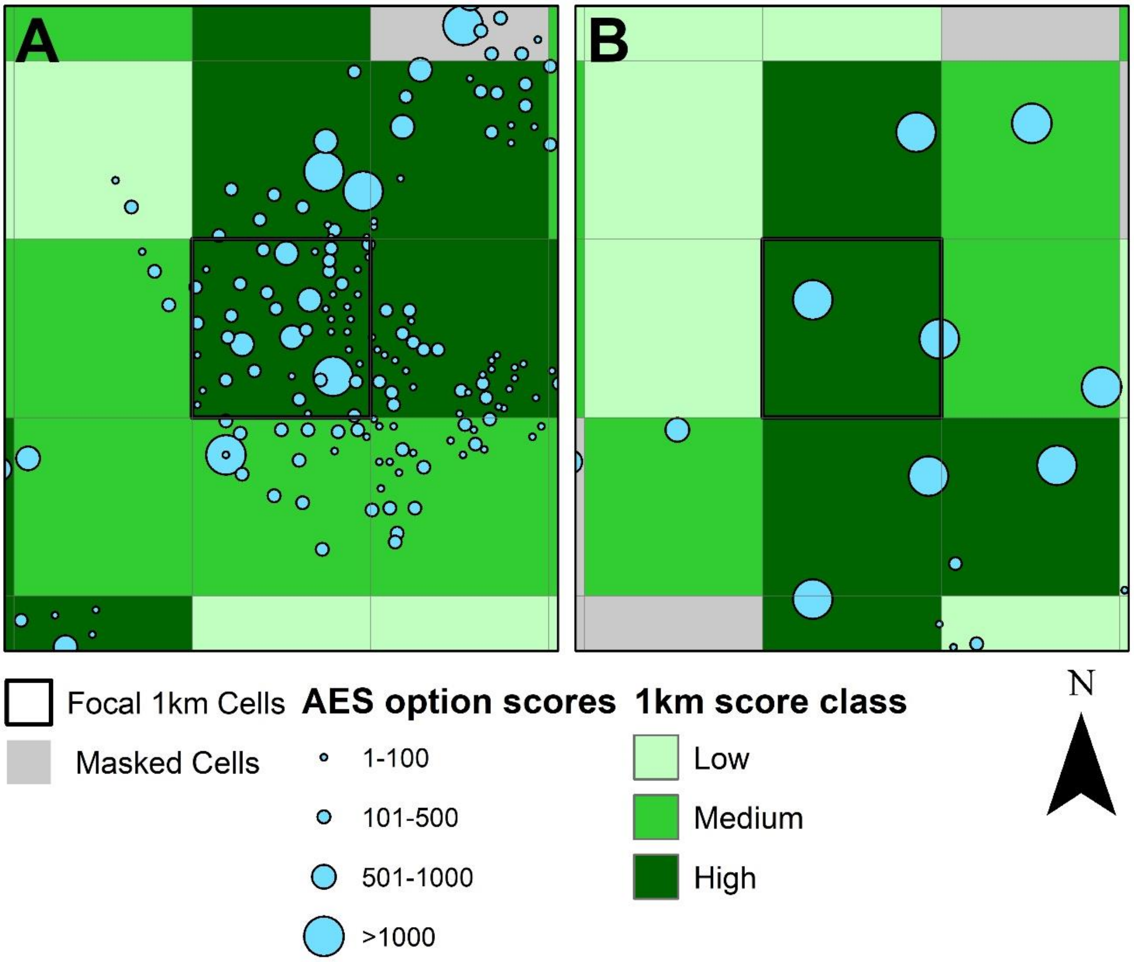

Figure 2.1.2 Examples of focal survey squares, with local (1 km^2) AES gradients in the highest scoring category and landscape (3 × 3 km) gradients in the medium intervention category, showing different configurations of options. A: Many scattered options with low-moderate scores or areas B: A few options with very high scores or areas. Reproduced from Staley et al. (2021) under a Creative Commons CC-BY licence.

The lowest category in each predicted AES gradient was dominated by 1 km squares with zero AES uptake, and included a few squares with gradient scores of up to 500. A gradient score of 100, for example, could represent 100 m of hedge in a basic hedgerow management option (EB3 cutting hedgerows once in 3 years; Natural England, 2013a). Patterns of AES option distribution were more varied within squares in the high gradient category (Figure 2.1.2). Within the high gradient category, some squares had scores from combinations of many smaller options with low to moderate scores or extent (e.g. arable options; Figure 2.1.2a), while others had a few AES options with particularly high scores or extensive areas (e.g. grassland management options covering the majority of the square; Figure 2.1.2b).

The three categories along each AES gradient give nine possible matrix combinations (Figure 2.1.1) across the orthogonal local and landscape AES gradients. Nine survey units were selected within each NCA, one from each matrix class, using a semi-randomised process that was weighted to increase the chance of each cell being filled in the matrix of contrasting local and landscape AES gradients. Selection was performed in R, using a dataset of every 1 km square in England, attributed with its gradient matrix class, the NCA within which the majority of its area fell and whether it met the criteria for exclusion described above. For each NCA, the sampling algorithm calculated the number of 1 km squares in each matrix class (Figure 2.1.1), selected the least well represented and chose a random focal square within this class. The focal square was excluded if more than three of the surrounding eight squares within the sampling unit met the exclusion criteria, otherwise it was appended to a list of selected sample units. A minimum separation distance of 4 km was specified between the outer edges of selected focal squares, in order to reduce the chance of target taxa moving regularly between sampling units. All squares less than 4 km from the selected focal square were removed from the dataset each time a sampling unit was selected. The algorithm recalculated the remaining 1 km squares in each matrix class and selected again at random from the least well represented, continuing this process until no more squares in the NCA were available for selection.

The number of potential survey squares selected within each AES gradient matrix class was determined for each NCA in England. An example for one of these NCAs, The Fens, is given in Figure 2.1.3. Some of NCAs were discounted due to difficulties gaining survey access (e.g. large military training areas).

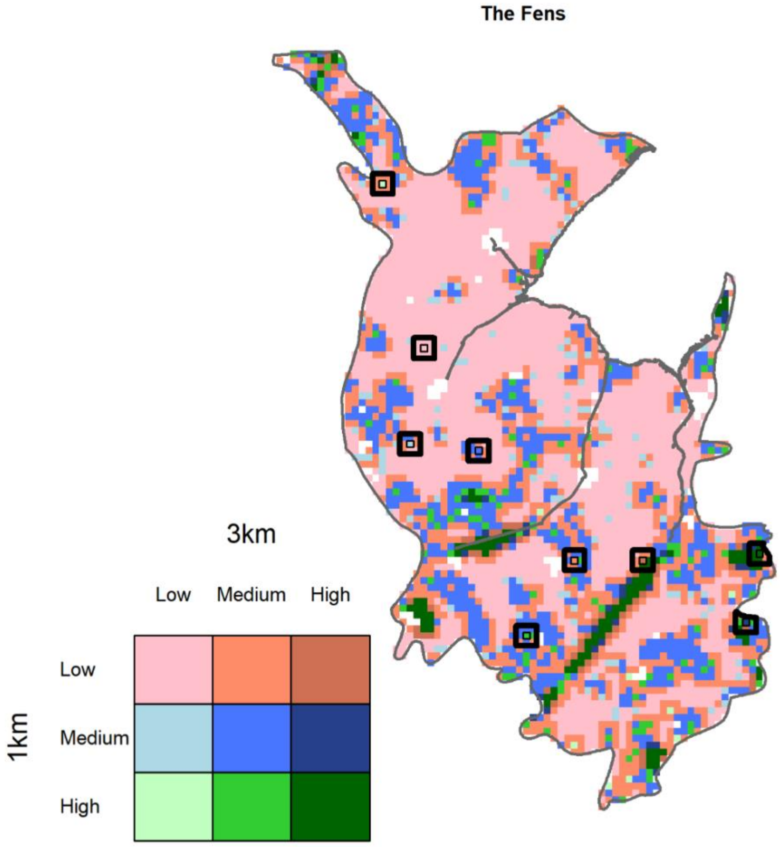

Figure 2.1.3 Super-imposed local (1 km^2) and landscape (3 × 3 km) gradients for survey squares for The Fens NCA. Landscape unit gradient is represented as the average of eight 1 km squares surrounding each focal 1 km square. Black outlined boxes show the nine landscape sampling units selected, based on contrast between local and landscape AES gradients. The bottom left grid shows the colour scheme by AES gradient intervention categories, e.g. dark blue is the medium intervention category along the local AES gradient and high intervention category along the landscape AES gradient. Previously published in Staley et al. (2021), reproduced under a Creative Commons CC-BY licence.

Four lowland and two upland NCAs were selected for field survey for the LandSpAES project (Table 2.1.2). Where multiple potential survey squares were available within a matrix class, up to three were randomly shortlisted from the selected sample units. Within each shortlist of three per matrix class per each of the NCAs, selection of the square for survey was pragmatic, based on obtaining permission for access and ensuring surveyor safety (avoiding firing ranges, quarries and motorways). If access permission was refused for > 30% of the land within a selected survey square, an alternative shortlisted square was used.

Table 2.1.2 Percentage of each surveyed region (National Character Area: NCA) in arable, agriculturally improved grassland and semi-natural grassland broad habitat classes (calcareous, neutral and acid grassland class plus fen, marsh and swamp). Broad habitat class data from Land Cover Map 2015 (Rowland et al., 2017).

	Percentage of area in broad habitat category		
NCA	**Arable**	**Improved grassland**	**Semi-natural grassland**
The Fens	84	7	1
South Suffolk & North Essex Claylands	71	14	0
Dunsmore & Feldon	53	32	0
High Weald	12	50	0
Yorkshire Dales	0	23	4
Dartmoor	2	28	2

Fifty-four survey squares were selected through the process described above, and confirmed as having adequate access agreed for field surveys (Figure 2.1.4).

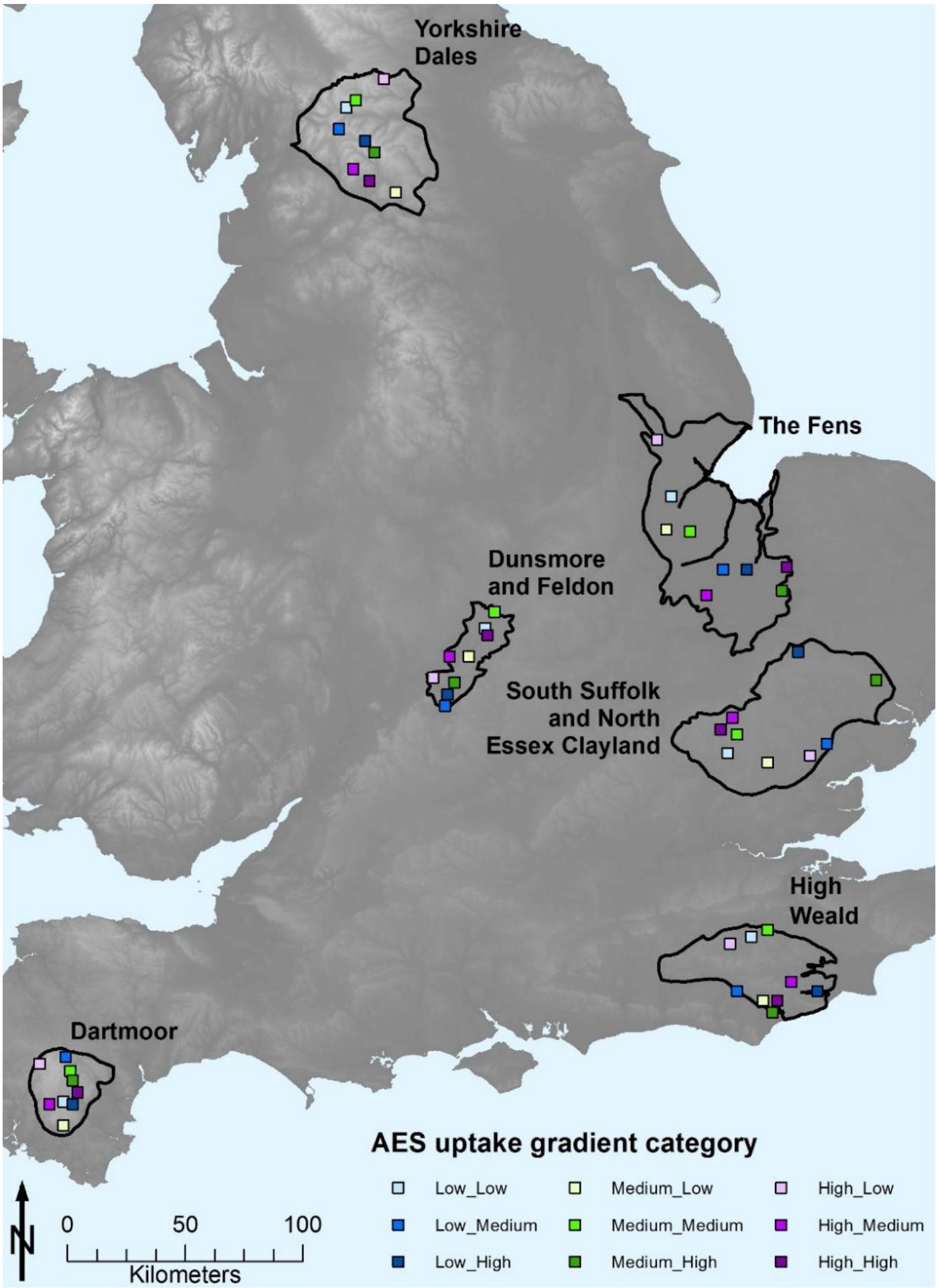

Figure 2.1.4 Landscape unit around each of the focal 1 km squares. Nine squares were surveyed in each of the six NCAs. The bottom right legend shows the colour scheme by AES gradient intervention categories, e.g. dark green is the medium intervention category along the local AES gradient and high intervention category along the landscape AES gradient.

2.2 Field survey monitoring methods

The protocols to monitor mobile taxa across the 1km survey squares were designed to use similar methods to national monitoring schemes where possible, to enable compatibility of data. The combined pan trap and insect transect survey used comparable methods to the Wider Countryside Butterfly Survey (WCBS, https://ukbms.org/wider-countryside-butterfly-survey) and the UK Pollinator Monitoring Scheme (PoMS, https://ukpoms.org.uk/). The bird spring and summer survey was comparable to the Breeding Bird Survey (BBS, https://www.bto.org/our-science/projects/bbs). For the insect transects (butterfly and bumblebees), and the bird spring and summer transects, surveys were more intensive than the WCBS and BBS surveys, to enable more accurate estimates of the species present and their abundance per 1km square to be made. LandSpAES butterfly and bumblebee transects were recorded four times a year, whereas WCBS butterfly transects are surveyed a minimum of twice a year. LandSpAES bird transects covered 3km length, in contrast to BBS transects which cover 2km per survey square. All other aspects (timing of survey, survey area, minimum weather conditions etc.) were identical between the LandSpAES and WCBS / BBS.

There were no comparable national surveys of bats or moths across 1km survey squares, or for birds during winter, so new protocols were developed for landscape monitoring of these taxa using established and existing methods from smaller spatial scales. An overview of the mobile taxa monitoring is in Table 2.2.1, summaries of the field survey protocols are in Sections 2.2.1 – 2.2.4 below, full detail of field protocols are in Appendix A1.

Spring and summer surveys for insects and birds took place in lowland NCAs during four years (2017, 2018, 2019 and 2021) and in upland NCAs for three years (2018, 2019, 2021), with the same number of winter surveys for birds only. Bat surveys took place in all NCAs for three years (2018, 2019 and 2021), following a pilot survey in two lowland NCAs in 2017 (Appendix A2). For each mobile taxon, repeat surveys were carried out across a field season within each year (details below).

In addition to monitoring mobile taxa, field data were collected from each survey square in order to map the broad habitats and AES options, to characterise the plant communities (abundance of each higher plant species, and of floral resources, and to assess the implementation and quality of the AES options. Data on floral resources (Section 2.2.1), and mapping of broad habitats and AES options, were collected in each of the same years as the spring/summer insect and bird surveys (Section 2.2.6). Data were collected on AES option implementation (Section 2.2.7) in 2017 and 2018, and on the plant community recorded in quadrats along insect transect routes (Section 2.2.5) in 2019 and 2021. Spring and summer surveys did not take place in 2020 due to the Covid-19 pandemic and related travel restrictions; these surveys were delayed to 2021.

Table 2.2.1 Summary of mobile species monitoring methods, used to collect abundance (or activity) data per species for each taxon in each survey square.

Mobile taxa	**Survey method for each 1km square**	**Survey season**	**Number visits a year**	**Time of day sampled**	**Weather constraints****	**Associated data collected?**	**Linked to established monitoring?**
Butterflies*	2km transect. Butterflies counted per species along fixed walk, within 5 × 5 × 5m moving box, for each transect section.	May – August	4	Daytime (10:00 – 16:00)	Min. 13°C, min. cloud cover (linked to temperature), max. wind speed 38 km/h.	Floral resources recorded to plant species, in each of two 10 × 5m quadrats per transect section.	UK and wider butterfly monitoring schemes https://ukbms.org/
Moths	6 light traps, specimens stored and identified to species.	Late May - August	2	Overnight (dusk to dawn)	Min. 10°C, min. 50% rain risk, max. wind speed 20 km/h.	Floral resources recorded to plant species, in a single 2m radius quadrat around each trap.	No
Bumblebees*	2km transect. Bumblebees counted per species along fixed walk, within 5 × 5 × 5m box.	May – August	4	Daytime (09:30 – 16:30)	Min. 13°C, min. cloud cover linked to temperature, max. wind speed 38 km/h	Floral resources recorded to plant species, in each of two 10 × 5m quadrats per transect section.	BeeWalk https://beewalk.org.uk/
Bees and hoverflies*	6 pan trap stations, specimens stored and identified to species.	May – August	4	Daytime (min. 6 h between 09:30 – 17:00)	Min. 13°C, min. cloud cover (linked to temp.), max. wind speed 38 km/h.	Floral resources recorded to plant species, in 2m radius quadrat per trap.	National Pollinator Monitoring Scheme https://ukpoms.org.uk/
Birds	3km transect – birds counted per species along fixed walks, within 100m either side of transect route.	April – July (summer), November – March (winter)	8 (4 each in summer and winter)	Early morning and during the day	Not in heavy rain		Breeding Bird Survey for summer surveys https://www.bto.org/our-science/projects/breeding-bird-survey
Bats	2 full spectrum acoustic recorders, activity per bat species.	May – August	4	Overnight, min. 4 consecutive nights.	Not in heavy rain		No

* Combined one-day protocol for butterfly and bumblebee transects, and pollinating insect pan traps. Full details in Appendix A1.2.

** Full details of weather constraints in monitoring protocols in Appendices A1.2 – A1.5, including details of minor differences at lowland and upland sites.

2.2.1 Butterfly and insect pollinator monitoring

2.2.1.1 Pan traps and transect insect surveys

Pan trap surveys and insect transects were conducted at each survey square once per month between May and August, resulting in four rounds of sampling each year of survey.
Trap locations and insect transect routes were set out prior to the first survey and were chosen using a set of criteria to gain optimum conditions for survey. These included access authorisation, square coverage, use of permanent linear features, habitat and AES option coverage and type. Places with high disturbance (both human and livestock) were avoided where possible for trap locations (Appendix A1.1 for details). Transect routes totalling 2km per square were split into 9-11 sections of similar length. Each transect section surveyed one habitat type. Six trap locations were dispersed across the square (minimum of 200m apart) and each was associated with a transect section.

During suitable weather conditions (defined weather criteria, see Appendix A1.2 for details), pan traps were set at stations across survey squares, with six stations operating on the same day. Pan trap stations were made using small bowls set at the same height as vegetation on a wooden stake (Figure 2.2.1). Three UV colours were used (yellow, white and blue) with approximately 100ml of water and surfactant mix added. Traps were left for a minimum of 6 hours with collected specimens retained in 70% ethanol. Samples were stored in a fridge at 4°C until species identification could take place. The location of all six pan trap stations was maintained throughout the project in the majority of cases (livestock presence or human disturbance sometimes required pan traps to be relocated, in such circumstances the new coordinates were recorded, return visits prioritised original locations).

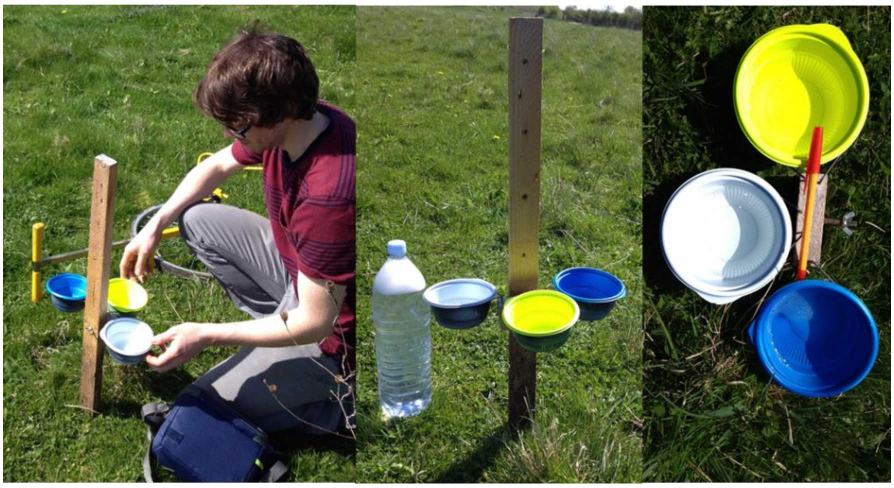

Figure 2.2.1 Pan trap station for sampling pollinating insects (photos courtesy of Claire Carvell, UKCEH).

Transects were walked at an even, steady pace and all butterflies and bumblebees observed within a 5 × 5 × 5m moving box around the surveyor were recorded (up to 5m in front, 5m above ground and 2.5m on either side, Figure 2.2.2).

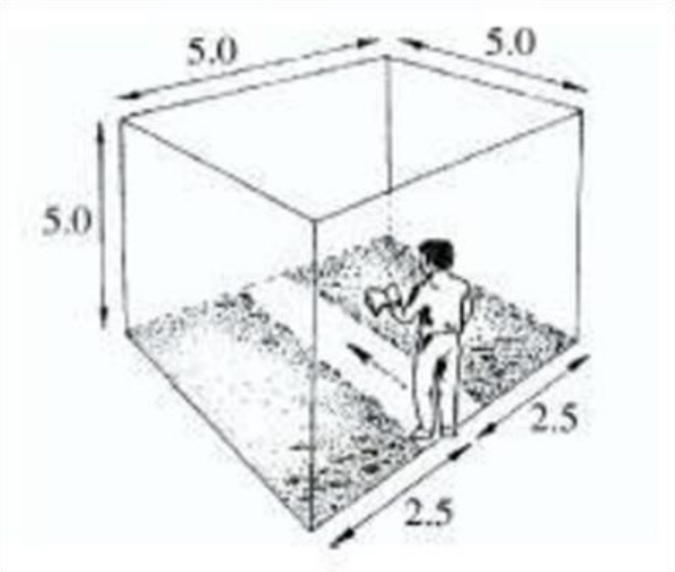

Figure 2.2.2 Moving box sampling approach for Pollard transects, used by WCBS and UKBMS (taken from van Swaay et al., 2012).

Bee and butterfly transects were walked separately during favourable weather conditions (for weather criteria see Appendix A1.2). Individuals were recorded to species level (and to caste for bumblebees) wherever possible, with abundance recorded per species per transect section. Where species level identification was impossible, surveyors recorded abundance of an aggregate, or for bumblebees a colour group, instead. Transect routes remained constant throughout the project, with only two sections having to be relocated due to access issues.

2.2.1.2 Floral resources along transect and around pan traps

On each occasion when pan traps were set or transects were walked, floral resources were recorded on the same day. Floral resources were recorded in each of two 10 × 5m quadrats placed ⅓ and ⅔ placed along the length of each transect section, and within a 2m radius circular quadrat around each of the six pan trap stations.

Floral resources were assessed as ‘floral units’ on each flowering herbaceous species (i.e. excluding grasses, sedges, rushes). Examples of floral units include a flower spike, umbel or flower head (Figure 2.2.3). Floral unit abundance per flowering species in the large 10 × 5m quadrats were assessed using an index (see Appendix A1.2 for details).

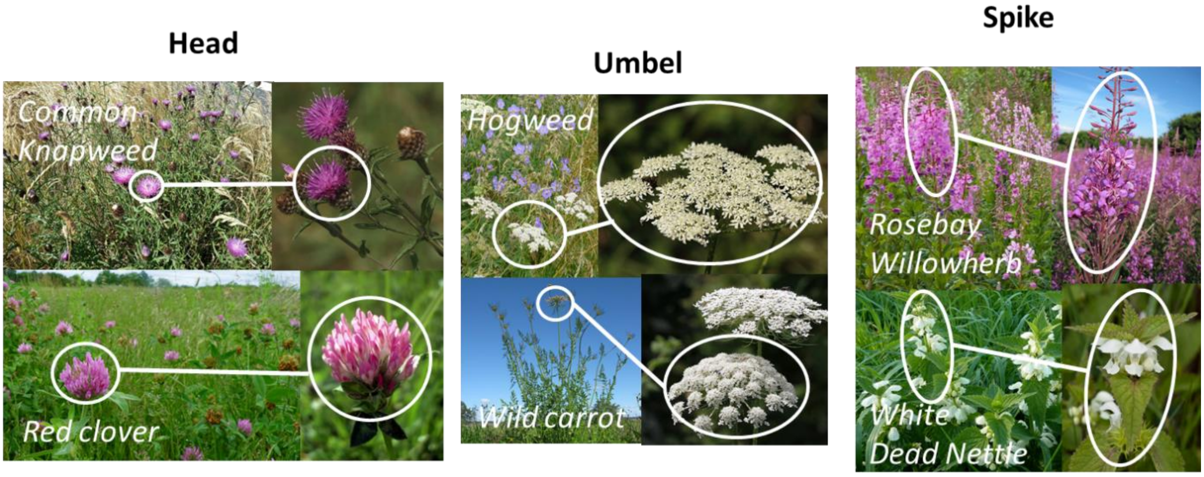

Figure 2.2.3 Examples of floral units, from PoMS target flower guide (Harvey et al., 2017).

2.2.2 Moth surveys

Moth surveys were undertaken twice per year on each survey square for all years of the survey (minus 2020 as detailed above). Dates were flexible to avoid full moon cycles and adverse weather conditions but fitted into two rounds; one early season (May/June) and one later season (July/Aug). A minimum gap of three weeks was specified between the two rounds at each site, and round one was completed before round two could be started.

Moth traps were placed at the six locations used for pan traps (due to livestock disturbance locations did sometimes change, but repeat visits always prioritised the original location). The six traps operated over the same night for a given square.

Trapping only took place if weather criteria were met (Appendix A1.3). Moth traps were designed to allow easy set up and collection in remote areas and were run with an actinic 6-watt bulb and 12-volt portable battery (Figure 2.2.4). Traps became operational at reduced light levels and ran throughout night hours. Moth traps were manually closed and collected in at sunrise the morning after being set. Ethyl acetate was used to euthanize catches on collection. All specimens from the trap were boxed carefully and stored in dry, cool conditions. Moths were then stored in a freezer at -20°C until accurate identification could take place.

Figure 2.2.4 Moth light trap at dawn in floristically enhanced option (HE10) in South Suffolk and North Essex Claylands NCA, 2017. © Judy Hart, UKCEH.

Full details of the moth survey protocol are in Appendix A1.3.

2.2.3 Bird monitoring

Within each survey square a 3km bird transect, split into section lengths following field boundaries with a single habitat / land use type on either side, was set up prior to the first visit, incorporating a variety of options and habitats typical of the square. Breeding bird survey transects were walked early in the morning on four occasions between April and July, distinguishing singing birds from other observations. Winter birds were surveyed using an adaptation of the summer protocol to reflect the differences in bird behaviour and detectability, and to sample key habitats effectively. The same transects routes were followed, over four visits, with specific searches of habitats that are expected to provide seed resources for birds, which were covered more intensively with a complete perimeter walk and coverage to within 50m of the interior.

Winter bird transects were walked at any time of day (apart from an hour after sunrise and an hour before sunset) on four occasions between November and March (inclusive).

In both spring and winter, all bird species seen or heard were recorded in distance bands of 0 - 25m, 25 - 100m and > 100m as well as flight only records, perpendicular to the transect and specific to each field / habitat on either side of the transect. Mammals, in particular Brown Hare, were also recorded on the bird transect route during both winter and spring visits.

Further details of the bird survey protocols are in Appendix A1.4.

2.2.4 Bat monitoring

For bats, a novel sampling approach was developed for large scale surveys using autonomous recording devices and standardised protocols for deploying bat detectors that had proven potential to provide high quality data for large-scale monitoring, comparable to those collected by bat specialists (Newson et al., 2017a; The Norfolk bat Survey: https://www.batsurvey.org).

2.2.4.1 Bat pilot survey 2018

Pilot sampling and analyses first demonstrated the applicability of the approach to the detection of habitat effects on bat species presence/absence per night (as a proxy for abundance), adapting sampling with full spectrum acoustic recorders, for which, importantly, the testing and analysis of data had been formally developed (Newson et al., 2017b). See Appendix A2 for further details of the bat pilot and A1.5 for the full bat monitoring protocol; below is a summary.

2.2.4.2 Bat survey 2018 – 2021

Two automated paired bat detectors (Wildlife Acoustics SM4Bat-FS detectors) were simultaneously deployed in a survey square at predetermined locations and left for four or more consecutive nights, before being collected. These sampling rounds were repeated four times between May and early September each year.

One detector of the pair was positioned in or by an AES option relevant to bats (e.g. field margin, nectar flower mix, watercourse buffer, hedgerow management or species-rich grassland), 5 - 6m from the field boundary and < 50m from field corners, and the second detector was placed ‘randomly’ within non-AES habitat in the square, again 5 - 6 m from a boundary, > 50m from corners and > 200m away from the first detector and any deployed moth trap or lighting. Where squares contained no AES habitat, the bat detectors were placed in matched locations near the centre of the square. After a sampling session, SD cards were removed and replaced, and the equipment was moved to a new square.

2.2.5 Botanical survey

Botanical surveys were conducted once during the survey season (May – August) on all squares in 2019 and 2021 only. Cover of each higher plant species was recorded in five 1 × 1m quadrats along each of the insect transect sections. Quadrats were regularly spaced in a zig zag line along the insect transect route, they were evenly spaced along each section lengths (avoiding the very ends) and across the transect width. A separate walk-over of the section was used to record any additional higher plant species that were not recorded in the quadrats. Further details of the botanical survey protocol are in Appendix A1.8.

2.2.6 Habitat and option mapping

Maps were prepared for each survey square using data from the LPIS database to define field boundaries, and polygons from the Land Cover Map 2007 (LCM; Morton, 2011) showing LCM broad habitat categories and enhanced with Ordnance Survey VectorMap Local data on small woodlands, waterbodies and built-up areas that fall below the minimum mappable unit of LCM 2007. For each field parcel, surveyors checked that the LCM broad habitat category was correct, added information on secondary habitats, and mapped any additional habitats > 0.5 ha in area. Habitat data were recorded directly using ESRI ArcPAD v10.0 on ruggedized tablet computers (Panasonic Toughpad FZ-G1) in the field in 2017 for lowland squares and 2018 for upland squares. In subsequent years paper maps based on the previous year’s records were produced and field verified annually. For the field validation, broad habitat classes were defined from the vegetation present in each habitat parcel, based on a habitat key developed for an established national survey (Maskell et al., 2008; UK-SCAPE, 2020).

Option mapping took place on separate maps but with the same base maps and method, i.e. directly in ArcPad in the initial year of survey and on paper for subsequent years. Various sources were used to complete accurate option mapping these included original agreement documents, speaking with agreement holders as well as on the ground verification. Multiple methods were required for accuracy due to changes to the agreement over its duration and especially for rotational options. Surveyors carrying out winter bird surveys assessed and mapped options specific to wintering birds.

Paper field verified maps for both habitat and option data were then digitised in ESRI ArcGIS V10.6.1. Full details of the protocol for mapping habitats and options are in Appendices A1.6 and A1.7.

2.2.7 AES option implementation surveys

Surveys of the implementation of AES options were carried out once per survey square in 2017 and 2018. A summary of the implementation survey methods is given in Section 4.2.1, and the full protocol in Appendix A1.9.

2.3 Landowner contact and access permission

This project would not be possible without the goodwill and access permission of those who own and manage the land on which surveys were carried out. Prior to commencing any survey all landowners and managers of all parcels of land within survey squares were contacted and access permission sought for the duration of the project.

Following postponement of the field survey in 2020 due to the Covid-19 lockdown, all access permissions were renewed for the final 2021 survey. Approximately 220 landowners, managers and other interested parties kindly allowed access for LandSpAES field surveys across 2017 – 2021.

2.4 Data handling, storage and quality assurance

Data across the field survey protocols were collected using Access data capture forms (tailored to each survey protocol), either directly onto ruggedized tablet computers (Panasonic Toughpad FZ-G1) in the field, or captured on paper forms and transferred to the same data capture later. Data were checked for entry errors, inconsistencies and typographical errors before being amalgamated into a project database in Oracle, with an Access front-end for easy data extraction and summary. Summaries of the amalgamated data were checked by survey square and round for each protocol, to make sure the species and survey data had not been incorrectly attributed (e.g. two sets of data for round 2 but none for round 3 in a given survey square and year, due to a data entry error).

The bird and majority of insect survey data were structured in a comparable manner to data from national recording schemes, and where possible we used data QA processes in line with the national recording scheme QA. All LandSpAES species level data were scrutinised through rigorous data QA processes. Existing species distribution records (e.g. published atlases, NBN gateway etc.) were used to check against LandSpAES species spatial locations. Species lists were also visually examined by species experts for any anomalies. Any potential errors flagged through the data QA processes were checked against paper data forms (where available) or confirmed with the surveyors who had recorded them.

For insects surveyed using pan traps, an additional taxonomic QA process was run jointly with PoMS (the National Pollinator Monitoring Scheme). Samples of pan trap specimens were swapped between LandSpAES and PoMS, so the LandSpAES pan trap determiner checked PoMS specimens and vice versa. The samples were chosen to include both difficult to identify specimens, and a random selection of specimens. Taxonomic QA run in 2018, 2019 and 2021 showed a high percentage of accuracy in pan trap specimen identification (97 – 100% accuracy, varying with year).

For bats, we made use of an acoustic classifier TADARIDA (a Toolbox for Animal Detection in Acoustic Recordings Integrating Discriminant Analysis; Bas, 2016; Bas et al., 2017). This entailed extraction of 150 measures of call characteristics from each recording, and a comparison of these against those from an extensive reference library of manually identified ultrasound recordings. The classifier assigns identities to a single recording according to probability distributions between detected and classified sound events. From these, species identities are assigned by the classifier with an estimated probability of correct classification. Manual inspection of a sample of spectrograms using software SonoBat (http://sonobat.com) was used as an independent check of the original species identities assigned by the TADARIDA classifier. For most UK bat species, the identification classifiers are well developed (Newson et al., 2015) but signal quality can vary, so for conservative identification, all data below the 50% threshold were discarded from the analyses and those above were manually checked except for Common and Soprano Pipistrelles, for which a sample of 1000 registrations each were manually verified. This method created a reduced, but stringent dataset of about 90,000 records from combining the years, 2018, 2019 and 2021.

2.5 Data manipulation and trait collation prior to analyses

For each taxonomic group, some data manipulation was needed prior to statistical analyses (see Section 2.6 for details of the analytical methods). In addition, for some of the more detailed statistical analyses, species were attributed to functional trait groups or other groupings wherever possible (e.g. red list species, generalist species, Farmland Bird Index groupings etc). A summary of this data manipulation and trait collation process for each taxon is provided below. Further details can be found in Appendix A3.

2.5.1 Insect data manipulation

The species recorded across a survey season can vary for insect taxa, depending on species turnover. For analyses of responses at the square level (Section 2.6.1), insect data were aggregated either by summing abundance across the survey locations within each square and across the survey visits within a year, or by calculating species richness or diversity in the same way (per survey square per year). Whole season species richness and diversity were considered most relevant for insects, as some AES management may specifically target early or late season species.

2.5.1.1 Aggregated data; minority of aggregate taxa and genus level records

The vast majority of data were recorded at species level for each of the insect taxa (98.4-99.8% for most taxa, with exception of bumblebees on transects 85.2%, see Appendix A3.1.1 for further details). For all insect taxa, individuals were occasionally recorded that could not be identified to species for various reasons: their behaviour made it impossible to see key identification features (e.g. a bumblebee flies quickly through the transect moving box); individuals were too worn or damaged; or there are some species groups/pairs in which the species (or certain castes/genders/forms of species) are very difficult to accurately split without further examination in the laboratory. For example, castes of certain bumblebee species such as *Bombus lucorum* and *B. terrestris* can be easily distinguished if queens or males are seen, but identification of workers is very difficult unless examined under a microscope in the laboratory. These may therefore be recorded as an aggregate species, depending on the caste and survey method.

We took a range of actions to deal with aggregate records and records to genus level, which are summarised here, with full details in Appendix 3.1. However, note these actions only affect calculation of species richness and diversity, and all aggregate and genus level records were included in insect abundance calculations.

In summary, the main approaches used to deal with aggregate insect records were:

- Where the aggregate records dominated and there were few or no records for the two component species, all records of the component species were allocated to the aggregate for species richness and diversity. This was usually where separation of two species is not possible in the field, even if the surveyor has a good view and the opportunity to catch the individual for further scrutiny. For example, the cryptic bumblebees *Bombus cryptarum* and *B. magnus* can be separated from *B. lucorum* as queens, but other castes cannot be separated, so all were aggregated to *B. lucorum* sensu lato.
- A very small number of aggregate records were recorded, but the vast majority of records were at species resolution for the two component species of the aggregate (e.g. Small and Essex Skipper butterflies). In these cases, the proportion of individuals observed within the square in that year was used to allocate the individuals recorded to aggregate to one of the constituent species.
- In a couple of cases, female hoverflies were recorded to an aggregate as these cannot be separated to species, but across the whole dataset males of only one of the two component species were recorded. In this case, the female records were allocated to the species for which males had been recorded. E.g. hoverfly females identified as *Cheilosia albitarus* sensu lato, for analyses were considered to be *C. albitarus*, as no *C. ranunculi* were recorded.

2.5.1.2 Pan trap bee data

The full species data were used in all analyses of insect data, with one exception. Honeybees were excluded from the pan trap bee data prior to analyses. The majority of honeybees are farmed, and their abundance will be strongly linked to the number and location of bee hives in the surrounding area. Honeybees were one of the more abundant bee species recorded in pan traps (Appendix 6.3). They were excluded as it was unlikely that honeybee presence and abundance would be driven by AES resources, and their high abundance meant that honeybees might obscure relationships between total bee abundance and the AES gradients.

2.5.2 Insect taxa trait data – approach and collation

A large number of insect species were recorded across the LandSpAES surveys (e.g. 35 butterfly and 925 moth species), and many insect species were recorded in low abundance, or in some but not all NCAs. Due to this, analyses of the abundance of individual insect species in relation to the AES gradient effects were not practical. In order to understand the responses of insect taxa to the AES gradients in more detail, beyond the analyses of headline community responses such as species richness of all butterflies, we grouped species to trait groupings within each insect taxon. The majority of traits analysed were functional (e.g. mobility, diet breadth), results of which allow a mechanistic understanding of how the ecology of species groups may be driving responses to habitat variables such as AES (Vandewalle et al., 2010, Kremen & M'Gonigle, 2015).

We included those functional traits that we hypothesised might affect the response of insect species to the AES gradients. For example, more mobile species in each taxon might be more likely to respond to AES management at larger spatial scales than less mobile species. It has been suggested that AES options could be tailored to provide resources for bee species that first emerge in early spring (Carvell et al., 2017), but AES management may currently cater more to species emerging in late spring / summer.

Red-list status was also included in trait analyses where possible, in order to test whether AES gradients affects the abundance of conservation priority species, due to their high policy-relevance. Finally, for pollinating insects, trait groupings were included for dominant pollinating species (Dicks et al., 2015, Carvell et al., 2016) and likely candidates for pollinator monitoring (Carvell et al., 2015).

The majority of functional trait groups were defined across several or all insect taxa (e.g. mobility) to enable comparisons to be drawn across taxa (Table 2.6.1). A minority of traits were only relevant for one or two insect taxa (e.g. larval food plant type). Some insect traits were based on quantitative data (e.g. wingspan as a proxy for mobility), others on categories (e.g. larval food plants: woody vs. forb vs. grass). For the quantitative traits, groups within each trait were defined based on threshold values. Table 2.6.1 gives the broad details of each trait included in analyses of insect data, and the groups within each trait per taxon.

Trait data were collated for each insect taxon from a range of published sources and existing trait databases. Detailed trait descriptions and definitions for each insect taxon, including full references of sources used to collate the trait data, are in Appendix A3.2.

Table 2.6.1 Trait groups used to aggregate insect species data for detailed analyses of responses to AES gradients.

Trait	**Butterflies**	**Bumblebees (transects)**	**Bees (pan traps)**	**Hoverflies**	**Moths**
Mobility	Wingspan as proxy. Large (most mobile) vs. medium vs. small (least mobile)	Forewing length as proxy. Large vs. small	Forewing length as proxy. Large vs. medium vs. small	Wing length as proxy. Large vs. medium vs. small	Forewing length as proxy. Large vs. medium vs. small vs. very small
Voltinism	Univoltine vs. bi- or multivoltine	Univoltine vs. bi- or multivoltine	Univoltine vs. bi- or multivoltine	Univoltine vs. bi- or multivoltine	Univoltine vs. bi- or multivoltine
First flight time	Early (first on wing in April or earlier) vs. summer (May or later)	Early (first on wing in April or earlier) vs. summer (May or later)	Early (first on wing in April or earlier) vs. summer (May or later)	Early (first on wing in April or earlier) vs. summer (May or later)	Early (first on wing in April or earlier) vs. summer (May or later)
Habitat generalist vs. specialist	Wider countryside generalists vs. habitat specialist species				Habitat specialist (1 or 2 primary habitat types) vs. generalist
Diet breadth	Limited (larvae feed 1 or 2 core host plants) vs. broad (3 or more)	Tongue length as proxy: short vs. mid vs. long	Oligolectic (pollen gathered from host species within single plant family) vs. polylectic		Larval host specificity: monophagous (single host species) vs. oligophagous (several hosts in one taxonomic family) vs. polyphagous
Larval food type	Larval food plant type: grass vs. forb vs. woody			Larval food source: predators vs. herbivores vs. detritivores	Larval host type: grass vs. forb vs. woody vs. other
Conservation status	Red list status: Critically endangered, Endangered, Vulnerable, Near threatened	Red list status: Critically endangered, Endangered, Vulnerable, Near threatened	Red list status: Critically endangered, Endangered, Vulnerable, Near threatened		Macro-moths only, Red list status: Critically endangered, Endangered, Vulnerable, Near threatened
Pest species	Crop pest species				
Sociality			Eusocial (or facultatively eusocial) vs. solitary		
Parasitic		Parasitic (cuckoo) vs. social	Parasitic vs. not parasitic		
Dominant crop pollinators		Six bee species (three bumblebees, three solitary bees) most commonly recorded in flowering crops (Dicks et al., 2015)			
Crop visitors		19 bee and hoverfly species identified as important crop pollinators for PoMS			
Monitoring candidates		37 bee and hoverfly species identified as candidates for PoMS monitoring			

2.5.3 Bird data manipulation and traits

Bird communities are essentially stable within seasons, and individuals (which are often territorial) are expected to be detected at a survey location on multiple visits (although behaviour and detectability vary through the season). Data for individual 1km squares were, therefore, summarised across survey visits within a season by taking maximum counts, which should approach the true local community composition by accounting for both rarely and consistently detectable species and individuals.

The bird survey methods were inclusive, i.e., recording all species detected. However, some of these species were not relevant to the potential breeding bird community in terrestrial landscape. For the headline community responses (abundance, richness and diversity), we used reduced species lists. There were 98 species in summer analyses (Table A3.5, Appendix A3.3) and 86 in winter analyses (Table A3.5). Excluded species included gulls (not terrestrial breeders), winter migrants and three species that were observed in only one year of the study across all NCAs. Unless otherwise stated, birds in flight were not considered since they may not be utilising resources in the given survey square. This list was also used when extracting Red Listed species. Red Listed species were those given in the Birds of Conservation Concern 5 (BoCC5; Stanbury et al., 2021) in the 'Red' category.

Due to the flocking behaviour of Woodpigeon, Jackdaw, Starling and Rook, which means that their numbers could dominate and distort bird community measures, these species were omitted from total abundance counts and diversity measures (but included for richness). In addition, following methodology from the BTO/JNCC/RSPB Breeding Bird Survey (BBS), large groups (more than ten individuals) of certain wader species recorded in a single transect section were filtered from the data, since these will almost certainly not consist of locally breeding, adult individuals. Counts of this form were excluded for Golden Plover and Curlew, and any Lapwing counts that occurred on visits three or four. In addition, any Golden Plover counts from lowland were not included.

We also examined associations with the AES gradients at the species-level. We included all farmland bird indicator (FBI) species, and species observed in at least five of the six National Character Areas likely to utilize hedgerows. Farmland Bird Indicator (FBI) species (Table A3.6, Appendix A3.3) are a specially selected list of species dependent on farmland for feeding and nesting, commonly thriving in such habitat. Note, however, that not all of these are targets for AES management and that, indeed, some have official 'pest' status in law (Jackdaw and Woodpigeon), so inclusion of all species is to aim to provide a complete ecological picture. Birds in flight were excluded (i.e. those not using resources in the given square), as were those with low detectability, such as Tawny Owl and Snipe. Zero-counts for species were included, provided that the species had been observed in at least one square within the same NCA, in any year. Therefore, if a species had never been observed in a particular NCA, all zero-counts were excluded for that species; this avoided misleading habitat relationships being included concerning NCAs that were outside a species' range. As in the abundance analysis, high counts were removed as these were likely to represent non-breeding flocks.

We explored whether groups of species with similar diets responded to AES management by taking total abundance counts per square per year. The two species groups we explored were defined using summaries of dietary components in Siriwardena et al. (2019), giving non-exclusive groups with diets consisting of (a) terrestrial ground/soil invertebrates and/or foliar ground invertebrates (Invertebrate group; Appendix 3.3 Table A3.7, Summer species and Table A3.8 Winter species), or (b) farmland weed seeds or crop seeds (Seed group; Table A3.9 Summer species and Table A3.10 Winter Species).

2.5.4 Bat data manipulation

Bat activity and detectability are highly variable seasonally, such that multiple sampling sessions are required to make inferences about an entire bat community (see Appendix A2). The bat sampling does not measure abundance directly; rather, it measures bat species identity and activity. Therefore, a simple maximum count for abundance estimation is not available and diversity cannot readily be calculated. Hence, it is more appropriate to consider abundance across visits using a repeated measure structure than attempting to find a maximum or total value across visits.

A core dataset was prepared with a row for every night of recording at each detector in every square for each of 12 species and one species pair, with a calculated value for both presence/absence and the maximum rate hourly of bat passes (activity). Whiskered/ Brandt's Bats *Myotis mystacinus/ brandtii* were treated as a species pair (herein termed, 'Myotis spp.') because they were inseparable by the detection method used. From the core dataset, bat data were processed as species richness and for individual species, as the maximum activity at both the square level per year, and nightly survey levels. A proxy for total bat abundance from total bat activity could have been used, but the dominance of the sample by Common Pipistrelle, in practice, meant that it would just have reflected the abundance of this species. All other analyses were, therefore, conducted at the species level. The bat species in the UK comprise a small fauna with no obvious way to sub-divide them into trait groups that is relevant for farmland habitats (such as with seed-eating birds for example), so trait analyses were not performed for bats.

2.6 Statistical analyses of taxa responses to the AES gradients

2.6.1 Taxa response variables

For each taxonomic group we calculated three headline response variables describing the overall community: species richness, Shannon diversity index and total abundance. These headline response variables were calculated in same way for each taxon, to allow comparisons across taxa. For some taxonomic groups, we also calculated these metrics for trait groupings or looked at the abundance of individual species (see Section 2.5 for details). Note, however, that metrics such as species richness may need to be interpreted differently for taxa like moths (hundreds of species) and bats (up to 15 species per location).

For the majority of analyses, we calculated responses at the square level (Section 2.6.2), aggregating over transect sections, traps or detectors. We also aggregated data over multiple visits within each year to reflect total richness, abundance or diversity across the year. This ensures that the focus is on the total community present, capturing any turnover in species that may occur across the survey season. For birds, maximum rather than total counts were used, and for bats, activity was captured instead of abundance. Abundance data were not collected for bats, so total abundance could not be calculated; a proxy for Shannon diversity was calculated using the proportion of sampled nights in which a species was detected as a proxy for abundance.

2.6.2 Analyses of taxa responses to the AES gradients at square level

The majority of analyses for each taxon were structured at the square level, as this was the scale at which the AES gradients were designed (Section 2.1), and the selection of survey squares across orthogonal local and landscape AES gradients was conducted (Section 2.1.3).

Relationships were assessed between each response variable and AES gradients within the surveyed focal square (1km or local AES gradient scale) and the surrounding landscape scale (3 × 3 km scale), including the interaction effect of the local and landscape AES gradients. AES scores at the local scale were based on field mapped data within 1km survey squares plus supplementary options, which were a good match to gradients derived from GIS data (see Section 3.1). Landscape level AES scores were derived from GIS data on option uptake attributed to parcel centroids (Section 2.1.2). Nesting of survey squares within NCAs and repeated visits to survey squares were accounted for in the models by including NCA and square level random effects.

For some taxa, additional covariates were included which can strongly determine the activity and abundance on a given survey, but were not of interest in themselves. For example, temperature was included for analyses of moth data. Full details of the modelling approach, including these taxon-specific covariates, are described in Appendix A4.1.

We do not yet have sufficient temporal replication or elapsed time to look at trends over time in response variables in relation to AES so all analyses consider relationships with AES over space. A future resurvey of the squares would be needed to assess how AES influences population change over time

2.6.2.1 Addition of habitat and plant covariates

In addition to the AES gradient effects, some models included habitat and plant covariates. Although we have previously demonstrated that habitat variables are broadly independent of AES gradients (Section 3.3), and the survey squares were not set up to look for habitat or plant variable effects, it is also possible that we may still have captured some relationships with the taxa response variables that are of interest. Correlations were also investigated between the botanical variables and the AES gradients, and there was no evidence of strong correlations. The habitat and plant variables included varied across the taxa, and were tailored according to the ecology of each taxon (Appendix A4.2.1).

Prior to inclusion in models, potential habitat and plant variables were tested for collinearity. Some habitat components (e.g. area of arable and area of semi-natural habitat) were strongly correlated with each other either positively or negatively. Including both terms in the model in such cases would risk incorrect conclusions about which variables are important, so where any pairs of variables had Pearson correlation coefficients of over 0.7, one was excluded (Dormann et al., 2013). Correlations between habitat variables were greater in analyses of data from the lowland NCAs only, compared to analyses of all data, further restricting the habitat variables that could be included in analyses of lowland only data.

Full details of the analyses that included habitat and plant covariates are in Appendices A4.2.1 and A4.2.2, including which covariates were analysed for each taxon (Table A4.2).

2.6.3 Multiple testing and attributing strength of relationships

The key outputs from the models are the estimates of the three AES terms (local AES, landscape AES and the interaction term), and the associated error around these. Usually, we would say that if these terms are statistically significant at $P < 0.05$, it would indicate evidence for a relationship between the response and the AES gradients. However, due to the large number of models produced in the project, it is to be expected that a number of 'significant' results would be identified simply by chance, in proportion to whatever threshold is applied (using a threshold of $P < 0.05$ we expect to report a significant result by change about once in every 20 models). Therefore, to be sure that we do not place excessive confidence on results that may be due to chance, we do not consider results as providing statistical support for an effect based on any strict threshold. As a general guide, however, we consider P-values of less than 0.01 as providing strong or good evidence for a relationship, and values of < 0.05 providing weak evidence of possible relationships (Muff et al., 2022).

2.6.4 Within-square analyses of butterfly and bumblebee responses to the presence of AES options

For a subset of responses, we also looked at within-square relationships to AES options. While the design of the study was focused on AES management at the 1km square scale, the data collected also provide a contrast between occurrence and abundance of the monitored taxa at the option patch scale. Subject to the degree of contrast that is actually delivered in practice between option and counterfactual habitat, analyses of the data at this scale could provide important additional inference about AES effects.

For butterflies and bumblebees monitored on transects we assessed whether the richness, diversity or abundance of insects was different between transect sections that were on or off AES option. Information on whether transect sections were on option was obtained from the mapped options (Section 2.2.6 above, further details in Appendix A4.2.3). We also scoped whether it would be possible to focus these within-square analyses on particular groups of options (e.g. those providing floral resources for pollinating insects), but replication was too low to allow such a subdivision of the option data. The within-square analyses thus consisted of a test of whether the insect response showed a relationship with whether the transect section was on or off AES option in that year of survey, regardless of the option identity. Taxon metrics at this scale are best interpreted as reflecting the degree of attraction of mobile animals to option patches, as opposed to the measurement of communities at the 1km square scale.

Due to the design of the insect transect surveys, where transect sections were allocated to on and off AES areas roughly proportionally to the level of local AES (Appendix A1.1), we did not include the local and landscape AES terms when analysing differences between on vs. off AES options. Therefore, the differences represent the average difference between transect sections on and off AES across all levels of local and landscape AES. The survey was not designed specifically to look for within-square AES effects, thus it was not possible to test whether the difference between on and off AES transects was conditional on the implementation of AES across the whole survey square or the wider landscape. Further details of the within-square analyses, including model structures, are in Appendix A4.2.3.

3 Results – Validation of AES gradients and survey design

3.1 Predicted vs. field validated AES gradients

The AES options present in each of the 54 survey squares were mapped each year in 2017 – 2021, as described in Section 2.2.6 above.

Figure 3.1 shows a good relationship between the predicted AES gradients (based on spatial uptake data) vs. validated AES gradient scores calculated using option extents mapped in the field, for each 1km survey square in each survey year. The small differences between predicted and validated options were mainly due to rotational options (e.g. pollen and nectar mix) with low spatial resolution in the uptake data and to some landowners choosing to add extra options, and so related to patterns of AES management on the ground that could not be predicted using spatial uptake data. The outlier with a validated AES gradient score around 40,000 in 2017 (Figure 3.1.1) was a survey square where additional fields of pollen and nectar mix option had been planted before the first year of field survey, beyond the options initially planned under the agri-environment agreement, and demonstrates the need for field mapping to verify the gradient scores. The validated gradient score for this outlier square reduced in subsequent years.

The correlation between the predicted and validated gradients was strong in all years, but reduced slightly in 2021. A few HLS agreements had short extensions to the original agreement end date in 2020, and so were ongoing in 2021. Options under these agreement extensions were mapped in the field (and agreement holders consulted where need be), and so are included in the validated AES gradients. However, the spatial uptake data did not include these extensions to the agreements. Inaccuracies in the spatial uptake data also led to slightly reduced AES gradient coverage in Dartmoor, compared to the original design, with fewer squares with low gradient scores for the verified local AES gradient than had been initially intended. As for the rotational and additional options, this shows the value of field mapping to verify AES gradient scores within the survey squares.

Overall, most changes in the validated AES gradient across years were small, and only rarely resulted in changes between gradient categories for individual survey squares. The strong, positive relationships between the predicted and validated AES gradients at the 1km square scale supports the use of the predicted AES gradient scores used in the sampling design (see Sections 2.1 and 2.2 for details).

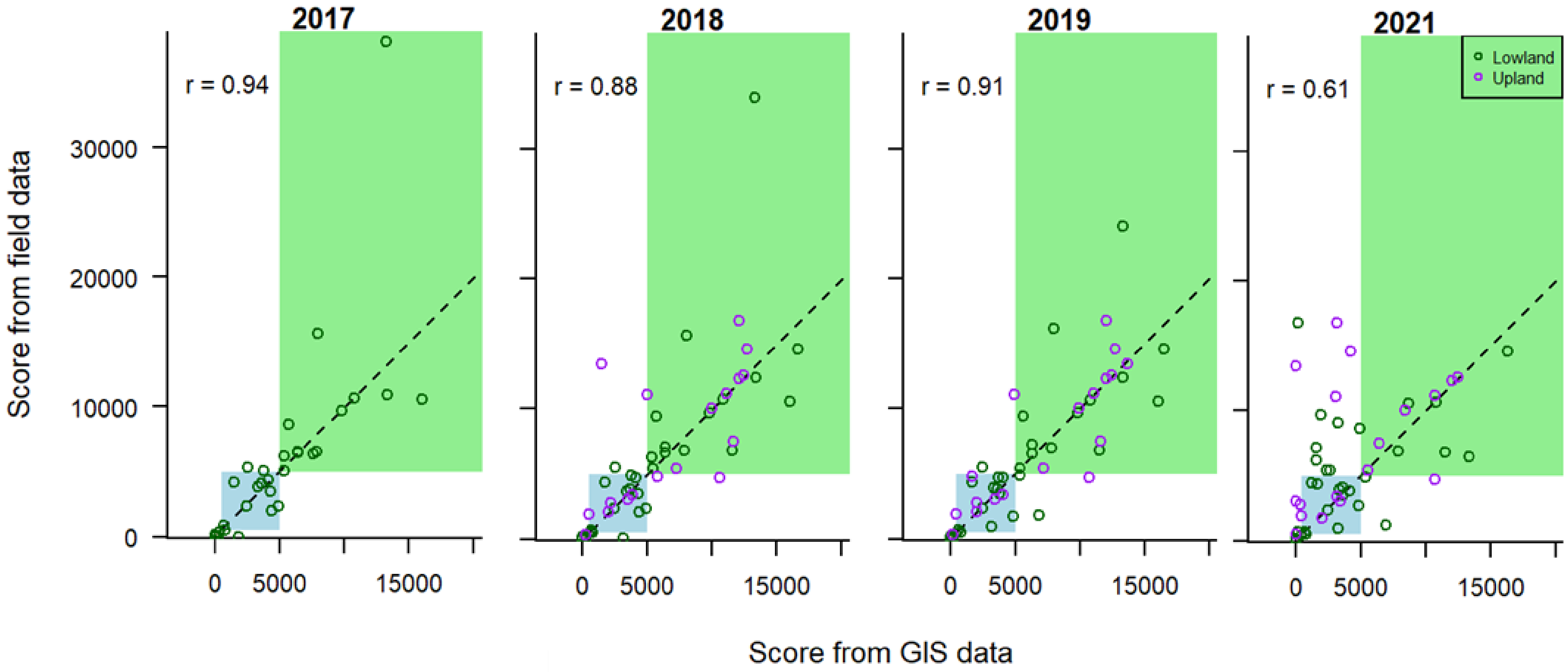

Figure 3.1.1 Relationship between AES gradients calculated using GIS uptake data (x axis), the 'predicted gradient' vs. field mapped options (y axis), the 'validated gradient, in lowland (green) and upland (pink) survey squares over each of the four years of field survey. The shaded green area denotes scores in the 'high' category from both GIS and field mapped gradients, blue shading shows 'medium' category scores, pink shading shows 'low' category scores (less apparent than other two categories as 'low' category scores ranged from 0-500).

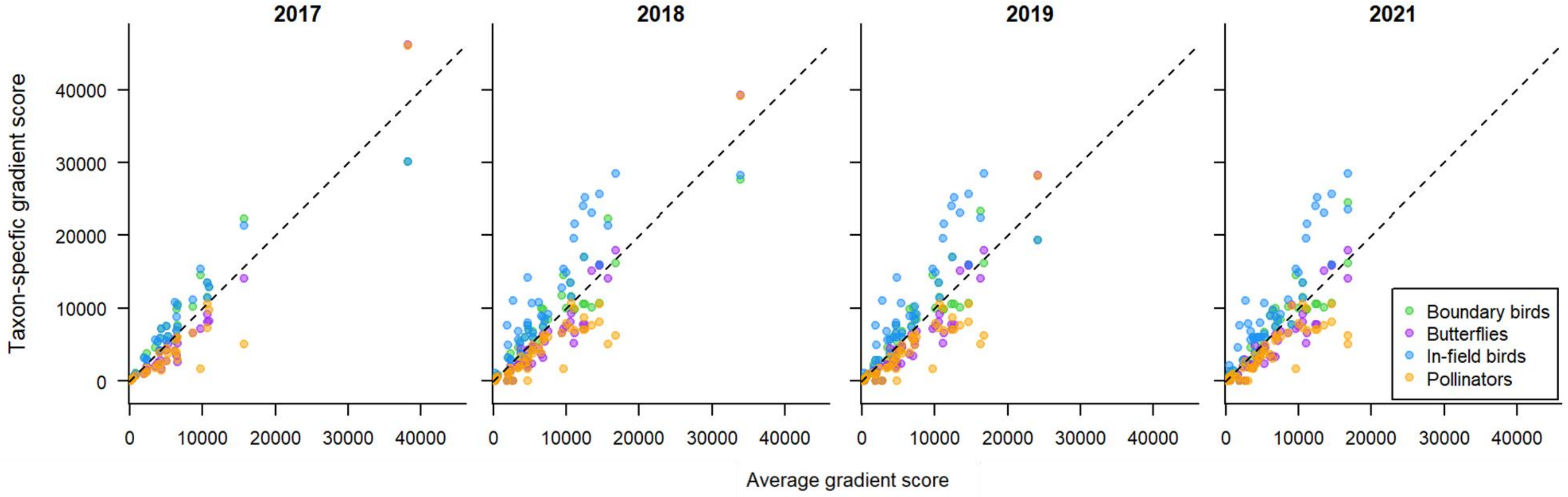

Figure 3.2.1 Relationship between average validated AES gradient calculated using field mapped options (x axis) and the validated AES gradient for each of the four taxa, shown for each year of field survey.

3.2 Average and taxon-specific validated AES gradients

Taxon-specific predicted AES gradients were calculated during the scoping of the survey design, and found to be closely enough related to the average predicted AES gradient to justify using the average gradient in square selection (Section 2.1.2). The gradients were calculated again for each of the four taxa using the mapped option data, and relationships between the validated gradients investigated (Figure 3.2.1).

The correlations between the average and each taxon-specific gradient were very strong in each of the survey years (Table 3.2.1). Correlations were strongest in 2017 and reduced slightly by 2021, although in all four survey years the correlation coefficients were 0.92 or above. These very strong correlations provide support for the use of an average AES gradient in square selection, co-location of sampling across taxa, and the use of the average validated gradient in the analyses of taxa responses to AES gradients (Section 5).

Table 3.2.1 Correlations (Spearman's coefficient) between the validated average AES gradients and each taxon-specific gradient, for each year of field survey.

	Boundary birds gradient	**Butterflies gradient**	**In-field birds gradient**	**Pollinating insects gradient**
Average gradient 2017	1.00	0.99	1.00	0.98
Average gradient 2018	0.96	0.97	0.95	0.93
Average gradient 2019	0.96	0.96	0.95	0.93
Average gradient 2021	0.96	0.96	0.95	0.92

3.3 Do validated AES gradients relate to other habitat variables?

Table 3.2 Correlations (Spearman's coefficient) between the validated average AES gradients and habitat variables (habitat diversity, area of arable land, area of semi-natural habitat) within the 1km surveys squares in each NCA, and across all survey squares.

NCA	**Habitat diversity**	**Arable**	**Semi-natural habitat**
High Weald	-0.02	0.07	0.45
South Suffolk & North Essex Claylands	0.17	-0.04	0.34
Dunsmore & Feldon	0.28	0.34	0.16
The Fens	0.45	-0.41	0.48
Dartmoor	0.11		-0.10
Yorkshire Dales	0.42		-0.22
All six surveyed NCAs	0.09	-0.24	0.36

Correlations between the validated average AES gradients and the three habitat variables (area of arable land, area of semi-natural habitat, habitat diversity calculated as per Appendix A4.1) were weak (<0.5) or very weak, both within each NCA and across all survey squares (Table 3.2). This demonstrates that the validated AES gradients are broadly independent of other background habitat variables, and supports the approach of aggregating survey sites within blocks of broadly homogenous landscape (NCAs).

Relationships between the predicted average AES gradients and other habitat variables, such as habitat diversity or area of arable land, were assessed within each of the six NCAs during the survey design process (Staley et al., 2016). These potential relationships were assessed again using the validated AES gradients calculated from the mapped options, and the mapped habitat data, within each 1km survey squares.

4 Results - AES option implementation

4.1 Introduction

Aim: To determine how much the AES gradient values attributed to individual 1 km survey squares would be altered by the inclusion of an assessment of the implementation of AES options. In order to achieve this, a scoring method was developed for implementation data collected during field surveys, to enable varying data across different option types to be combined.

The gradient values described in Section 2.1 above do not incorporate the quality or individual implementation of each option contributing to that gradient. Previous monitoring of management quality and compliance to AES prescriptions has revealed wide variation in the quality of implementation between landowners (Staley et al., 2018). Outcomes also differ considerably between and within options (Boatman et al., 2013). In order to establish if the gradient scores for overall squares reflect what is on the ground, data were collected in 2017 and 2018 to determine the quality of implementation of AES options. This field data collection built upon previously established techniques of assessing AES option and agreement quality, used in other projects (Boatman et al., 2013; Staley et al., 2016; Jones et al., 2019).

Overall, 394 implementation surveys were completed and covered a broad range of options covering a wide variety of AES management aims (Table 4.3.1 - Table 4.). Those options that were represented by more than two surveys were scored using protocols clustered to reflect option aims and objectives. Due to time constraints and project priorities not all parcels of each option type that were mapped for the project had an implementation survey, therefore there are option parcels that are present within the AES gradient calculation that do not have an associated implementation score.

4.2 Methods

4.2.1 Survey methodology

Field implementation data were collected for AES options within each 1km survey square where relevant options were present (squares with a local AES gradient score of zero contained no options and therefore had no implementation data collected). Where options were very common within a square (more than five patches of option), e.g. hedgerow and grass margins, surveyors were asked to carry out assessments of five examples spread evenly over the square. Implementation recording took place where an accurate assessment could be made in a single visit by a surveyor to an option parcel. This visit was made when the management prescriptions were likely to be evident (e.g. before the hay cut for meadows) where possible.

Assessments consisted of botanical surveys, and surveyors answering questions regarding management prescriptions and whether there was evidence of these being carried out, e.g. grazing requirements, cutting regimes etc. The management prescriptions were generic for each option and followed the HLS and CS handbooks, they were not tailored specifically for individual agreements or field parcels.

Botanical surveys were carried out for each option type. Five 1m^2 botanical quadrats were assessed per parcel / patch / margin under lowland enclosed AES option management, and 2 × 2 m quadrats were used for upland, unenclosed option parcels. On linear options (margins, headlands), five 1m^2 quadrats were spaced approximately equally. On whole parcels or patches, quadrats were spaced out along a ‘W’ walk to cover the whole area. Given that many options are designed to provide nectar and pollen sources, or seeds for birds, floral assessments were made for all option types. Species and numbers of flowers were recorded for options within the quadrats. In upland habitats broad habitat types were also recorded, and an implementation survey conducted for each broad habitat within an option, as options could cover several habitats on unenclosed land. Further details of survey methods and data capture can be found in Appendix A5.1.

4.2.2 Scoring methodology

Options occurring within the selected survey squares have been clustered into similar groups referred to as option clusters (a full list of options and their associated cluster is in Tables 4.3.1 – 4.3.3). Characteristics or attributes that contribute to those options being successful were listed and itemised. Attributes were selected that allowed for the quality of the option implementation to be assessed, representing general benefits for target taxa as well as fulfilling generic management prescriptions for that option cluster. These included specific management prescriptions as laid out for the option, condition indicators, floral diversity and abundance and other general features that lead to successful delivery of that option.

Thresholds were assigned to each attribute, some simple, such as YES/NO e.g. was there evidence of fertilizer use where there should not have been. Other attributes were more graduated e.g. percentage cover of indicator species, in which case a scale of scores was used. Evidence to support the use of these thresholds came from existing agri-environment handbooks, FEP manuals, and discussions with experts and published evidence (Natural England 2010, Natural England 2013, Natural England 2015).

A score was given to each of the attributes and threshold criteria. When prescribed favourable management activities had been observed, a higher score was given. Scores for beneficial and advantageous attributes, e.g. more floral resources, also scored higher numbers of points than less flower rich areas. Full detailed scoring protocols for each of the option clusters can be found in Appendix A5.1.

Collected field survey data from 2017 and 2018 were used and scored according to the protocols.

Option luster descriptions are as follows:

Arable plant: Options within this cluster are used to create opportunities for rare arable plants to germinate, flower, set seed and complete their life-cycle.

Arable floral: These are arable, cultivated options which should provide areas of flowering plants to boost essential food sources and habitat for beneficial pollinators and for other foraging invertebrates and birds. If successfully implemented, there should be an abundant supply of pollen and nectar-rich flowers throughout the summer and pollinating insects such as bumblebees, solitary bees, butterflies and hoverflies using the flowers.

Resource protection: These are options that cover a strip or area of land, maintained as permanent vegetation, so as to protect existing features including hedgerows, trees and archaeology, as well as water bodies. They can develop into valuable wildlife habitats in their own right and can contribute to the mosaic and connectivity of habitats in the wider landscape.

Hedgerow: Hedge management options and prescriptions are designed to increase the availability of blossom for invertebrates and will allow fruit and berries to ripen to provide food for overwintering birds. These options should improve the structure and longevity of hedgerows. If successful these options will deliver taller, denser and wider hedges bearing blossom and berries, dense cover and an improvement to overall hedge condition (Gov.uk 2015).

Winter bird food: These options aim to provide important food resources for farmland birds in autumn and winter. If successful there will be an abundant and available supply of small seeds during the autumn and winter months and farmland birds eating the seeds from October. Some seed mixes may also support beneficial insects including bumblebees, solitary bees, butterflies and hoverflies using the flowers during the summer.

Grassland - target feature: options under this cluster are aimed at maintaining or increasing the quantity of the targeted habitat, species or features. This may be carried out by increasing areas for nesting, hibernating or sheltering birds or insect pollinators.

Species-rich grassland: These options are specifically designed to enhance and maintain existing or potential species rich grassland swards.

Grassland – wet: These options are used for maintaining or restoring wet grasslands that already or could provide suitable habitat for wintering populations of wildfowl and waders. They should look to create a varied sward structure by the end of the growing season through grazing and/or cutting for hay with little or no winter grazing and poaching.

Upland unenclosed options (Table 4.2.1): often cover a large area of land but differ from lowland or those on enclosed land as an individual option may cover different underlying habitats, each with its own ecological importance. Management prescriptions and attributes are often associated with the habitat under the options rather than the option on its own. Upland unenclosed option scoring protocols (Appendix A5.7) were therefore clustered and written per broad habitat to reflect the importance of management for these habitats, in addition to generic option prescriptions and objectives. This meant that subsequent scoring would also reflect both management related to underlying habitat and overarching option aims.

Table 4.2.1 Table of upland options and code descriptions on unenclosed land surveyed for implementation 2018.

Upland unenclosed Options	Option code description
UP2	Management of rough grazing for birds
UP3	Management of moorland
EL6	Unenclosed moorland rough grazing
HL8	Creation of moorland
HL9	Maintenance of moorland
HL10	Restoration of moorland

4.3 Results

4.3.1 Coverage of options and option clusters

Implementation scoring was carried out on 394 examples of options within the eight lowland and enclosed upland option scoring clusters, and three upland unenclosed broad habitat types. Some additional surveys had been carried out, but where an option did not have sufficient replication within the dataset, scoring was not completed. Therefore, the following option list is not an exhaustive one of all options within the project survey squares. However, the options listed did cover, on average, 71% of all land under AES within a survey square. They cover a broad range of options and also are the most common options across the project that can be scored; other options within the original gradient scoring approach include supplements which cannot be scored for implementation.

Tables 4.3.1 – 4.3.3 show the option codes, option code descriptions, score cluster and the number of surveys for each from Countryside Stewardship (CS) and Environmental Stewardship (HLS and ELS). There are fewer CS options within the sample due to the distribution of agreements and age of agreements within the main project design.

Appendix A5.2 has detailed tables of the differences in the implementation of individual attributes within option clusters.

Table 4.3.1 Countryside Stewardship option codes, code description and implementation scoring cluster group and the number of examples of each surveyed for this project.

Option code	Option code description	Implementation score cluster	Number of implementation surveys
AB1	Nectar Flower mix	Floral	5
AB8	Flower-rich margins and plots	Floral	6
AB9	Winter bird food	Winter bird food	7
AB11	Cultivated areas for arable plants	Arable plant	2
BE3	Management of hedgerows	Hedgerow	3
BN5	Hedgerow laying/m	Hedgerow	1
GS13	Management of grassland for target features	Grassland - target feature	4
GS6	Management of species-rich grassland	Grassland - species rich	2
GS7	Restoration towards species-rich grassland	Grassland - species rich	4
SW1	4-6m buffer strip on cultivated land	Resource protection	20
SW3	In-field grass strips	Resource protection	2
	Total		**56**

Table 4.3.2 Environmental Stewardship option codes, implementation clusters and number of examples of each surveyed. Continued on next page.

Option code	Option code description	Implementation score cluster	Number of implementation surveys
EB10	Combined hedge and ditch management (incorporating EB3 Hedgerow management for landscape and wildlife)	Hedgerow	7
EB3	Hedgerow management for landscape and wildlife	Hedgerow	43
EB9	Combined hedge and ditch management (incorporating EB2 Hedgerow management for landscape)	Hedgerow	2
EE1	2 m buffer strips on cultivated land	Resource protection	6
EE12	Supplement to add wildflowers to field corners and buffer strips on cultivated land	Floral	5
EE3	6 m buffer strips on cultivated land	Resource protection	20
EE6	6 m buffer strips on intensive grassland	Resource protection	5
EE9	6 m buffer strips on cultivated land next to a watercourse	Resource protection	22
EF1	Management of field corners	Resource protection	16
EF2	Winter bird food	Winter bird food	3
EF4	Nectar Flower mix	Floral	6
EF7	Beetle banks	Resource protection	3
EF11	Uncropped cultivated margins for rare plants	Arable plants	5
HB11	Management of hedgerows of very high environmental value (both sides)	Hedgerow	5
HB12	Management of hedgerows of very high environmental value (one side)	Hedgerow	5
HE10	Flower rich margins	Floral	36
HE2	4 m buffer strips on cultivated land	Resource protection	4
HE3	6 m buffer strips on cultivated land	Resource protection	10
HF1	Management of field corners	Resource protection	1
HF4	Nectar Flower mix	Floral	11
HF7	Beetle banks	Resource protection	3
HF20	Cultivated fallow plots or margins for arable plants (rotational or non-rotational)	Arable plants	13
HF12	Winter bird food	Winter bird food	20

Option code	Option code description	Implementation score cluster	Number of implementation surveys
HK10	Maintenance of wet grassland for wintering waders and wildfowl	Grassland - wet	1
HK12	Restoration of wet grassland for wintering waders and wildfowl	Grassland - wet	4
HK15	Maintenance of grassland for target features	Grassland - target feature	8
HK6	Maintenance of species-rich, semi-natural grassland	Grassland - species rich	17
HK7	Restoration of species-rich, semi-natural grassland	Grassland - species rich	7
HK9	Maintenance of wet grassland for breeding waders	Grassland - target feature	1
OB9	Combined hedge and ditch	Hedgerow	2
OE2	4 m buffer strips on rotational land	Resource protection	1
OE3	6 m buffer strips on rotational land	Resource protection	2
OHE3	6 m buffer strips on rotational land	Resource protection	6
OHF4	Nectar Flower mix	Floral	5
	Total		**305**

Table 4.3.3 The number of implementation surveys completed and scored in unenclosed upland habitats.

Upland broad habitats	Number of implementation surveys
Acid grassland	17
Bog	10
Heathland	6
Total	**33**

Six unenclosed upland habitats were surveyed for implementation but only three had sufficient replication to be scored (there was only a single example of each of Fen Marsh Swamp, Calcareous grassland and Purple moor grass / rush pasture / Culm grassland habitats, and so they were not scored for implementation).

4.3.2 Lowland option clusters and enclosed upland option implementation scoring results

Across each option scoring cluster, there was a wide range of implementation scores, both within and between the option types (codes). Figure 4.3.1 shows the distribution of implementation scores across the option scoring clusters. The majority of parcels have scores above 0.5 and could be considered as being well-implemented following this scoring methodology. Nonetheless, there are still a few examples of less well implemented options in each of the scoring clusters, demonstrating that option implementation varied on the ground for each cluster of options, despite tightening and refinement of the scoring protocols.

Across the four lowland NCAs median implementation was similar (Figure 4.3.2). The upland NCAs are included in this figure as both had enclosed grassland options, but the majority of options in upland NCAs are covered by the unenclosed upland scoring protocols (Appendix A5.7).

Within each AES scoring cluster, there were variable levels of implementation (Figures 4.3.3 – 4.3.10). Median implementation scores of arable plants (Figure 4.3.3) and hedgerow options (Figure 4.3.7) were the greatest. Those options with targets that differ more between HLS agreements, depending on local targeting, did not score as well, e.g. grassland for target taxa. As these options are very much targeted at different taxa depending on local priorities, it is difficult to assess their delivery in a general sense, although the scoring protocol did include some multi-taxa attributes e.g. floral resources and structural components.

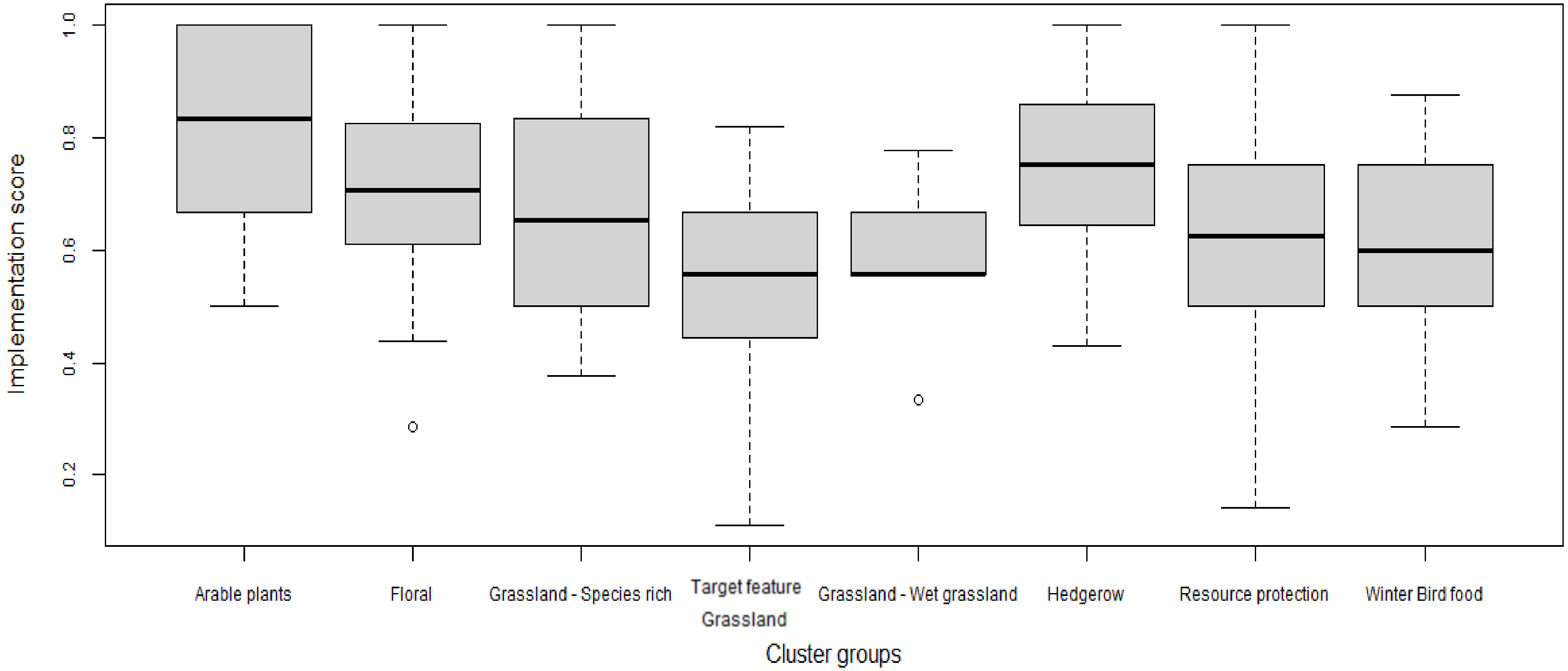

Figure 4.3.1 Variation in implementation score (median ± quartiles) for lowland option clusters, and enclosed upland options that were covered in these clusters. Implementation score is 0-1 with 1 being higher quality and better implemented. Number of parcels or patches surveyed varied between option clusters.

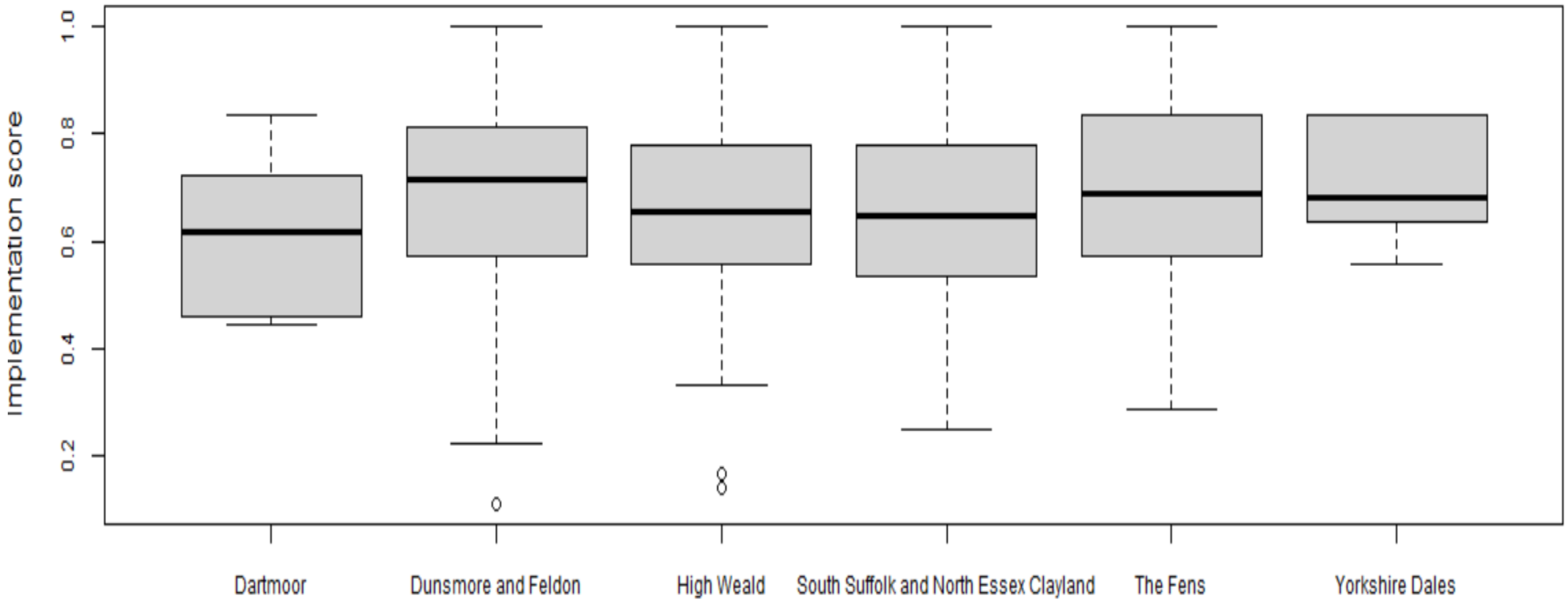

Figure 4.3.2 Variation in implementation score (median ± quartiles) between NCA's for lowland options and upland enclosed options. Implementation score is 0-1 with 1 being higher quality and better implemented. Number of parcels or patches surveyed varied between option clusters.

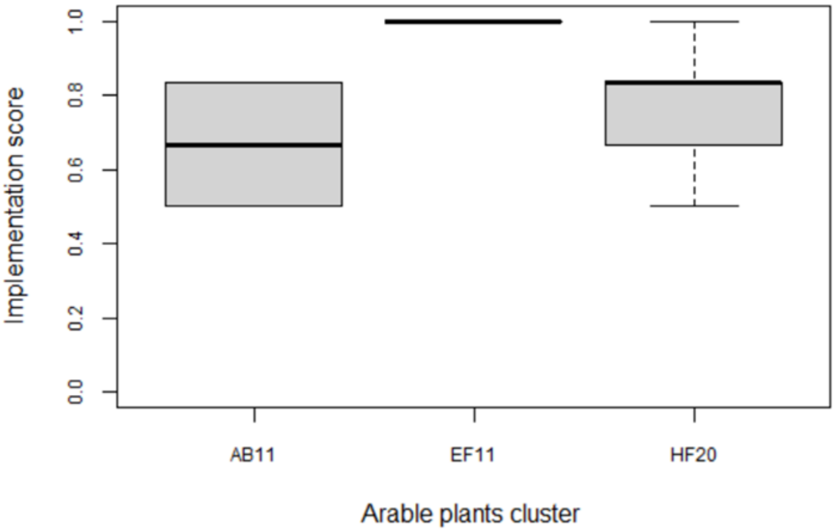

Figure 4.3.3 Implementation scores (median ± quartiles) at an option level for arable plant cluster, showing variation in scores for fields assessed. Implementation scores were scaled to be between 0 and 1. Option code descriptions are in Table 4.3.1- Table 4..

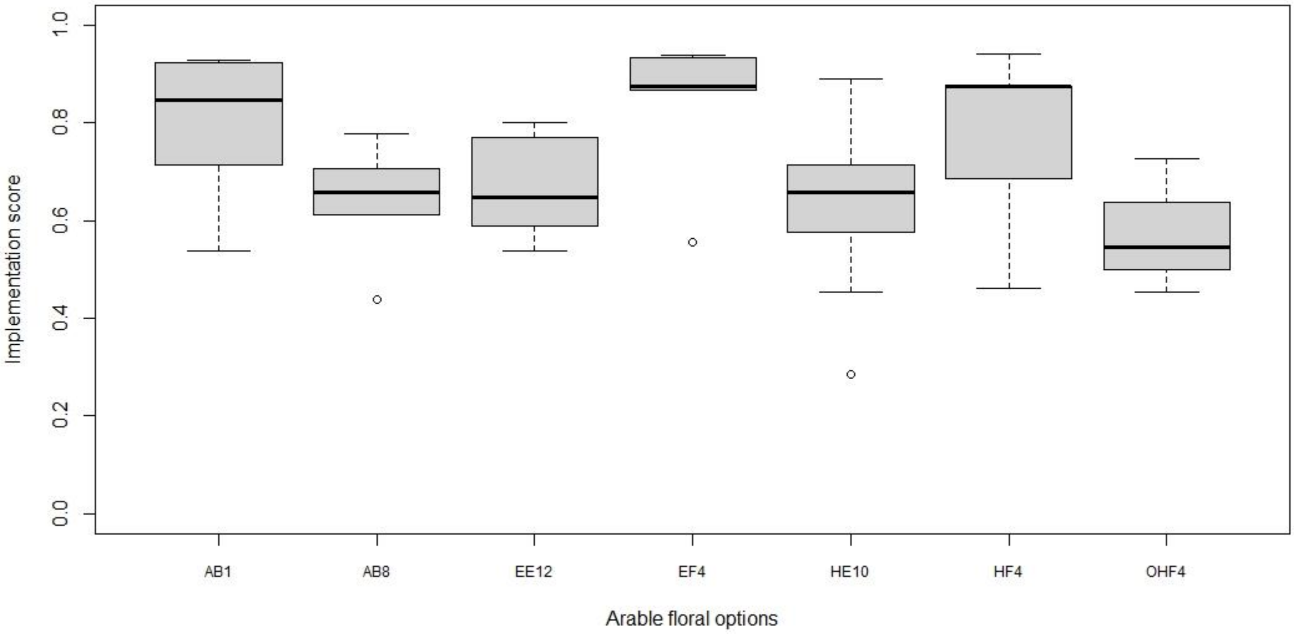

Figure 4.3.4 Implementation scores (median ± quartiles) at an option level for options within the arable floral cluster, showing variation in scores for fields assessed. Implementation scores were scaled to be between 0 and 1. Option code descriptions are in Tables 4.3.1 – 4.3.3.

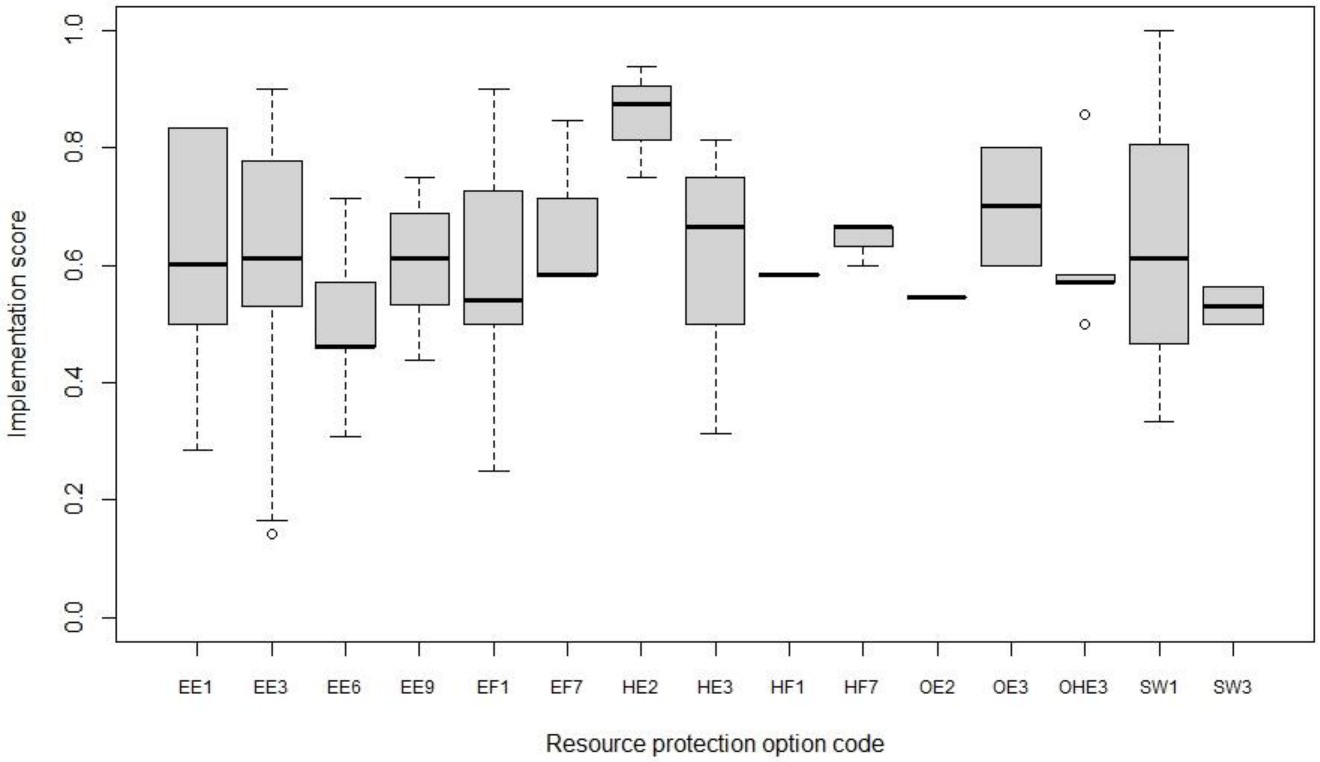

Figure 4.3.5 Implementation scores (median ± quartiles) at an option level for options within the resource protection cluster, showing variation in scores for fields assessed. Implementation scores were scaled to be between 0 and 1. Option code descriptions are in Tables 4.3.1 – 4.3.3.

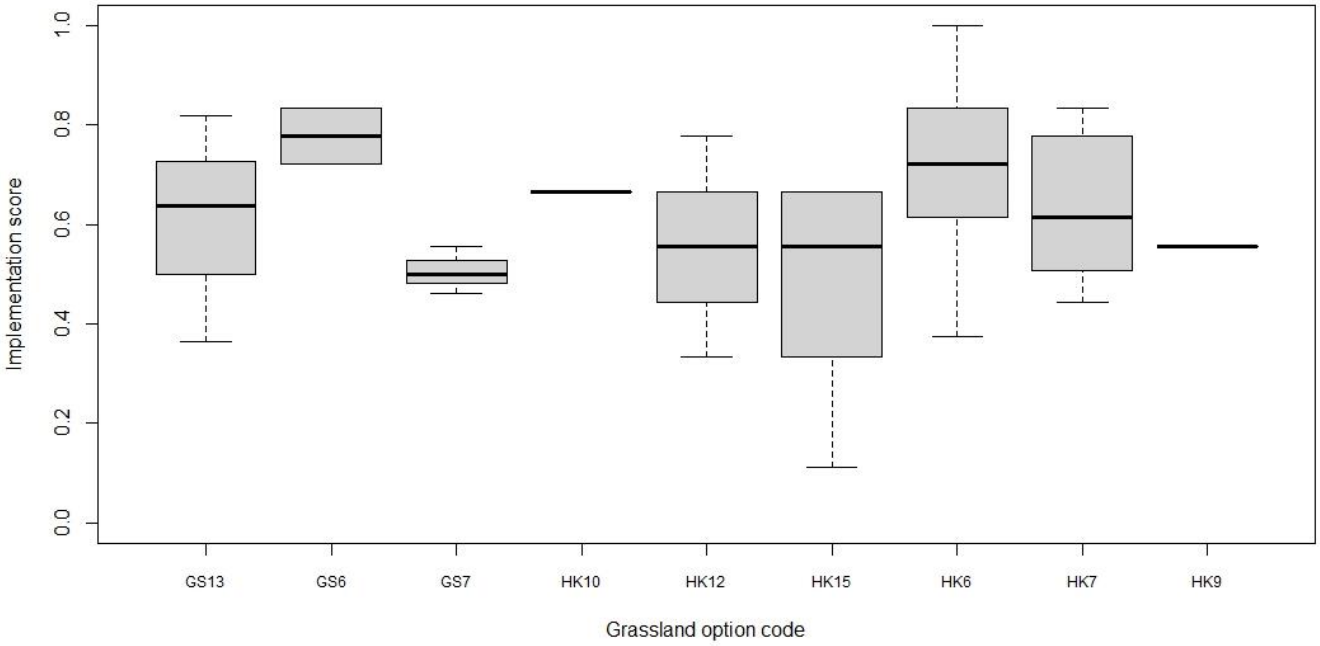

Figure 4.3.6 Implementation scores (median ± quartiles) at an option level for grassland options, including upland enclosed options showing variation in scores for fields assessed. Implementation scores were scaled to be between 0 and 1. Option code descriptions are in Tables 4.3.1 – 4.3.3.

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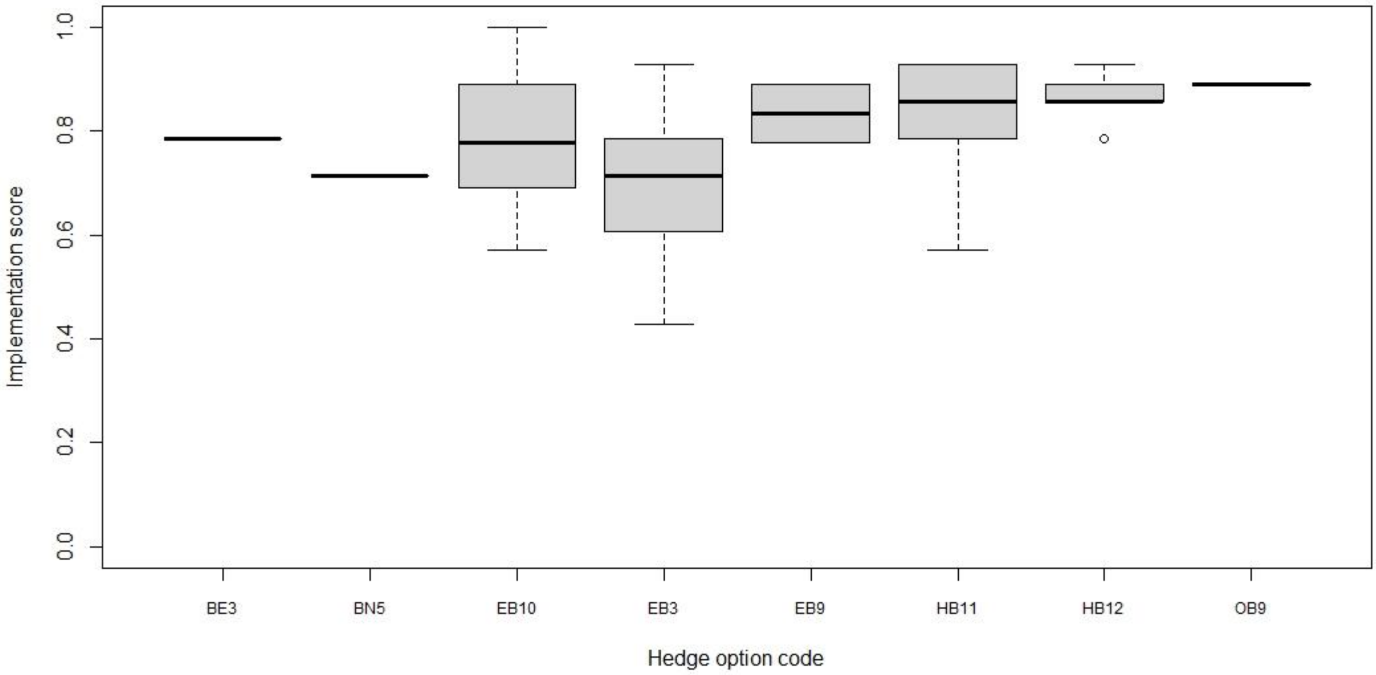


Figure 4.3.7 Implementation scores (median ± quartiles) at an option level for hedgerow options showing variation in scores for fields assessed. Implementation scores were scaled to be between 0 and 1. Option code descriptions are in Tables 4.3.1 – 4.3.3.

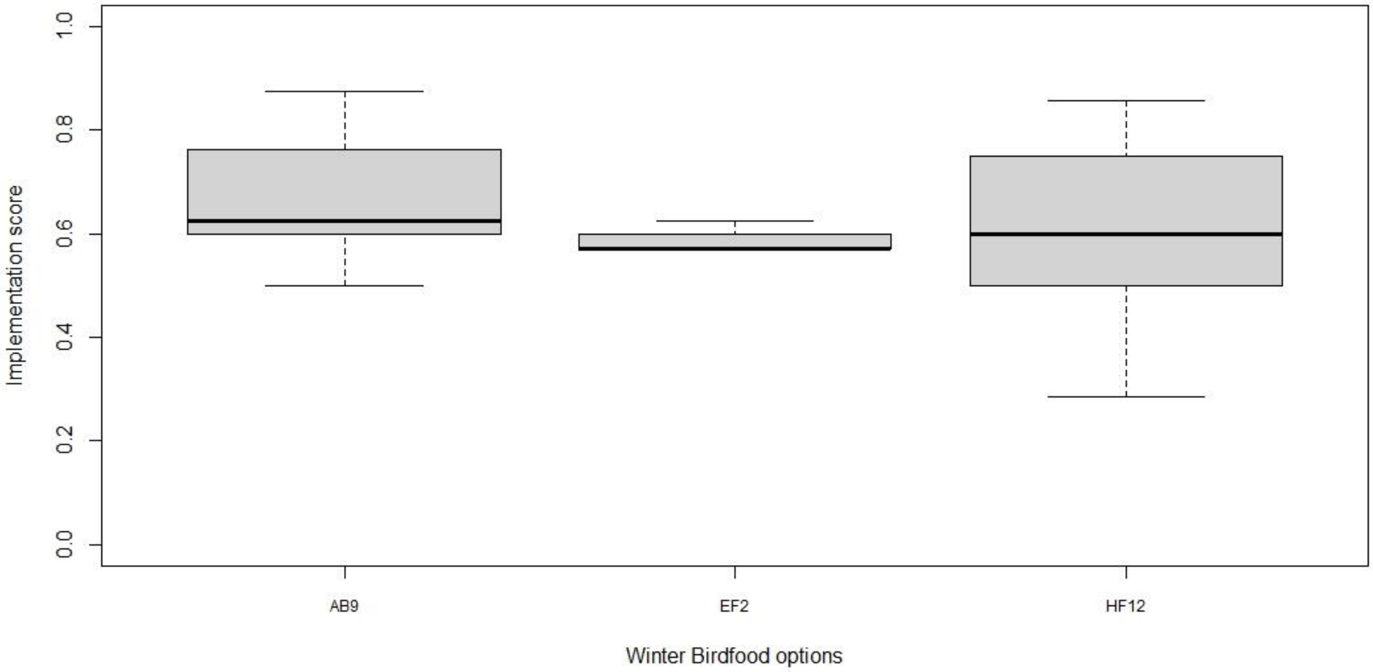


Figure 4.3.8 Implementation scores (median ± quartiles) at an option level for winter bird food options showing variation in scores for fields assessed. Implementation scores were scaled to be between 0 and 1. Option code descriptions are in Tables 4.3.1 – 4.3.3.

4.3.3 *Upland unenclosed option implementation scoring results – at broad habitat level*

Options on acid grassland had higher median implementation scores than bog or heath habitats (**Figure 4.3.**) with Option EL6 having higher median implementation score than other upland options across all habitats (Figure 4.3.). Whilst other options were included in the protocol, sufficient data were not available from the field survey to use in suitable manner for scoring.

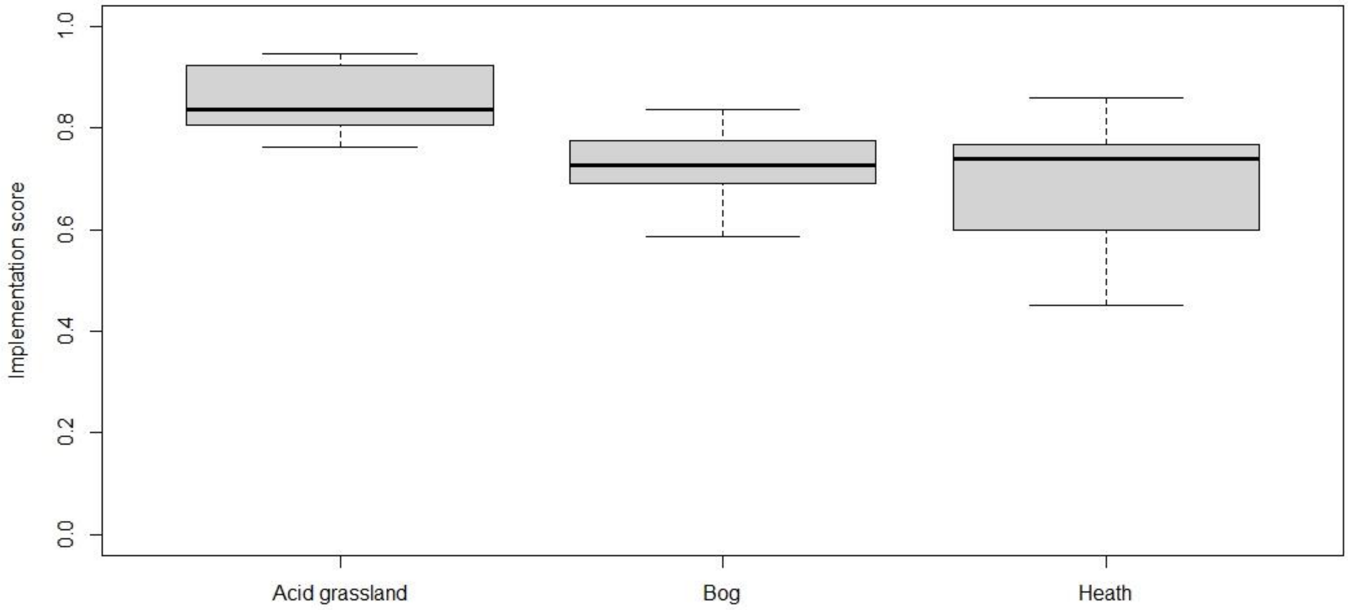


Figure 4.3.9 Implementation scores (median ± quartiles) for upland unenclosed habitats, showing variation in scores for fields under option assessed. Implementation scores were scaled to be between 0 and 1.

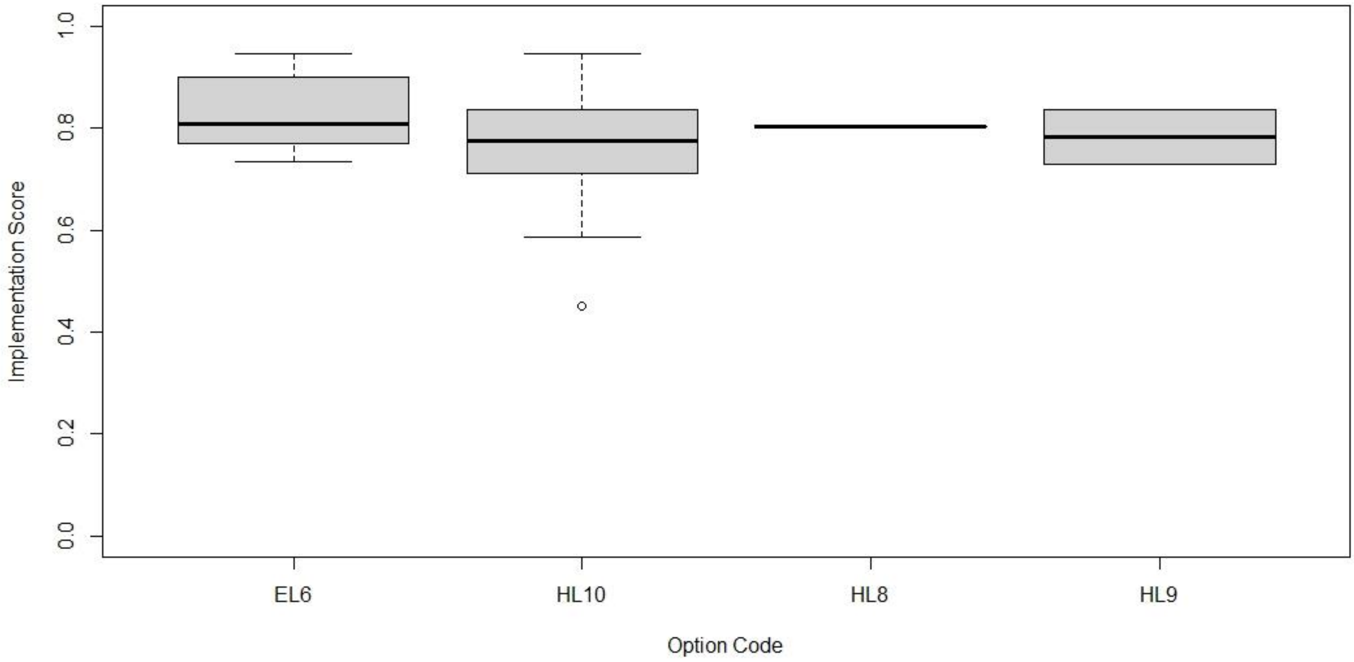


Figure 4.3.10 Implementation scores (median ± quartiles) for upland unenclosed options, showing variation in scores for fields assessed. Implementation scores were scaled to be between 0 and 1. Option code descriptions are in Table 4.2.1.

4.3.4 *Gradient analysis*

The aim of this work to determine how much the AES gradient values attributed to individual 1km sample squares would be altered by the inclusion of an assessment of the implementation of AES options. To achieve this, scores across multiple instances of one option code within a 1km survey square were averaged to give a single estimate of implementation score per option code at a square level. These were then weighted by the proportion of gradient value made up of that option within the square, to give an implementation weighted AES gradient value (Figure 4.3.11).

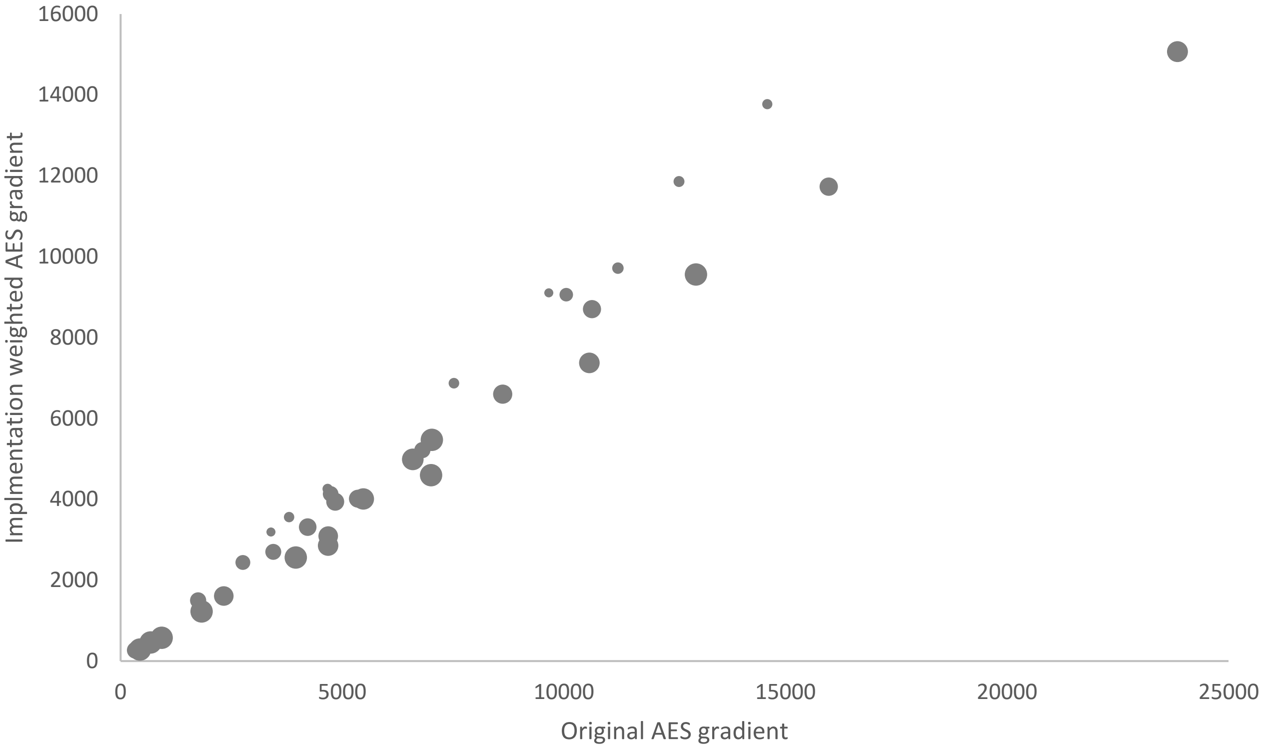


Figure 4.3.11 Implementation weighted AES gradient score against original AES gradient score calculated from field mapped options. Size of points is proportional to % AES score formed of implementation scored options (larger points have more options that have been scored up to max of 100%).

The majority of survey squares had similar scores for the original AES gradient and the implementation-weighted AES gradient, at the 1km square scale (Figure 4.3.11). For those squares where gradient scores do differ, implementation weighted AES gradients are consistently slightly lower than the original AES gradients, as expected given not all options were perfectly implemented. The relative positions of survey squares along the original AES gradient are hardly changed when the average implementation of options in each survey square is factored into the gradient calculation. This suggests that the widely variable option implementation found for individual option parcels does not scale up to variable implementation at the scale of the whole survey square, thus there is no evidence of systematic bias in the gradient. Due to this relationship, final analyses of mobile taxa responses have used the mapped AES gradient (Section 3), with no weighting for option implementation.

5 Results – mobile taxa responses at survey square scale to AES local and landscape gradients

5.1 Summary across taxa

Results for the responses of each taxon to the local and landscape AES gradient effects, using the analytical approach described in Section 2.6.2, are presented in detail in Sections 5.2 – 5.7 below. This includes response variables calculated across a whole taxon (e.g. total butterfly abundance, total moth species richness), described in the sections below as ‘headline responses’, and the more detailed analyses of trait groupings and abundance of individual species that vary between the taxa.

In order to enable comparisons to be made across the taxa, Table 5.1.1 below presents a summary of the results from Sections 5.2 – 5.7. Positive relationships in Table 5.1.1 (‘+’) are those where an increase in the AES gradient score resulted in an increase in the response variable (e.g. butterfly abundance increased as the landscape AES gradient score increased).

Evidence for a main effect of one or both AES gradients (or a covariate) is only described as ‘strong’ in Table 5.1.1 where $P \leq 0.01$, in order to avoid placing excessive confidence on results that may be due to chance (Section 2.6.3). Weaker evidence of possible effects of AES gradients are included in Table 5.1.1, but given the large number of models fitted in this project, some of these results with weak evidence are likely to have occurred by chance (Section 2.6.3). Note that strong / weak refers to the strength of evidence for the relationship tested (e.g. between local AES gradient and butterfly species richness), not the strength of the relationship itself. Variable refers to differences in strength of evidence between two or more of the more detailed responses (functional group or species abundance).

Table 5.1.1 does not include a column for the effects of the interaction between the local and landscape AES gradient but does indicate the taxa for which evidence of an interaction were found. Full details of any interactions between the two AES gradients are in Sections 2.2 – 2.7 below, including graphs of the interaction effects (e.g. Figure 5.5.1).

Table 5.1.1 Summary of taxon responses to main effects of local and landscape AES gradients, and to covariates (habitat and plant variables). SR = species richness, div. = diversity. S = section in Chapter 5 below with full details of results.

Taxon / response group	Local AES gradient effect	Landscape AES gradient effect	Covariate effects?	
			Habitats	**Plants**
Butterfly headline responses	No	+, strong (abundance, S5.2)	+, weak (habitat div., S5.2.3)	+, strong (plant div. & % graminoids S5.2.3)
Butterfly trait groups	+, strong (one group: low mobility species, lowland only, S5.2.4)	+, variable (several groups including Red list species, S5.4.2)		
Bumblebee transects headline responses	No	No	+, strong (woodland area, woody linear length, S5.3.1.3)	+, strong (plant div. & floral abundance, S5.3.1.3)
Bumblebee trait groups transects	+, weak (summer species, lowlands only, S5.3.1.4)	+/-, weak (summer and cuckoo species, lowlands only, S5.3.1.4)		
Bee headline responses pan traps	No	No	+/-, strong (habitat div., mass-flowering crops, woodland, S5.3.2.3)	+, strong (plant div., S5.3.2.3)
Bee trait groups pan traps	-, weak (parasitic species only, S5.3.3)	No		
Hoverfly headline responses	No	No	+, strong (arable area, S5.4.3)	+, weak (% graminoids S5.4.3)
Hoverfly trait groups	No	+, variable (SR and abundance more mobile species, detritivore larvae, S5.4.4)		
Moth headline responses *	+, variable (SR, div. and abundance, lowlands only, S5.5.2)	+, weak (SR, lowlands only)	+, strong (habitat div., woody linear length, S5.5.3.2)	+, strong, (plant div., % graminoids, S5.5.3.1)
Macro-moth headline responses	+, weak (SR, abundance, S5.5.2)	+, weak (SR, div. S5.5.2)	+/-, variable (habitat div., woody linear length)	+, strong (plant div., % graminoids)
Micro-moth headline responses *	+, variable (SR, S5.5.2)	No	+/-, variable (habitat div., water linear feature length)	+, strong (plant div., % graminoids)
Moth trait groups *	+, variable (several groups inc. low mobility, oligophagous)	+, weak (medium and high mobility species, multivoltine, S5.5.4)		

* taxon / response group also showed one or more responses to the interaction between local and landscape AES (interaction effects not summarised in Table 5.1.1).

Table 5.1.1 continued Summary of taxon responses to main effects of local and landscape AES gradients, and to covariates (habitat and plant variables). SR = species richness, div. = diversity. S = section in Chapter 5 below with full details of results. FBI = farmland bird index.

Taxon / response group	Local AES gradient effect	Landscape AES gradient effect	Covariate effects?	
			Habitats	Plants
Breeding bird headline responses	+, weak (SR, lowland only, S5.6.1.2)	No	+, variable (habitat div., woodland, improved grassland, S5.6.1.2)	
Breeding bird trait groups *	+, weak (invertebrate feeder abundance, seed feeder abundance)	No	+/-, variable (habitat div., woodland, all NCAs, S5.6.1)	
Breeding bird FBI species abundance	+, weak (Reed Bunting, S5.6.1.4)	-, variable (Goldfinch, Yellow Wagtail, S5.6.1.4)	+/-, strong (habitat div., mainly +ve, one species -ve)	
Winter bird headline responses *	+, weak (abundance, lowland only, S5.6.2.2)	No	+, variable (habitat div., improved grassland)	
Winter bird trait groups *	No	No	+, strong (habitat div., improved grassland, S5.6.2)	
Winter bird FBI species abundance *	+, variable (Reed Bunting, Starling, S5.6.2.4)	-, weak (Greenfinch, S5.6.2.4)	+, strong (habitat div., some species, S5.6.2.4)	
Bat headline responses [1]	No	No	+, variable (habitat div., S2.7.3)	+, strong (plant SR, S2.7.3)
Bat species presence-absence* [1]	No	+, strong (Barbastelle, Daubenton's, S2.7.2)	strong (habitat div., S2.7.3)	strong (plant SR, S2.7.3)

* taxon / response group also showed one or more responses to the interaction between local and landscape AES (interaction effects not summarised in Table 5.1.1).

[1] Bat data were analysed twice in relation to AES gradient effects, first with data aggregated per year and survey square (as for other taxa), and secondly with data per survey night per square. Results from analyses of bat data aggregated per year (as for the other taxa) are summarised above. Results from bar data aggregated per survey night are in Appendix A6.

5.2 Butterflies

5.2.1 *Summary of butterfly surveys*

We observed a total of 66,056 butterflies across four survey years, with the highest counts of butterflies recorded in 2019 when 19,792 butterflies were recorded. We recorded 35 unique species across the four years of survey, with the highest richness (33 species) recorded in 2018. For a full list of all species recorded see Appendix A7.1.

Table 5.2.1 Total numbers of butterfly individuals and species seen in each survey year

	2017	**2018**	**2019**	**2021**
Total number of butterflies seen	11,732	18,413	19,792	16,119
Number of butterfly species observed	27	33	31	32

Butterfly species richness per survey square varied between NCAs, with lowest absolute richness in the uplands (Figure 5.2.1). This might be expected, given that the butterfly species pool is smaller in some upland regions.

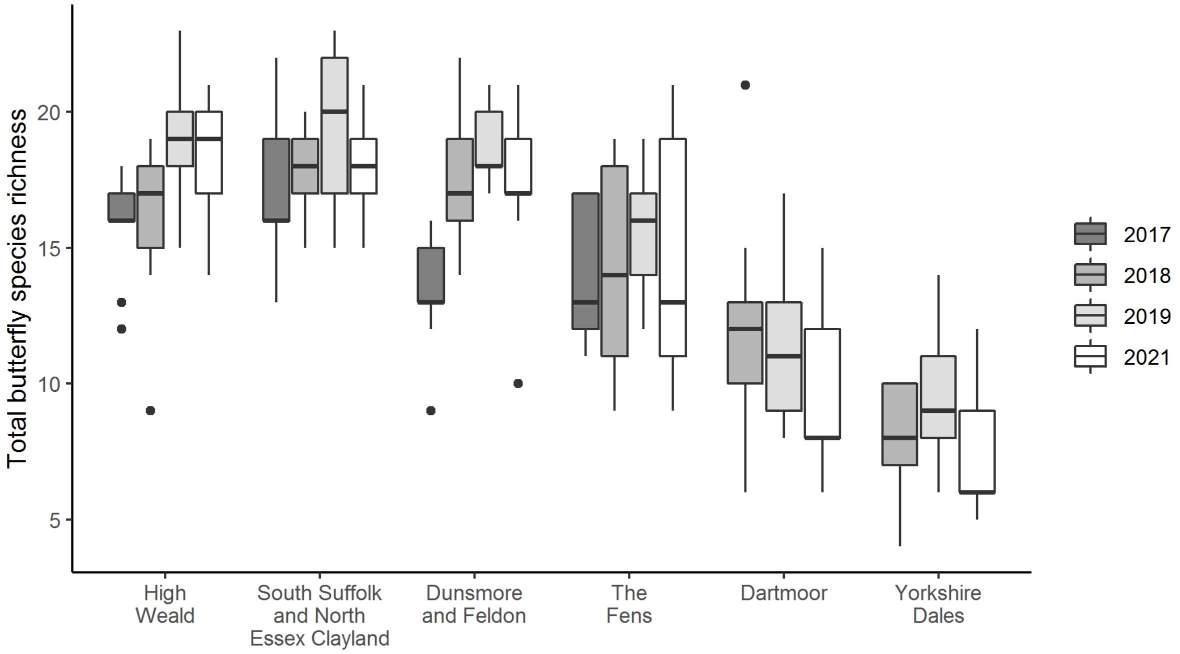


Figure 5.2.1 Variation in butterfly species richness between NCA and survey year.

5.2.2 Are there relationships between butterflies and AES gradients?

Table 5.2.2 Relationships between headline butterfly responses and AES gradient scores, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Butterfly species richness	0.017 (0.026) $P = 0.514$	0.015 (0.025) $P = 0.560$	-0.018 (0.026) $P = 0.501$
	Butterfly diversity	0.047 (0.038) $P = 0.217$	0.026 (0.036) $P = 0.478$	-0.041 (0.033) $P = 0.209$
	Butterfly abundance	-0.016 (0.064) $P = 0.798$	**0.161 (0.062)** $\mathbf{P = 0.009}$	0.017 (0.056) $P = 0.768$
Lowland NCAs only	Butterfly species richness	0.026 (0.029) $P = 0.361$	0.024 (0.029) $P = 0.409$	-0.013 (0.033) $P = 0.690$
	Butterfly diversity	0.068 (0.051) $P = 0.185$	0.01 (0.051) $P = 0.842$	-0.065 (0.054) $P = 0.237$
	Butterfly abundance	0.113 (0.066) $P = 0.089$	0.052 (0.067) $P = 0.444$	-0.103 (0.071) $P = 0.150$

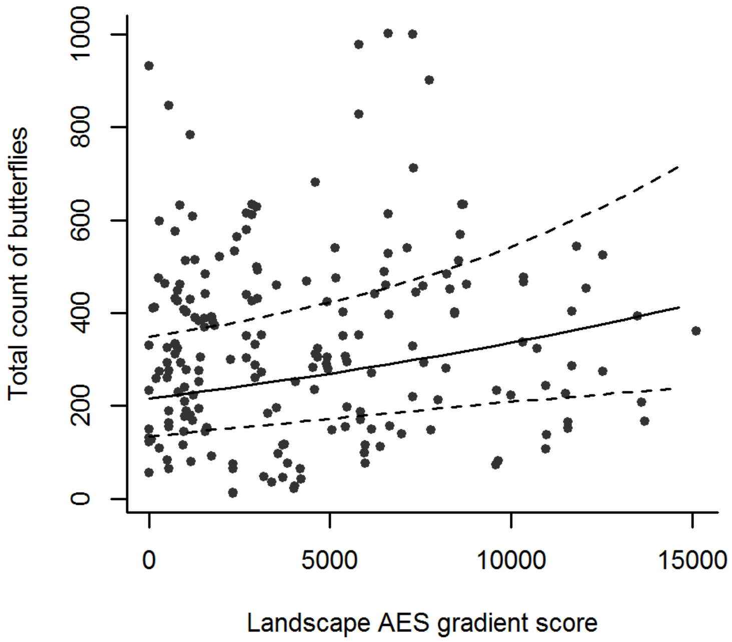
5.2.2.1 Butterfly richness and diversity

No relationships were observed between either butterfly richness or butterfly diversity and AES gradients. This was the case both in the analysis of data from all six NCAs and when only lowland NCAs were analysed (Table 5.2.2).

5.2.2.2 Butterfly abundance

A positive relationship was observed between the total abundance of butterflies and the landscape (3 x 3 km) AES gradient (Figure 5.2.2; Table 5.2.2). However, this relationship was only observed if the analysis included data from all NCAs surveyed, and not if only lowland NCAs were analysed (Figure 5.2.2). Fewer butterflies overall were recorded in upland NCAs (Figure 5.2.3).

The estimated relationship suggests that for an increase in landscape AES gradient score from 250 to 10,000, we would expect an average increase across NCAs of 117 butterflies, a 53% increase. However, the confidence intervals shown in Figure 5.2.2 reflect substantial uncertainty around the actual numbers of butterflies expected so much smaller or much higher differences could occur. These average abundances are across all four survey rounds per year, for the whole square (for each round of butterfly survey, approximately 2km of transect length was surveyed per 1km square, see Section 2.2.1).



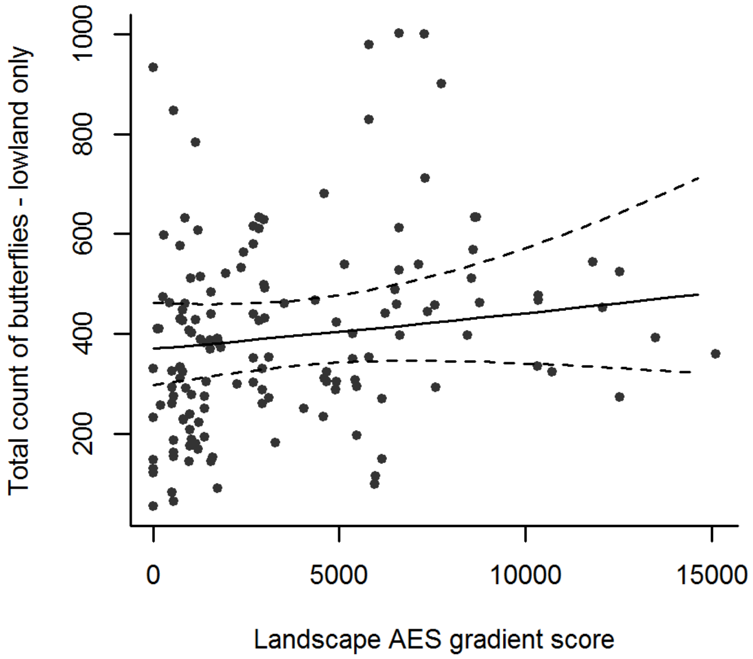


Figure 5.2.2 Relationships between total butterfly abundance and landscape gradient scores across all four survey years in all NCAs (n = 198) and in lowland NCAs only (n = 144). The fitted line indicates the estimated slope of the relationship, with confidence intervals around this slope indicated by dotted lines. There is strong evidence of a relationship with landscape level AES in all NCAs, but not in lowlands only analysis.

5.2.3 Do non-AES covariates explain butterfly responses?

The addition of the three plant community variables (Table 5.2.3) and the four habitat variables (Table 5.2.4) in the models did not change the broad relationships with the AES gradients for butterfly response variables.

5.2.3.1 Do plant communities affect butterfly responses?

Table 5.2.3 Relationships between butterfly responses and vegetation variables, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Botanical diversity**	**Percentage graminoids**	**Floral resources**
All NCAs	Butterfly species richness	**0.413 (0.082)** ***P* < 0.001**	-0.008 (0.031) *P* = 0.803	0.028 (0.024) *P* = 0.233
	Butterfly diversity	0.210 (0.129) *P* = 0.110	-0.099 (0.047) *P* = 0.038	0.037 (0.026) *P* = 0.154
	Butterfly abundance	**1.107 (0.21)** ***P* < 0.001**	0.109 (0.077) *P* = 0.156	0.079 (0.038) *P* = 0.038
Lowland NCAs only	Butterfly species richness	**0.404 (0.093)** ***P* < 0.001**	0.011 (0.036) *P* = 0.763	0.017 (0.024) *P* = 0.496
	Butterfly diversity	0.161 (0.175) *P* = 0.363	**-0.204 (0.069)** ***P* = 0.006**	0.065 (0.031) *P* = 0.039
	Butterfly abundance	**0.899 (0.212)** ***P* < 0.001**	**0.28 (0.085)** ***P* = 0.001**	-0.003 (0.042) *P* = 0.935

Butterfly species richness and abundance were strongly positively linked to total botanical diversity (Table 5.2.3). There was evidence that percentage graminoids was positively linked to butterfly abundance and negatively linked to butterfly diversity in lowland NCAs.

5.2.3.2 Does habitat affect butterfly responses?

No habitat effects were found on butterfly abundance (Table 5.2.4). For habitat diversity, there was weak evidence of a positive relationship with butterfly species richness, both in analyses of all data and of lowland NCA only data.

There were more strong correlations between habitat variables in the lowland only data, than when all data were analysed together (see Section A.4.2.1 for details). Due to this, care must be taken in interpreting relationships with habitat diversity in the lowland only data, as it is strongly correlated with both the area of woodland and the length of hedgerows per survey square. It is not possible to separate the effects of these three habitat variables in the lowland only analyses.

Table 5.2.4 Relationships between butterfly responses and habitat variables, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Habitat diversity**	**Total woodland**	**Length of woody linear features**	**Length of water linear features**
All NCA	Butterfly species richness	0.226 (0.094) *P* = 0.016	-0.133 (0.391) *P* = 0.733	0.072 (0.037) *P* = 0.049	-0.058 (0.028) *P* = 0.040
	Butterfly diversity	0.280 (0.143) *P* = 0.054	1.001 (0.621) *P* = 0.113	-0.077 (0.059) *P* = 0.199	-0.074 (0.048) *P* = 0.128
	Butterfly abundance	0.216 (0.254) *P* = 0.396	-1.646 (1.152) *P* = 0.153	0.198 (0.109) *P* = 0.069	-0.078 (0.09) *P* = 0.383
Lowland NCAs only	Butterfly species richness	0.304 (0.132) P = 0.021	-	-	0.028 (0.054) P = 0.604
	Butterfly diversity	0.22 (0.168) P = 0.197	-	-	-0.083 (0.058) P = 0.158
	Butterfly abundance	0.304 (0.132) P = 0.021	-	-	0.028 (0.054) P = 0.604

5.2.4 Do relationships vary between butterfly trait groups?

No relationships between AES and species richness or diversity were observed in any of the butterfly trait groups studied. For those trait groups with some evidence of a relationship between abundance and the AES gradients, trends towards positive relationships with the landscape AES gradient were demonstrated that were broadly similar to the relationship for total butterfly abundance (Table 5.2.5). The exception was for abundance of butterfly species with relatively low mobility, for which a positive relationship with the local AES gradient was found for lowland NCA data only. Further detail of the butterfly trait group results is given in the subsections below.

Table 5.2.5 Relationships between abundance of butterfly trait groups and AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Abundance response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Crop pest butterflies	0.027 (0.103) *P* = 0.79	-0.027 (0.087) *P* = 0.753	-0.155 (0.098) *P* = 0.114
	Non-crop pest butterflies	-0.009 (0.067) *P* = 0.89	**0.201 (0.064)** ***P* = 0.002**	0.04 (0.057) *P* = 0.483
	Early butterflies	-0.057 (0.067) *P* = 0.392	0.126 (0.067) *P* = 0.06	-0.121 (0.065) *P* = 0.062
	Summer butterflies	-0.021 (0.079) *P* = 0.79	0.14 (0.075) *P* = 0.063	0.104 (0.064) *P* = 0.101
	Butterflies with forb larval hosts	-0.018 (0.072) *P* = 0.805	0.114 (0.072) *P* = 0.114	-0.132 (0.069) *P* = 0.053
	Butterflies with grass larval hosts	-0.015 (0.079) *P* = 0.855	0.159 (0.076) *P* = 0.036	0.092 (0.065) *P* = 0.158
	Butterflies with low host breath	0.116 (0.074) *P* = 0.12	0.112 (0.073) *P* = 0.122	-0.116 (0.071) *P* = 0.102
	Butterflies with high host breadth	-0.026 (0.07) *P* = 0.712	0.157 (0.067) *P* = 0.02	0.02 (0.061) *P* = 0.735
	Butterflies with low mobility	0.154 (0.101) *P* = 0.127	0.122 (0.092) *P* = 0.185	-0.03 (0.087) *P* = 0.73
	Butterflies with medium mobility	-0.022 (0.067) *P* = 0.742	0.157 (0.065) *P* = 0.016	-0.027 (0.061) *P* = 0.663
	Butterflies with high mobility	0.068 (0.084) *P* = 0.416	0.184 (0.082) *P* = 0.025	-0.135 (0.079) *P* = 0.087
	Wider countryside butterflies	-0.02 (0.065) *P* = 0.764	0.159 (0.063) *P* = 0.011	0.018 (0.057) *P* = 0.748
	Red list butterflies	-0.076 (0.169) *P* = 0.652	0.347 (0.145) *P* = 0.017	0.118 (0.111) *P* = 0.284
Lowland NCAs only	Crop pest butterflies	0.057 (0.117) *P* = 0.63	-0.036 (0.097) *P* = 0.712	-0.172 (0.117) *P* = 0.143
	Non-crop pest butterflies	0.149 (0.075) *P* = 0.046	0.071 (0.076) *P* = 0.351	-0.101 (0.078) *P* = 0.192
	Early butterflies	0.029 (0.073) *P* = 0.695	0.01 (0.074) *P* = 0.992	-0.191 (0.086) *P* = 0.026
	Summer butterflies	0.16 (0.094) *P* = 0.089	0.005 (0.094) *P* = 0.956	-0.073 (0.094) *P* = 0.441
	Butterflies with forb larval hosts	0.061 (0.077) *P* = 0.432	-0.029 (0.079) *P* = 0.712	-0.209 (0.091) *P* = 0.022
	Butterflies with grass larval hosts	0.168 (0.094) *P* = 0.073	0.021 (0.094) *P* = 0.822	-0.084 (0.095) *P* = 0.375
	Butterflies with low host breath	0.183 (0.084) *P* = 0.029	0.046 (0.084) *P* = 0.584	-0.162 (0.095) *P* = 0.087
	Butterflies with high host breadth	0.107 (0.073) *P* = 0.144	0.051 (0.076) *P* = 0.499	-0.103 (0.079) *P* = 0.194
	Butterflies with low mobility	**0.339 (0.117)** ***P* = 0.004**	-0.047 (0.118) *P* = 0.691	-0.286 (0.128) *P* = 0.025
	Butterflies with medium mobility	0.095 (0.07) *P* = 0.177	0.06 (0.073) *P* = 0.412	-0.086 (0.076) *P* = 0.255
	Butterflies with high mobility	0.08 (0.087) *P* = 0.353	0.119 (0.085) *P* = 0.164	-0.15 (0.099) *P* = 0.13
	Wider countryside butterflies	0.115 (0.067) *P* = 0.087	0.05 (0.069) *P* = 0.472	-0.105 (0.073) *P* = 0.15

5.2.4.1 Crop pests vs non-crop pests

Total abundance of non-crop pest butterfly species showed the same positive relationship with the landscape AES gradient as all butterflies and there was strong evidence of a relationship with $P < 0.01$. No relationships with AES gradients were seen when abundance of the two crop pest species (*Pieris brassicae* and *P. rapae*) were analysed separately.

5.2.4.2 Early vs summer butterflies

No relationships were observed with AES gradients for either early or late subsets of butterflies. There was an indication of a possible interaction effect between AES gradients for early butterflies if lowlands only were analysed, which was not found for late butterflies.

5.2.4.3 Butterflies with forb vs grass larval hosts

There were no strong relationships with AES gradients (at $P < 0.01$) observed when butterflies were split by larval host type. There was an indication of a possible interaction effect for butterflies with forb larval hosts in lowlands.

5.2.4.4 Butterflies with high vs low host breadth

There was no strong evidence of relationships at $P < 0.01$. There was some indication, however, that butterfly species with low host breadth were positively related to the local scale AES gradient, whereas those with high host breadth were potentially related to the landscape AES gradient.

5.2.4.5 Butterflies with low, medium or high mobility

There was a clear indication that, in contrast to the relationships observed with all butterflies, when only the abundance of those butterfly species in the low mobility group were analysed a relationship with the local scale AES gradient was observed, although this was only seen in lowland NCAs (Figure 5.2.3). No strong evidence of relationships was found for medium or high mobility taxa, but there were possible indications ($P < 0.03$) that both responded to the landscape AES gradient across all NCAs.

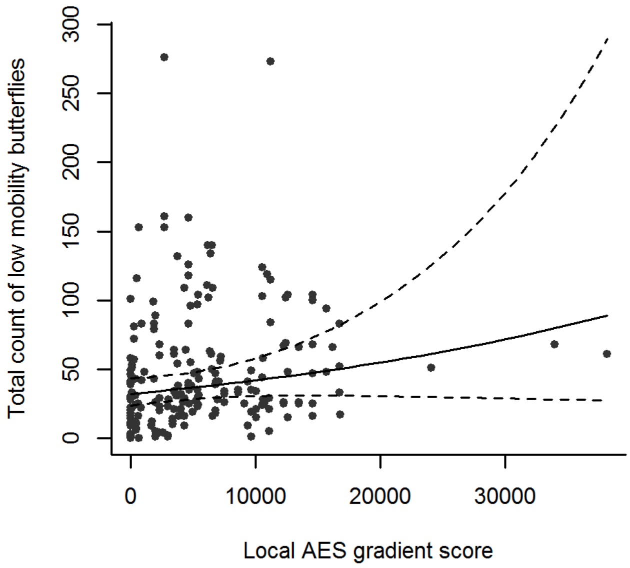


Figure 5.2.3 Relationship between abundance of low mobility butterflies and the local AES gradient score across all four survey years but including only lowland NCAs (n = 144). The fitted line indicates the estimated slope of the relationship, with confidence intervals around this slope indicated by dotted lines. There is strong evidence of a relationship with local level AES at $P < 0.01$.

5.2.4.6 Wider countryside vs specialist butterflies

The abundance of wider countryside butterflies followed the same pattern as all butterflies across all NCAs, with moderate evidence of a relationship with the landscape AES gradient. There were not sufficient data to model the abundance of habitat specialist butterflies.

5.2.4.7 Red list butterflies

Ten red list butterfly species were recorded on the LandSpAES project. The most common red list butterfly species recorded were Small Heath (*Coenonympha pamphilus*) with 3,146 individuals, and Dark Green Fritillary (*Speyeria aglaja*) with 238 individuals. Fewer than 30 individuals were recorded for each of the other red list butterflies.

There was weak evidence of a positive relationship between the landscape AES gradient and red list butterflies (Figure 5.2.4) across all NCAs (Table 5.2.5). There were not sufficient data to analyse lowland red list butterfly abundance separately.

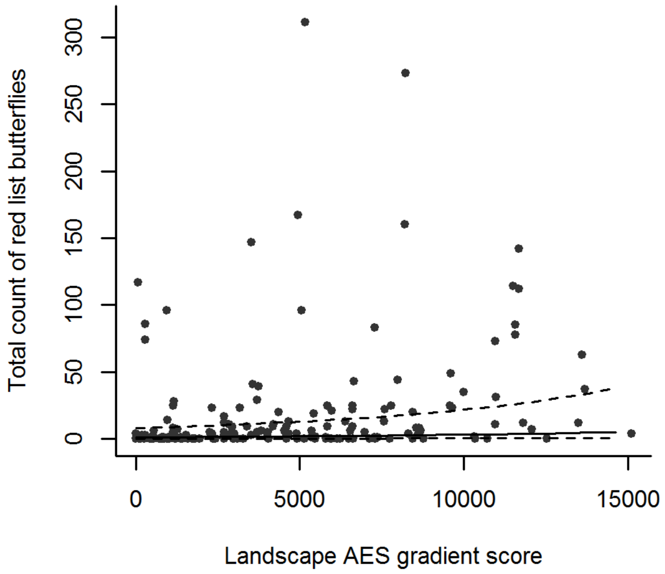


Figure 5.2.4 Relationship between abundance of red list butterflies and the landscape AES gradient score across all four survey years (n = 198). The fitted line indicates the estimated slope of the relationship, with confidence intervals around this slope indicated by dotted lines. There is some evidence for a positive relationship with landscape level AES.

5.2.5 Summary and discussion of butterfly results

The abundance of all butterfly species surveyed on the LandSpAES project showed a strong, positive relationship with the landscape (3 × 3km) AES gradient, when data from all NCAs were analysed. This suggests that the presence of AES options within the landscape is having a positive effect on butterfly abundance. This relationship with the landscape AES gradient was also found for butterfly abundance once two crop pest species were removed. There was weaker evidence for similar relationships for the abundance of several trait groupings of butterfly species: species with red list status, larger species of high or medium mobility, multivoltine species, wider countryside generalist species and species with a high larval host breadth (i.e. larvae feed on three or more core host plant species). These last three trait groups are all indicative of the more generalist butterfly species. Butterfly species in these more generalist groups seem to be responding more to the landscape AES gradient, similar to the abundance of all butterflies. The response of red list butterfly abundance is likely to have been driven by Small Heath (*Coenonympha pamphilus*), which made up 91% of the total red list butterfly abundance.

There were indications that two butterfly trait groupings responded differently to the AES gradients. Total abundance of the smaller, less mobile butterfly species showed strong evidence for a positive relationship with the local, $1km^2$ AES gradient when data were analysed from lowland NCAs, but no relationship with the landscape gradient, as might be expected given their mobility and likely flight distances. Total abundance of the butterfly species with more specialist larvae (those that feed on just one or two core host plant species) also showed weak evidence for a positive relationship with the local AES gradient.

The species richness and diversity of butterflies were not related to AES gradients in any analyses, and appear to be driven more by plant diversity and habitat. Both these sets of covariates were largely independent of the AES gradients (Section 3.3).

Butterfly species richness and total butterfly abundance had strong, positive relationships with the diversity of higher plants, both in the analyses of all NCAs and of lowland NCAs. This suggests that some additional, rarer butterfly species were recorded in squares with higher plant diversity, but the butterfly abundance was still dominated by more common species (as there no relationship was found between plant diversity and butterfly diversity). Butterfly diversity had a strong, negative relationship with the percentage of graminoids, which indicates that the presence of more forbs may support a more diverse butterfly assemblage.

There was weak evidence of a positive effect of habitat diversity on butterfly species richness, in both analyses of all NCAs and of lowland NCAs. In lowland NCAs habitat diversity was strongly positively correlated with the length of hedgerows (woody linear features), area of semi-natural habitat and area of woodland (Section 3.4). Thus, to improve lowland agricultural land for butterfly diversity, there needs to be a greater diversity of habitats including areas of semi-natural habitat and woody linear features.

5.3 Bees

5.3.1 Bumblebees (transects)

5.3.1.1 Summary of bumblebee transect surveys

We observed a total of 39,646 bumblebees along transects across four years of survey. The largest number of bumblebees was observed in 2017 with 11,550 bees seen, despite only 36 out of 54 survey squares sampled that year. Bumblebee counts were lowest in 2018 with only 7,897 bees seen across 54 squares. The BeeWalks monitoring scheme found a similar national pattern of reduced bumblebee abundance in 2018, likely driven by an unusually cold early spring followed by a summer heatwave (Comont and Miles, 2019).

A total of 19 bumblebee species were seen across the four years, with 2018 being the most species rich survey (17 unique species) despite fewer bees being seen overall. A full list of species observed in each year is found in Appendix A7.2.

Table 5.3.1 Summary of bumblebee individuals and unique species seen per year.

	2017	2018	2019	2021
Total number of bumblebees seen	11,550	7,897	9,524	10,675
Number of bumblebee species observed	15	17	15	16

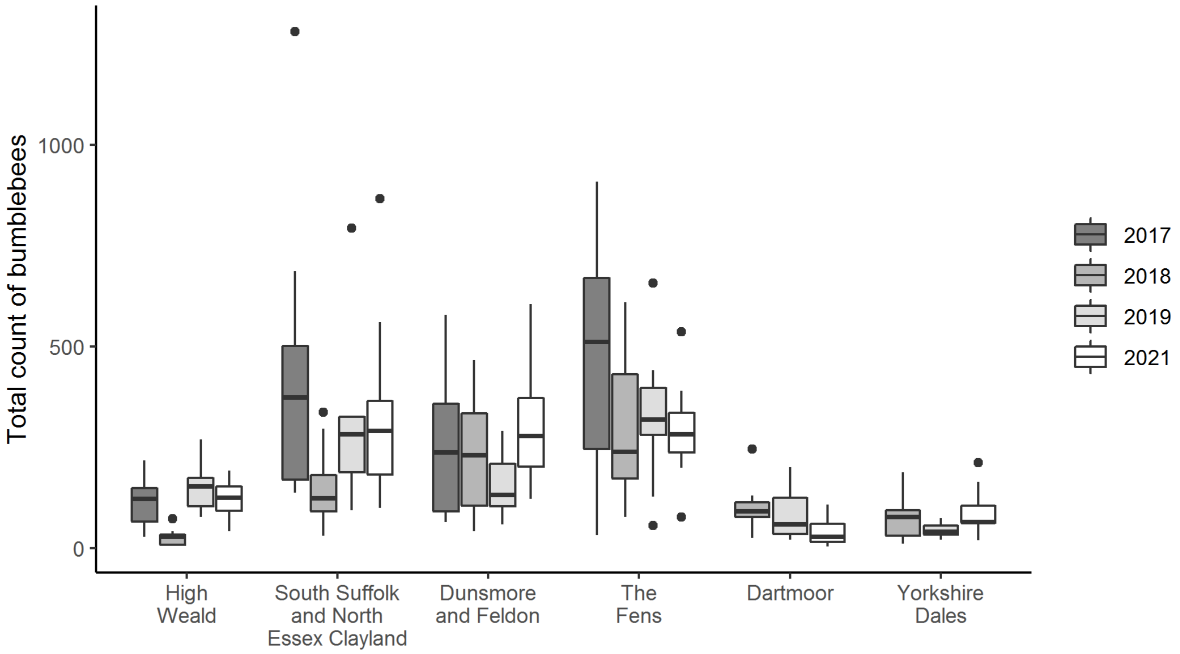


Figure 5.3.1 Variation in bumblebee abundance observed on transects between survey year and NCA.

Fewer bumblebees were observed in the two upland NCAs, and the High Weald also had lower numbers of bees observed compared to the three other lowland NCAs (Figure 5.3.1).

5.3.1.2 Are there relationships between bumblebees observed on transects and AES gradients?

No relationships were observed between overall bumblebee richness, diversity or abundance and either the local or landscape AES gradients (Table 5.3.2).

Table 5.3.2 Relationships between bumblebee responses (observed on transects) and AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Bumblebee species richness	0.027 (0.036) $P = 0.461$	-0.042 (0.036) $P = 0.239$	-0.069 (0.038) $P = 0.067$
	Bumblebee diversity	0.032 (0.074) $P = 0.663$	-0.106 (0.07) $P = 0.136$	-0.134 (0.067) $P = 0.049$
	Bumblebee abundance	0.039 (0.086) $P = 0.652$	0.01 (0.083) $P = 0.907$	-0.067 (0.08) $P = 0.400$
Lowland NCAs only	Bumblebee species richness	0.035 (0.04) $P = 0.381$	-0.031 (0.041) $P = 0.443$	-0.059 (0.047) $P = 0.205$
	Bumblebee diversity	0.032 (0.073) $P = 0.666$	-0.053 (0.073) $P = 0.467$	-0.087 (0.084) $P = 0.306$
	Bumblebee abundance	0.164 (0.1) $P = 0.102$	-0.105 (0.1) $P = 0.291$	-0.206 (0.11) $P = 0.060$

5.3.1.3 Do non-AES covariates explain responses?

The addition of the three plant community variables (Table 5.3.3) and the five habitat variables (Table 5.3.4) in the models did not change the broad relationships with the AES gradients for bumblebee response variables.

5.3.1.3.1 Do plant communities affect bumblebee responses?

There was strong evidence that the total number of bumblebees observed on transects was positively related to the botanical diversity within survey squares in both all NCA and lowland only analyses. There was strong evidence that the amount of floral resource had an impact only when all NCAs were included in analysis (Table 5.3.3), although there was also weaker evidence for this relationship in lowland analysis. No relationships were seen with bumblebee richness or diversity, or with the percentage cover of graminoids.

Table 5.3.3 Relationships between bumblebee responses and the vegetation surveyed in survey squares, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Botanical diversity**	**Percentage graminoids**	**Floral resource abundance**
All NCAs	Bumblebee species richness	0.204 (0.114) $P = 0.075$	-0.016 (0.043) $P = 0.705$	0.065 (0.034) $P = 0.054$
	Bumblebee diversity	0.334 (0.25) $P = 0.189$	0.007 (0.091) $P = 0.937$	0.079 (0.058) $P = 0.174$
	Bumblebee abundance	**0.844 (0.203)** **$P < 0.001$**	0.011 (0.073) $P = 0.885$	**0.267 (0.06)** **$P < 0.001$**
Lowland NCAs only	Bumblebee species richness	0.058 (0.155) $P = 0.710$	0.019 (0.062) $P = 0.761$	0.097 (0.045) $P = 0.033$
	Bumblebee diversity	0.334 (0.274) $P = 0.231$	0.000 (0.107) $P = 1.00$	0.061 (0.069) $P = 0.378$
	Bumblebee abundance	**0.979 (0.301)** **$P = 0.001$**	0.013 (0.117) $P = 0.910$	0.182 (0.074) $P = 0.015$

5.3.1.3.2 Does habitat affect bumblebee responses?

Table 5.3.4 Relationships between bumblebee responses and habitat variables, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Habitat diversity**	**Area of mass flowering crops**	**Total woodland**	**Length of woody linear features**	**Length of water linear features**
All NCA	Bumblebee species richness	0.022 (0.14) $P = 0.876$	0.27 (0.233) $P = 0.247$	0.708 (0.574) $P = 0.218$	0.087 (0.054) $P = 0.111$	0.017 (0.040) $P = 0.677$
	Bumblebee diversity	-0.208 (0.24) $P = 0.391$	0.637 (0.362) $P = 0.080$	**3.41 (1.004)** **$P = 0.001$**	**0.317 (0.096)** **$P = 0.002$**	0.036 (0.075) $P = 0.634$
	Bumblebee abundance	0.176 (0.327) $P = 0.591$	0.326 (0.404) $P = 0.420$	0.739 (1.347) $P = 0.583$	0.152 (0.126) $P = 0.229$	-0.067 (0.107) $P = 0.529$
Lowland NCAs only	Bumblebee species richness	**-0.238 (0.087)** **$P = 0.006$**	0.158 (0.226) $P = 0.485$	-	-	0.001 (0.03) $P = 0.969$
	Bumblebee diversity	-0.214 (0.244) $P = 0.389$	0.338 (0.365) $P = 0.356$	-	-	-0.038 (0.078) $P = 0.627$
	Bumblebee abundance	-0.044 (0.58) $P = 0.939$	0.17 (0.362) $P = 0.639$	-	-	-0.093 (0.124) $P = 0.453$

There was strong evidence that bumblebee diversity was positively related to total area of woodland and length of woody linear features, in analyses of data across all NCAs (Table 5.3.4). There was also evidence of a negative relationship between richness and habitat diversity in the lowland NCAs. It was not possible to include woodland area and woody linear feature length in analyses of lowland only data, due to their strong correlations with habitat diversity. Thus, from the analyses of lowland only data, it is not possible to attribute these apparent habitat diversity relationships with any confidence to habitat diversity itself, as one of the other correlated habitat variables may be driving these relationships.

5.3.1.4 Do relationships vary between trait groups?

No relationships were observed between AES gradients and either bumblebee richness or diversity for any trait group.

There was good evidence of an interaction between local and landscape AES gradients in relation to the abundance of summer bumblebees (bumblebee species with flight period that start from May onwards), in analyses of lowland NCA data (Table 5.3.5 and Section 5.3.1.4.2). A similar relationship was found in analyses of all NCA data, but the evidence for this was not as strong.

Table 5.3.5 Relationships between abundance of bumblebee trait groups and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Abundance response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Cuckoo bumblebees	0.059 (0.165) P = 0.721	-0.316 (0.166) P = 0.057	-0.242 (0.177) P = 0.172
	Social bumblebees	0.047 (0.094) P = 0.615	0.003 (0.09) P = 0.972	-0.079 (0.085) P = 0.356
	Early bumblebees	0.039 (0.093) P = 0.671	0.007 (0.09) P = 0.939	-0.073 (0.084) P = 0.386
	Summer bumblebees	0.205 (0.224) P = 0.360	-0.293 (0.222) P = 0.187	-0.571 (0.245) P = 0.020
	Low mobility bumblebees	0.099 (0.106) P = 0.349	-0.048 (0.103) P = 0.644	-0.196 (0.094) P = 0.036
	High mobility bumblebees	0.048 (0.096) P = 0.622	-0.028 (0.093) P = 0.768	-0.074 (0.089) P = 0.403
	Short tongue length bumblebees	-0.019 (0.084) P = 0.818	-0.021 (0.081) P = 0.794	-0.066 (0.077) P = 0.395
	Mid tongue length bumblebees	0.149 (0.163) P = 0.362	0.032 (0.162) P = 0.844	-0.097 (0.15) P = 0.518
	Long tongue length bumblebees	0.036 (0.112) P = 0.747	-0.05 (0.108) P = 0.647	-0.211 (0.104) P = 0.042
	Univoltine bumblebees	0.021 (0.104) P = 0.842	0.069 (0.101) P = 0.495	-0.026 (0.094) P = 0.784
	Multivoltine bumblebees	-0.028 (0.098) P = 0.776	-0.133 (0.093) P = 0.155	-0.096 (0.1) P = 0.336
Lowland NCAs only	Cuckoo bumblebees	0.201 (0.186) P = 0.279	-0.439 (0.187) P = 0.019	-0.319 (0.21) P = 0.129
	Social bumblebees	0.171 (0.103) P = 0.097	-0.109 (0.102) P = 0.284	-0.197 (0.113) P = 0.080
	Early bumblebees	0.162 (0.102) P = 0.111	-0.108 (0.101) P = 0.284	-0.19 (0.111) P = 0.086
	Summer bumblebees	0.498 (0.231) P = 0.031	-0.48 (0.238) P = 0.044	**-0.73 (0.267)** **P = 0.006**
	Low mobility bumblebees	0.149 (0.112) P = 0.184	-0.086 (0.114) P = 0.454	-0.184 (0.117) P = 0.117
	High mobility bumblebees	0.182 (0.109) P = 0.093	-0.166 (0.107) P = 0.122	-0.228 (0.121) P = 0.061
	Short tongue length bumblebees	0.067 (0.092) P = 0.464	-0.111 (0.09) P = 0.220	-0.159 (0.103) P = 0.121
	Mid tongue length bumblebees	0.333 (0.169) P = 0.049	-0.262 (0.172) P = 0.128	-0.287 (0.195) P = 0.140
	Long tongue length bumblebees	0.127 (0.116) P = 0.275	-0.101 (0.119) P = 0.393	-0.241 (0.122) P = 0.047
	Univoltine bumblebees	0.189 (0.119) P = 0.112	-0.103 (0.118) P = 0.381	-0.185 (0.128) P = 0.148
	Multivoltine bumblebees	-0.03 (0.094) P = 0.746	-0.141 (0.089) P = 0.114	-0.038 (0.109) P = 0.731

5.3.1.4.1 Cuckoo vs social bumblebees

Abundance of social bumblebees showed no relationships with AES gradients. The abundance of cuckoo bumblebees did not show any relationships with strong evidence at $P < 0.01$ but there was a trend towards a negative relationship between the abundance of cuckoo bumblebees and the landscape scale AES gradient (Table 5.3.5).

5.3.1.4.2 Early vs summer bumblebees

Early bumblebees (species with flight periods that start in April or earlier) showed no relationships with AES gradients. There was evidence of an interaction between local and landscape AES gradients observed for summer bees in the lowland NCA analysis (Figure 5.3.2; Table 5.3.5). This suggested that at low levels of landscape AES, there was a more positive relationship with local AES and vice versa. However, note the high levels of uncertainty and relatively low number of summer bumblebees seen, which suggest this relationship should be interpreted with caution.

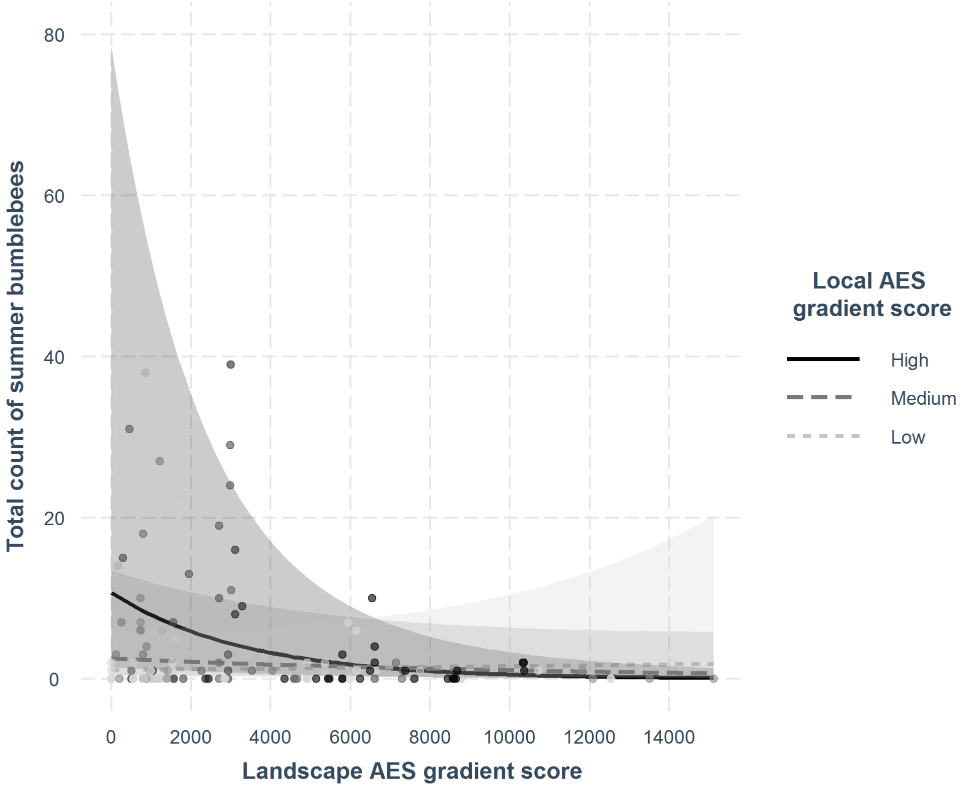


Figure 5.3.2 Interaction plot demonstrating the interactive effects of local (1km) and landscape (3km) AES gradient score on summer bumblebee abundance. Each line demonstrates the estimated relationship between summer bumblebee abundance and local level (1km) AES gradient score for three levels of landscape level (3km) AES gradient score. The three levels of local AES category are derived from the mean value of the three terciles derived splitting the data into three equal parts. Points are shaded in relation to their local AES score, with darker points indicating higher score. 95% confidence intervals around the estimated lines are shown but differences between slopes have not been formally tested.

5.3.1.4.3 Low vs high mobility bumblebees

There was a possible indication of an interaction effect for low mobility bees in the all NCA analysis, however there was only moderate evidence for this in the all NCA analysis and no evidence in the lowland only analysis.

5.3.1.4.4 Bumblebees with low, medium or long tongue length

No differences were observed between abundance responses of different tongue length groups with no strong evidence of relationships of any trait group with the AES gradients.

5.3.1.4.5 Univoltine vs multivoltine bumblebees

There was no evidence that abundance of either univoltine or multivoltine bees responded to the AES gradients.

5.3.2 Bees (pan traps)

5.3.2.1 Summary of total bee pan trap survey

We observed a total of 11,593 bees in pan traps across four years of survey. This figure does not include honeybees which were excluded from all analyses as their numbers will be largely determined by beekeeping activities (Section 2.5.1.2). The largest number of bees was observed in 2019 with 3,759 bees caught (Table 5.3.6). A total of 139 species of bee were seen across the four years, with 2019 being the most species rich survey. Across all four years solitary bees comprised 75% of bees caught, with the remaining 25% being bumblebees.

Solitary bees comprised the majority of species richness, with 117 species of solitary bee recorded and 19 species of bumblebee, plus three aggregate groupings. Two bumblebee species were identified from pan traps and not in the transect surveys: *Bombus cryptarum* (cryptic white-tailed bumblebee) and *B. magnus* (Northern white-tailed bumblebee). Both *B. cryptarum* and *B. magnus* are difficult to distinguish from *B. lucorum*, and only queens and males of these species can be distinguished from specimens. Queens of these species were observed during transect surveys in the uplands, but due to the difficulty in reliably separating the species surveyors were instructed to record all three as *B. lucorum* sensu lato (or for workers the lucorum/terrestris aggregate). One bumblebee species (*B. ruderarius*) was recorded in low numbers on transects but not in pan traps.

A full list of species observed in each year is in Appendix A7.3.

Table 5.3.6 Summary of total bee, solitary bee and bumblebee individuals and unique species seen per year in pan traps.

	2017	**2018**	**2019**	**2021**
Total number of bees	2,512	2,627	3,759	2,695
Total number of solitary bees	1,858	1,938	2,903	1,938
Total number of bumblebees	654	689	856	757
Number of bee species observed	75	108	112	104
Number of solitary bee species	61	88	91	85
Number of bumblebee species	13	18	18	16

Counts of bees were variable between NCAs and years, with generally lower numbers recorded in the Yorkshire Dales (Figure 5.3.3).

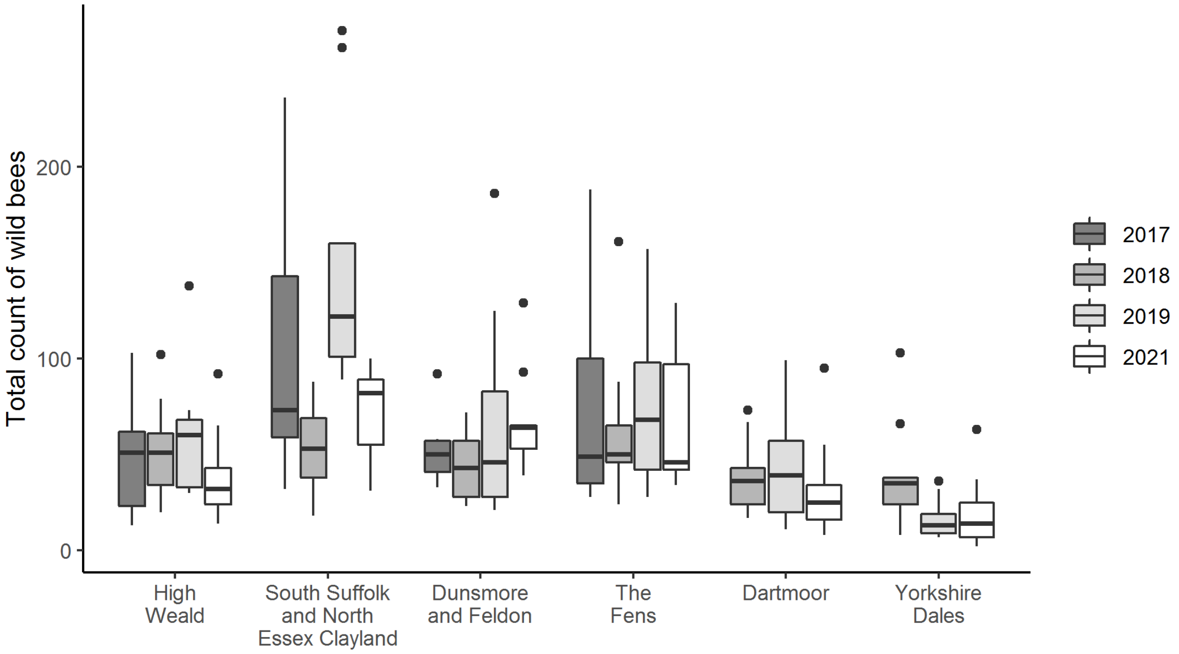


Figure 5.3.3 Variation in total bee numbers from pan traps between NCAs and survey years.

5.3.2.2 Are there relationships between bees and AES gradients?

No relationships between AES gradients and richness, diversity or abundance responses were seen for either all bees, solitary bees or bumblebees from pan traps.

5.3.2.3 Do non-AES covariates explain responses?

The addition of the four plant community variables (Table 5.3.7) and the five habitat variables (Table 5.3.8) in the models did not change the broad relationships with the AES gradients for bee response variables.

5.3.2.3.1 Are bee responses explained by plant variables?

Botanical diversity had a positive effect on total bee abundance across all NCAs, but there was less evidence for this relationship if only lowland NCAs are considered (Table 5.3.7). There was also some evidence of a positive relationship between bee richness and botanical diversity, strongest in the lowland NCAs. We included the abundance of both floral resources recorded in transects and those recorded around pan traps as predictors, but neither showed any relationship with bee responses (Table 5.3.7).

Once solitary bee and bumblebees were separated there was weak evidence of a relationship between abundance and botanical diversity for both groups, suggesting they may both respond positively to botanical diversity.

Table 5.3.7 Relationships between responses for all bees in pan traps and the vegetation surveyed in survey squares, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Botanical diversity**	**Percentage graminoids**	**Floral resources - transects**	**Floral resources – pan traps**
All NCAs	Bee species richness	0.332 (0.130) *P* = 0.011	0.013 (0.049) *P* = 0.793	0.000 (0.030) *P* = 0.988	0.002 (0.029) *P* = 0.931
	Bee diversity	0.469 (0.564) P = 0.410	0.081 (0.205) *P* = 0.693	0.148 (0.153) *P* = 0.334	0.004 (0.128) P = 0.978
	Bee abundance	**0.644 (0.217)** ***P* = 0.003**	0.067 (0.081) *P* = 0.404	0.044 (0.054) *P* = 0.808	-0.042 (0.048) *P* = 0.383
Lowland NCAs only	Bee species richness	**0.379 (0.12)** ***P* = 0.002**	0.032 (0.047) *P* = 0.503	0.003 (0.029) *P* = 0.919	-0.014 (0.036) *P* = 0.700
	Bee diversity	1.305 (0.729) *P* = 0.083	0.176 (0.285) *P* = 0.542	0.204 (0.182) *P* = 0.264	-0.054 (0.204) *P* = 0.792
	Bee abundance	0.509 (0.276) *P* = 0.065	0.087 (0.112) *P* = 0.435	-0.011 (0.056) *P* = 0.847	-0.017 (0.062) *P* = 0.780

5.3.2.3.2 Does habitat affect pan trap bee responses?

Across all NCAs the strongest relationship observed was a negative relationship between the area of mass flowering crops and diversity of bees (Table 5.3.8). This relationship was also present in lowland only analysis, although the evidence for this was weaker. There was weak evidence for positive effects of area of mass flowering crops in bee abundance, and of habitat diversity on bee richness and diversity.

Table 5.3.8 Relationships between bee responses and habitat variables, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Habitat diversity**	**Area of mass flowering crops**	**Total woodland**	**Length of Woody linear features**	**Length of water linear features**
All NCA	Bee species richness	0.273 (0.135) *P* = 0.044	-0.094 (0.156) *P* = 0.548	1.066 (0.554) *P* = 0.054	0.05 (0.052) *P* = 0.337	-0.03 (0.042) *P* = 0.473
	Bee diversity	1.305 (0.571) *P* = 0.026	**-2.24 (0.837) *P* = 0.008**	3.373 (2.404) *P* = 0.167	-0.145 (0.228) *P* = 0.527	-0.121 (0.18) *P* = 0.506
	Bee abundance	0.164 (0.265) *P* = 0.537	0.632 (0.298) *P* = 0.034	1.169 (1.04) *P* = 0.261	0.114 (0.096) *P* = 0.235	-0.06 (0.08) *P* = 0.452
Lowland NCAs only	Bee species richness	0.004 (0.077) *P* = 0.955	-0.089 (0.155) *P* = 0.564	-	-	-0.049 (0.029) *P* = 0.092
	Bee diversity	1.271 (0.586) *P* = 0.038	-2.161 (0.884) *P* = 0.016	-	-	-0.111 (0.187) *P* = 0.558
	Bee abundance	-0.28 (0.144) *P* = 0.052	0.529 (0.255) *P* = 0.038	-	-	-0.142 (0.056) *P* = 0.011

When solitary bees were separated from bumblebees there were still some weak evidence of a negative relationship between bee diversity and mass flowering crop area, and of a positive relationship between solitary bee abundance and area of mass flowering crops (Table 5.3.9). There was also strong evidence of a positive relationship between solitary bee richness and total area of woodland. It was not possible to evaluate whether this relationship held in the lowland only analysis as we were unable to include total woodland in these analyses due to collinearity with habitat diversity. Across both all NCA and lowland only analyses there were indications that solitary bee responses were positively related to habitat diversity.

When bumblebees from pan traps were analysed we found strong evidence of a negative relationship between bumblebee species richness, diversity and abundance and habitat diversity in the lowlands only (Table 5.3.10). As discussed above, in the lowlands there were more strong correlations between habitat diversity and other habitat variables (including the total area of woodland and woody linear feature length). Thus, relationships found with ‘habitat diversity’ in the lowland only data could be driven by other, correlated habitat variables.

Table 5.3.9 Relationships between solitary bee responses and habitat variables, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Habitat diversity**	**Area of mass flowering crops**	**Total woodland**	**Length of woody linear features**	**Length of water linear features**
All NCA	Solitary bee species richness	0.465 (0.184) *P* = 0.011	-0.114 (0.186) *P* = 0.539	**1.922** **(0.75)** ***P* = 0.010**	0.037 (0.071) *P* = 0.603	-0.021 (0.058) *P* = 0.719
	Solitary bee diversity	**1.474** **(0.535)** ***P* = 0.008**	-1.953 (0.771) *P* = 0.012	5.474 (2.248) *P* = 0.018	-0.156 (0.214) *P* = 0.469	-0.122 (0.17) *P* = 0.477
	Solitary bee abundance	0.644 (0.375) *P* = 0.086	0.798 (0.334) *P* = 0.017	2.218 (1.561) *P* = 0.155	0.126 (0.15) *P* = 0.400	-0.026 (0.122) *P* = 0.831
Lowland NCAs only	Solitary bee species richness	0.14 (0.093) *P* = 0.130	-0.147 (0.183) *P* = 0.420	-	-	-0.08 (0.036) *P* = 0.024
	Solitary bee diversity	**1.662** **(0.55)** ***P* = 0.006**	-2.063 (0.847) *P* = 0.016	-	-	-0.16 (0.178) *P* = 0.375
	Solitary bee abundance	-0.043 (0.229) *P* = 0.852	0.615 (0.304) *P* = 0.043	-	-	-0.178 (0.088) *P* = 0.043

Table 5.3.10 Relationships between bumblebee responses (from pan traps) and habitat variables, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Habitat diversity**	**Area of mass flowering crops**	**Total woodland**	**Length of woody linear features**	**Length of water linear features**
All NCA	Bumblebee species richness	-0.204 (0.141) *P* = 0.148	0.02 (0.249) *P* = 0.935	-0.61 (0.659) *P* = 0.355	0.012 (0.053) *P* = 0.817	0.041 (0.033) *P* = 0.212
	Bumblebee diversity	-0.682 (0.437) *P* = 0.123	0.201 (0.705) *P* = 0.776	-2.525 (1.986) *P* = 0.209	0.174 (0.157) *P* = 0.275	0.157 (0.114) *P* = 0.178
	Bumblebee abundance	-0.248 (0.216) *P* = 0.253	0.151 (0.343) *P* = 0.66	-0.93 (1.006) *P* = 0.355	-0.123 (0.077) *P* = 0.112	0.048 (0.059) *P* = 0.414
Lowland NCAs only	Bumblebee species richness	**-0.374** **(0.108)** ***P* = 0.001**	-0.033 (0.272) *P* = 0.903	-	-	0.019 (0.035) *P* = 0.586
	Bumblebee diversity	**-1.028** **(0.357)** ***P* = 0.006**	0.051 (0.775) *P* = 0.948	-	-	0.091 (0.131) *P* = 0.493
	Bumblebee abundance	**-0.734** **(0.174)** ***P* < 0.001**	0.263 (0.309) *P* = 0.394	-	-	0.032 (0.067) *P* = 0.634

5.3.2.4 Do relationships vary between trait groups?

No evidence of relationships between any tested trait groupings for pan trap bees and AES gradients was found.

The only relationships observed that had some support were weak evidence for a negative effect of the local AES gradient on parasitic bees in all NCA and lowland only analysis (coefficient = -0.313, s.e. of coefficient = 0.127, $P = 0.013$ across all NCAs) and a possible negative effect of the landscape AES gradient on the abundance of dominant crop pollinators across all NCAs (coefficient = -0.175, s.e. of coefficient = 0.073, $P = 0.017$).

5.3.3 Summary and discussion of bee results

There was no strong evidence that either the local or the landscape AES gradients affected the abundance, species richness or diversity of bumblebees or solitary bees. Bumblebees were surveyed using two separate methods, transects and pan traps.

For transect counts of bumblebee species that first fly in May or later (‘summer bumblebees’), strong evidence (at $P < 0.01$) was found of the interaction between the two AES gradients, which suggests that the effect of the local AES gradient on summer bumblebee abundance was stronger where the landscape AES gradient score was lower. There were eight bumblebee species in this trait group, and total abundance was dominated by *Bombus ruderatus*, which made up made up 77% of the summer bumblebee abundance. This result does need to be interpreted with some caution, as there was only weak evidence of main effects of the two AES gradients. It has been suggested that bumblebee species which first fly earlier in spring may face a shortage of resources, which could potentially be filled by tailored AES options (Carvell et al., 2017). However, along the generalized AES gradients used here, there is some weak indication that it is the bumblebee species which first fly in May or later that may be benefitted by AES options currently.

There was also weak evidence of negative relationships between the landscape AES gradient and abundance of parasitic (cuckoo) bumblebee species on transects in lowland NCAs, and the local AES gradient and parasitic bee abundance from pan traps. Previous studies have shown that cuckoo bumblebees community metrics are driven by a range of factors, and may not respond to farming practices in the same way as their host bumblebees (Howard et al., preprint 2019). Parasitic bees, including cuckoos, may also respond more strongly to the density of their host bee’s nests, than to resource availability (for example abundance of flowers) or to host bee abundance.

Total abundance, species richness and diversity of all the bumblebee species on transects were found to relate more strongly to the plant and habitat covariates than they did to the AES gradients. The strongest relationships for bumblebee abundance on transects were positive relationships with both floral abundance and botanical diversity. This is similar to previous studies that have shown a strong link between bumblebee abundance and floral abundance (e.g. Pywell et al., 2011; Carvell et al., 2015; O’Connor et al., 2019). No relationship was found between the total abundance of floral resources within the survey square and the local AES gradient, which suggests that when data are aggregated across all options in a survey square, AES interventions are not delivering increased floral resources. Analyses of the option implementation data suggested that across the 1km square, implementation did not vary significantly enough to substantially change the local AES gradient scores, or the relative positions of squares along the gradient (Section 4.3.4). Details of the implementation assessment for the sown arable floristically enhanced margin options show that cover of sown species was frequently low (Appendix A5.2.1 and Table A5.2.2).

Pan trap surveys were included in this project to enable solitary bees and hoverflies to be surveyed, but pan traps also differ in the abundance and type of bumblebee species sampled, compared to transect bumblebee surveys. O'Connor et al. (2019) compared the two methods, and found that more bumblebees were sampled along transects, and that transect samples were more dominated by common bumblebee species than pan trap samples. On transects, 39,646 bumblebees were observed in the four years of LandSpAES fieldwork, and 2,965 bumblebees were collected in pan traps.

For total bees surveyed with pan traps, no strong (at $P < 0.01$) relationships were found with floral abundance, in contrast to the strong, positive relationship found for bumblebees on transects. There was strong evidence for a positive relationship between botanical diversity and total bee abundance, and weaker evidence for a positive relationship with species richness. O'Connor et al. (2019) found stronger, positive relationships between bumblebee abundance and the abundance of nectar resources when surveyed on transects, than on pan traps, in line with these results. Relationships between floral resources and pan trap bee abundance are more complex, and can in some contexts be negative (Wood et al., 2015), though no evidence of any negative relationships was found in the analyses of bee data reported here.

Weak evidence was found of a positive relationship between the total abundance of bees surveyed in pan traps and the area of mass-flowering crops in the 1km focal survey square. There was strong evidence of a negative relationship between bee diversity and area of mass-flowering crops, and no evidence of a relationship with bee species richness. This suggests that common bee species may be more abundant where there is more mass-flowering crop present. The solitary bees also showed evidence for positive relationships with habitat diversity, with strong evidence for bee diversity ($P < 0.01$, across all NCAs and in lowlands only) and weaker evidence for bee species richness (across all NCAs). Total woodland area also related positively to solitary bee species richness, across all NCAs.

For bumblebees in lowland NCAs only, there was strong evidence for negative relationships between habitat diversity and bumblebee species richness, diversity and abundance. However, as discussed above several other habitat variables correlated with habitat diversity in the lowlands, so habitat diversity effects cannot be separated from other habitat variables in lowland NCA analyses.

5.4 Hoverflies

5.4.1 Summary of hoverfly survey

We observed a total of 9,106 hoverflies across four years of survey. The largest number of hoverflies were seen in 2019. A total of 101 species of were seen across the four years, with the most unique species seen in 2021. A full list of species observed in each year is found in Appendix A7.4.

Table 5.4.1 Summary of hoverfly individuals and unique species seen per year in pan traps.

	2017	**2018**	**2019**	**2021**
Total number of hoverflies seen	1,562	2,345	3,036	2,163
Number of hoverfly species observed	53	75	71	82

5.4.2 Are there relationships between hoverflies and AES gradients?

There was no evidence of relationships between hoverfly responses and the AES gradients.

5.4.3 Do non-AES covariates explain responses?

The addition of the four plant community variables and the five habitat variables (Table 5.4.2) in the models did not change the broad relationships with the AES gradients for hoverfly response variables.

5.4.3.1 Are hoverfly responses explained by plant variables?

There was no strong evidence of relationships between hoverfly responses and the plant variables tested (botanical diversity, % graminoid cover, abundance of floral resources across survey square, abundance of floral resources surrounding pan traps).

A possible positive relationship was seen between hoverfly diversity and the percentage cover of graminoids (coefficient = 0.487, s.e. of coefficient = 0.214, $P = 0.025$).

5.4.3.2 Are hoverfly responses explained by habitat variables?

There was a positive relationship between the area of arable land and hoverfly abundance (Table 5.4.2). It wasn’t possible to test for this relationship in the lowland-only analysis due to collinearity with other habitat variables. There was a negative correlation between habitat diversity and arable area in the lowlands (see Section A.3.2.1), which may be picking up a similar relationship between hoverflies and the surrounding landscape in lowland NCAs.

Table 5.4.2 Relationships between hoverfly responses and habitat variables, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Habitat diversity**	**Area of mass flowering crops**	**Arable area**	**Total woodland**	**Length of woody linear features**	**Length of water linear features**
All NCA	Hoverfly species richness	0.255 (0.144) *P* = 0.076	0.205 (0.199) *P* = 0.304	0.19 (0.137) *P* = 0.165	-0.196 (0.573) *P* = 0.732	-0.073 (0.047) *P* = 0.123	0.004 (0.035) *P* = 0.917
	Hoverfly diversity	0.577 (0.507) *P* = 0.261	0.507 (0.92) *P* = 0.582	-0.88 (0.643) *P* = 0.186	-0.631 (2.034) *P* = 0.758	-0.073 (0.183) *P* = 0.69	0.036 (0.14) *P* = 0.802
	Hoverfly abundance	0.234 (0.304) *P* = 0.442	0.576 (0.448) *P* = 0.199	**1.005** **(0.294)** ***P* = 0.001**	0.643 (1.185) *P* = 0.587	-0.216 (0.098) *P* = 0.027	0.013 (0.073) *P* = 0.856
Lowland NCAs only	Hoverfly species richness	-0.125 (0.076) *P* = 0.101	0.246 (0.196) *P* = 0.209	-	-	-	-0.018 (0.027) *P* = 0.512
	Hoverfly diversity	0.321 (0.455) *P* = 0.49	0.364 (0.909) *P* = 0.69	-	-	-	-0.061 (0.148) *P* = 0.682
	Hoverfly abundance	**-0.753** **(0.188)** ***P* < 0.001**	0.982 (0.41) *P* = 0.017	-	-	-	-0.001 (0.068) *P* = 0.992

5.4.4 Do relationships vary between trait groups?

Relationships between diversity, richness and abundance of 10 hoverfly trait groups and AES gradients were analysed, with the majority of the analyses showing no relationships. Strong evidence for relationships was only observed for richness of high mobility hoverflies, which was positively related to the landscape AES gradient in both all NCA and lowland only analyses (coefficient = 0.132, s.e. of coefficient = 0.047, *P* = 0.005 across all NCAs). The model predicted one additional species of high mobility hoverfly on average in a square with a landscape gradient score of 10,000 compared to a landscape gradient score of 250, suggesting a fairly small effect. There was also a possible relationship between abundance of high mobility hoverflies and the landscape gradient (coefficient = 0.227, s.e. of coefficient = 0.095, *P* = 0.017 in lowlands, weaker evidence across all NCAs).

There was an indication of a positive relationship between abundance of hoverflies with detritivorous larvae and the landscape AES gradient in lowlands only (coefficient = 0.219, s.e. of coefficient = 0.087, *P* = 0.012) and a possible interaction between gradients on abundance of early hoverflies (coefficient = -0.181, s.e. of coefficient = 0.087, *P* = 0.038), however there was no evidence for either main effect.

5.4.5 National Pollinator Monitoring Scheme pollinator trait groups

We also analysed the richness, diversity and abundance of two groups of pollinators identified by the Pollinator Monitoring Scheme (Carvell et al., 2016), which contained both hoverflies and bees. These were the PoMS crop visitors and PoMS monitoring candidates (Section 2.5.2), which are fully described in Appendix A3.2.4. No strong relationships were found between these groups and the AES gradients.

5.4.6 Summary and discussion of hoverfly results

No evidence was found that the AES gradients affected the total abundance, species richness or diversity of hoverflies. Just one of the hoverfly trait groups, larger species that were more mobile, had strong evidence ($P < 0.01$) of a positive relationship between species richness and the landscape AES gradient, and weaker evidence of a positive relationship between abundance and the landscape gradient. There was also weak evidence that abundance of the larger, more mobile butterfly species had a positive relationship with the landscape gradient (Section 5.2.4), showing that across these two insect taxa the more mobile species may respond to AES management at larger spatial scales.

The other hoverfly trait group for which weak evidence was found of a positive relationship with the landscape AES gradient was those with detritivorous larvae. No relationships were found with AES gradients for hoverfly species with predatory or phytophagous larvae.

The total abundance of hoverflies related more strongly to the habitat variables than the AES gradients, with a strong positive relationship with the area of arable land. This may be driven a few dominant hoverfly species with predatory larvae, which feed on aphids that are prevalent on cereal crops. The five most abundant hoverfly species sampled across the four years all had predatory larvae, and made up 58% of the total hoverfly abundance. Hoverflies with predatory larvae have been shown previously to have a positive relationship with the extent of arable agriculture in several studies (reviewed in Rodríguez-Gasol et al., 2021).

5.5 Moths

5.5.1 Summary of moth survey

A total of 110,779 moths were recorded across four years of survey. The survey in 2019 contributed by far the most individuals, with 42,245 individuals observed. A total of 925 species were observed, with the highest richness also seen in 2019. Overall more macro-moths were seen (61,853) than micro-moths (48,926). In the lowlands counts were split fairly evenly between macro-moths and micro-moths, but macro-moths comprised 75% of upland moths. The full moth species list is in Appendix A7.5.

Table 5.5.1 Summary of moth individuals and unique species seen per year in moth traps.

	2017	**2018**	**2019**	**2021**
Total moth abundance	22,315	25,363	42,245	20,856
Total micro-moth abundance	11,634	10,248	19,722	7,322
Total macro-moth abundance	10,681	15,115	22,523	13,534
Number of moth species	551	590	671	628
Number of micro-moth species	305	309	370	337
Number of macro-moth species	246	281	301	291

5.5.2 Are there relationships between moths and AES gradients?

We analysed relationships separately for all moths, macro-moths and micro-moths (Table 5.5.2).

Table 5.5.2 Relationships between moth responses and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Moth richness	0.055 (0.032) *P* = 0.081	0.039 (0.031) *P* = 0.211	**-0.075 (0.029)** ***P* = 0.009**
	Macro-moth richness	0.038 (0.029) *P* = 0.185	0.055 (0.028) *P* = 0.051	-0.049 (0.025) *P* = 0.054
	Micro-moth richness	0.09 (0.037) *P* = 0.015	0.014 (0.037) *P* = 0.702	**-0.100 (0.036)** ***P* = 0.006**
	Moth diversity	0.498 (0.263) *P* = 0.062	0.226 (0.259) *P* = 0.387	-0.096 (0.25) *P* = 0.702
	Macro-moth diversity	0.239 (0.203) *P* = 0.242	0.173 (0.199) *P* = 0.387	-0.099 (0.187) *P* = 0.599
	Micro-moth diversity	0.447 (0.22) *P* = 0.046	0.094 (0.218) *P* = 0.667	0 (0.213) *P* = 0.998
	Moth abundance	0.087 (0.049) *P* = 0.075	0.009 (0.051) *P* = 0.855	**-0.138 (0.048)** ***P* = 0.004**
	Macro-moth abundance	0.113 (0.054) *P* = 0.038	0.066 (0.052) *P* = 0.203	-0.111 (0.051) *P* = 0.032
	Micro-moth abundance	0.077 (0.065) *P* = 0.233	-0.042 (0.065) *P* = 0.522	**-0.198 (0.064)** ***P* = 0.002**
Lowland NCAs only	Moth richness	**0.072 (0.024)** ***P* = 0.003**	0.05 (0.025) *P* = 0.042	-0.047 (0.029) *P* = 0.107
	Macro-moth richness	0.055 (0.022) *P* = 0.012	0.057 (0.022) *P* = 0.011	-0.039 (0.026) *P* = 0.134
	Micro-moth richness	**0.093 (0.032)** ***P* = 0.004**	0.038 (0.033) *P* = 0.249	-0.063 (0.038) *P* = 0.098
	Moth diversity	0.598 (0.28) *P* = 0.040	0.505 (0.288) *P* = 0.088	0.282 (0.335) *P* = 0.405
	Macro-moth diversity	0.223 (0.189) *P* = 0.246	0.462 (0.194) *P* = 0.022	0.283 (0.225) *P* = 0.215
	Micro-moth diversity	0.517 (0.275) *P* = 0.068	0.16 (0.282) *P* = 0.574	0.152 (0.327) *P* = 0.644
	Moth abundance	0.09 (0.042) *P* = 0.033	0.059 (0.044) *P* = 0.175	-0.113 (0.05) *P* = 0.024
	Macro-moth abundance	0.108 (0.051) *P* = 0.034	0.082 (0.052) *P* = 0.118	-0.101 (0.059) *P* = 0.088
	Micro-moth abundance	0.094 (0.06) *P* = 0.118	0.026 (0.063) *P* = 0.678	-0.159 (0.072) *P* = 0.027

5.5.2.1 Species richness of moths, macro-moths and micro-moths

Analyses of all moths showed strong evidence of an interaction effect, suggesting the effect of local AES on total moth species richness was dependent on the surrounding landscape

AES, when data from all NCAs were analysed (Table 5.5.2; Figure 5.5.1). We found the same relationship for micro-moth species richness across all NCAs but not for macro-moths.

When only lowland data were analysed then the relationships observed changed slightly. Instead of an interaction, there was a strong effect of local level AES on both all moth and micro-moth species richness. We estimated an additional 12 moth species, or a 14% increase, would be present across on average with an AES gradient score of 10,000 compared to an AES score of 250, suggesting a moderate effect size. These numbers reflect the average number of moth species across 6 moth traps per square and two rounds of survey. A similar difference of 20% was estimated for micro-moth richness, however in both cases there is substantial uncertainty around these average estimates, so much smaller or much higher differences could occur. There was also a possible positive local AES effect on macro-moth species richness. There was stronger evidence for both the local and landscape AES relationships with macro-moth species richness if the outlier square with very high local AES (see Appendix A3 for details) was excluded.

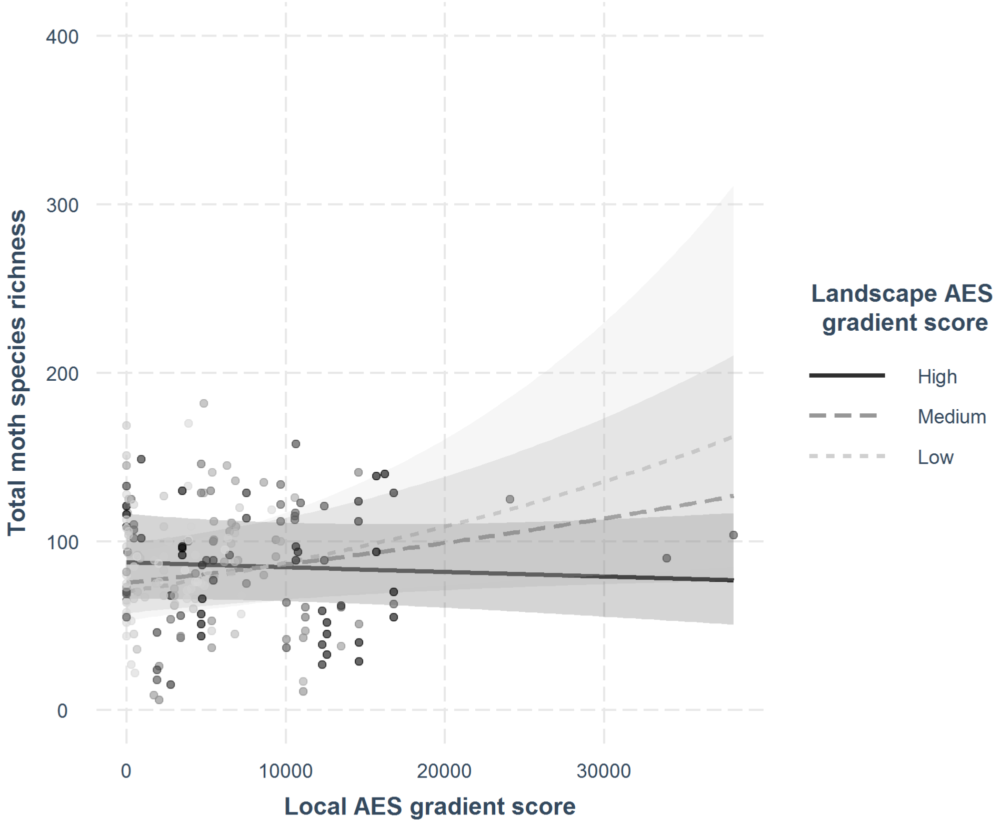


Figure 5.5.1 Interaction plot demonstrating the interactive effects of local (1km) and landscape (3km) AES gradient score on total moth species richness. Each line demonstrates the estimated relationship between moth richness and local level (1km) AES gradient score for three levels of landscape level (3km) AES gradient score. The three levels of landscape gradient score are the mean values of the three terciles derived splitting the data into three equal parts. Points are shaded in relation to their landscape AES score, with darker points indicating higher score. 95% confidence intervals around the estimated lines are shown but differences between slopes have not been formally tested.

5.5.2.2 Diversity of moths, macro-moths and micro-moths

There were no relationships across all NCAs or lowland NCAs between moth diversity and AES gradients at *P* < 0.01. However, we found that for both all moths and micro-moths there was a strong positive effect of the local level gradient on diversity in lowland NCAs (Figure 5.5.2; coefficient = 1.186, s.e. of coefficient = 0.326, *P* = 0.001 for all moths), if the outlier with very high local AES was removed.

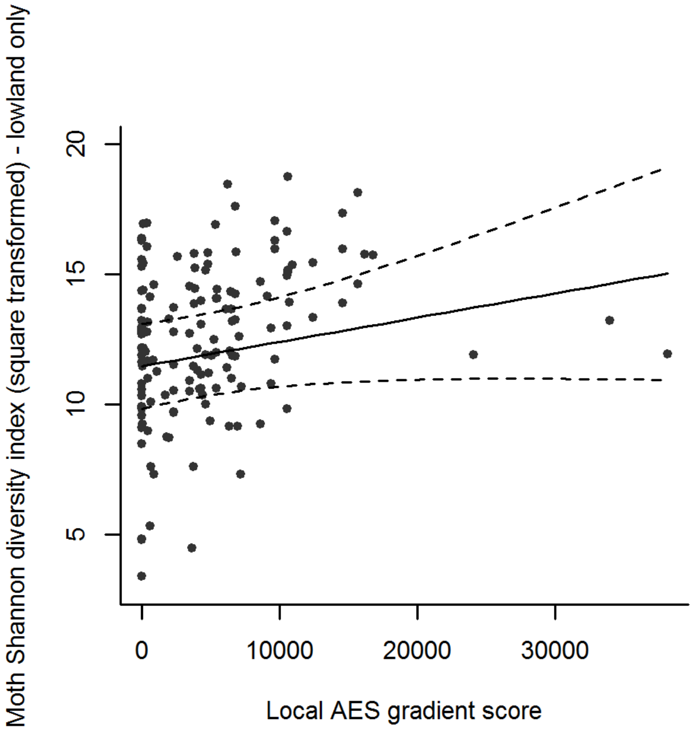


Figure 5.5.2 Relationship between moth diversity and the local AES gradient score across all four survey years but including only lowland NCAs (n = 144). The fitted line indicates the estimated slope of the relationship, with confidence intervals around this slope indicated by dotted lines. There is strong evidence for the relationship with local level AES if the outlier with very high local AES is excluded.

5.5.2.3 Abundance of moths, macro-moths and micro-moths

There was evidence of an interaction between the two AES gradients for both all moths and micro-moths in the all NCA analysis, suggesting a stronger effect of local AES on abundance in a low AES landscape (Figure 5.5.3). However, these relationships were less clear in the lowlands.

There was a suggestion of a possible positive relationship between macro-moth abundance and local AES.

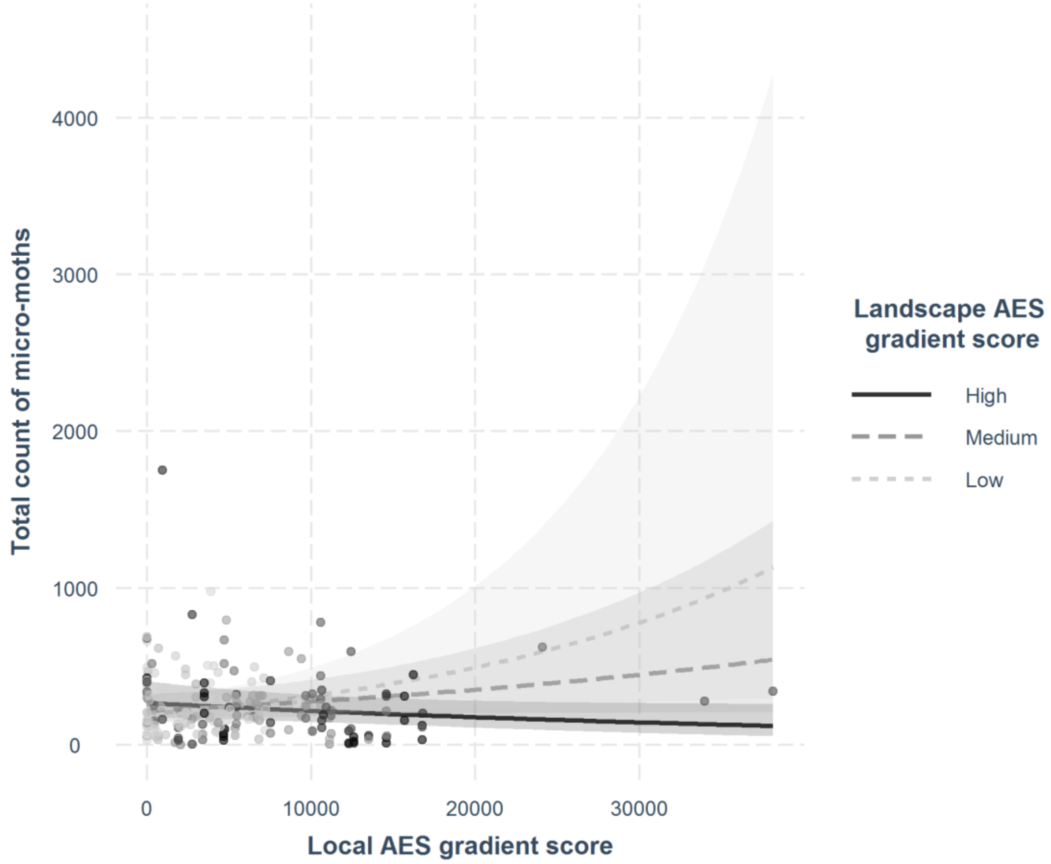


Figure 5.5.3 Interaction plot demonstrating the interactive effects of local (1km) and landscape (3km) AES gradient score on total micro-moth abundance. Each line demonstrates the estimated relationship between micro-moth abundance and local level (1km) AES gradient score for three levels of landscape level (3km) AES gradient score. The three levels of landscape gradient score the mean value of the three terciles derived splitting the data into three equal parts. Points are shaded in relation to their landscape AES score, with darker points indicating higher score. 95% confidence intervals around the estimated lines are shown but differences between slopes have not been formally tested.

5.5.3 Do non-AES covariates explain responses?

The addition of the three plant community variables (Table 5.5.3) and the four habitat variables (Table 5.5.4) in the models did not change the broad relationships with the AES gradients for moth response variables.

5.5.3.1 Do plant communities affect moth responses?

There was strong evidence that the species richness of all moths, macro-moths and micro-moths were positively influenced by botanical diversity in the survey square (Table 5.5.3). This relationship was evident across all NCAs and in the lowlands only. There was also evidence that botanical diversity was positively related to moth and macro-moth diversity, but this pattern was only shown in the analysis of data from all NCAs.

There were also positive relationships between moth and macro-moth abundance and the percentage cover of graminoids in lowland NCAs, but no evidence of this relationship across all NCAs. There was no relationship between any moth response and the abundance of floral resources.

Table 5.5.3 Relationships between moth, macro-moth and micro-moth responses and the vegetation surveyed in survey squares, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Botanical diversity**	**Percentage graminoids**	**Floral resource abundance**
All NCAs	Moth species richness	**0.35 (0.115)** ***P* = 0.002**	0.031 (0.042) *P* = 0.468	-0.001 (0.021) *P* = 0.974
	Macro-moth species richness	**0.331 (0.106)** ***P* = 0.002**	0.019 (0.04) *P* = 0.641	0.016 (0.018) *P* = 0.397
	Micro-moth species richness	**0.366 (0.122)** ***P* = 0.003**	0.034 (0.045) *P* = 0.457	-0.028 (0.028) *P* = 0.315
	Moth diversity	**2.486 (0.839)** ***P* = 0.005**	-0.252 (0.306) *P* = 0.414	0.138 (0.214) *P* = 0.519
	Macro-moth diversity	**2.151 (0.664)** ***P* = 0.002**	-0.128 (0.241) *P* = 0.599	0.191 (0.15) *P* = 0.206
	Micro-moth diversity	1.231 (0.726) *P* = 0.096	-0.318 (0.264) *P* = 0.235	-0.011 (0.193) *P* = 0.955
	Moth abundance	0.278 (0.149) *P* = 0.062	0.069 (0.057) *P* = 0.222	-0.008 (0.039) *P* = 0.843
	Macro-moth abundance	0.184 (0.158) *P* = 0.243	0.127 (0.065) *P* = 0.052	0.031 (0.043) *P* = 0.471
	Micro-moth abundance	0.505 (0.227) *P* = 0.026	0.014 (0.081) *P* = 0.858	-0.071 (0.054) *P* = 0.184
Lowland NCAs only	Moth species richness	**0.346 (0.081)** ***P* < 0.001**	0.039 (0.031) *P* = 0.204	-0.018 (0.02) *P* = 0.387
	Macro-moth species richness	**0.307 (0.079)** ***P* < 0.001**	0.05 (0.029) *P* = 0.091	0.008 (0.017) *P* = 0.631
	Micro-moth species richness	**0.393 (0.11)** ***P* < 0.001**	0.022 (0.043) *P* = 0.601	-0.05 (0.029) *P* = 0.078
	Moth diversity	1.873 (1.046) *P* = 0.083	-0.51 (0.408) *P* = 0.221	-0.071 (0.265) *P* = 0.788
	Macro-moth diversity	1.006 (0.709) *P* = 0.166	-0.451 (0.275) *P* = 0.113	0.031 (0.175) *P* = 0.858
	Micro-moth diversity	1.012 (1.06) *P* = 0.347	-0.372 (0.415) *P* = 0.376	-0.012 (0.252) *P* = 0.961
	Moth abundance	0.324 (0.145) *P* = 0.026	**0.153 (0.058)** ***P* = 0.008**	-0.002 (0.04) *P* = 0.958
	Macro-moth abundance	0.419 (0.17) *P* = 0.014	**0.221 (0.068)** ***P* = 0.001**	0.033 (0.042) *P* = 0.435
	Micro-moth abundance	0.273 (0.18) *P* = 0.128	0.116 (0.077) *P* = 0.132	-0.021 (0.06) *P* = 0.731

5.5.3.2 Does habitat affect moth responses?

Table 5.5.4 Relationships between moth, macro-moth and micro-moth responses and the habitat composition of survey squares, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Habitat diversity**	**Total woodland**	**Length of woody linear features**	**Length of water linear features**
All NCAs	Moth species richness	**0.314 (0.113)** **P = 0.006**	0.358 (0.464) P = 0.441	0.037 (0.045) P = 0.406	-0.026 (0.036) P = 0.474
	Macro-moth species richness	0.211 (0.112) P = 0.058	0.487 (0.45) P = 0.278	0.061 (0.043) P = 0.158	-0.01 (0.035) P = 0.770
	Micro-moth species richness	**0.42 (0.124)** **P = 0.001**	0.079 (0.508) P = 0.876	0.028 (0.049) P = 0.571	-0.04 (0.038) P = 0.293
	Moth diversity	**2.461 (0.892)** **P = 0.008**	-0.469 (3.709) P = 0.900	0.632 (0.353) P = 0.079	-0.395 (0.274) P = 0.156
	Macro-moth diversity	1.666 (0.646) P = 0.013	-2.55 (2.7) P = 0.35	**0.9 (0.256)** **P = 0.001**	0.139 (0.2) P = 0.492
	Micro-moth diversity	1.416 (0.821) P = 0.090	0.694 (3.407) P = 0.839	0.088 (0.325) P = 0.788	-0.542 (0.252) P = 0.037
	Moth abundance	0.067 (0.171) P = 0.695	0.092 (0.756) P = 0.903	-0.081 (0.062) P = 0.193	0.002 (0.047) P = 0.962
	Macro-moth abundance	0.112 (0.161) P = 0.488	-0.433 (0.779) P = 0.579	**-0.169 (0.062)** **P = 0.006**	-0.06 (0.046) P = 0.189
	Micro-moth abundance	0.211 (0.242) P = 0.382	0.909 (1.003) P = 0.365	0.089 (0.094) P = 0.344	0.063 (0.073) P = 0.394
Lowland NCAs only	Moth species richness	0.183 (0.081) P = 0.025	-	-	-0.023 (0.024) P = 0.33
	Macro-moth species richness	0.16 (0.071) P = 0.024	-	-	-0.012 (0.023) P = 0.596
	Micro-moth species richness	0.197 (0.115) P = 0.086	-	-	-0.037 (0.032) P = 0.237
	Moth diversity	2.187 (0.843) P = 0.015	-	-	-0.564 (0.261) P = 0.039
	Macro-moth diversity	1.692 (0.619) P = 0.010	-	-	0.009 (0.191) P = 0.963
	Micro-moth diversity	0.933 (0.86) P = 0.288	-	-	-0.53 (0.272) P = 0.060
	Moth abundance	-0.074 (0.133) P = 0.575	-	-	0.038 (0.038) P = 0.308
	Macro-moth abundance	**-0.289 (0.101)** **P = 0.004**	-	-	-0.013 (0.041) P = 0.759
	Micro-moth abundance	-0.108 (0.118) P = 0.360	-	-	0.003 (0.046) P = 0.946

We found evidence that habitat diversity was a positive driver of moth species richness and diversity, although the evidence for these relationships was strongest in the all NCA analysis (Table 5.5.4). Evidence of positive effects were seen for both micro and macro-moths, though the strongest effects ($P < 0.01$) were found for species richness of all moths and micro-moths, and diversity of all moths.

The length of woody linear features had a positive effect on macro-moth diversity and a negative effect on macro-moth abundance across all NCAs. We weren't able to evaluate woody linear feature effects in the lowlands due to high collinearity with habitat diversity. It is interesting however to note that in the lowlands, macro-moth abundance showed a negative relationship with habitat diversity, suggesting the pattern attributed to woody features is being picked up in the habitat diversity relationship.

5.5.4 Do relationships vary between trait groups?

Relationships between moth richness, diversity and abundance and the AES gradients were all shown to vary between trait groups (Tables 5.5.6 to 5.5.12).

5.5.4.1 Early vs late flying moths

When only early flying moths were assessed there was no evidence of relationships between moth responses and the AES gradients (Table 5.5.6). Summer moths (species that first fly in May or later) showed similar patterns to all moths, with evidence of interaction terms across all NCAs for richness and abundance, and evidence of a local AES effect on richness of summer flying moths in the lowlands.

These early vs. summer flying trait groups were defined in the same way for moths as for the other insect taxa, for consistency (see Section 2.5.2). However, moths were sampled twice a year, and the first round of moth surveys was generally later (late May / June) than the first round of transect and pan trap surveys in May. Due to this sampling difference, and the high turnover of moth species, it is possible that moth species that first fly in April or earlier were undersampled, and are therefore less likely to show relationships with the AES gradients than the 'summer' moth species that first fly in May or later.

Table 5.5.6 Relationships between early and late (summer) flying moths and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Richness of early moths	0.055 (0.034) *P* = 0.108	-0.018 (0.034) *P* = 0.611	-0.052 (0.035) *P* = 0.146
	Diversity of early moths	0.087 (0.055) *P* = 0.118	-0.015 (0.054) *P* = 0.778	-0.066 (0.052) *P* = 0.209
	Abundance of early moths	-0.024 (0.071) *P* = 0.731	-0.025 (0.068) *P* = 0.716	-0.028 (0.066) *P* = 0.674
	Richness of summer moths	0.057 (0.032) *P* = 0.073	0.044 (0.031) *P* = 0.157	**-0.076 (0.029)** ***P* = 0.008**
	Diversity of summer moths	0.483 (0.247) *P* = 0.055	0.2 (0.244) *P* = 0.414	-0.1 (0.235) *P* = 0.672
	Abundance of summer moths	0.102 (0.052) *P* = 0.047	0.015 (0.054) *P* = 0.776	**-0.155 (0.051)** ***P* = 0.002**
Lowland NCAs only	Richness of early moths	0.047 (0.029) *P* = 0.113	0.009 (0.03) *P* = 0.768	0.001 (0.036) *P* = 0.986
	Diversity of early moths	0.264 (0.172) *P* = 0.133	0.055 (0.177) *P* = 0.758	-0.043 (0.206) *P* = 0.836
	Abundance of early moths	-0.03 (0.063) *P* = 0.631	0.032 (0.065) *P* = 0.628	0.077 (0.076) *P* = 0.309
	Richness of summer moths	**0.075 (0.026)** ***P* = 0.004**	0.055 (0.026) *P* = 0.033	-0.054 (0.031) *P* = 0.079
	Diversity of summer moths	0.585 (0.269) *P* = 0.037	0.452 (0.277) *P* = 0.111	0.221 (0.321) *P* = 0.495
	Abundance of summer moths	0.108 (0.047) *P* = 0.021	0.061 (0.048) *P* = 0.204	**-0.142 (0.055)** ***P* = 0.010**

5.5.4.2 Moths with grass, forb, woody or other host plants

When moths were split between trait groups according to the type of larval host plant, there was only strong evidence of relationships with the AES gradients for moth species whose caterpillars feed on grass host plants (Table 5.5.7). These moths showed both evidence of an interaction term for richness and abundance across all NCAs and lowland NCAs, plus strong evidence of a positive effect of local AES in the lowlands, and weak evidence of the same relationship in analyses of data from all NCAs.

Table 5.5.7 Relationships between moths with grass, forb, woody or other host plants and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Richness of moths with grass larval hosts	0.055 (0.022) *P* = 0.012	0.036 (0.022) *P* = 0.101	**-0.065 (0.022) *P* = 0.004**
	Diversity of moths with grass larval hosts	0.214 (0.116) *P* = 0.071	0.071 (0.113) *P* = 0.531	-0.035 (0.115) *P* = 0.76
	Abundance of moths with grass larval hosts	0.076 (0.062) *P* = 0.221	0.084 (0.063) *P* = 0.182	**-0.164 (0.061) *P* = 0.007**
	Richness of moths with forb larval hosts	0.036 (0.032) *P* = 0.263	0.054 (0.032) *P* = 0.086	-0.064 (0.029) *P* = 0.028
	Diversity of moths with forb larval hosts	0.232 (0.232) *P* = 0.320	0.254 (0.228) *P* = 0.269	-0.158 (0.22) *P* = 0.472
	Abundance of moths with forb larval hosts	0.085 (0.049) *P* = 0.083	0.02 (0.049) *P* = 0.418	-0.099 (0.048) *P* = 0.041
	Richness of moths with woody larval hosts	0.066 (0.043) *P* = 0.127	0.027 (0.043) *P* = 0.527	-0.072 (0.039) *P* = 0.066
	Diversity of moths with woody larval hosts	0.031 (0.231) *P* = 0.893	0.329 (0.226) *P* = 0.149	-0.21 (0.207) *P* = 0.311
	Abundance of moths with woody larval hosts	0.133 (0.069) *P* = 0.054	0.013 (0.068) *P* = 0.851	-0.095 (0.063) *P* = 0.131
	Richness of moths with other larval hosts	0.067 (0.045) *P* = 0.133	0.001 (0.045) *P* = 0.985	-0.066 (0.044) *P* = 0.138
	Diversity of moths with other larval hosts	0.036 (0.047) *P* = 0.452	-0.009 (0.047) *P* = 0.846	-0.029 (0.046) *P* = 0.526
	Abundance of moths with other larval hosts	0.136 (0.1) *P* = 0.174	-0.143 (0.097) *P* = 0.138	-0.247 (0.097) *P* = 0.011
Lowland NCAs only	Richness of moths with grass larval hosts	**0.064 (0.022) *P* = 0.004**	0.028 (0.023) *P* = 0.219	**-0.076 (0.027) *P* = 0.005**
	Diversity of moths with grass larval hosts	0.231 (0.132) *P* = 0.089	0.09 (0.136) *P* = 0.511	-0.019 (0.159) *P* = 0.905
	Abundance of moths with grass larval hosts	0.117 (0.059) *P* = 0.048	0.062 (0.061) *P* = 0.306	**-0.228 (0.069) *P* = 0.001**
	Richness of moths with forb larval hosts	0.056 (0.027) *P* = 0.035	0.051 (0.027) *P* = 0.060	-0.045 (0.031) *P* = 0.140
	Diversity of moths with forb larval hosts	0.315 (0.264) *P* = 0.240	0.427 (0.271) *P* = 0.124	0.034 (0.314) *P* = 0.914
	Abundance of moths with forb larval hosts	0.103 (0.042) *P* = 0.015	0.071 (0.043) *P* = 0.099	-0.067 (0.05) *P* = 0.184
	Richness of moths with woody larval hosts	0.059 (0.038) *P* = 0.122	0.075 (0.039) *P* = 0.054	-0.006 (0.046) *P* = 0.902
	Diversity of moths with woody larval hosts	0.212 (0.239) *P* = 0.380	0.377 (0.244) *P* = 0.130	-0.149 (0.276) *P* = 0.591
	Abundance of moths with woody larval hosts	0.112 (0.05) *P* = 0.026	0.102 (0.05) *P* = 0.043	0.002 (0.06) *P* = 0.978
	Richness of moths with other larval hosts	0.06 (0.039) *P* = 0.123	0.061 (0.04) *P* = 0.131	0.008 (0.046) *P* = 0.868
	Diversity of moths with other larval hosts	0.043 (0.045) *P* = 0.341	0.063 (0.046) *P* = 0.175	0.006 (0.055) *P* = 0.915
	Abundance of moths with other larval hosts	0.071 (0.098) *P* = 0.470	-0.002 (0.097) *P* = 0.980	-0.036 (0.113) *P* = 0.751

There was some indication of a possible response of the species richness of moths with forb host plants to an interaction between the two the AES gradients.

5.5.4.3 Monophagous, oligophagous and polyphagous moths

Table 5.5.8 Relationships between monophagous, oligophagous and polyphagous moths and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Richness of monophagous moths	0.07 (0.044) *P* = 0.115	0.046 (0.044) *P* = 0.292	-0.103 (0.046) *P* = 0.026
	Diversity of monophagous moths	0.073 (0.047) *P* = 0.125	0.034 (0.047) *P* = 0.466	-0.081 (0.046) *P* = 0.08
	Abundance of monophagous moths	0.023 (0.103) *P* = 0.820	0.092 (0.1) *P* = 0.357	-0.119 (0.091) *P* = 0.193
	Richness of oligophagous moths	**0.076 (0.029)** ***P* = 0.010**	0.031 (0.029) *P* = 0.289	**-0.073 (0.028)** ***P* = 0.010**
	Diversity of oligophagous moths	0.371 (0.213) *P* = 0.087	0.135 (0.21) *P* = 0.523	0.02 (0.206) *P* = 0.922
	Abundance of oligophagous moths	0.08 (0.054) *P* = 0.138	0.02 (0.056) *P* = 0.72	**-0.166 (0.054)** ***P* = 0.002**
	Richness of polyphagous moths	0.03 (0.032) 0.04 *P* = 0.218	0.048 (0.032) *P* = 0.133	-0.06 (0.029) *P* = 0.040
	Diversity of polyphagous moths	0.534 (0.556) *P* = 0.34	0.577 (0.551) *P* = 0.298	-0.387 (0.549) *P* = 0.482
	Abundance of polyphagous moths	0.105 (0.055) *P* = 0.056	-0.01 (0.055) *P* = 0.854	-0.102 (0.053) *P* = 0.055
Lowland NCAs only	Richness of monophagous moths	0.083 (0.043) *P* = 0.053	0.061 (0.043) *P* = 0.157	-0.1 (0.052) *P* = 0.053
	Diversity of monophagous moths	0.303 (0.169) *P* = 0.083	0.203 (0.174) *P* = 0.253	-0.303 (0.204) *P* = 0.145
	Abundance of monophagous moths	0.167 (0.076) *P* = 0.029	0.081 (0.078) *P* = 0.298	-0.207 (0.087) *P* = 0.017
	Richness of oligophagous moths	**0.09 (0.027)** ***P* = 0.001**	0.038 (0.027) *P* = 0.160	-0.063 (0.032) *P* = 0.052
	Diversity of oligophagous moths	0.519 (0.251) *P* = 0.046	0.165 (0.258) *P* = 0.525	0.103 (0.298) *P* = 0.731
	Abundance of oligophagous moths	0.082 (0.049) *P* = 0.094	0.056 (0.051) *P* = 0.274	**-0.176 (0.059)** ***P* = 0.003**
	Richness of polyphagous moths	0.047 (0.023) *P* = 0.036	0.058 (0.023) *P* = 0.012	-0.011 (0.027) *P* = 0.675
	Diversity of polyphagous moths	0.483 (0.64) *P* = 0.452	1.362 (0.661) *P* = 0.041	0.69 (0.78) *P* = 0.377
	Abundance of polyphagous moths	0.101 (0.05) *P* = 0.043	0.054 (0.051) *P* = 0.282	-0.027 (0.059) *P* = 0.645

Only oligophagous moths showed strong relationships with AES gradients at $P < 0.01$ (Table 5.5.8). These moths showed both positive relationships between species richness and local AES, and AES gradient interaction effects for richness and abundance.

5.5.4.4 Mobility trait moth groupings

There was evidence that the diversity and richness of low mobility moths was positively related to local AES gradients both in all NCA and lowland only analysis (Table 5.5.9). Strong evidence for interaction effects was observed for the richness and abundance of medium mobility moths in the analyses across all NCAs.

No strong relationships were seen for the larger, more mobile moths, suggesting local AES may be more important for less mobile moths. However, there was a weak indication of a positive effect of the landscape AES gradient on the abundance of high mobility moth species, when data from across all NCAs were analysed, and on the species richness of high mobility species in lowland only analyses.

It was not possible to analyse richness and diversity responses for the least mobile moths, due to the small number of species seen. Only abundance of the very low mobility moth species group was analysed (Table 5.5.9), and very weak evidence was found for a positive effect of the local AES gradient in analyses of lowland-NCA only data.

Table 5.5.9 Relationships between moths with very low, low, medium or high mobility and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold. It was not possible to analyse richness and diversity responses for the least mobile moths, due to the small number of species seen.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Abundance of very low mobility moths	0.134 (0.102) *P* = 0.192	0.059 (0.095) *P* = 0.532	-0.187 (0.101) *P* = 0.063
	Richness of low mobility moths	0.093 (0.037) *P* = 0.013	0.015 (0.037) *P* = 0.686	-0.08 (0.037) *P* = 0.032
	Diversity of low mobility moths	**0.549 (0.181) *P* = 0.004**	0.196 (0.18) *P* = 0.282	-0.117 (0.18) *P* = 0.518
	Abundance of low mobility moths	0.072 (0.069) *P* = 0.293	-0.081 (0.069) *P* = 0.239	-0.157 (0.066) *P* = 0.018
	Richness of medium mobility moths	0.045 (0.028) *P* = 0.111	0.044 (0.028) *P* = 0.117	**-0.076 (0.026) *P* = 0.003**
	Diversity of medium mobility moths	0.243 (0.207) *P* = 0.244	0.081 (0.203) *P* = 0.693	-0.122 (0.198) *P* = 0.539
	Abundance of medium mobility moths	0.111 (0.055) *P* = 0.042	0.037 (0.05) *P* = 0.452	**-0.16 (0.05) *P* = 0.001**
	Richness of high mobility moths	0.032 (0.041) *P* = 0.436	0.053 (0.04) *P* = 0.193	0.008 (0.04) *P* = 0.837
	Diversity of high mobility moths	0.039 (0.042) *P* = 0.353	0.016 (0.042) *P* = 0.704	0.012 (0.04) *P* = 0.756
	Abundance of high mobility moths	0.047 (0.08) *P* = 0.562	0.174 (0.079) *P* = 0.028	-0.018 (0.077) *P* = 0.817
Lowland NCAs only	Abundance of very low mobility moths	0.223 (0.106) *P* = 0.036	0.047 (0.102) *P* = 0.645	-0.236 (0.124) *P* = 0.057
	Richness of low mobility moths	**0.094 (0.034) *P* = 0.007**	0.038 (0.035) *P* = 0.279	-0.05 (0.041) *P* = 0.225
	Diversity of low mobility moths	**0.629 (0.206) *P* = 0.003**	0.308 (0.213) *P* = 0.151	-0.048 (0.251) *P* = 0.849
	Abundance of low mobility moths	0.059 (0.069) *P* = 0.392	0.001 (0.069) *P* = 0.987	-0.077 (0.078) *P* = 0.321
	Richness of medium mobility moths	0.053 (0.022) *P* = 0.016	0.056 (0.023) *P* = 0.013	-0.051 (0.026) *P* = 0.053
	Diversity of medium mobility moths	0.242 (0.206) *P* = 0.247	0.31 (0.212) *P* = 0.152	0.272 (0.247) *P* = 0.276
	Abundance of medium mobility moths	0.115 (0.054) *P* = 0.033	0.088 (0.056) *P* = 0.117	-0.157 (0.063) *P* = 0.013
	Richness of high mobility moths	0.047 (0.036) *P* = 0.191	0.083 (0.037) *P* = 0.025	0.054 (0.046) *P* = 0.237
	Diversity of high mobility moths	0.055 (0.042) *P* = 0.200	0.074 (0.043) *P* = 0.094	0.074 (0.05) *P* = 0.147
	Abundance of high mobility moths	0.092 (0.073) *P* = 0.208	0.139 (0.074) *P* = 0.059	-0.07 (0.085) *P* = 0.412

5.5.4.5 Univoltine vs multivoltine moths

Only univoltine moths showed strong evidence (at $P < 0.01$) of relationships with the AES gradients, with similar relationships observed as for all moths (Table 5.5.10).

Table 5.5.10 Relationships between univoltine and multivoltine moths and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect ($P < 0.01$) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCA	Richness of univoltine moths	0.069 (0.032) P = 0.032	0.032 (0.032) P = 0.313	**-0.089 (0.03) P = 0.002**
	Diversity of univoltine moths	0.448 (0.24) P = 0.066	-0.075 (0.234) P = 0.749	-0.139 (0.223) P = 0.533
	Abundance of univoltine moths	0.091 (0.054) P = 0.092	0.062 (0.053) P = 0.241	**-0.155 (0.053) P = 0.003**
	Richness of multivoltine moths	0.036 (0.033) P = 0.277	0.05 (0.032) P = 0.120	-0.045 (0.031) P = 0.140
	Diversity of multivoltine moths	0.511 (0.541) P = 0.348	1.096 (0.536) P = 0.045	-0.214 (0.529) P = 0.687
	Abundance of multivoltine moths	0.079 (0.063) P = 0.208	0.005 (0.061) P = 0.938	-0.101 (0.059) P = 0.088
Lowland only	Richness of univoltine moths	**0.089 (0.027) P = 0.001**	0.043 (0.027) P = 0.118	-0.055 (0.033) P = 0.098
	Diversity of univoltine moths	0.519 (0.285) P = 0.077	0.089 (0.292) P = 0.762	0.148 (0.332) P = 0.659
	Abundance of univoltine moths	0.098 (0.05) P = 0.049	0.09 (0.052) P = 0.082	**-0.163 (0.06) P = 0.006**
	Richness of multivoltine moths	0.048 (0.026) P = 0.065	0.061 (0.026) P = 0.019	-0.032 (0.03) P = 0.287
	Diversity of multivoltine moths	0.676 (0.649) P = 0.304	1.572 (0.667) P = 0.024	0.037 (0.78) P = 0.963
	Abundance of multivoltine moths	0.097 (0.049) P = 0.047	0.037 (0.05) P = 0.466	-0.054 (0.058) P = 0.353

5.5.4.6 Habitat specialist vs habitat generalist moths

We found that local AES had a positive effect on habitat specialist moth diversity and species richness but did not affect habitat specialist moth abundance (Table 5.5.11). There was evidence of an interaction effect on habitat generalist moth abundance across all NCAs.

Table 5.5.11 Relationships between habitat specialist and habitat generalist moths and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Richness of habitat generalist moths	0.045 (0.031) *P* = 0.143	0.035 (0.03) *P* = 0.256	-0.067 (0.028) *P* = 0.016
	Diversity of habitat generalist moths	0.405 (0.243) *P* = 0.099	0.144 (0.238) *P* = 0.548	-0.06 (0.225) *P* = 0.790
	Abundance of habitat generalist moths	0.088 (0.049) *P* = 0.072	0.012 (0.049) *P* = 0.799	-0.134 (0.048) *P* = 0.005
	Richness of habitat specialist moths	**0.118 (0.04)** ***P* = 0.003**	0.054 (0.04) *P* = 0.172	**-0.125 (0.042)** ***P* = 0.003**
	Diversity of habitat specialist moths	0.109 (0.044) *P* = 0.017	0.091 (0.044) *P* = 0.045	-0.106 (0.044) *P* = 0.019
	Abundance of habitat specialist moths	0.124 (0.092) *P* = 0.179	-0.045 (0.092) *P* = 0.625	-0.13 (0.093) *P* = 0.163
Lowland NCAs only	Richness of habitat generalist moths	0.06 (0.025) *P* = 0.017	0.047 (0.026) *P* = 0.065	-0.042 (0.03) *P* = 0.165
	Diversity of habitat generalist moths	0.49 (0.268) *P* = 0.076	0.339 (0.275) *P* = 0.225	0.252 (0.316) *P* = 0.430
	Abundance of habitat generalist moths	0.097 (0.042) *P* = 0.021	0.064 (0.043) *P* = 0.135	-0.114 (0.05) *P* = 0.023
	Richness of habitat specialist moths	**0.128 (0.039)** ***P* = 0.001**	0.065 (0.039) *P* = 0.098	-0.098 (0.046) *P* = 0.032
	Diversity of habitat specialist moths	**0.151 (0.048)** ***P* = 0.002**	0.094 (0.049) *P* = 0.058	-0.105 (0.058) *P* = 0.072
	Abundance of habitat specialist moths	0.091 (0.1) *P* = 0.362	-0.011 (0.101) *P* = 0.912	-0.102 (0.116) *P* = 0.380

5.5.4.7 Conservation status moths

No relationships were observed between the abundance of red list moths and the AES gradients (Table 5.5.12). Richness and diversity responses could not be analysed as too few species were observed.

Table 5.5.12 Relationships between abundance of red list macro-moth species and local and landscape AES gradients, given as coefficient (standard error of coefficient) P value. Relationships with strong evidence of an effect (*P* < 0.01) are highlighted in bold.

	Response	**Local AES**	**Landscape AES**	**Local x landscape AES interaction**
All NCAs	Abundance of red list macro-moths	0.202 (0.104) *P* = 0.052	0.079 (0.101) *P* = 0.436	-0.121 (0.091) *P* = 0.184
Lowland NCAs only	Abundance of red list macro-moths	0.195 (0.101) *P* = 0.054	0.123 (0.102) *P* = 0.229	-0.127 (0.118) *P* = 0.283

5.5.5 Summary and discussion of moth results

Moths show more evidence of strong responses to the AES gradients than the other insect taxa surveyed. The species richness of all moths and micro-moths both showed a strong positive relationship (*P* < 0.01) with the local AES gradient in the lowland NCAs, and there was weak evidence of a similar relationship for macro-moth species richness. When data were analysed across all NCAs there was only weak evidence of a relationship between the local AES gradient and micro-moth richness. There might be greater difference in the quality and / or type of habitat between farmed habitats under AES vs. farmland not in AES management in the lowlands than the uplands (though this was not specifically tested in the analyses above), which may partly help explain why fewer strong relationships were found when all NCAs were analysed. However, the interaction between the two AES gradients did affect richness of all moths and micro-moths, which suggests that the effects of local AES gradients were stronger when the landscape AES gradient was low.

Many of the moth trait groups that showed a positive relationship with the local AES gradient, or a strong interaction between the two AES gradients, were broadly those associated with greater specialism, for example requiring more specialist habitat or food plant requirements and those that are less mobile. Univoltine species also showed stronger effects of AES than multivoltine species.

Univoltine species may be less able to respond to an increase in resources within a season than multivoltine species, similarly moth species with more specialist habitat requirements and those that are oligophagous rather than polyphagous will have less potential to use a wide range of resources. These results suggest that AES are important in providing a wider range of resources both temporally and spatially, promoting numbers of more specialised species that are most strongly affected by seasonal availability of specific resources.

Moths with grass-feeding larvae showed a similar response to the AES gradients to all moth species combined, and there was also a positive effect of the % graminoids on the abundance of all moths and macro-moths in the lowland-only analyses. Moths with grass-feeding larvae may dominate the abundance across the LandSpAES survey squares.

Moth mobility groups differed in their response to the AES gradients. The low and medium mobility species showed some relationships either with the local AES gradients or with the interaction between the two AES gradients, which differed between the analyses of all data vs. lowland only data. No strong relationship was found for the high mobility moths with either AES gradient, but there was a weak indication of a positive effect of landscape AES gradient.

Similar to the other insect taxa, moths also showed strong relationships with some of the habitat and botanical variables. In analyses of data from all NCAs, habitat diversity had a positive relationship with both moth species richness and diversity, while the length of woody linear features had a positive relationship with macro-moth diversity and a negative relationship with abundance. This suggests that for macro-moths, hedgerows may support some of the less abundant macro-moth species.

Botanical diversity had a strong, positive relationship with the species richness of all moths, macro- and micro-moths. The majority of moth caterpillars feed on plants, and a greater botanical diversity provides a greater range of host plant species and is also likely to help create greater structural diversity (e.g. varied sward heights), resulting in greater moth species richness. Unlike bees, moths showed no relationship with the abundance of floral resources. The floral resources were surveyed here across the whole survey square and in day time, so may not relate to the floral resources available in the vicinity of the moth traps. Floral resources were also surveyed during the day and may not have been available to night-flying moths. In addition, whilst the majority of butterfly, bee and hoverfly species visit flowers for nectar, many moth species do not feed at all as adults. Finally, moth trapping is an active survey method which uses light to attract moths, and this light signal may have over-ridden any effect of floral resources in moths. This is in contrast to the transect surveys which are a passive method that includes counts of butterflies and bumblebees foraging on flowers, and thus may be expected to show a stronger relationship with the abundance of floral resources.

The intensity of moth sampling (two visits per year) was lower than for the other insect taxa, mainly due to the limited number of survey nights that met the minimum weather criteria. Nonetheless, the moth dataset collected for LandSpAES is substantial, with almost all specimens identified to species level (99.8% of 110,779 moths). Most studies investigating relationships between moths and AES management focus on a subset of larger moth species that can be easily identified in the field, mainly macro-moth species (e.g. Merckx et al., 2012; Alison et al., 2017). Here, identification included dissection for the species that are harder to identify, many of which are micro-moth species. As a result, relationships with the AES gradients could be explored for a large proportion of the moth community present in the survey squares, and not just for a subset of the more easily identified species.

5.6 Birds

5.6.1 Breeding bird surveys

5.6.1.1 Summary of breeding bird survey results

We recorded 145 species across all four years and across all surveyed squares. Considering individual years, 96 species were detected in 2017 (lowland only NCAs), 127 in 2018, 125 in 2019 and 135 in 2021 (Table 5.6.1). Therefore, there were 46 species not detected in 2017, although the only record of Stone Curlew was from this incomplete first year of surveying. Thirteen species were recorded in only one year, highlighting the importance of multi-year surveying to identify the contribution of species that are difficult to detect or present at low densities to community composition.

Table 5.6.1 Total bird species recorded per NCA.

	Total bird species recorded			
NCA	**2017**	**2018**	**2019**	**2021**
Dunsmore & Feldon	62	75	76	86
High Weald	67	76	74	80
South Suffolk	67	77	75	83
The Fens	75	88	88	89
Dartmoor	NA	69	71	69
Yorkshire Dales	NA	85	88	89
All	96	127	125	135

5.6.1.2 Are there relationships between birds, AES gradients and habitat?

We considered a species list including 98 species in analysis. Bird species richness per survey square varied between NCAs, with both lowest and highest richness observed in the upland NCAs (Figure 5.6.1). Among lowland NCAs, relatively low richness in 2017 probably reflects the late survey start that year and resultant reduced detectability of some species.

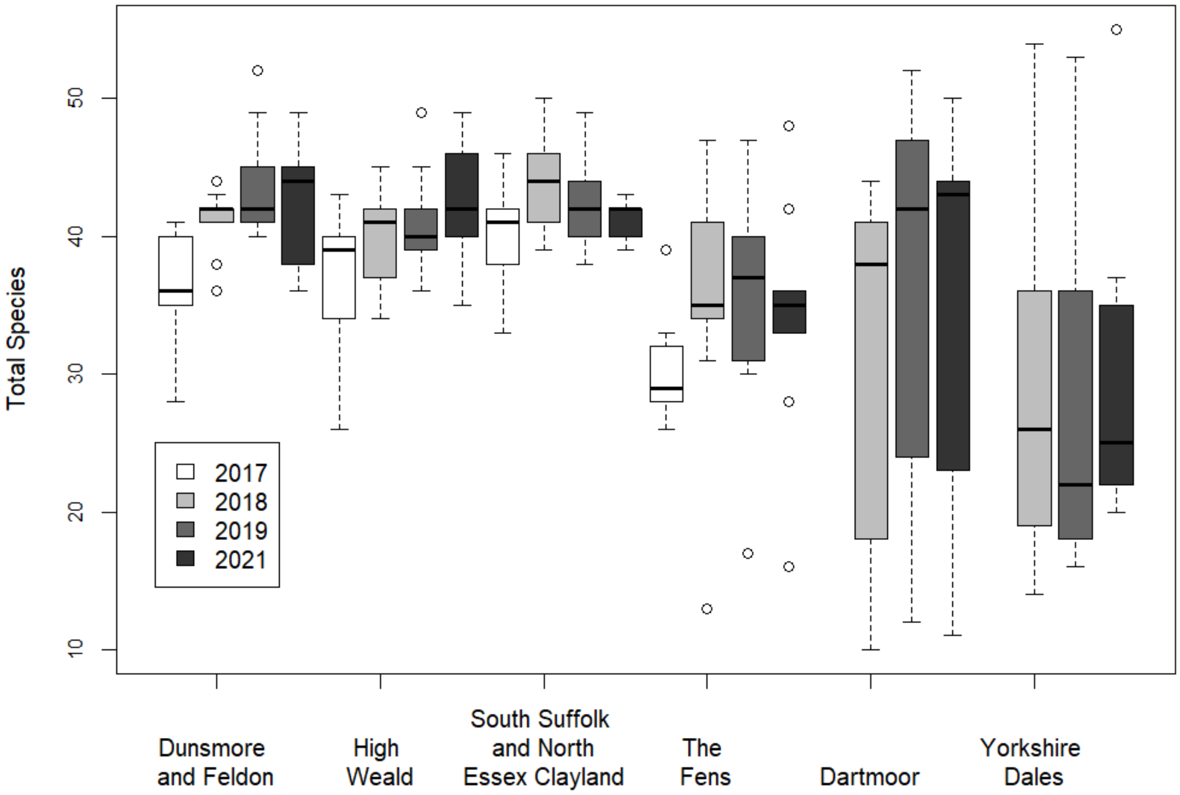


Figure 5.6.1 Variation in bird species richness between NCA and survey year.

In the analyses of total abundance of bird species, there was a strong positive association with habitat diversity both across all NCAs (estimate = 0.274, *P* = 0.007), with the positive result being maintained, but weaker, in lowland areas only (estimate = 0.234, *P* = 0.016). There was no evidence for further relationships, including no relationships with the AES gradients (Table 5.6.2).

There was no evidence for relationships between bird species richness and AES or habitat across all NCAs. In lowland-only analyses, there was a strong positive association with habitat diversity (estimate = 0.213, *P* = 0.001), and indication of an association with local AES (estimate = 0.035, *P* = 0.041; Figure 5.6.2). The estimated relationship suggests that, for an increase in local AES gradient score from 250 to 10,000, we would expect an average increase across NCAs of three bird species. However, the confidence intervals in Figure 5.6.2 show considerable uncertainty around the actual richness of bird species, so smaller or higher differences could have occurred. However, following removal of the outlying lowland square with high AES gradient, the relationship between species richness and local AES was weaker (estimate = 0.045, *P* = 0.052; Figure 5.6.2). This shows a potential positive effect of local AES on bird species richness in lowland areas.

The associations between diversity and predictors were more varied, with improved grassland and woodland positively associated across all NCAs, and habitat diversity positive and strong in lowland only analyses, but no evidence for relationships with AES gradients (Table 5.6.2).

Table 5.6.2 Relationships between bird responses, AES gradients and habitat variables. Strong relationships with *P* < 0.01 are highlighted in bold.

Response	Predictor	NCA	Estimate	SE	p-value
Abundance	Improved grassland	All	0.124	0.189	0.510
	Habitat diversity	**All**	**0.274**	**0.101**	**0.007**
	Woodland	All	0.492	0.445	0.269
	Local AES	All	0.016	0.026	0.550
	Landscape AES	All	-0.002	0.026	0.935
	Interaction AES	All	-0.007	0.023	0.764
	Improved grassland	Lowland	0.264	0.185	0.154
	Habitat diversity	Lowland	0.234	0.097	0.016
	Local AES	Lowland	0.019	0.028	0.496
	Landscape AES	Lowland	0.027	0.028	0.342
	Interaction AES	Lowland	0.006	0.032	0.854
Richness	Improved grassland	All	0.385	0.220	0.080
	Habitat diversity	All	0.205	0.127	0.107
	Woodland	All	0.944	0.547	0.084
	Local AES	All	0.025	0.029	0.390
	Landscape AES	All	-0.015	0.028	0.605
	Interaction AES	All	-0.030	0.025	0.226
	Improved grassland	Lowland	0.203	0.111	0.068
	Habitat diversity	**Lowland**	**0.213**	**0.063**	**0.001**
	Local AES	Lowland	0.035	0.017	0.041
	Landscape AES	Lowland	0.017	0.017	0.331
	Interaction AES	Lowland	-0.010	0.021	0.638
Diversity	Improved grassland	All	0.665	0.282	0.020
	Habitat diversity	All	0.049	0.154	0.749
	Woodland	All	1.726	0.782	0.031
	Local AES	All	0.036	0.034	0.292
	Landscape AES	All	0.027	0.033	0.408
	Interaction AES	All	-0.020	0.027	0.464
	Improved grassland	Lowland	0.153	0.166	0.361
	Habitat diversity	Lowland	0.218	0.080	0.013
	Local AES	Lowland	0.026	0.026	0.322
	Landscape AES	Lowland	0.019	0.026	0.469
	Interaction AES	Lowland	0.003	0.030	0.917

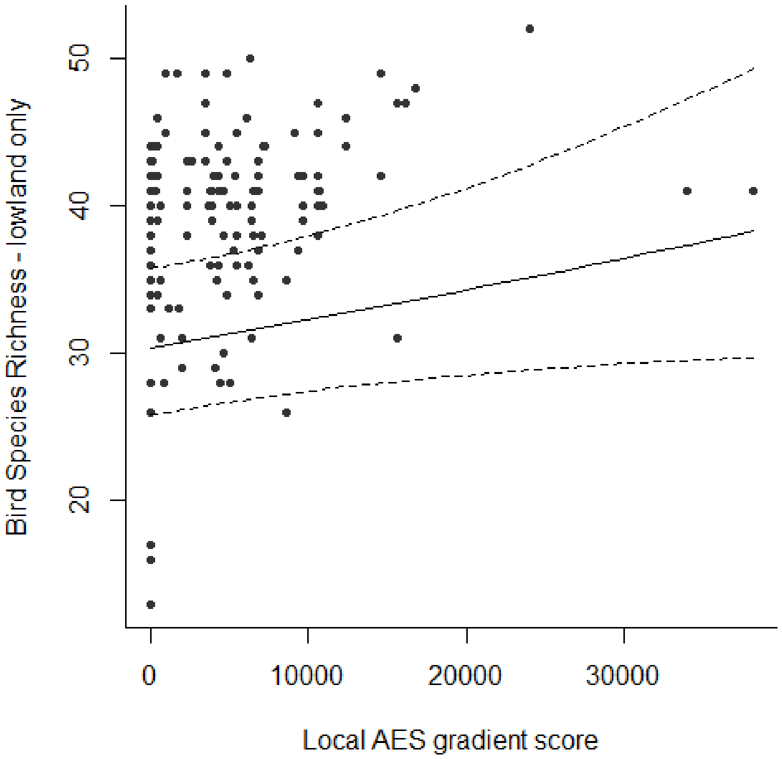


Figure 5.6.2 Relationship between bird species richness and local gradient score across all four survey years in lowland NCAs only (n = 143). The fitted line indicates the estimated slope of the relationship, with confidence intervals around this slope indicated by dotted lines. There was evidence of a weak relationship (*P* = 0.041).

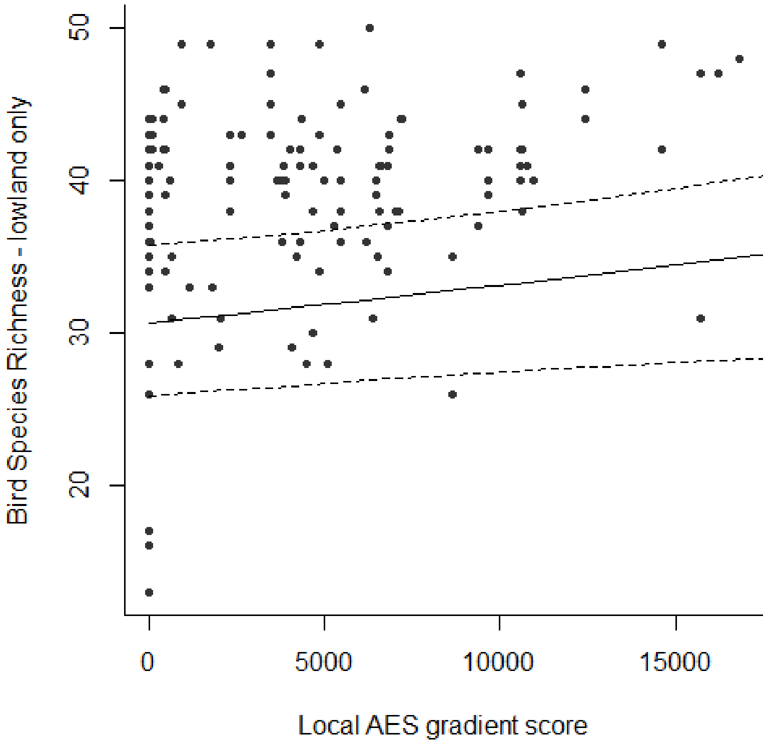


Figure 5.6.3 Relationship between bird species richness and local gradient score across all four survey years in lowland NCAs only, following removal of an outlying square (n = 140). The fitted line indicates the estimated slope of the relationship, with confidence intervals around this slope indicated by dotted lines. There was little evidence of a relationship (*P* = 0.052).

5.6.1.3 Red-listed bird species

Over four years of surveying, 33 UK Red-listed species and 45 Amber listed species from the BoCC5 list were recorded. The highest number of Red-listed species was recorded in The Yorkshire Dales, whilst among lowland NCAs, the highest number was recorded in The Fens (Table 5.6.3).

Table 5.6.3 Total recorded bird species by UK BoCC5 list status per NCA (R = Red, A = Amber, G = Green).

	2017			**2018**			**2019**			**2021**		
NCA	**R**	**A**	**G**	**R**	**A**	**G**	**R**	**A**	**G**	**R**	**A**	**G**
Dunsmore & Feldon	14	17	31	17	22	36	14	20	40	17	27	40
High Weald	16	19	32	15	21	40	15	22	36	15	23	41
South Suffolk	14	19	34	18	22	36	17	20	38	17	23	43
The Fens	16	24	34	20	26	42	19	26	43	18	29	42
Dartmoor	NA	NA	NA	15	21	33	17	20	34	16	20	33
Yorkshire Dales	NA	NA	NA	20	28	36	20	28	38	20	31	38
All	**20**	**28**	**47**	**33**	**39**	**54**	**31**	**38**	**55**	**32**	**45**	**55**

For Red List species abundance, there was evidence of a negative association with woodland habitat across all NCAs, an indication of a negative relationship with habitat diversity in lowland only analyses (Table 5.6.4). For Red List species richness, there was indication of a negative interaction term across all NCAs (P = 0.032). No other strong associations were detected, including no relationships with the AES gradients (Table 5.6.4).

Table 5.6.4 Relationships between Red List bird responses, AES gradients and habitat variables.

Response	Predictor	NCA	Estimate	SE	p-value
Red List Abundance	Improved grassland	All	0.487	0.418	0.244
	Habitat diversity	All	-0.071	0.232	0.759
	Woodland	All	-2.332	1.035	0.024
	Local AES	All	0.041	0.055	0.464
	Landscape AES	All	0.054	0.055	0.319
	Interaction AES	All	-0.029	0.047	0.539
	Improved grassland	Lowland	1.023	0.532	0.054
	Habitat diversity	Lowland	-0.771	0.337	0.022
	Local AES	Lowland	0.036	0.081	0.656
	Landscape AES	Lowland	0.108	0.079	0.173
	Interaction AES	Lowland	-0.002	0.085	0.985
Red List Richness	Improved grassland	All	0.333	0.227	0.143
	Habitat diversity	All	0.257	0.133	0.054
	Woodland	All	-0.184	0.529	0.727
	Local AES	All	0.054	0.034	0.114
	Landscape AES	All	-0.031	0.034	0.362
	Interaction AES	All	-0.075	0.035	0.032
	Improved grassland	Lowland	0.287	0.250	0.250
	Habitat diversity	Lowland	0.008	0.172	0.964
	Local AES	Lowland	0.061	0.037	0.104
	Landscape AES	Lowland	-0.006	0.039	0.878
	Interaction AES	Lowland	-0.062	0.047	0.186

5.6.1.4 Farmland Bird Indicator (FBI) species and other individual species

We also examined associations with AES management at the species-level. We included all farmland bird indicator (FBI) species, and species observed in at least five of the six National Character Areas likely to utilize hedgerows. There were 25 species of interest (Table 5.6.5).

Table 5.6.5 Species analysed for individual species abundance. Species in bold indicate FBI species and those with an asterisk indicate (rare) species with low non-zero observations.

Species code	**Species name**	**# NCA**	**Total records**	**Zero records**	**Non-zero records**	**% Non-zero**
BF	Bullfinch	5	170	74	96	0.56
CB	Corn Bunting	2	71	45	26	0.37 *
CC	Chiffchaff	6	197	57	140	0.71
CH	Chaffinch	6	197	22	175	0.89
D.	Dunnock	6	197	32	165	0.84
GO	Goldfinch	6	197	30	167	0.85
GR	Greenfinch	6	197	90	107	0.54
HS	House Sparrow	6	197	73	124	0.63
JD	Jackdaw	6	197	50	147	0.75
K.	Kestrel	6	197	99	98	0.50 *
L.	Lapwing	5	170	123	47	0.28 *
LI	Linnet	6	197	54	143	0.73
MP	Meadow Pipit	6	197	111	86	0.44 *
P.	Grey Partridge	4	134	108	26	0.19 *
RB	Reed Bunting	6	197	97	100	0.51
S.	Skylark	6	197	21	176	0.89
SD	Stock Dove	6	197	36	161	0.82
SG	Starling	6	197	79	118	0.60
ST	Song Thrush	6	197	56	141	0.72
TD	Turtle Dove	3	107	98	9	0.08 *
TS	Tree Sparrow	2	71	53	18	0.25 *
WH	Whitethroat	5	170	29	141	0.83
WP	Woodpigeon	6	197	15	182	0.92
Y.	Yellowhammer	5	170	46	124	0.73
YW	Yellow Wagtail	3	107	56	51	0.48 *

It was not possible to fit models for some species due to convergence warnings in the modelling process. The species we were unable to model were Corn Bunting, Chiffchaff, Kestrel and Turtle Dove. Some other species models produced convergence warnings but using an alternative optimizer in modelling removed such warnings. It must be noted that model results for species observed in less than five NCAs (Grey Partridge, Tree Sparrow and Yellow Wagtail) should be treated with caution since the random effects structure of the model did not have a sufficient number of levels for estimating variance attributable to the random term. In addition, due to low detectability Lapwing and Meadow Pipit, model results for these species should also be treated with care. All model results are summarised in Table 5.6.6.

From the 21 remaining species where modelling was possible, there were twelve species with strong associations to habitat diversity (Bullfinch, Chaffinch, Dunnock, Goldfinch, Greenfinch, Jackdaw, Meadow Pipit, Reed Bunting, Stock Dove, Song Thrush, Tree Sparrow and Woodpigeon). Three such associations were negative (Meadow Pipit, Reed Bunting and Tree Sparrow), whilst the remaining were positive.

Table 5.6.6 Results for bird single species models. Strong relationships with *P* < 0.01 are highlighted in bold. See Table 5.6.5 for details of species codes.

Response	Predictor	Estimate	SE	p-value
BF	Habitat diversity	1.014	0.433	0.019
	Local AES	-0.048	0.120	0.690
	Landscape AES	0.125	0.121	0.303
	Interaction AES	0.202	0.121	0.096
CH	**Habitat diversity**	**1.063**	**0.305**	**<0.001**
	Local AES	0.107	0.085	0.210
	Landscape AES	-0.128	0.081	0.114
	Interaction AES	-0.002	0.065	0.979
D.	**Habitat diversity**	**0.624**	**0.216**	**0.004**
	Local AES	-0.021	0.060	0.721
	Landscape AES	-0.046	0.059	0.432
	Interaction AES	0.057	0.057	0.316
GO	**Habitat diversity**	**1.053**	**0.343**	**0.002**
	Local AES	0.020	0.114	0.858
	Landscape AES	-0.235	0.110	0.033
	Interaction AES	-0.064	0.115	0.578
GR	**Habitat diversity**	**1.325**	**0.522**	**0.011**
	Local AES	-0.236	0.157	0.134
	Landscape AES	-0.244	0.163	0.135
	Interaction AES	0.333	0.140	0.018
HS	Habitat diversity	0.860	0.613	0.160
	Local AES	-0.123	0.228	0.590
	Landscape AES	-0.049	0.165	0.768
	Interaction AES	-0.025	0.167	0.879
JD	**Habitat diversity**	**1.789**	**0.470**	**<0.001**
	Local AES	0.108	0.154	0.484
	Landscape AES	0.056	0.157	0.724
	Interaction AES	-0.048	0.146	0.743
L.	Habitat diversity	-1.294	1.085	0.233
	Local AES	0.888	0.476	0.062
	Landscape AES	0.352	0.358	0.326
	Interaction AES	-0.432	0.369	0.241
LI	Habitat diversity	0.413	0.451	0.360
	Local AES	-0.048	0.141	0.735
	Landscape AES	0.002	0.139	0.990
	Interaction AES	-0.075	0.125	0.547
MP	**Habitat diversity**	**-1.165**	**0.394**	**0.003**
	Local AES	0.174	0.134	0.196
	Landscape AES	0.124	0.129	0.334
	Interaction AES	-0.097	0.097	0.320
P.	Habitat diversity	-0.236	1.262	0.852
	Local AES	-0.622	0.757	0.411
	Landscape AES	-0.048	0.458	0.917
	Interaction AES	-0.095	0.606	0.876

Response	**Predictor**	**Estimate**	**SE**	**p-value**
RB	Habitat diversity	-1.130	0.490	0.021
	Local AES	0.349	0.155	0.024
	Landscape AES	0.118	0.153	0.441
	Interaction AES	-0.294	0.149	0.048
S.	Habitat diversity	-0.359	0.278	0.197
	Local AES	0.095	0.057	0.099
	Landscape AES	-0.130	0.067	0.054
	Interaction AES	-0.013	0.048	0.794
SD	**Habitat diversity**	**0.780**	**0.275**	**0.005**
	Local AES	0.083	0.094	0.379
	Landscape AES	-0.126	0.098	0.201
	Interaction AES	-0.200	0.108	0.065
SG	Habitat diversity	0.639	0.613	0.297
	Local AES	-0.287	0.224	0.201
	Landscape AES	0.041	0.225	0.854
	Interaction AES	-0.243	0.250	0.332
ST	**Habitat diversity**	**1.581**	**0.275**	**<0.001**
	Local AES	0.008	0.079	0.916
	Landscape AES	-0.026	0.080	0.748
	Interaction AES	0.028	0.077	0.711
TS	Habitat diversity	-2.614	1.072	0.015
	Local AES	-0.291	0.528	0.582
	Landscape AES	0.181	0.450	0.687
	Interaction AES	0.594	0.554	0.284
WH	Habitat diversity	-0.368	0.346	0.288
	Local AES	0.220	0.094	0.019
	Landscape AES	-0.056	0.098	0.566
	Interaction AES	-0.170	0.104	0.102
WP	**Habitat diversity**	**1.123**	**0.268**	**<0.001**
	Local AES	0.026	0.082	0.751
	Landscape AES	-0.106	0.080	0.187
	Interaction AES	-0.010	0.076	0.891
Y.	Habitat diversity	-0.084	0.526	0.873
	Local AES	0.026	0.119	0.824
	Landscape AES	0.160	0.140	0.254
	Interaction AES	0.133	0.119	0.266
YW	Habitat diversity	-1.441	0.770	0.061
	Local AES	0.123	0.308	0.689
	Landscape AES	**-0.663**	**0.235**	**0.005**
	Interaction AES	-0.137	0.257	0.593

Table 5.6.6 continued Results for bird single species models. Strong relationships with $P < 0.01$ are highlighted in bold. See Table 5.6.5 for details of species codes.

There was weak indication of positive relationships with the local AES gradient ($P < 0.05$) for Reed Bunting and Whitethroat abundance. The relationships estimated suggest that, for an increase in local AES gradient score from 250 to 10,000, we would expect an average increase across all NCAs of two Reed Buntings per 3km of transect, and an average increase across five NCAs of three Whitethroats per 3km of transect.

Both Goldfinch and Yellow Wagtail abundances were negatively associated with landscape AES gradients, with Yellow Wagtail abundance showing a strong relationship (*P* = 0.005). Estimated relationships suggest that, for an increase in landscape AES score from 250 to 10,000, we would expect an average decrease of three Yellow Wagtail per 3km of transect across three NCAs, and an average decrease of one Goldfinch across all six NCAs. Greenfinch abundance and Reed Bunting abundance exhibited interaction effects; the association was positive for Greenfinch and negative for Reed Bunting. There were no other strong relationships detected between individual species abundance and AES gradients (Table 5.6.6).

The only strong relationship observed between species abundances and AES gradients was for Yellow Wagtail abundance and landscape AES score (estimate = -0.633, *P* = 0.005; Figure 5.6.4). However, we note that this species was only observed in three NCAs, so model results should be treated with caution due to the random effect structure. The relationship was maintained (estimate = -0.553, *P* = 0.009) following removal of an outlying count (Yellow Wagtail abundance = 39; Figure 5.6.4). In Figure 5.6.5, we can see that the majority of non-zero counts (excluding the outlying count) for Yellow Wagtail were from the Fens NCA, with only five of the 51 counts from the South Suffolk NCA. Note that this species is commonly associated with particular spring-sown broadleaf arable crops in landscapes like the Fens, as opposed to semi-natural wet meadows, which is probably the most relevant AES option in landscapes with more grassland. Therefore, much of the AES gradient in better areas for Yellow Wagtail is not relevant to the species.

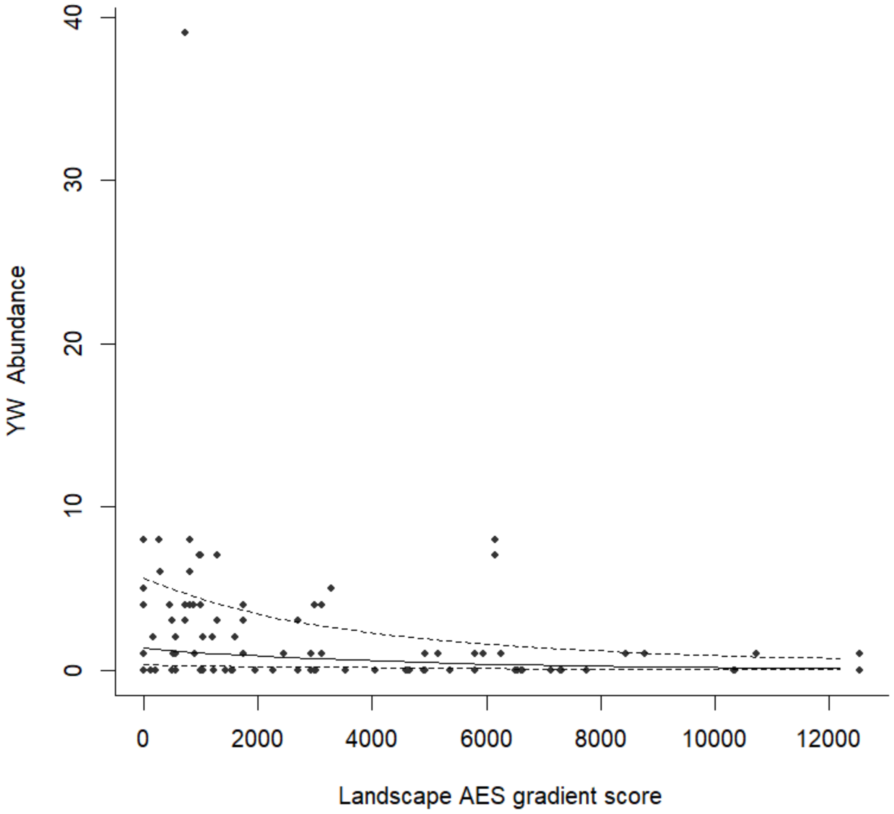


Figure 5.6.4 Relationship between landscape level AES score and Yellow Wagtail abundance across all four years for each survey square. The fitted line indicates the estimated slope of the relationship, with 95% confidence intervals around this slope indicated by dotted lines. There was a strong indication of a relationship (*P* = 0.005).

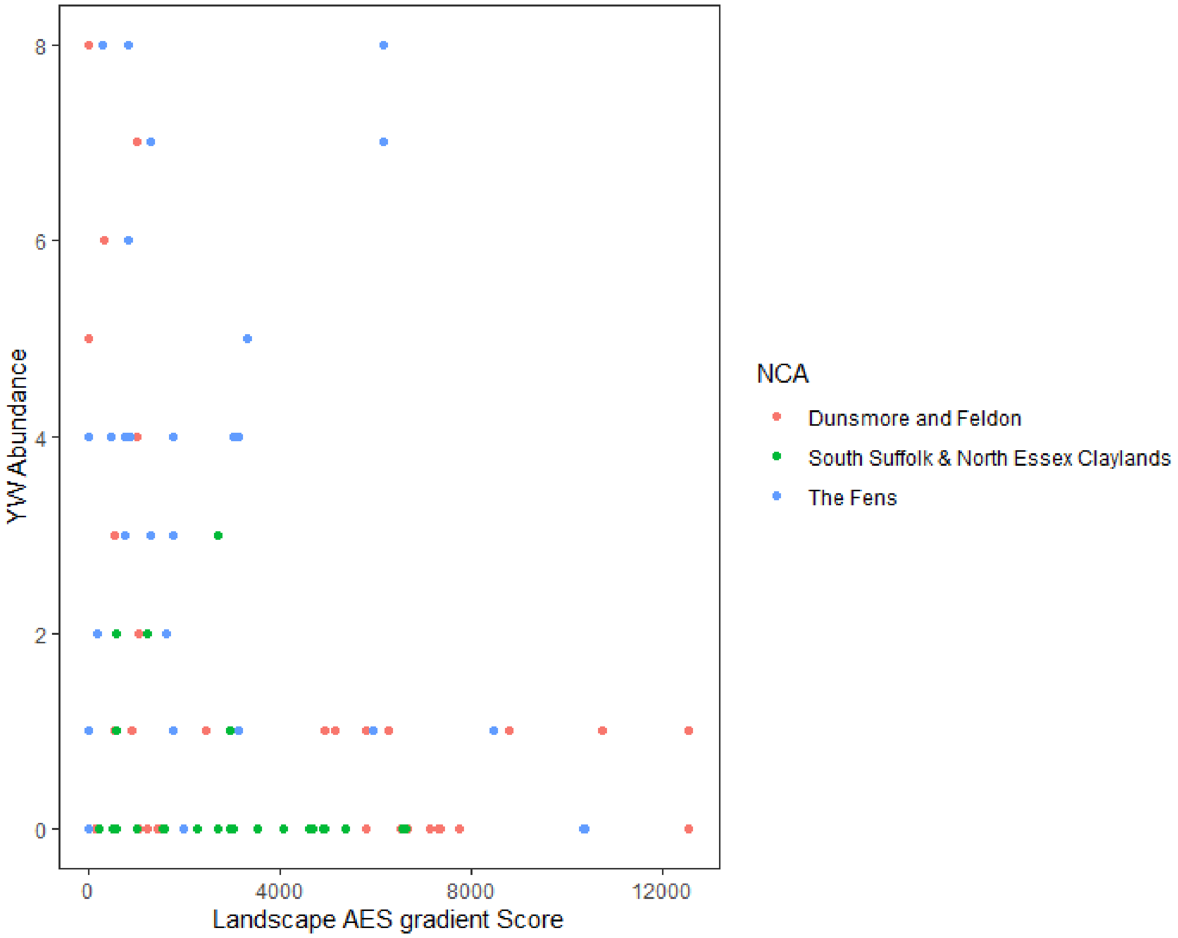


Figure 5.6.5 Square- and year-specific counts of Yellow Wagtail counts, indexed by NCA. Note that this species was only recorded in three NCAs.

5.6.1.5 Is diet preference associated with AES gradients?

In both the invertebrate and seed groups, there was indication of a positive effect of local AES gradient on species abundance (*P* = 0.040 and *P* = 0.046, respectively; Table 5.6.7). For seed-eaters, there was a strong negative relationship between area of woodland habitat and species abundance (*P* = 0.010), and a strong positive association between habitat diversity and species abundance across all NCAs (*P* <0.001; Table 5.6.7). The relationships estimated suggest that, for an increase in local AES gradient score from 250 to 10,000, we would expect an average increase in abundance across all NCAs of 18 individuals per 3km of transect of invertebrate eating species, and nine individuals of seed-eating species. However, in lowland-only analyses across both groups, there were no evident effects.

Table 5.6.7 Relationships between diet group abundance responses, AES gradients and habitat variables. Strong relationships with *P* < 0.01 are highlighted in bold.

Response Group	**Predictor**	**NCA**	**Estimate**	**SE**	**p-value**
Invertebrate	Improved grassland	All	0.253	0.217	0.244
	Habitat diversity	All	0.184	0.117	0.115
	Woodland	All	-1.036	0.505	0.040
	Local AES	All	0.066	0.032	0.040
	Landscape AES	All	-0.041	0.031	0.178
	Interaction AES	All	-0.036	0.029	0.211
	Improved grassland	Lowland	0.432	0.298	0.147
	Habitat diversity	Lowland	-0.007	0.131	0.959
	Local AES	Lowland	0.083	0.044	0.061
	Landscape AES	Lowland	-0.040	0.042	0.342
	Interaction AES	Lowland	-0.063	0.048	0.185
Seed	Improved grassland	All	0.009	0.261	0.973
	Habitat diversity	**All**	**0.506**	**0.144**	**<0.001**
	Woodland	**All**	**-1.599**	**0.620**	**0.010**
	Local AES	All	0.074	0.037	0.046
	Landscape AES	All	-0.061	0.036	0.086
	Interaction AES	All	-0.027	0.033	0.410
	Improved grassland	Lowland	0.035	0.300	0.908
	Habitat diversity	Lowland	0.197	0.170	0.247
	Local AES	Lowland	0.026	0.046	0.567
	Landscape AES	Lowland	-0.003	0.044	0.938
	Interaction AES	Lowland	-0.014	0.049	0.784

5.6.2 *Winter bird surveys*

5.6.2.1 Summary of winter bird surveys

In total, 128 bird species were recorded across all six NCAs in the four years of winter surveying. The highest number of unique species was recorded in The Fens (81) in winter 2021, and the lowest in Dartmoor (61) in winter 2019 (Table 5.6.8). Fewer species were recorded 2017 due to incomplete surveying in the upland NCAs, and fewer species were observed in the uplands when surveyed.

Table 5.6.8 Total bird species recorded per NCA area.

	Total bird species recorded			
NCA	**2017**	**2018**	**2019**	**2020**
Dunsmore & Feldon	71	69	74	81
High Weald	68	69	74	74
South Suffolk	74	72	65	69
The Fens	79	80	79	81
Dartmoor	NA	67	61	67
Yorkshire Dales	NA	68	70	70
All	96	107	112	117

5.6.2.2 Are there relationships between birds, AES gradients and habitat?

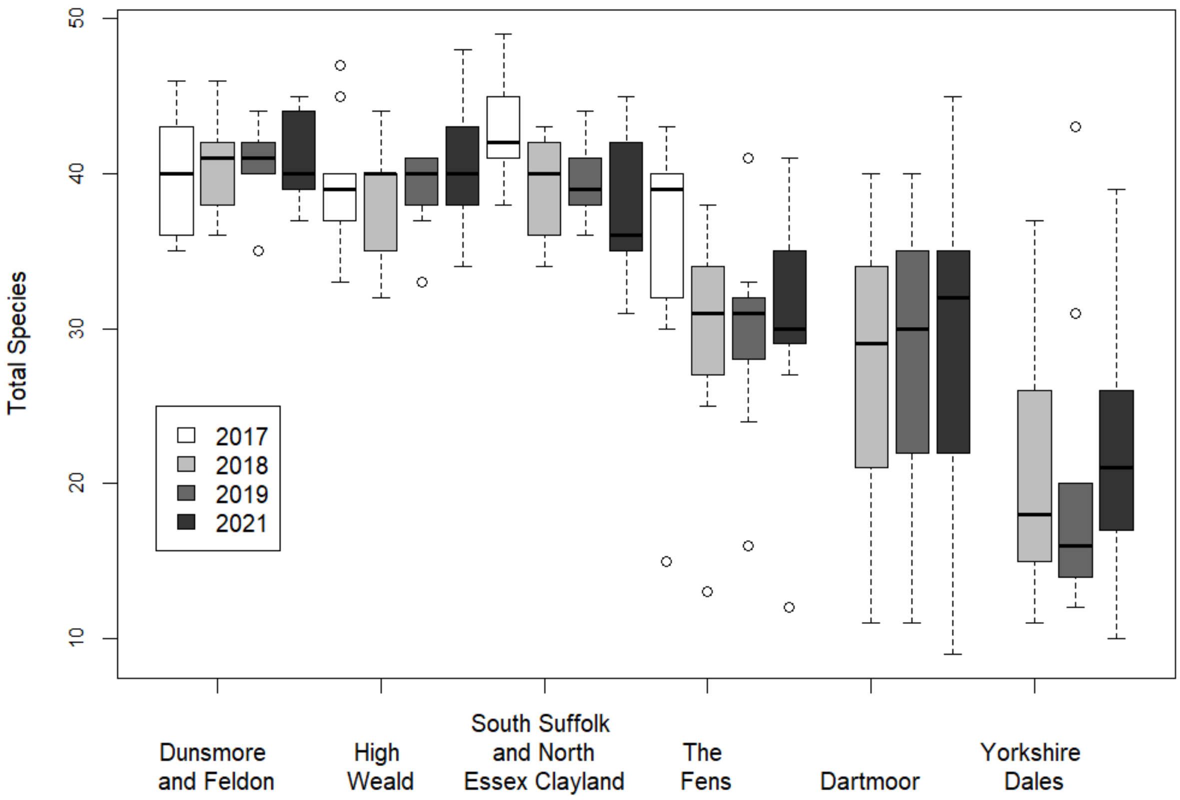


Figure 5.6.6 Variation in winter bird species richness between NCA and survey year.

There were 86 species included in analysing the responses to AES gradients. Bird species richness per survey square varied between NCAs, with the largest range of species observed in the upland NCAs (Figure 5.6.6).

Table 5.6.9 Relationships between bird responses, AES gradients and habitat variables. Strong relationships with $P < 0.01$ are highlighted in bold.

Response	Predictor	NCA	Estimate	SE	p-value
Abundance	**Improved grassland**	**All**	**1.584**	**0.516**	**0.002**
	Habitat diversity	All	0.088	0.277	0.751
	Woodland	All	1.336	1.218	0.272
	Local AES	All	0.062	0.071	0.385
	Landscape AES	All	0.023	0.070	0.737
	Interaction AES	All	-0.099	0.062	0.112
	Improved grassland	Lowland	0.737	0.425	0.083
	Habitat diversity	Lowland	-0.388	0.172	0.024
	Local AES	Lowland	0.142	0.066	0.031
	Landscape AES	Lowland	-0.029	0.065	0.658
	Interaction AES	Lowland	-0.157	0.076	0.040
Richness	Improved grassland	All	0.397	0.193	0.040
	Habitat diversity	All	0.269	0.110	0.015
	Woodland	All	0.676	0.474	0.154
	Local AES	All	0.017	0.027	0.528
	Landscape AES	All	-0.008	0.026	0.769
	Interaction AES	All	-0.019	0.024	0.425
	Improved grassland	Lowland	0.229	0.134	0.087
	Habitat diversity	**Lowland**	**0.215**	**0.071**	**0.003**
	Local AES	Lowland	0.027	0.021	0.197
	Landscape AES	Lowland	0.013	0.021	0.540
	Interaction AES	Lowland	-0.012	0.025	0.641
Diversity	Improved grassland	All	0.124	0.313	0.694
	Habitat diversity	All	0.180	0.167	0.284
	Woodland	All	0.761	0.732	0.304
	Local AES	All	-0.026	0.045	0.565
	Landscape AES	All	-0.027	0.044	0.535
	Interaction AES	All	-0.001	0.041	0.983
	Improved grassland	Lowland	0.388	0.224	0.103
	Habitat diversity	Lowland	0.351	0.089	0.013
	Local AES	Lowland	-0.012	0.039	0.757
	Landscape AES	Lowland	0.010	0.040	0.803
	Interaction AES	Lowland	-0.003	0.046	0.954

In analyses of total species abundance, there was evidence of a strong association with improved grassland (estimate = 1.584, $P = 0.002$) across all NCAs. In lowland-only analyses, there was an indication of a positive relationship between total bird abundance and local AES gradient (estimate = 0.142, $P = 0.031$; Figure 5.6.7), a negative relationship with habitat diversity, and a negative interaction term between the local and landscape AES gradients

(Table 5.6.9). The estimated relationship suggests that for an increase in local AES gradient score from 250 to 10,000, we would expect an average increase across NCAs of 284 individual birds per 3km of transect. However, the confidence intervals in Figure 5.6.7 indicate significant uncertainty around the abundance of birds, so far smaller or far higher differences are possible. After removal of the outlying lowland square with high AES gradient, evidence of the relationship between bird species abundance and local AES was not observed (estimate = 0.050, *P* = 0.523; Figure 5.6.7).

Habitat diversity was positively associated with bird species richness both in all NCAs and in lowland only analyses (Table 5.6.9). In addition, in all NCA analyses, there was strong evidence of a positive relationship with improved grassland. No other strong associations were detected, including no relationships with the AES gradients (Table 5.6.9).

Bird species diversity showed indication of a positive association with habitat diversity in lowland only analyses (estimate = 0.351, *P* = 0.013; Table 5.6.9), but no other associations were found both across all NCAs and within lowland only areas.

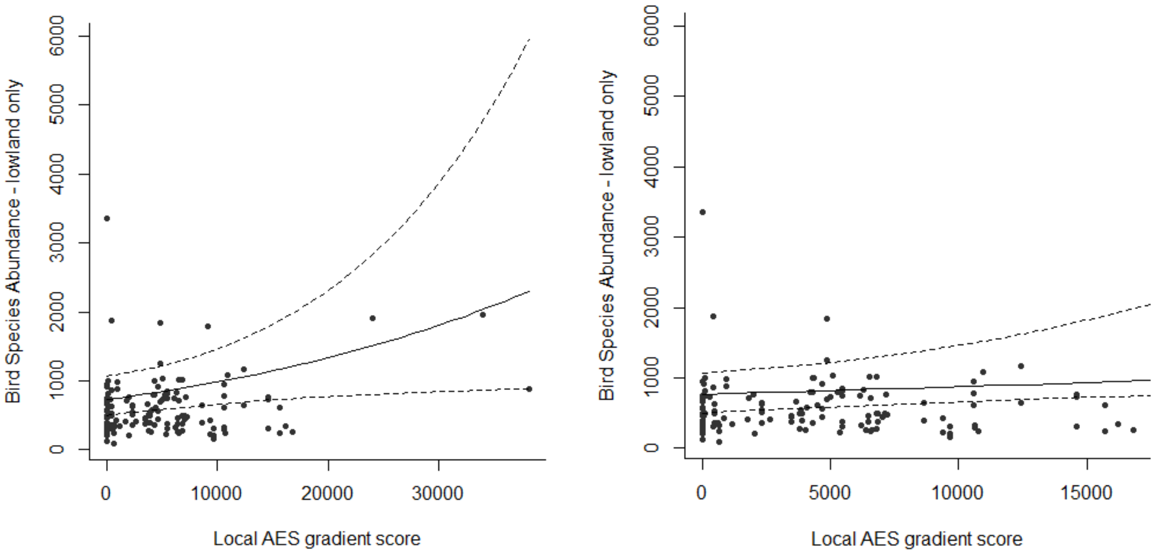


Figure 5.6.7 Relationships between bird abundance and local gradient scores across all four survey years in lowland NCAs only (n = 144). The fitted line indicates the estimated slope of the relationship, with confidence intervals around this slope indicated by dotted lines. There was evidence of a relationship with local level AES in all lowland NCAs (*P* = 0.031), but not when the outlying lowland square was removed.

5.6.2.3 Red-listed bird species

From the full list of 86 species, 24 Red-listed species and 24 Amber species were observed over the four years of surveying (Table 5.6.10).

Table 5.6.10 Numbers of BoCC5 species per NCA and year for winter birds.

	2017			**2018**			**2019**			**2021**		
NCA	**R**	**A**	**G**	**R**	**A**	**G**	**R**	**A**	**G**	**R**	**A**	**G**
Dunsmore & Feldon	13	16	27	13	16	27	13	17	26	13	16	34
High Weald	13	17	28	11	16	29	12	17	25	11	16	32
South Suffolk	13	17	26	14	16	28	12	16	27	13	15	28
The Fens	16	18	26	13	18	25	12	18	26	13	18	26
Dartmoor	NA	NA	NA	13	16	28	11	16	27	11	17	28
Yorkshire Dales	NA	NA	NA	11	17	26	12	17	27	12	17	26
All	**18**	**20**	**33**	**19**	**23**	**35**	**21**	**23**	**34**	**21**	**23**	**37**

There was evidence of a strong positive association between improved grassland and Red List abundance across all NCAs, whilst for lowland only NCAs there was indication of a negative interaction, along with a trend for a positive local gradient effect. There was a strong relationship between Red List richness and habitat diversity across all NCAs, but there were no observed relationships in lowland-only analyses. No relationships with the AES gradients were detected (Table 5.6.11).

Table 5.6.11 Relationships between Red List bird responses and habitat variables. Strong relationships with $P < 0.01$ are highlighted in bold.

Response	Predictor	NCA	Estimate	SE	p-value
Red List Abundance	**Improved grassland**	**All**	**2.022**	**0.722**	**0.005**
	Habitat diversity	All	0.392	0.398	0.324
	Woodland	All	0.302	1.729	0.862
	Local AES	All	0.051	0.100	0.610
	Landscape AES	All	0.106	0.102	0.298
	Interaction AES	All	-0.036	0.089	0.686
	Improved grassland	Lowland	0.791	0.528	0.134
	Habitat diversity	Lowland	-0.415	0.316	0.188
	Local AES	Lowland	0.143	0.083	0.086
	Landscape AES	Lowland	-0.003	0.080	0.967
	Interaction AES	Lowland	-0.200	0.095	0.036
Red List Richness	Improved grassland	All	0.118	0.229	0.606
	Habitat diversity	**All**	**0.332**	**0.129**	**0.010**
	Woodland	All	-0.689	0.558	0.217
	Local AES	All	0.009	0.035	0.801
	Landscape AES	All	-0.030	0.036	0.396
	Interaction AES	All	-0.001	0.037	0.971
	Improved grassland	Lowland	0.002	0.251	0.993
	Habitat diversity	Lowland	0.086	0.147	0.557
	Local AES	Lowland	0.001	0.039	0.974
	Landscape AES	Lowland	-0.011	0.040	0.779
	Interaction AES	Lowland	0.008	0.047	0.862

5.6.2.4 Farmland Bird Indicator (FBI) species and other individual species

We explored associations with AES management at the species-level; with methods as for summer analyses (see Section 5.6.1.3). Three of the 19 FBI species (Turtle Dove, Whitethroat and Yellow Wagtail) were not observed over the winter surveying period. In total there were 21 species of interest (Table 5.6.12).

Table 5.6.12 Species analysed for individual species abundance. Species in bold indicate FBI species and those with an asterisk indicate (rare) species with high numbers of zero-counts.

Species code	Species name	# NCA	Total records	Zero records	Non-zero records	% Non-zero
BF	Bullfinch	6	198	86	112	57
CB	Corn Bunting	2	72	60	12	17 *
CH	Chaffinch	6	198	27	171	86
D.	Dunnock	6	198	34	164	83
GO	Goldfinch	6	198	48	150	76
GR	Greenfinch	5	171	73	98	57
HS	House Sparrow	6	198	89	109	55
JD	Jackdaw	6	198	51	147	74
K.	Kestrel	6	198	58	140	71
L.	Lapwing	5	171	112	59	35 *
LI	Linnet	6	198	100	98	49 *
MP	Meadow Pipit	6	198	42	156	79
P.	Grey Partridge	3	108	77	31	29 *
RB	Reed Bunting	5	171	57	114	67
S.	Skylark	6	198	43	155	78
SD	Stock Dove	6	198	67	131	66
SG	Starling	6	198	53	145	73
ST	Song Thrush	6	198	51	147	74
TS	Tree Sparrow	3	108	96	12	11 *
WP	Woodpigeon	6	198	24	174	88
Y.	Yellowhammer	5	171	55	116	68

Due to convergence warnings in model fitting, it was not possible to analyse the abundances of Kestrel, Lapwing and Tree Sparrow. Other convergence warnings were present in model fitting for some species, but alternative optimizing methods removed warnings. Due to low detectability, model results for Corn Bunting, Linnet and Grey Partridge should be treated with caution.

Table 5.6.13 Results for bird single species models. Strong relationships with *P* < 0.01 are highlighted in bold.

Response	**Predictor**	**Estimate**	**SE**	**p-value**
BF	Habitat diversity	1.028	0.529	0.052
	Local AES	-0.015	0.134	0.912
	Landscape AES	0.196	0.132	0.139
	Interaction AES	-0.118	0.133	0.375
CB	Habitat diversity	-4.476	3.463	0.196
	Local AES	0.320	1.937	0.869
	Landscape AES	-0.290	1.284	0.822
	Interaction AES	-0.001	1.901	1.000
CH	Habitat diversity	1.056	0.530	0.047
	Local AES	-0.051	0.135	0.709
	Landscape AES	-0.043	0.142	0.765
	Interaction AES	-0.195	0.118	0.098
D.	Habitat diversity	0.566	0.240	0.018
	Local AES	-0.063	0.066	0.347
	Landscape AES	-0.018	0.065	0.789
	Interaction AES	0.021	0.063	0.737
GO	**Habitat diversity**	**1.184**	**0.432**	**0.006**
	Local AES	0.185	0.145	0.200
	Landscape AES	-0.280	0.148	0.058
	Interaction AES	-0.315	0.161	0.051
GR	Habitat diversity	1.435	0.753	0.057
	Local AES	-0.220	0.214	0.304
	Landscape AES	-0.459	0.221	0.038
	Interaction AES	0.402	0.190	0.034
HS	Habitat diversity	0.823	0.674	0.222
	Local AES	-0.295	0.297	0.320
	Landscape AES	-0.282	0.204	0.166
	Interaction AES	-0.224	0.222	0.313
JD	Habitat diversity	1.399	0.656	0.033
	Local AES	0.262	0.213	0.220
	Landscape AES	-0.026	0.218	0.904
	Interaction AES	-0.260	0.206	0.207
LI	Habitat diversity	0.326	0.956	0.733
	Local AES	0.114	0.301	0.705
	Landscape AES	-0.245	0.299	0.414
	Interaction AES	0.494	0.291	0.090
MP	Habitat diversity	-0.630	0.362	0.082
	Local AES	0.246	0.172	0.153
	Landscape AES	0.261	0.149	0.079
	Interaction AES	-0.137	0.148	0.353
P.	Habitat diversity	-0.332	2.180	0.879
	Local AES	0.239	0.952	0.801
	Landscape AES	0.220	0.781	0.779
	Interaction AES	-0.289	0.664	0.663

Response	Predictor	Estimate	SE	p-value
RB	Habitat diversity	-1.854	0.728	0.011
	Local AES	**0.752**	**0.232**	**0.001**
	Landscape AES	-0.061	0.247	0.805
	Interaction AES	-0.432	0.228	0.058
S.	Habitat diversity	-1.111	0.556	0.046
	Local AES	0.292	0.157	0.063
	Landscape AES	0.149	0.167	0.373
	Interaction AES	-0.050	0.133	0.708
SD	**Habitat diversity**	**1.130**	**0.418**	**0.007**
	Local AES	0.169	0.152	0.266
	Landscape AES	-0.267	0.143	0.061
	Interaction AES	0.097	0.157	0.534
SG	Habitat diversity	1.733	0.724	0.017
	Local AES	-0.465	0.229	0.043
	Landscape AES	0.292	0.251	0.245
	Interaction AES	0.267	0.239	0.264
ST	Habitat diversity	0.683	0.281	0.015
	Local AES	0.086	0.074	0.242
	Landscape AES	-0.005	0.076	0.945
	Interaction AES	-0.103	0.078	0.185
WP	**Habitat diversity**	**1.526**	**0.430**	**<0.001**
	Local AES	-0.065	0.145	0.652
	Landscape AES	-0.234	0.142	0.099
	Interaction AES	-0.078	0.135	0.563
Y.	Habitat diversity	-0.819	0.824	0.320
	Local AES	-0.013	0.257	0.959
	Landscape AES	-0.023	0.255	0.928
	Interaction AES	0.165	0.253	0.514

Table 5.6.13 continued Results for bird single species models. Strong relationships with $P < 0.01$ are highlighted in bold.

From the 18 single species models there were ten species with strong associations with habitat diversity. Relationships for Chaffinch, Dunnock, Goldfinch, Jackdaw, Stock Dove, Starling, Song Thrush and Woodpigeon were positive, whilst those for Reed Bunting and Skylark were negative (Table 5.6.13). Both Reed Bunting and Starling displayed associations with local AES gradient. The evidence for a relationship for Reed Bunting was strong (estimate = 0.752, $P = 0.001$), and for Starling there was indication of an effect (estimate = -0.465, $P = 0.043$; Table 5.6.13). Estimated relationships suggest that, for an increase in local AES score from 250 to 10,000, we would expect an average increase of 25 Reed Buntings per 3km of transect across five NCAs, and an average decrease of four Starlings per 3km of transect across all six NCAs. However, we must note that confidence intervals for these predictions were very wide, so actual numbers could be much lower or much higher.

There was evidence of a negative association between Greenfinch abundance and landscape AES gradient (estimate = 0.459, $P = 0.038$), and indication of a positive interaction (estimate = 0.402, $P = 0.034$; Table 5.6.13). Similarly for Goldfinch, there was some evidence for a negative relationship with landscape AES (estimate = -0.280, $P = 0.058$) and a negative interaction (estimate = -0.315, *P* = 0.051). Model results for all other species showed no association to AES gradients (Table 5.6.13).

5.6.2.5 Are diet trait groups associated with AES?

In the invertebrate-feeding species group, there was a strong relationship between improved grassland and abundance across all NCAs and in lowland only areas, whilst there was indication of an association between habitat diversity and abundance in the lowland squares. There was no evidence of relationships for the seed-eating group of species (Table 5.6.14). Note that, for lowland NCAs only, both the interaction for invertebrate-feeders (negative, *P* = 0.055) and the local AES gradient for seed-eaters (positive, *P* = 0.058; Table 5.6.14) showed some indication of an effect.

Table 5.6.14 Relationships between diet group responses, AES gradients and habitat variables. Strong relationships with *P* < 0.01 are highlighted in bold.

Response Group	Predictor	NCA	Estimate	SE	p-value
Invertebrate	**Improved grassland**	**All**	**2.233**	**0.628**	**<0.001**
	Habitat diversity	All	-0.188	0.334	0.574
	Woodland	All	1.932	1.501	0.198
	Local AES	All	0.046	0.086	0.589
	Landscape AES	All	0.054	0.084	0.520
	Interaction AES	All	-0.076	0.074	0.302
	Improved grassland	**Lowland**	**1.745**	**0.532**	**0.001**
	Habitat diversity	Lowland	-0.418	0.205	0.041
	Local AES	Lowland	0.151	0.093	0.104
	Landscape AES	Lowland	0.018	0.095	0.851
	Interaction AES	Lowland	-0.197	0.102	0.055
Seed	Improved grassland	All	0.725	0.487	0.137
	Habitat diversity	All	0.398	0.258	0.124
	Woodland	All	1.194	1.105	0.280
	Local AES	All	0.108	0.070	0.125
	Landscape AES	All	-0.099	0.066	0.134
	Interaction AES	All	-0.064	0.062	0.299
	Improved grassland	Lowland	0.354	0.513	0.490
	Habitat diversity	Lowland	0.025	0.286	0.929
	Local AES	Lowland	0.154	0.081	0.058
	Landscape AES	Lowland	-0.087	0.075	0.243
	Interaction AES	Lowland	-0.059	0.087	0.503

5.6.3 Discussion of bird results

Birds respond to the environment at large spatial scales, reflecting their mobility and use of different habitats for nesting, singing and feeding, for example, as well as showing species-specific specialisation to the broad range of features in farmed landscapes: responses to in-field features are weaker than those to field boundary structures and gross landscape character (Siriwardena et al., 2012). The expected and potential impact of AES management is therefore to modify the response to overall landscape type. The results of this project reflect this general pattern: relationships with habitat diversity and land cover variables tended to be stronger than those with the AES gradients. Nevertheless, there was some, limited evidence for positive associations between AES management and the bird community.

No individual bird community measures were strongly related to the AES gradients, but there were weak, positive associations with local-scale AES for abundance in the winter, species richness in the winter and Red-List species abundance in winter. There was also some evidence for positive associations with the spring abundance of breeding season invertebrate feeders and winter seed-eaters, with weak evidence that the seed-eater relationship was also found in winter. There was no evidence for effects of the landscape-scale gradient and only further, weak, positive interactions between the scales for overall and Red-List abundance in winter. There was no evidence for negative relationships. These results are not definitive, because the evidence is not strong and there are, fundamentally, just three independent tests involve, involving spring and winter abundance, and spring richness. However, the patterns suggest a positive effect of local-scale (1km square) AES and no effect at the landscape scale.

Considering the abundance of individual species, there was little evidence for any real AES effect: the only strong relationship involved Yellow Wagtail and the landscape-level gradient, and is unlikely to reflect a real AES influence. Otherwise, there was a mixture of weak, positive (for Whitethroat and Reed Bunting) and negative (for Goldfinch, Greenfinch and Stock Dove) associations, in the breeding season and/or in winter, as well as two, weak, interactions in the data for each season. Given the number of tests conducted at the species level and the lack of ecological cohesiveness in these results (such as a shared pattern among seed-eaters), there can be little confidence that these patterns do not show spurious, chance results. Note that species-level relationships with AES may tend to be obscured by the use of gradients that include a wide range of management options that will not all be relevant to any given species and the small sample size: local non-AES effects on counts have an increasing potential effect on the observable relationships as sample size falls. Other studies that have found positive effects of AES on bird species have generally considered temporal change in abundance, as measured at an appropriate scale, with highly variable benefits across different option types (e.g. Baker et al. 2012, Walker et al. 2018). The biggest benefits have involved in-field options such as unsprayed over-winter stubbles, or whole-farm comparisons including such options. Here, these options were rare in the sample and they contributed little to the AES gradients that were found, giving little opportunity to detect their effects. Further, it is to be expected that spatial responses to AES management may be weaker than temporal ones, as noted above. Previous work has found positive spatial associations with field boundary and margin management for certain farmland species, but via analyses at the habitat patch scale, rather than the 1km-square scale (Davey et al. 2010). Planned analyses using the data from this project at this scale should provide more power to detect such patterns, while the intended repeat of the surveys to measure medium-term change should also deliver more definitive evidence of responses that are relevant to bird population change.

It is surprising that the community-level relationships with birds are at the local scale alone, rather than at least some being at the landscape scale. Given the mobility of birds, especially between seasons (e.g. Siriwardena et al., 2007), we would expect at least some dependence on the wider landscape, such as due to management of wintering habitats for seed-eaters affecting breeding abundance. This may indicate that the results are more reflective of background habitat structural factors than AES management per se, but we also expect the latter to affect changes in abundance over time rather than purely spatial variation in abundance. These effects can only be assessed using data from a repeat survey period and a comparison with the data that are described here.

5.7 Bats

5.7.1 Summary of bat surveys

5.7.1.1 Bat richness

Over the course of the three sample years, across all NCAs, 16 bat species were detected. Six species were too scarce to include in any formal analysis of activity at the species level (Bechstein's *Myotis bechsteinii,* Alcathoe *Myotis alcathoe,* Grey Long-eared *Plecotus australis*, Greater Horseshoe and Lesser Horseshoe Bats, and Nathusius' Pipistrelle). Among the 10 species with larger and more widely distributed data sets, eight were detected in all six NCAs, while the Yorkshire Dales NCA lies beyond the current distributional range of Serotine and Barbastelle. Of these species, the total data set was heavily dominated by Common Pipistrelle, which accounted for over 76% of all bat pass records and was recorded at least once at all detector locations in all survey squares. The sampling activity and species richness data per NCA are summarised in Table 5.7.1. Richness data are also summarised by detector location within a square. In practice, the two paired detectors 1 and 2 were not always aligned to AES and non-AES habitats respectively (43% of 162 pairs), both according to the original design (in squares with zero AES) and because fieldworkers had to place detectors carefully with respect to other issues, for example to avoid damage or theft.

Species richness varied considerably between NCAs, but little between years (with the exception of the High Weald in 2021 when three additional rarer bats species were detected; Figure 5.7.1). It is also noteworthy that richness varied relatively little between squares within NCAs (see error bars in Figure 5.7.1). Bat richness was notably higher at lower latitudes, reflecting climate effects on species' ranges.

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Table 5.7.1 Summary table showing the final sampling rate for the bat detectors in each year for each NCA and the total range of bat species detected in each NCA. The final two columns show the detection rate, that is, the average number of species detected each night within a survey square at each of two paired detectors (termed Box 1 and Box 2). In the end, 43% of paired detectors were arranged like this, while, for 28%, both detectors were adjacent to AES habitat and, for 29%, both detectors were adjacent to non-AES habitat. Box data were pooled by location with respect to AES habitat before summaries were made.

National Character Area	**1-km squares sampled**	**Months sampled (May to August: aka 'visits')**	**Mean nights sampled per square (rounded)**	**Year**	**Total species count**	**Mean species richness value per detector, per night**	
						Boxes adjacent to AES options (where possible)	**Boxes adjacent to non-AES habitat (where possible)**
Yorkshire Dales	9	4	18	2018	7	6.00	5.25
	9	4	26	2019		6.71	6.00
	9	4	25	2021		7.00	6.50
The Fens	9	4	16	2018	11	6.00	6.71
	9	4	24	2019		7.00	7.50
	9	4	25	2021		7.66	8.10
Dunsmore & Feldon	9	4	25	2018	11	8.0	8.25
	9	4	22	2019		9.71	9.33
	9	4	26	2021		9.00	9.12
Suffolk & North Essex	9	4	22	2018	11	6.28	6.14
	9	4	21	2019		9.61	9.31
	9	4	22	2021		7.28	7.14
High Weald	9	4	24	2018	14	8.16	8.00
	9	4	16	2019		9.97	9.38
	9	4	23	2021		9.17	9.00
Dartmoor	9	4	22	2018	13	8.50	7.25
	9	4	30	2019		10.7	9.75
	9	4	27	2021		9.80	8.31
				Mean (sd)		**8.14 (1.4)**	**7.84 (1.3)**

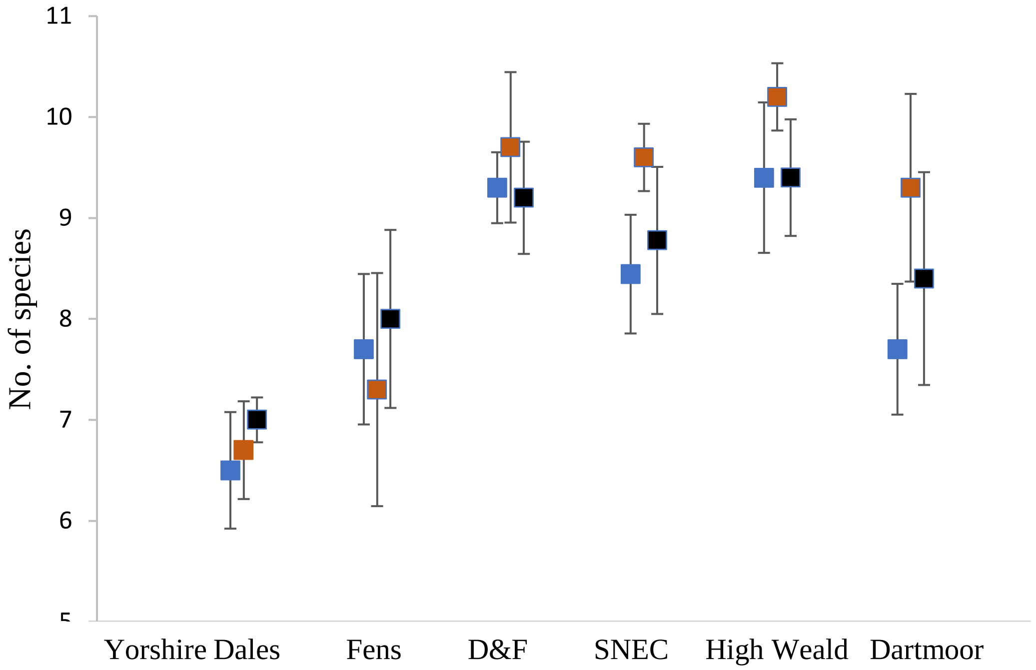

Figure 5.7.1 The distribution of annual mean species richness values per survey square (with 95% CI) between the six NCAs (2018 = blue, 2019 = red and 2021 = black). A predictable latitudinal reduction in the number of species encountered is range-related but note that the detection rate of different species, per night in Table 5.7.1, was lowest in The Fens landscape. Key: D&F = Dunsmore & Feldon NCA, SNEC = Suffolk & North Essex NCA.

5.7.1.2 Overall bat encounter rates

Total encounters are summarised in Table 5.7.2, within which there were sufficient data available for ten species to feature in the analysis of individual species responses to AES and six rarely encountered species that were not analysed at the specie level.

Table 5.7.2 Encounter rate (from total number of checked recordings across all nights of sampling from the original data set) for 16 bats species recorded during the survey, combining all years 2018, 2019, 2021, and all 54 survey squares. The true relationship between total recordings and true abundance is not known and there are strong differences in detectability between species, but the total recordings and the range of each species show the scale of the data set.

Species	**Total no. recordings**	**Total no. of 1-km squares**
Common Pipistrelle *Pipistrellus pipistrellus*	778,841	54
Soprano Pipistrelle *Pipistrellus pygmaeus*	178,575	54
Noctule *Nyctalus noctula*	61,455	54
Leisler's Bat *Nyctalus leisleri*	3,567	42
Daubenton's Bat *Myotis daubentonii*	26,528	54
Natterer's Bat *Myotis nattereri*	27,047	54
Whiskered/Brandt's Bats *Myotis mystacinus/brandtii*	34040	53
Barbastelle Bat *Barbastella barbastellus*	11,885	29
Brown Long-eared Bat *Plecotus auritus*	13,973	54
Serotine *Eptesicus serotinus*	1,306	31
Rarer bats		
Nathusis' Pipistrelle *Pipistrellus nathusii*	224	10
Lesser Horseshoe Bat *Rhinolophus hipposideros*	415	10
Greater Horseshoe Bat *Rhinolophus ferrumequinum*	538	9
Grey Long-eared Bat *Plecotus australis*	2	1
Alcathoe Bat *Myotis alcathoe*	1	1
Bechstein's Bat *Myotis bechsteinii*	4	2

5.7.2 Are there relationships between bats and AES gradients?

Analyses with respect to AES gradient score values were conducted with data summarised at the square level across each year, the same structure as the insect and bird analyses reported previously in Section 5. Analyses were conducted for all NCAs and for the four lowland NCAs only. A within-square analysis of AES versus non-AES was not conducted but remains a possibility for future work. The two detectors therefore effectively operated as paired sampling points within each survey square for better representation.

An additional analysis was conducted on data gathered at the survey sampling level (presence-absence per night) with data from the two detectors aggregated, details are in Appendix A6. The latter aggregation was analysed by considering the replication in the data explicitly using a repeated measures structure.

5.7.2.1 Species richness and diversity responses

Table 5.7.3 Bat species richness responses to AES score a) species richness (Poisson error term), b) Shannon Diversity response variable (normal error term). Relationships where *P* < 0.01 are highlighted in bold.

a. Species richness	**All six NCAs**			**Four lowland NCAs**		
	Sign	**Estimate**	***P***	**Sign**	**Estimate**	***P***
Local AES score	+	0.011	0.71	-	0.009	0.94
Landscape AES score	+	0.008	0.75	-	0.013	0.73
Local*landscape score	-	0.02	0.36	**-**	0.042	0.22
Botanical richness	+	**0.03**	**0.001**	+	0.052	0.25

b. Shannon diversity	**All six NCAs**			**Lowland NCAs only**		
		Estimate	***P***		**Estimate**	***P***
Local AES score	-	0.016	0.44	-	0.09	0.87
Landscape AES score	-	0.011	0.60	-	0.08	0.63
Local*landscape score	-	0.04	0.31	-	0.069	0.34
Botanical richness	+	0.03	0.04	+	0.33	0.09

For bat species richness, summarised at the square and year level, there was no evidence for a response to AES gradients at either the local or landscape scale or when background habitat or plant community variables were included (Table 5.7.3 shows the latter model). There was, similarly, no evidence for effects of AES gradients on Shannon diversity (albeit calculated using the sum of a species' presences across each sampling night, rather than true abundance data which was not known; Table 5.7.3). Note that there was some evidence for effects of background habitat and plant community variables, suggesting that the approach had sufficient power, in principle, to detect such habitat influences (Table 5.7.3a).

Strong evidence for responses in bat species richness to AES were only detected from the additional, repeated measures analysis of the data, conducted at the within square, per-night level of replication (see Appendix A6.1).

5.7.2.2 Activity responses – presence-absence by species

There was evidence for AES gradient effects on two individual species at the square level of replication (i.e. aggregated across nights per year as for the other taxa), with positive relationships with presence of Barbastelle and Daubenton's Bat at the landscape gradient scale (Table 5.7.5a), which was also found in analyses of lowland only NCAs (i.e. without Dartmoor; Table 5.7.5b). Although the response to landscape AES appears strong, the effect sizes are small. For Barbastelle, the slope represents an approximate 0.8% increase in the probability of the species being present across the entire landscape AES gradient score range or 0.7% increase across the range from 250 to 10,000 **(**for the full NCA set and the lowland NCA set respectively**).** For Daubenton's Bat, the slope represents an approximate 0.5% increase in the probability of the species being present across the landscape AES score range from 250 to 10,000. There was strong evidence for relationships with background habitat diversity effects for all bat species where models converged, with both sets of data (Table 5.7.5).

Strong evidence for responses by individual bat species to AES, especially at the landscape scale, were detected for a greater range of bat species from the additional, repeated measures, analysis of the data conducted at the within square, per-night level of replication (see Appendix A6.2).

Table 5.7.5 Species level GLIMMIX output for occurrence (presence) responses to AES scores at two scales (local and landscape). The full dataset includes all six NCAs (Table (a), but for Serotine and Barbastelle only the five ‘within-range’ NCAs) and (b) lowland NCA only analyses. AES variables were standardised and appropriate background variables were selected for each species’ model according to a preliminary analysis. For the background variables, the probability values are summarised as: * *P* < 0.05, ** *P* < 0.02, *** *P* < 0.001.

(a) All six NCAs

Bat species	**Local AES gradient score**		**Landscape AES gradient score**		**Local AES*Landscape interaction term**		**Background habitat variables**
	Est	*P*	Est	*P*	Est	*P*	
Barbastelle	0.17	0.38	**1.2**	**0.0001**	0.38	0.03	Bot-rich***
Daubenton’s	-0.13	0.21	**0.34**	**0.001**	-0.15	0.09	Hab-div***
Whiskered/ Brandt’s	Model did not converge						
Natterer’s	0.05	0.63	0.14	0.14	-0.003	0.97	Hab-div***
Leisler’s	0.21	0.18	-0.51	0.03	-0.13	0.44	Bot-rich***
Noctule	-0.033	0.71	0.029	0.75	-0.019	0.79	Hab-div***
Serotine	Model did not converge						
Common Pipistrelle	-0.12	0.11	0.07	0.36	0.07	0.29	Bot-rich** Hab-div
Soprano Pipistrelle	-0.01	0.28	0.08	0.40	0.09	0.23	Hab-div***, Bot-rich***
Brown Long-eared	0.01	0.88	-0.10	0.25	-0.05	0.53	Hab-div***, Bot-rich***

(b) Four lowland NCAs

Bat species	**Local AES gradient score**		**Landscape AES gradient score**		**Local AES*Landscape interaction term**		**Background habitat variables**
	Est	*P*	Est	*P*	Est	*P*	
Barbastelle	-0.34	0.28	**1.4**	**0.0001**	0.44	0.11	Hab-div***, Bot-rich**
Daubenton’s	-0.027	0.89	**0.40**	**0.003**	-0.08	0.53	Hab-div*** Water-linear
Whiskered / Brandt’s	Did not converge						
Natterer’s	-0.049	0.72	0.04	0.78	0.011	0.93	Hab-div***
Leisler’s	Did not converge						
Noctule	0.071	0.54	0.075	0.55	-0.21	0.10	Hab-div**
Serotine	Did not converge						
Common Pipistrelle	0.037	0.60	-0.005	0.93	-0.08	0.30	Hab-div* Bot-rich
Soprano Pipistrelle	0.058	0.69	-0.22	0.15	-0.36	0.03	Hab-div***, Bot-rich
Brown Long-eared	0.06	0.12	-0.13	0.30	-0.19	0.15	Hab-div***, Bot-rich

5.7.3 Do non-AES covariates explain bat responses?

Non-AES covariates are included in the models fitted above as co-variates, where they were found to be important in preliminary analyses. These patterns show that these background habitat variables were usually, if not always, much stronger influences on bat presence and species richness than the AES gradients.

5.7.4 Summary and discussion of bat results

5.7.4.1 Main analysis

This project presents the first application of static detector bat recording to a question involving a range of AES management options with large geographic representation, though Froidevaux et al. (2019) carried out work at a regional level targeting the implications just of hedge management for bats. The present study required the development of a novel and systematic field deployment regime that would suit the purpose of the large-scale monitoring of bat responses to environmental variables. As such, the strong response by bat species to the non-AES background variables was consistent with both expectation and with earlier studies (Froidevaux et al., 2019), and so demonstrates that the field methods used were effective for detecting habitat relationships. At the species level, strong evidence was found for positive relationships with AES at the landscape scale for Barbastelle and Daubenton’s bats, but no evidence was found for relationships with the AES gradients and either bat species richness or diversity. Effect sizes were small, at less than a 1% increase in the likelihood of a species being present in a 1km squares across the AES gradient range, suggesting that the provision of AES was probably only a marginal contributor to the presence of Barbastelle and Daubenton’s bats, and not a core driver.

5.7.4.2 Additional analyses, caveats and limitations

Marginal effects on the presence of organisms are difficult to detect in complex (‘noisy’) circumstances, without a high level of independent sampling replication to increase analytical power. Within the constraints of the existing project framework, one opportunity to explore further was to analyse bat responses at the within-year level of replication, while acknowledging important analytical caveats to this extra analysis (Appendix 6.3). By analysing data per-night, this disaggregated the data to increase replication rate, but meaning that the data are likely to include considerable autocorrelation where bat activity is similar from night to night. For mobile foraging bats, this is not as extreme as would be the case for breeding birds on territory, where the same individuals are present at that location throughout the season. For bats, this was accounted for here by using a formal repeated measures structure in models, but this may still have left pseudo-replication that then over-inflated the precision of parameter estimates.

Potentially, there is evidence from the additional analyses that a response to AES by some additional bat species (Natterer’s Bats, Whiskered/Brandt’s Bats and Noctule, with Leisler’s

Bat being inconsistent; Appendix 6.2) might have been detectable at a higher level of sampling replication. A conservative conclusion would be that there is evidence from this additional analysis for positive relationships between bat richness and some species to AES gradients, but that there are stronger, clearer relationships with background habitats (again consistent with Froidevaux et al., 2019 especially for highly mobile species such as Barbastelle (this study) and Noctule (both studies)). This is not surprising, since most farmed landscapes in England are heterogeneous in structure, with woodland, built areas and waterways, for example, influencing the presence of bats species (with other taxa) and with AES playing a contributory role. The presence, diversity and quantity of such features will determine the overall bat assemblage (and their foraging behaviours), with management from AES and other influences tending to provide revisions to the overall pattern

The form of the data for bats is different to the data for other taxa, in that activity is recorded, rather than counts of individuals. The pilot analyses found that presence/absence per night provided the most sensitive form of recorder data, as it avoided the high stochastic variability of raw activity records (see Appendix A2). Unsurprisingly, using this form of analysis then provided considerably more power to species richness analyses, compared to a total of the number of species that were detected in a square annually. The overall richness of bats considered only up to 16 species, with six of those very rare in the data and one near-ubiquitous. Given the high mobility of bats and the intensive sampling that was conducted here, differences in detected richness across a whole season, within an NCA, are likely to be driven by the occasional detection of rare species, a process that might effectively be random with respect to square location and management. Numbers detected per night (as used in Appendix 6) are more likely to reveal real differences in bat assemblage structure, as rarer species are detected on fewer nights, on average, but even here, though there is strong evidence of a local effect of AES gradient, a near-significant negative result at the landscape level suggests an inconsistent response by species richness (Appendix A6). At the species level, the lack of response to AES provision by Common Pipistrelle could be an effect of analysing the presence/absence metric for this species because it was regularly present in all sample squares, so with low variation within the metric. This species and Soprano Pipistrelle might be worth analysing further using activity data.

5.7.4.3 Conclusions

Overall, there was strong evidence for positive associations between bat presence and AES gradients at landscape level, for two species when analysed at the core level of replication that was applied to all taxa. However, the effect sizes were small with an estimated increase of less than 1% likelihood of bats being present in a survey square. The species responses are ecologically plausible, with expected landscape responses for mobiles species (Froidevaux et al., 2019). Barbastelle is considered a moth specialist bat (Rydall et al 1996, Zeale et al. 2011), and given that there were strong positive responses by moth assemblages to the AES gradients in this study (Section 5.5), its relationship with the landscape AES gradient may be driven by that of its prey. There was no strong evidence for a relationship between species richness and the AES gradients, but the bat community is a small fauna in the UK and the species richness data may be relatively insensitive.

There was an indication that a higher rate of sampling replication might have improved analytical sensitivity for detecting bat responses to AES at both species and community levels. However, this analysis has important caveats associated with it (see Section 5.7.4.2 above) and so the conclusion would require formal testing on a spatially upscaled modification to the survey design, incorporating more survey squares. These patterns only reflect spatial variation; a resurvey would allow analyses of temporal responses to AES. There is also an opportunity to exploit the paired box design to investigate the selection of AES versus off-option habitats at the option patch scale, similar to Section 6 for butterflies and bees. Such analyses would provide useful inference about small-scale AES effects on bats and are recommended for further work.

6 Results – mobile taxa responses within survey squares

6.1 Summary

In addition to the between square analyses reported in Section 5, we conducted a limited number of within-square assessments of insect responses to AES. There is already evidence supporting the beneficial impact of AES at option scale so it was informative to know whether this expected effect was present in our analysis, particularly for responses where we did not see a relationship with the AES gradients at whole square level.

For insects, we chose to limit this analysis to butterflies and bumblebees monitored on transects. This was due to the more complex relationships expected with AES options within squares for insects surveyed using pan and moth traps, where the traps attract insects across varying distances depending partly on the insect family and habitat (e.g. Merckx and Slade 2014).

In addition, we were interested to compare the within-square responses to AES for butterfly abundance, which has shown a positive relationship with the landscape AES gradient, and bumblebee abundance on transects, which showed no relationship to the AES gradients in the across-square analyses.

6.2 Butterflies

6.2.1 Are there relationships between butterflies and AES at transect section level?

Table 6.2.1. Differences in butterfly abundance between on and off AES transect sections (coefficients are on log scale). The total number of transect sections included in analysis was 1,942.

	All NCA analysis	**Lowland only analysis**
Butterfly richness	**0.155 (0.024) *P* < 0.001**	**0.169 (0.026) *P* < 0.001**
Butterfly diversity	**0.068 (0.025) *P* = 0.006**	**0.083 (0.028) *P* = 0.003**
Butterfly abundance	**0.455 (0.045) *P* < 0.001**	**0.477 (0.049) *P* < 0.001**

6.2.1.1 Butterfly richness

Butterfly richness was much higher on transect sections on option in both all NCA and lowland NCA analyses (Table 6.2.1). On average across all NCAs the difference in richness between transect sections on and off AES option was 0.86 species, with an average of 6.25 species recorded across all sections.

6.2.1.2 Butterfly diversity

Butterfly diversity was also higher on transect sections that were on AES option (Table 6.2.1), although the effect size was small. On average the increase in Shannon diversity was 0.068, and the average Shannon diversity was 1.26, suggesting only a small increase in diversity related to on option transect sections.

6.2.1.3 Butterfly abundance

We found that butterfly abundance was greater on transect sections that were on AES option, both across all NCAs and in lowland NCAs (Table 6.2.1). The effect size was substantial, with an estimated average difference of 11.13 butterflies between off and on option transect sections per year. The average number of butterflies seen on any transect section in a year was 34. The effect of being on option was particularly noticeable in the lowlands (Figure 6.2.1).

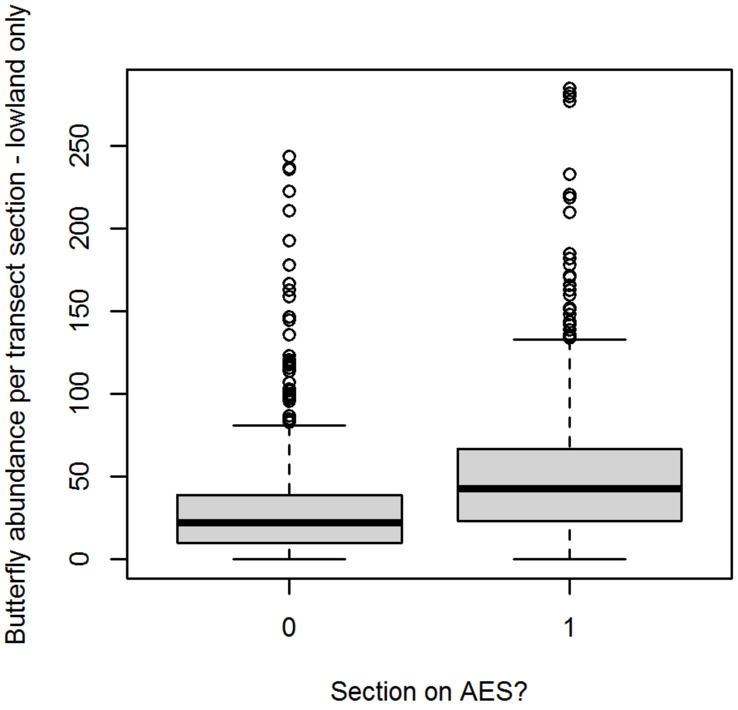

Figure 6.2.1. Boxplot of butterfly abundance seen per transect section by whether the transect section was off (0) or on (1) an AES option. Thick horizontal lines show the median, with the box representing the interquartile range.

6.2.2 Summary and discussion of butterfly results

There was strong evidence that, as expected, butterflies responded positively to AES at the transect section level. For abundance there was evidence that the landscape AES gradient score also influenced the total numbers of butterflies per square (Section 5.2.2.2) but no relationships with AES gradients at square level were seen for butterfly richness or diversity.

This suggests that, whilst individual butterflies within 1km squares may be attracted to parts of the square with AES options, leading these areas to have higher apparent local richness and diversity, the total number of butterfly species per square is not influenced by relative amounts of AES across the square or in the surrounding landscape.

6.3 Bumblebees on transects

6.3.1 Are there relationships between bumblebees and AES at transect section level?

Table 6.2.2. Differences in bumblebee abundance between on and off AES transect sections (coefficients are on log scale). The total number of transect sections included in analysis was 1,944.

	All NCA analysis	**Lowland only analysis**
Bumblebee richness	**0.208 (0.031) $P < 0.001$**	**0.224 (0.034) $P < 0.001$**
Bumblebee diversity	**0.131 (0.025) $P < 0.001$**	**0.154 (0.029) $P < 0.001$**
Bumblebee abundance	**0.585 (0.056) $P < 0.001$**	**0.658 (0.064) $P < 0.001$**

6.3.1.1 Bumblebee richness

Bumblebee richness was higher on transect sections on option, both in all NCA and lowland NCA analyses (Table 6.2.2). However, total counts of bumblebee species per transect section were quite low, so model results should be interpreted with caution as our models may not perform well with low counts. We estimated that transect sections on option had on average 0.68 more species of bumblebee, but the average number of species observed over the year on one transect section was only 3.76.

6.3.1.2 Bumblebee diversity

Bumblebee diversity was also found to be high on transect sections on option (Table 6.2.2) and the effect size was estimated to be moderate, with an average increase in diversity of 0.13. The average diversity across all transect sections across all NCAs was 0.74.

6.3.1.3 Bumblebee abundance

Bumblebee abundance was found to be higher on transect sections on option (Table 6.2.2) with an average increase in the number of bumblebee individuals of 6.30. Given an average number of bumblebees seen per transect section of 20.4, this increase represents quite a substantial effect of AES option-patches. This effect was even higher in lowlands, where there were an estimated additional 10.7 bumblebees seen on transect sections with AES. Looking at the distribution of the data, we can see that although the median is higher in transect sections on option, there is also a much higher likelihood of having a very high count of bees if the transect section is on option (Figure 6.2.2).

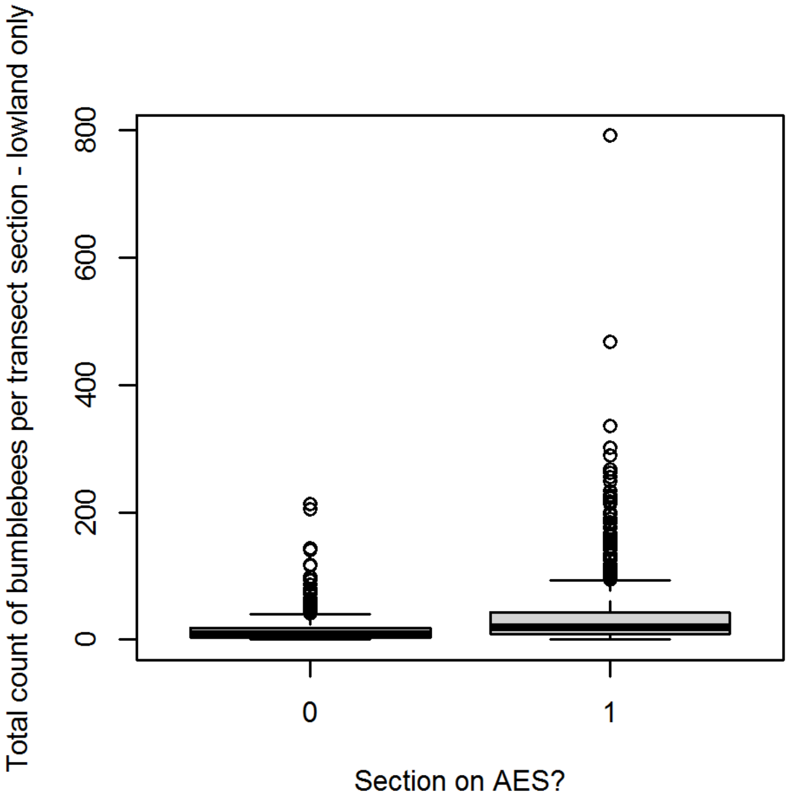

Figure 6.2.2. Boxplot of butterfly abundance seen per transect section by whether the transect section was off (0) or on (1) an AES option. Thick horizontal lines show the median, with the box representing the interquartile range.

6.3.2 Summary and discussion of bumblebee results

All metrics of bumblebee communities showed that bumblebees responded positively to AES at the scale of the transect section. However, there was very limited evidence of responses at the scale of the survey square (Section 5.3.1). This means that, although there was a difference in the number of bees between transect sections within squares, this did not always translate into a difference in the total number of bees, or species richness, when aggregated at square level. This might indicate a re-distribution effect, such that AES option patches attracts bees within squares without necessarily affecting overall numbers. However, it may also reflect the greater power to detect effects at transect section level due to the much larger number of observations.

6.4 Discussion of within-square insect results

Both butterfly and bumblebee abundance were increased substantially on AES options in these within-square analyses compared to off-option patches, although only butterfly abundance was affected by AES (the landscape gradient) in analyses across squares (Section 5). This, together with the very high bumblebee abundances on a minority of AES option patches, may indicate that bumblebees are redistributing more strongly within squares in response to resources such as the abundance of flowers. In contrast, while butterflies may be distributed on option patches to some extent, the across-square analyses (Section 5.2) suggest butterfly abundance is less strongly related to the abundance of floral resources than bumblebee abundance, and butterfly abundance may also be responding to a range of resources delivered by AES at the larger, landscape scale.

These results suggest that, in common with the implications from other large-scale AES studies (Carvell et al., 2007, Pywell et al., 2011), effects observed when comparing options vs. non-option parcels within the same square do not necessarily scale up when comparing across squares with different overall levels of AES. Whilst detecting such effects at the landscape scale is likely to be more challenging, the fact that this study (which was specifically set up to maximise the chance of detecting such effects) has not done so for some taxa, suggests that the lack of response at the 1km square level may be due to insufficient quality or quantity of the relevant options for those specific taxa. There are suggestions that in some taxa and for some responses (e.g. butterfly abundance, moth responses), AES uptake may be achieving beneficial effects at the whole-square and landscape scales.

7 Discussion and conclusions

In this project we applied a novel, pseudo-experimental design in order to collect a baseline survey dataset of the responses of mobile taxa to local and landscape AES gradients over four years, from 54 survey squares across six regions (NCAs) in England. This is the first project to monitor the responses of multiple mobile taxa to generalised AES gradients across large spatial extents, applied to arable, grassland and upland agricultural systems, in order specifically to address impacts beyond AES option or agreement boundaries.

This baseline dataset supports a novel, unbiased, landscape-scale assessment of spatial associations between AES management and taxon abundance (or activity), species richness and diversity. Relationships between AES gradients and taxon responses were shown for several taxa. A future resurvey should be conducted to support analyses of the changes in target taxa in response to AES management, against this baseline.

7.1 Brief summary of key findings

Strong evidence for relationships with local and / or landscape AES gradients were found for one or more response variables analysed for three taxa: butterflies, moths and bats, and weaker evidence for relationships with the AES gradients for birds (Table 5.1.1). Positive relationships with AES gradients were found with almost all those response variables for which strong evidence of an AES effect was shown, whereby an increase in gradient score was associated with greater species richness, diversity or abundance (either in total abundance of a taxon, or the abundance of an individual species or a trait grouping of species). Evidence for an interaction between the local and landscape AES gradients, whereby the score of one gradient modifies the effects of the second gradient on a taxon's response, was also found for one or more responses for moths and birds.

Despite this strong evidence of AES gradient effects for a few responses, the majority of headline, community response variables analysed (e.g. butterfly species richness) showed no, or weaker, evidence for relationships with the local and landscape AES gradients. We have included the weaker evidence of possible responses in Sections 5 above (summary in Table 5.1.1). Whilst some of these results with 'weak' evidence are likely to be indicative of genuine relationships with AES gradients, given the large number of models fitted in this project, others are likely to have occurred by chance (Section 2.6.3).

In addition to testing the effects of AES gradients on taxa responses, habitat and plant covariates were included in analyses of the taxa headline community variables, and in some analyses of individual species, in order to account for the well-known effects of these variables on species responses. Both the habitat and plant covariates were shown to be independent of the AES gradients (Sections 2.1.3 and 5.6.2.1), so the effects of these covariates can be interpreted separately to those of the AES gradients. Across the responses of some taxa, stronger evidence was found for relationships with the habitat or plant variables for certain response variables, while for other responses there was stronger evidence of AES gradient effects (e.g. butterflies, Section 5.2). The identification of strong effects of habitat and plant variables on taxon metrics is encouraging for the power of the study in general, as it indicates that the sampling that has been undertaken is sufficient to detect well-known relationships with these variables, and thus has the potential to detect AES effects, where they occurred. However, it is not surprising that habitat effects are frequently stronger than AES gradient ones, as most AES options modify existing landscape structure (i.e. composition, configuration or quality of habitats), rather than changing it dramatically.

7.2 Patterns across results for different taxa

The strongest evidence for relationships with the AES gradients, within the taxa surveyed, was found for Lepidoptera (butterflies and moths, Sections 5.2 and 5.5) and bats (Section 5.7), with weaker evidence for associations with bird metrics (Section 5.6) and little or no evidence of AES gradient relationships found for either bees or hoverflies (Sections 5.3 and 5.4).

Strong evidence was found for positive relationships between total butterfly abundance and the landscape AES gradient, and between the abundance of low mobility butterfly species and the local AES gradient (the latter in lowland NCAs only). Where there was strong evidence for a relationship, the effect size was fairly substantial, for example an average increase in abundance of 117 butterflies (a 53% increase across a survey square and all visits within a year) in 1km squares at the high end of the landscape AES gradient, compared to squares at the low end (though these average estimates do have substantial uncertainty).

In addition, weaker evidence was found for positive relationships with the landscape AES gradient and abundance of several butterfly trait groups: larger species with high or medium mobility, multivoltine species, species with high larval host breadth, wider countryside species, and species with red list status. The trait group of species with low larval host breadth also showed weak evidence for a positive relationship with the local AES gradient. The butterfly trait groups which showed relationships between abundance and the landscape AES gradient were the more generalist groupings (wider habitat species and those with larvae that feed on three or more core host plant species), which may have been driven by some of the abundant, grass-feeding generalist butterfly species (e.g. Meadow Brown, Ringlet). In contrast to abundance, butterfly species richness and diversity were more strongly related to the habitat and plant variables than the AES gradients.

The larger number of species and greater abundance of moths meant that it was possible to subdivide the moth data more for analyses. The moths showed more varied and complex relationships with the AES gradients than the butterflies, with strong evidence found that moth species richness and diversity were affected by the AES gradients, in addition to moth abundance. The relationships found between moth responses and the AES gradients also varied more between analyses conducted using the whole dataset vs. data from lowland NCAs only, compared to the other insect taxa. When the full dataset was analysed, there was strong evidence for an interaction between the AES gradients for species richness and abundance (both for moths and micro-moths), whereby the effects of the local AES gradient was stronger at the lower end of the landscape AES gradient. In the lowland-only dataset, there was strong evidence for main effects of the local AES gradient, but not for this interaction. These relationships between the local AES gradient and moth species richness had moderate effect sizes. An increase in average species richness of 14% (12 species) for all moths, and 20% for micro-moths, was found for 1km squares at the higher end of the local AES gradient, compared to those at the low end (species richness calculated across six moth traps per square and two survey rounds per year), though these average estimates do have substantial uncertainty (Section 5.5.2.1).

Many of the moth trait groups that showed strong evidence for a positive relationship with the local AES gradient, or a strong interaction between the two AES gradients, were broadly those associated with greater specialism, for example species found in fewer broad habitats, or that feed on fewer food plant species as larvae. However, weak evidence was also found that the moth habitat generalists had a positive relationship with the local AES gradient. This suggests that for moths, the only difference between habitat specialist and generalist species responses lies in the strength of evidence for a relationship with the local AES gradient, rather than a difference in the scale of the AES gradient that is responded to.

Similarly to butterflies, moth headline responses were found to relate to both habitat and botanical covariates. There was strong, consistent evidence for a positive relationship between botanical diversity and species richness of both butterflies and moths (all moths, micro- and macro-moths). The majority of Lepidoptera caterpillars feed on plants, and a greater botanical diversity provides a greater range of host plant species and is also likely to help create greater structural diversity (e.g. varied sward heights; Section 5.5.5).

In contrast to the Lepidoptera, the bees and hoverflies showed little or no association with the AES gradients. No strong evidence of AES gradient effects was found for any of the bee community responses, either for bumblebees surveyed on transects or for bees monitored with pan traps. Similarly, no strong evidence was found for relationships between the hoverfly headline community variables and the AES gradients. The larger, more mobile hoverfly species had a positive relationship with the landscape AES gradient, but this was the only strong evidence found for hoverfly responses, and the effect size was relatively small (Section 5.4.4). Larkin and Stanley (2021) found that in meadows, bumblebees related to grassland management intensity (assessed as indicator plant presence) in the areas surveyed (along transect routes), while butterflies responded to intensity in the surrounding landscape, similar to the patterns found for these two taxa here with more generalised AES gradients.

Overall, bees and hoverflies showed stronger relationships with the habitat and plant covariates than with the AES gradients. In particular, strong evidence was found for a positive relationship between the abundance of bumblebees surveyed on transects and the abundance of floral resources, as shown previously (e.g. Pywell et al., 2011; Carvell et al., 2015; O’Connor et al., 2019; Larkin & Stanley, 2021). The plant and habitat covariates showed no strong relationship with the AES gradients (Section 2.6.2.1). While this allowed their effects to be tested independently to the AES gradients here, it also means that at the scale of a 1km survey square, floral resources are not consistently being delivered in greater abundance at the higher end of the AES gradients. Delivery of floral resources is a key objective of those AES options that target conservation of pollinating insects. The use of generalised AES gradients that capture a broad range of AES options across a range of upland and lowland agricultural habitats, may be one reason why little evidence was found for relationships between pollinating insects and AES gradients. However, because the generalised gradients showed strong correlations with taxon-specific gradients, this result also suggests that AES provision may not make sufficient contribution to the overall floral resource available in the 1km survey square for this relationship to appear.

The one trait group that showed a consistent response across several insect taxa was the larger, more mobile species. For butterflies, moths and hoverflies, evidence was found that either the abundance or species richness of the more mobile groups respond to AES management at larger, landscape spatial scales. This could show an underlying effect of high-AES landscapes supporting more of these species, or that these species move into areas with high levels of AES resources at a large scale (reflecting the mobility of the larger species). Both factors probably interact, with more mobile species being both better able to locate AES resources (and thus relocate to landscapes with higher AES scores) and to benefit from spatially distributed AES options once in the landscape (and thus increase populations). Indeed, we would expect beneficial impacts of AES to work in this way, with species first being attracted to AES options, then concentrating in immediate vicinity and finally deriving sufficient benefit to increase populations within the landscape, as has been demonstrated elsewhere for bumblebees (Redhead et al., 2015; Carvell et al., 2017). Thus, the relationships observed here between more mobile species and landscape but not local AES scores, suggests that these species are not simply relocating to the highest AES areas but may also be deriving some increases across wider scales.

For butterflies and moths, there was also strong evidence that the smaller, less mobile species had a positive relationship with the local AES gradient, as might be expected given their more limited ability to forage and disperse at the landscape scale, but only when the lowland-NCA dataset was analysed.

Both birds and bats are, on average, probably more mobile than even the largest invertebrates, but they showed different associations with the AES gradients. For birds, there was some evidence for positive effects of local AES scores, but little evidence of such effects at the landscape scale. The single nominally strong effect was at the species level, and was probably an artefact reflecting the small sample size and a scarce species. The patterns involved were broadly consistent between the winter and spring survey bird data, although the details of the effects that were identified varied. The local AES score effects could indicate the combination of various species-level population effects or a tendency for birds to select AES habitats (or areas adjacent to them) for feeding or nesting. However, the evidence here was not strong, statistically.

In contrast to birds, two bat species showed stronger evidence for AES effects at the landscape scale. In common with those invertebrate groups that are attracted to flower-rich AES patches, this is likely to show the aggregation of these mobile species around rich resources, where they are also detected. Barbastelle, one of the two bat species with a relationship with landscape AES, is a moth specialist (Rydell et al., 1996; Zeale et al. 2011), with adaptations to avoid detection by moths (Goerlitz et al. 2010). Given the strong evidence that moth abundance relates to the AES gradients (Section 5.5), Barbastelle may be following the response of its prey to AES.

Birds, conversely, are more often recorded when perched or flying, calling or singing, as opposed to foraging. Many bird species are territorial as well, so while they may use AES patches within a territory or home range, the association of detected individuals (often on song posts) with those patches may well be weaker than that with nesting habitat or high perches. Territoriality also reduces the extent to which birds can respond to AES, with even the most resource rich 1km landscapes becoming “saturated” with breeding territories (Redhead et al., 2018), meaning that positive effects above a certain level of abundance would only be apparent via ‘spillover’ into other areas or habitats. This will tend to weaken associations with AES at the patch level in particular, but it would also be expected that AES management will tend to modify habitat quality (say improving foraging conditions or breeding success), rather than driving basic habitat suitability (and therefore species presence). Therefore, AES effects on spatial patterns in abundance would be expected to be smaller than those on temporal changes, which would need to be investigated in a repeat survey. It is also important to note that the analyses here were inclusive, deliberately, aiming to reveal responses across species within a taxon, in addition to the more detailed trait group and species analyses. However, some of the bird species considered are not AES targets, while some (e.g. Woodpigeon) have ‘pest’ status, meaning that positive effects would be unwelcome. Further, different species are likely to respond to different AES options, complicating relationships with combined gradients. Temporal analyses at species-level have revealed effects of AES at large scales in previous studies (e.g. Baker et al. 2012; Walker et al. 2018; Dallimer et al. 2010).

7.3 Comparison of across-square AES gradient results and within-square option results

This survey was designed to detect effects of local and landscape AES gradients at the scale of 1km survey squares, and the majority of analyses focussed on this primary objective across all the taxa surveyed (Section 5). In addition, just for butterflies and bumblebees surveyed on transects, limited within-square analyses were carried out that compared on vs. off AES option at the patch-level (Section 6). Analogous analyses for birds and bats are possible, and could be conducted subject to resource availability. Species richness, diversity and abundance of both butterflies and bumblebees were higher on AES options compared to off-option patches in these within-square analyses, although only butterfly abundance was affected by the AES gradients (the landscape gradient) in analyses across squares (Section 5).

These results suggest that, in common with the implications from other large-scale AES studies (Carvell et al., 2007; Pywell et al., 2011; Larkin & Stanley, 2021), effects observed when comparing options vs. non-option parcels within the same square do not necessarily scale up when comparing across 1km survey squares with different overall levels of AES for bumblebees. There are ten times more observations when data are aggregated at the level of transect section for these within-square analyses, compared to the main analyses using data aggregated for across-square analyses, so these tests have more power to detect relationships. Detecting effects at the landscape scale may also be more challenging due to the increased number of confounding variables and influences. However, the fact that our study (which was specifically set up to maximise the chance of detecting such effects) has not done so for bumblebees which demonstrably respond at the scale of individual AES options, suggests that at least some of the lack of response at the 1km square level may be due to insufficient quality or quantity of the relevant options to drive responses across the wider countryside.

7.4 LandSpAES survey design and future resurvey

The design used to underpin the data collected in this study gives strong power for testing hypotheses about AES gradient effects at the local and landscape spatial scales. This is due to: 1) the survey squares having been selected along the full range of orthogonal local and landscape AES gradients (Section 2.1), and 2) the AES gradients being independent of key potential confounding variables, such as habitat diversity (Section 3.3; Staley et al., 2021).

Notwithstanding this strong survey design, two aspects of the survey design may have made it challenging to detect spatial AES effects (Section 5). Firstly, the level of replication (54 survey squares) is relatively small, when distributed among six, contrasting landscapes, and much lower than established national recording schemes (e.g. WCBS, approx. 750 survey squares; BeeWalks, approx. 240 squares; BBS approx. 2300 squares). Power analysis undertaken during the scoping of this design (project LM0457, Staley et al., 2016) suggested that 100-200 sites might be needed to detect AES effects on some taxon responses. The power analysis was structured to estimate the replication needed to show AES effects on change in taxa responses over time, and thus is not directly applicable to the spatial analyses carried out here, but may give some indication that 54 is at the low end of the number of survey squares needed.

Secondly, unenclosed, upland systems have much larger habitat parcels, and the effects of AES management may operate at different spatial scales in the uplands compared to the lowlands. While the AES gradients were designed to be applicable to the full range of agricultural systems in England, and to cover options that benefit biodiversity across the agricultural systems, it does not necessarily follow that the effects of AES gradients at given spatial scales will be the same on mobile taxa within each agricultural system. There is some indication that, for moths and birds, AES gradient effects could be detected in the smaller, lowland-only dataset that were not apparent in the full dataset (Section 2.1). The use of more NCAs in lowland agricultural systems, instead of including the upland areas, might have resulted in stronger evidence of AES gradient effects for these taxa. However, this would inevitably have limited the applicability of the results to lowland agricultural systems.

The use of generalised gradients is positive for integrating across multiple taxa (especially when considering community metrics), is the only plausible way of combining multiple AES options with different objectives into contrasting local- and landscape-scale gradients, and is supported by strong correlations between average gradients and taxon-specific gradients

(Section 3.2). However, individual species or trait groups may respond particularly strongly to subsets of the overall range of options that are relevant to a broader taxon group.

As discussed above (Sections 2.6.2 and 7.5), the results presented here are from analyses of baseline data and, hence, focus on spatial effects. Spatial responses of taxa to current AES interventions may be affected by the history of AES management. We did not have data of sufficient spatial resolution to include AES history in the analyses, but did control for recent changes by excluding potential survey squares that had undergone major changes in level of AES uptake in the three years immediately preceding the start of this project (Staley et al., 2016, 2021), or were likely to change during the survey (Table 2.1.1 above). A future resurvey would allow change in the mobile taxa responses to be analysed in relation to the AES gradients and would address a primary purpose of the AES interventions: to increase populations of target species.

AES clustering (e.g. on two adjacent farms) at smaller scales are not distinguishable in the LandSpAES design from larger management quantities within the survey squares. However, our results did not support a multiplicative response to AES management at local and landscape scales that would suggest synergistic effects, as the few significant interactions found between AES at these two scales were negative. Rather, these interactions support a greater value for management within the 1km survey square where there is less in the surrounding landscape, reflecting patterns found in previous studies on the amount of semi-natural habitat in the landscape surrounding AES (e.g. Tscharntke et al. 2005). However, interactions were not considered at other scales, and the generalised AES gradients mean that high values of local and landscape AES may reflect different individual options that may not be perceived as clustered habitat resources by responding species.

7.5 Policy relevance

Since the LandSpAES survey was designed, there have been major changes to AES policy, such that CS will be replaced by ELMS. It is unknown how this change will affect the quantities of AES management in and around the survey squares, and it is possible that the AES option types and quantities will change. The current AES gradients are dominated by HLS agreements and options, particularly in squares at the high end of the gradient scores. These agreements include the management and restoration of higher quality habitats under AES management (including priority habitats) and while the details of the ELMS are still in development, it seems likely there will be some continuity of AES management in these areas.

An important precursor to a future survey will be a spatial analysis of the quantities of AES interventions in the sample squares, and how they have changed over time as the transition to ELMS proceeded. This would inform what the local and landscape AES gradients are at that time. The gradients would not have to be the same as they are for the present project, but they would have to provide sufficient independent variation in AES quantities to deliver analytical power. The LandSpAES AES gradient design is likely to be a useful tool in understanding the response of key mobile taxa to the new ELM schemes.

Results from this baseline survey also have wider policy relevance, beyond assessing spatial effects of current AES on mobile species. Targets for terrestrial species abundance, a key commitment under the Environment Act, were recently proposed (https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/). Preliminary results from LandSpAES modelling for butterflies and birds were used to parameterise scenario modelling of the potential effects of future AES, in order to inform the setting of species abundance targets (Isaac et al., 2022).

LandSpAES was conceived to fill a gap for landscape-scale AES monitoring across multiple taxa and this form of monitoring will remain critical in respect of future schemes, such as ELMS. Some taxa are well-monitored by independent data sources that can be co-opted for an AES context, but intensive, co-located monitoring for these and other taxa requires bespoke sampling. Given that future schemes are likely to share the multi-taxa targeting of CS and ES, it is important that they too are monitored similarly broadly. It is recommended that similar designs are considered to monitor ELMS in the long term, albeit taking further account of the recommendations for sample sizes that were produced by the scoping study that preceded LandSpAES (Staley et al., 2016). The analyses here have provided encouraging evidence that the approach has the required power to detect spatial AES effects, and the potential to support temporal change analyses.

7.6 Key conclusions and recommendations

Key conclusions	Details
1. Strong evidence for relationships with local and / or landscape AES gradients were found for one or more response variable for most of the mobile taxa surveyed. The strength of evidence for these relationships varied between taxa, as did the number of response variables showing a relationship with AES gradients.	Strong evidence was found for relationships with local and / or landscape AES gradients for butterflies, moths, and bats, in terms of either community responses (e.g. total butterfly abundance, moth species richness) or individual species responses (e.g. presence/ absence of Barbastelle and Daubenton’s bats). Weaker evidence was found for relationships with the local AES gradient for some bird community responses and individual bird species abundance. No or very limited evidence was found for relationships with the AES gradients for bees and hoverflies, at the 1km survey square scale.
2. Positive relationships were found between mobile taxa surveyed and AES gradients.	Where evidence was found for relationships between mobile taxa and AES gradients, the relationships were mostly positive (for most response variables and for all whole community responses). These positive relationships indicate that an increase in AES uptake was associated with greater species richness, diversity, abundance or presence.
3. For insects, more mobile species respond to AES gradients at larger spatial scales.	For butterflies, moths and hoverflies, evidence was found that either the abundance or species richness of the more mobile groups respond to AES management at the larger, landscape (3 × 3km) spatial scale. This suggests that having landscapes of high AES uptake is most important for the most mobile invertebrate taxa.
4. There is some evidence for spatial effects of AES on birds. Temporal change (repeat survey) and patch-level spatial analyses may be more powerful.	Effects of AES on birds may be more detectable in terms of species-level, long-term, patterns, or the selection of AES habitats at the patch scale (in future analyses). These will complement the existing evidence for AES benefits for birds that is based on long-term studies and farm-scale comparisons.
6. There were positive responses of two bat species to AES management at the landscape scale. The large-scale responses suggest that AES effects on the bat foraging community apply mostly across broad landscapes.	There was strong evidence for positive effects on Barbastelle and Daubenton’s Bat in respect of landscape-scale AES management, albeit with small effect sizes.

Recommendations	**Details**
1. Relationships found with the AES gradients assessed in the LandSpAES project should inform design of ELMS, in combination with other evidence.	The positive, spatial relationships shown with the AES gradients by several taxa suggest that current AES schemes are benefiting some mobile species. While the AES gradients used here do not support analyses of individual options (Section 2.1), the gradients are dominated by options targeted at biodiversity within long-standing HLS agreements, and thus provide broad support for AES management for biodiversity under current, ongoing schemes.
2. LandSpAES findings can be used to inform conservation policy beyond AES design.	Targets for terrestrial species abundance, a key commitment under the Environment Act, were recently proposed (https://consult.defra.gov.uk/natural-environment-policy/consultation-on-environmental-targets/). Preliminary results from LandSpAES modelling for butterflies and birds were used to parameterise scenario modelling of the potential effects of future AES, to inform the setting of these species abundance targets (Isaac et al. 2022). This demonstrates the potential to use of LandSpAES results to inform wider conservation policy.
3. A future resurvey should be conducted to deliver the full potential of LandSpAES data, by allowing an assessment of population changes in response to AES.	One of the goals of AES is to increase population growth, or reverse the decline in populations, for key mobile species (e.g. Farmland Bird Index species and pollinating insects). The LandSpAES survey was designed to allow temporal change to be assessed in relation to the local and landscape AES gradients. A future multi-year resurvey, in 5-8 years' time, should be conducted to capitalise on the results of this multi-year baseline, by enabling temporal change to be assessed.
4. Future evaluations of land management for bats can make use of passive acoustic detectors.	The application of passive acoustic detectors to measure AES effects on bats in LandSpAES was novel, and shown to be sensitive to known habitat effects. The method is valuable because it is logistically easy (low effort), but also easily standardised. It is important to note that it informs about habitat use and species presence as foragers, rather than roost locations, absolute abundance or population size. The sampling and analytical approach forms a proven technique for assessing variation in the foraging bat community that can be incorporated into future monitoring of AES and other land management effects.
5. ELMS monitoring would benefit from following a similar, structured design to LandSpAES	This study has demonstrated the power provided by the co-located, intensive survey approach, with sampling along the full range of contrasting gradients to maximise power. While some monitoring of ELMS is likely to be possible using independent data sources, potentially for birds and butterflies, it would be valuable to repeat the LandSpAES structured approach to monitor scheme impacts across multiple taxa. Both this structured approach, and evaluation approaches using schemes like the Breeding Bird Survey or Wider Countryside Butterfly Survey, require that management measures undertaken by farmers on ELMS are recorded quantitatively.

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