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Research article

Designing a survey to monitor multi-scale impacts of agri-environment schemes on mobile taxa

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ABSTRACT

Agri-environment schemes (AES) are key mechanisms to deliver conservation policy, and include management to provide resources for target taxa. Mobile species may move to areas where resources are increased, without this necessarily having an effect across the wider countryside or on populations over time. Most assessments of AES efficacy have been at small spatial scales, over short timescales, and shown varying results. We developed a survey design based on orthogonal gradients of AES management at local and landscape scales, which will enable the response of several taxa to be monitored. An evidence review of management effects on butterflies, birds and pollinating insects provided data to score AES options. Predicted gradients were calculated using AES uptake, weighted by the evidence scores. Predicted AES gradients for each taxon correlated strongly, and with the average gradient across taxa, supporting the co-location of surveys across different taxa.

Nine 1 × 1 km survey squares were selected in each of four regional blocks with broadly homogenous background habitat characteristics. Squares in each block covered orthogonal contrasts across the range of AES gradients at local and landscape scales. This allows the effects of AES on species at each scale, and the interaction between scales, to be tested. AES options and broad habitats were mapped in field surveys, to verify predicted gradients which were based on AES option uptake data. The verified AES gradient had a strong positive relationship with the predicted gradient. AES gradients were broadly independent of background habitat within each block, likely allowing AES effects to be distinguished from potential effects of other habitat variables. Surveys of several mobile taxa are ongoing.

This design will allow mobile taxa responses to AES to be tested in the surrounding countryside, as well as on land under AES management, and potentially in terms of population change over time. The design developed here provides a novel, pseudo-experimental approach for assessing the response of mobile species to gradients of management at two spatial scales. A similar design process could be applied in other regions that require a standardized approach to monitoring the impacts of management interventions on target taxa at landscape scales, if equivalent spatial data are available.

1. Introduction

The ongoing loss of biodiversity and impacts on ecosystem service provision (Powney et al., 2019) are major drivers of conservation policy. Such policies include agri-environment schemes (AES), key mechanisms to deliver conservation across Europe (Geppert et al., 2020), North America (Morandin et al., 2014), Australia (Ansell et al., 2016) and elsewhere. Under AES, landowners receive financial incentives to implement management to meet environmental objectives, including the establishment or maintenance of habitats for target taxa.

Research into biodiversity responses to AES has largely focused on efficacy at the scale of specific management options (Geppert et al.,

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2020; Pywell et al., 2012) or farms (Staley et al., 2018), over short timescales and has shown varying results (Kleijn et al., 2011; Scheper et al., 2013). This scale of research is necessary to test and improve AES management prescriptions, and assess whether AES interventions benefit target taxa on land directly under AES management (Carvell et al., 2007; Staley et al., 2016a). 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 more sustained at the population level and from local to landscape scales, for some taxa (butterflies, Brereton et al., 2007; birds, Baker et al., 2012; Redhead et al., 2018; and 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 linking population change and AES interventions. This may be partly because the sites within such schemes are not located to show sufficient contrast in the extent of AES management (Oliver, 2014), and potentially also due to inter-correlations between AES uptake across spatial scales, and with other landscape variables.

The variation between taxa in the available evidence of landscape-scale effects of AES thus makes the evaluation of responses across taxa difficult. To determine if 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: (i) are abundance changes sustained over time in terms of population growth (or reduced rates of decrease), and (ii) does increased abundance extend more widely onto surrounding land under less or no AES support (spill-over effects)?

The targeted selection of sites that contrast in key landscape variables (Garratt et al., 2017), or lie along one or more environmental gradients (Geppert et al., 2020; Gillespie et al., 2017; Rundlöf et al., 2018), is increasingly being used to test ecological questions at large spatio-temporal scales, which are hard or impossible to address using traditional manipulative field experiments. The power of such 'pseudo-experimental' studies is maximized by selecting sites (i) to represent the full range of values for variables of interest, and (ii) to ensure that variables are not correlated, to allow more accurate estimation of their effects (Pasher et al., 2013). Despite major investment in AES across Europe and elsewhere, and significant policy shifts towards the greening of agriculture (Concepción et al., 2020), there remains no approach or framework to monitor the impacts of AES management on mobile species at landscape scales, that is standardized across agricultural habitats and taxa.

We developed a survey design to monitor the response of mobile species to AES interventions at large spatial scales, specifically considering impacts beyond farm or AES agreement boundaries and across multiple taxa. In order to identify AES management options that benefit key mobile taxa, we conducted a substantial review of the AES evidence (see Supplementary Material 1 and 2 for further details). Results from the review were used alongside national datasets of AES option uptake to calculate evidence-based AES gradients at two contrasting spatial scales (Fig. 1). This resulted in gradients of AES management likely to affect the key taxa, and excluded options that target other objectives (e.g. water protection, educational access). This design has the potential to test spill-over effects, for example by comparing species responses from sites with no or little AES intervention, which are surrounded by land along an AES gradient (row 1, Fig. 1). AES uptake is often clustered and may be positively correlated at different spatial scales (Hodge and Reader, 2010), and the potential to create independent AES gradients varying in scale has not previously been assessed.

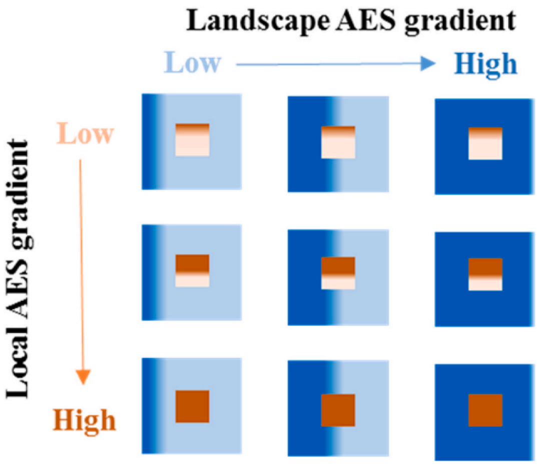

Fig. 1. Contrasting gradients of taxon-relevant AES intervention at local and landscape scales, split into three levels of intervention. The local gradient is represented by shading from cream (low AES intervention) to brown (high intervention) in the focal 1 km squares in which mobile taxa will be monitored, and the landscape AES gradient by pale blue (low intervention) to dark blue (high intervention) in the surrounding landscape (3 × 3 km) units. (See the online version of this article for the colour figure.)

Other landscape variables, such as area of semi-natural habitat, can modify the response of mobile taxa to AES management (Scheper et al., 2013). To reduce the chance that AES gradients and other habitat variables co-vary, which is likely at a national scale, sites were grouped within regional blocks with cohesive habitat characteristics. An objective site selection process was designed to assess whether survey sites could be selected to:

1) Cover orthogonal predicted gradients of multiple AES interventions at local and landscape scales,
2) Ensure that integrated AES gradients are relevant to several target mobile taxa and to multiple agricultural habitats (arable, grassland and mixed),
3) Ensure that AES gradients are independent of other background landscape variables, through aggregation within broadly homogenous regional blocks.

Predicted gradients, based on spatial uptake data, were verified by mapping in the field of AES options and broad habitats at 36 sites selected across four regions. Our findings present a novel design process that can be applied at multiple scales for effective monitoring of the impacts of current and future land management on biodiversity.

2. Methods

The following steps were used to design and calculate predicted AES gradients: 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 of 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

Table 1
Combined scores of the type and impact of evidence, attributed from evidence review data and used to allocate scores to AES options groups per taxon or functional group. Where multiple evidence sources existed, the highest score for each taxon and option group was given.

Score	Criteria for combined score
0	No evidence or no effect
1	Evidence from expert opinion or a non-significant effect from grey and peer-reviewed literature
2	Evidence of a significant effect from one or more studies at small/local spatial scales in peer-reviewed literature with empirical evidence of significant effect, and all significant effects from grey literature regardless of scale
3	Evidence of a significant effect from landscape scale or temporal studies in peer-reviewed literature

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 Fig. 1, within homogenous regional blocks. Sections 2.1–2.5 provide the detail for each of these steps.

2.1. Evidence review of AES management effects on target taxa

In order to determine which AES management options were likely to affect key mobile taxa, we conducted structured searches of peer-reviewed papers and grey literature. Five taxa were reviewed: birds, bats, butterflies, moths and a subset of other pollinating insects (bees and hoverflies), chosen due to their mobility and conservation status. The methods used for searching the literature, shortlisting papers and extracting data are detailed in the supplementary material (SM1 Section 1.1). Sufficient empirical evidence for scoring of AES management effects was found for three of the taxa reviewed: 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.

2.2. Scoring evidence for the effects of AES management options on mobile taxa

Individual AES options were rarely identified in the literature, thus options were grouped by type of management and habitat for scoring (e.g. grass buffer strip options). Data collected in the evidence review were used to attribute scores based on (i) the type of available evidence and (ii) the impact of the AES management for each taxon/functional group (SM1 Table 3).

A single evidence score was allocated per AES option group for each taxon/functional group with sufficient evidence, based on the combination of the evidence type and impact scores, using the scoring system in Table 1. Where multiple evidence sources existed, 1) results from peer-reviewed studies were used in preference to opinion/grey literature, and 2) for multiple peer-reviewed evidence sources, the maximum score for each taxon/option group was given. Combined evidence scores were used to calculate evidence-weighted 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).

2.3. Calculating evidence-based AES gradients

The data collated from 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.

National Character Areas (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). The UKCEH Land Cover Map 2007 data (LCM, 2007; Morton et al., 2011) 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. Spatial data handling was performed in ArcGIS 10.3 (© ESRI, 2016; Redlands, CA) and R (version 3.2.2; R Core Development Team, 2016).

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, in the absence of definitive ecological data on the relative value per unit area of each option for each target group. 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. Payments for each option were compiled from AES handbooks (Natural England, 2013a; b, 2015). Gradient scores were summed across the option types to give a total predicted gradient score per taxon and 1 km square.

Predicted 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. 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 (see Section 3.2), thus an average AES gradient across taxa was calculated for each 1 km square and landscape unit, and used for site selection and validation as described in the following sections.

2.4. Selecting survey sites and regional blocks (National Character Areas)

The gradient scores (average scores across the taxa) were used to define a matrix of contrasting local and landscape AES gradients (Fig. 1). 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

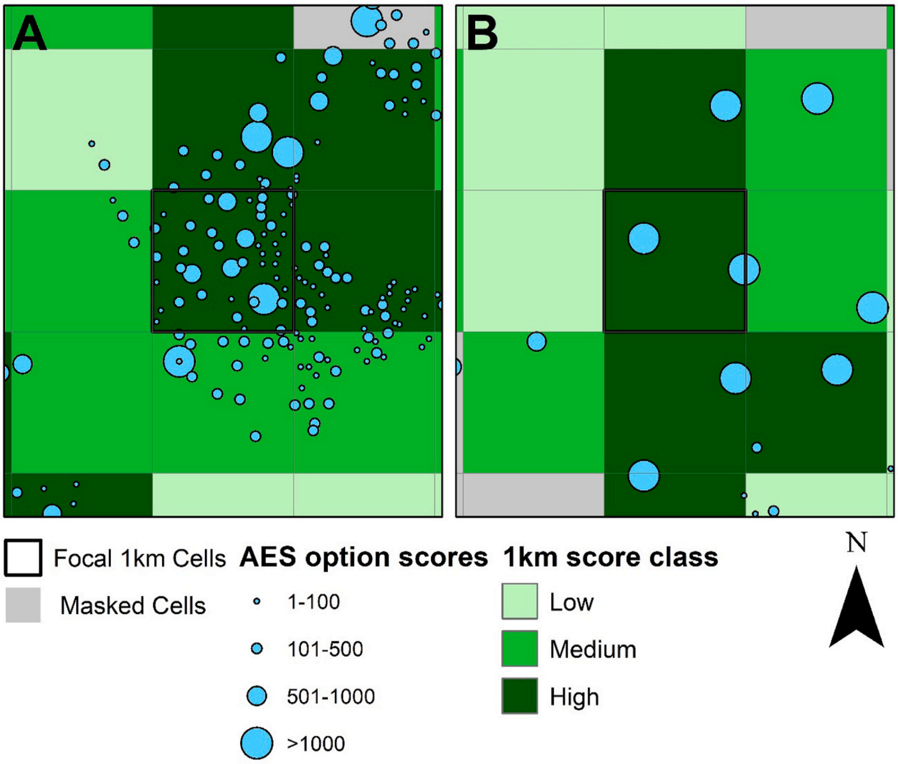

Fig. 2. Examples of focal survey squares, with local (1 km^2) AES gradients in the highest scoring category and landscape (3 × 3 km) gradients in the medium intervention category, showing different configurations of options. **A:** Many scattered options with low-moderate scores or areas **B:** A few options with very high scores or areas. (See online version of this article for the figure in colour).

anomalously high scoring cells, and probably resulting from limitations in the spatial accuracy of the input data (see Section 2.5).

The three categories along each AES gradient give nine possible matrix combinations (Fig. 1) across the orthogonal local and landscape AES gradients. Nine survey units were selected within each NCA, one from each matrix class, using a 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 (Fig. 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. Eighteen NCAs contained at least one candidate survey unit in all nine of the matrix classes. Some of these NCAs were discounted due to difficulties gaining survey access (e.g. large military training areas). Resources dictated that one square per matrix class in each of four NCAs was the maximum that could be surveyed, from the list of potential sampling units. Four lowland NCAs were selected for field validation of the AES gradient scores through mapping of AES options, and also for mapping of habitats. These four NCAs covered the main lowland agricultural habitats in England. 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 four 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.

2.5. *Validating AES intervention gradients and their relationship with habitat variables*

AES option uptake data were spatially attributed by field centroid locations, so there is the potential for error in predicted gradients. For example, management options can straddle a square boundary, or the location of rotational options can change annually. Land cover map (LCM) broad habitat classes differ in the probability of correct attribution, so accuracy varies depending on the habitats present (Morton et al., 2011). To verify the AES gradients and their relationship with habitat variables on the ground, broad habitats and AES options were mapped in the field in 2017 in the 36 survey squares. Base maps for field survey were derived from LCM 2007 (Morton et al., 2011), 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. Maps were edited and annotated by surveyors across each focal survey square, using ESRI ArcPAD v10.0 on ruggedized tablet computers (Panasonic Toughpad FZ-G1). AES option locations and sizes were verified, along with the LCM broad habitat class and size for each land parcel. 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;

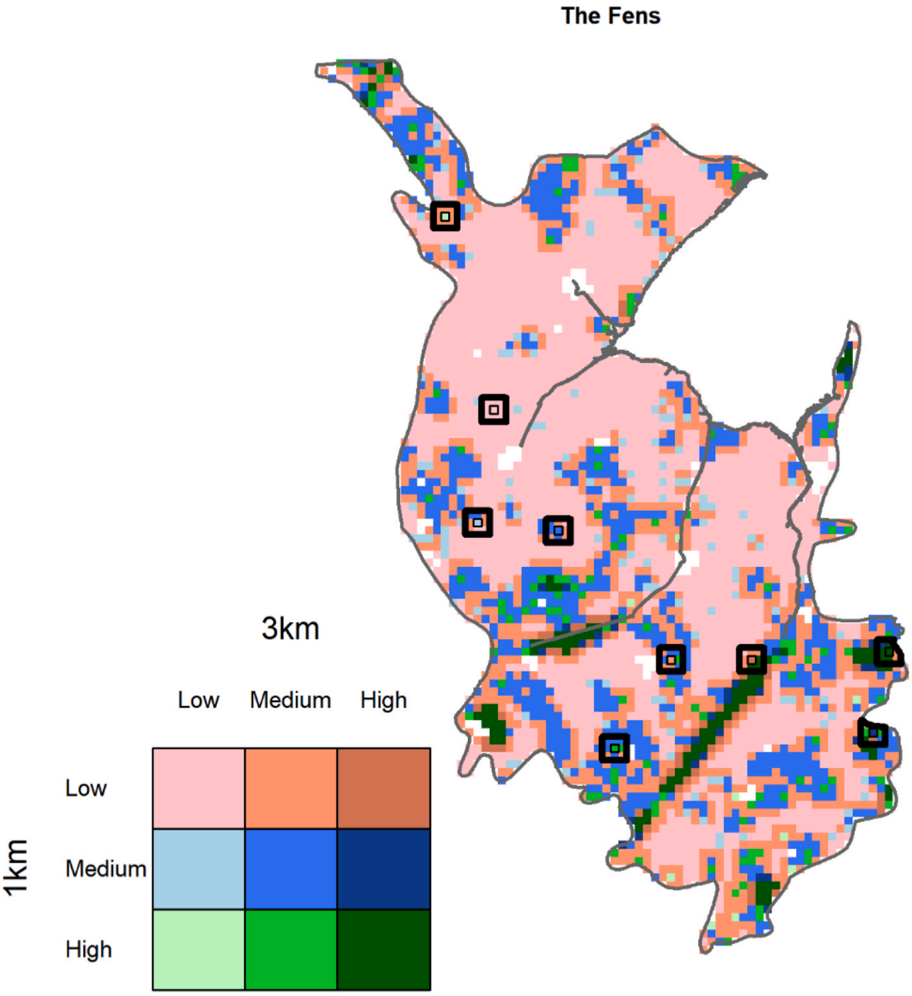

Fig. 3. Super-imposed local (1 km^2) and landscape (3 × 3 km) gradients for survey squares for The Fens NCA. Landscape unit gradient is represented as the average of eight 1 km squares surrounding each focal 1 km square. Black outlined boxes show the nine landscape sampling units selected, based on contrast 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. (See the online version of this article for the figure in colour.)

UK-SCAPE, 2020).

2.6. *Analyses of predicted and verified gradients*

Correlation tests were carried out both for predicted gradients (at local and landscape scales), and verified gradients calculated using mapped options (at local scale only). Mapped habitat classes were combined to 1) area of semi-natural habitat (SNH: sum of acid grassland, calcareous grassland; species rich and semi-improved neutral grassland, broadleaved woodland, heathland, fen marsh and swamp and bog) and 2) habitat diversity (Shannon-Weiner diversity of the 16 habitat classes). Spearman's rank correlation tests were used to investigate relationships between the three mapped habitat variables (area of arable habitat, SNH and habitat diversity) and verified AES gradients across the nine survey squares in each NCA, including Holm adjustment for multiple comparisons.

3. Results

3.1. *Evidence review and evidence scores*

The amount and type of evidence available on the effects of AES management on mobile species differed between taxa (see SM1 and SM2 for details). Combined evidence scores were attributed to 53 groups of AES options for the four taxa scored (SM1 Table 4). More maximum scores were attributed to the two bird functional groupings than either

Table 2

Number of regions (National Character Areas: NCAs) within each correlation strength category (number NCAs in analysis = 155). Correlations are between predicted AES intervention gradients for two taxa at a) local (1 km^2) and b) landscape (3 × 3 km) scale. T = Kendall's tau correlation coefficient.

a. 1 km^2	Boundary birds and:			Butterflies and:		Pollinators and:
Strength of correlation	In field birds	Butterflies	Pollinators	Pollinators	In field birds	In field birds
$0 < T < 0.4$	7	3	5		12	17
$0.4 \leq T < 0.6$	5	18	33	3	29	39
$0.6 \leq T < 1$	143	134	117	152	114	99

b. 3 × 3 km	Boundary birds and:			Butterflies and:		Pollinators and:
Strength of correlation	In field birds	Butterflies	Pollinators	Pollinators	In field birds	In field birds
$0 < T < 0.4$	9		2		10	13
$0.4 \leq T < 0.6$	2	11	15	2	15	17
$0.6 \leq T < 1$	144	144	138	153	130	125

Table 3
Percentage of each surveyed region (National Character Area: NCA) in arable, agriculturally improved grassland and semi-natural grassland broad habitat classes. Broad habitat class data from Land Cover Map (2007) (Morton et al., 2011; https://www.ceh.ac.uk/services/land-cover-map-2007).

NCA	Percentage of area in broad habitat category		
	Arable	Improved grassland	Semi-natural grassland
The Fens	84	7	2
South Suffolk and North Essex Clayland	69	16	2
Dunsmore and Feldon	53	30	5
High Weald	20	44	4

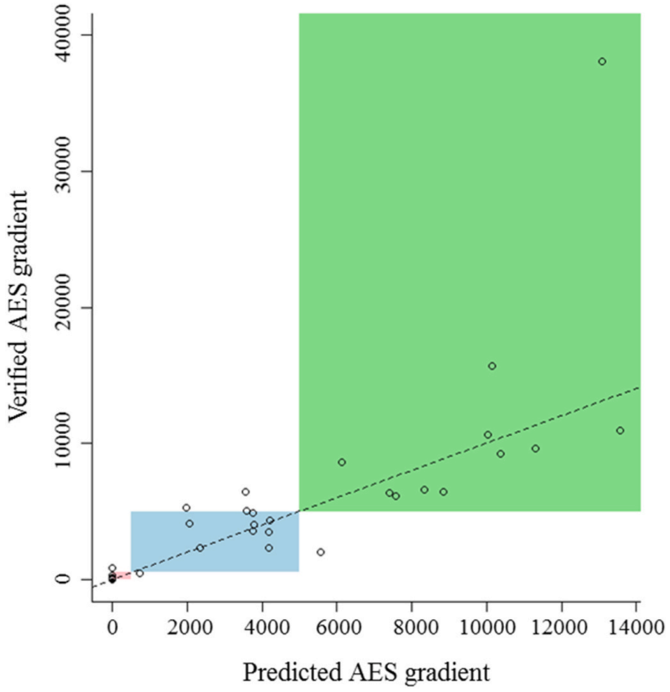

Fig. 4. Relationship between predicted AES gradient calculated using spatial uptake data vs. verified AES gradients calculated using options mapped in 2017. Green = gradient scores in the 'high' category, blue = 'medium' scores, pink = 'low' scores; categories used for survey square selection, described in Section 2.4. (See the online version of this article for the figure in colour.)

butterflies or pollinating insects. This reflects the greater prevalence of bird studies that have tested AES effects at larger spatial scales, or on bird population responses as opposed to short-term responses.

3.2. Predicted AES gradients at two spatial scales and survey site selection

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 (Fig. 2). Within the high gradient category, some squares had a few AES options with particularly high scores or extensive areas (e.g. grassland management options covering the majority of the square), while others had scores from combinations of many smaller options with low to moderate scores or extent (e.g. arable options; Fig. 2a). Predicted AES gradients at local and landscape scales were successfully calculated, and focal survey squares selected in each of the nine matrix classes (Fig. 1) in 18 NCAs (example in Fig. 3). This demonstrates that while AES uptake may be clustered (Hodge and Reader, 2010), there is sufficient spatial variation to test orthogonal gradients at these different scales, meeting Objective 1 above.

The majority of correlations between the predicted AES gradients calculated for each of the four taxa within NCA blocks were strongly positive. 88% of correlation coefficients were >0.6, and over 95% were >0.4 (Table 2). In less than 5% of cases correlations were weak (<0.4), most involving correlations between the in-field bird AES gradients and each of the other three taxa gradients. This may reflect a lower dependence of in-field birds on SNH and their management than is associated with the other taxa. In the minority of cases where weak correlations were found between taxon gradients, these were all in fourteen NCAs, all but one of which were not dominated by a major agricultural habitat (SM1 Table 5), and thus not suitable locations for AES monitoring. The remaining majority of 117 NCAs were dominated by a range of habitats, including the main lowland agricultural habitats in England (arable and pastoral). Of the four NCAs chosen for survey, two were dominated by arable land, one had substantial coverage of both arable and grassland, and the fourth was predominantly agriculturally improved grassland (Table 3). Thus, the design meets Objective 2 above; average AES gradients calculated from weighted uptake data are relevant to several target mobile taxa, and to multiple agricultural habitats.

3.3. Validation of AES gradients and habitats

Validated AES gradients, calculated from mapped options on the ground, were closely related to the predicted AES gradients ($R = 0.78$, $P < 0.001$; Fig. 4). The small differences were 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 on-line spatial uptake data. One outlier square had a verified AES gradient score around 40,000 (Fig. 4), where additional fields of pollen and nectar mix option had been planted beyond the options initially planned under the agri-environment agreement, and demonstrates the need for field mapping to verify the gradient scores. As for the predicted gradients, correlations between validated gradients calculated separately for each of the four taxa were strongly positive in the surveyed squares (Fig. 5), and each validated taxon gradient correlated strongly ($0.94 < R < 0.98$) with the average gradient across taxa.

The diversity of mapped broad habitats, and cover of SNH and arable land, were not significantly correlated with the validated AES gradient at the local scale, both within each of the four surveyed NCAs and across the total pool of 36 survey squares (Table 4). In one NCA (High Weald) the validated gradient and area of arable land had a correlation of R = 0.68, providing some indication of a positive relationship, but this was not statistically significant. In the other NCAs tested, the correlations between AES gradient and proportion of arable land were weak (<0.3), and across all the survey squares in the four NCAs it was 0.09. The design therefore meets Objective 3 above; that AES gradients are broadly independent of other background habitat variables, and validates the approach of aggregating survey sites within blocks of broadly homogenous landscape (NCAs).

4. Discussion

Here, we present a novel approach to overcome challenges in the design of national scale, long-term monitoring of the impacts of land management on biodiversity. We show that gradients of AES management options relevant to several mobile taxa can be constructed at contrasting spatial scales. This pseudo-experimental approach will allow the responses of target species to AES management interventions to be tested independently at local and landscape spatial scales, as well as responses to interactions between the two scales of AES gradient. For example, Daskalova et al. (2019) found no overall effect of AES

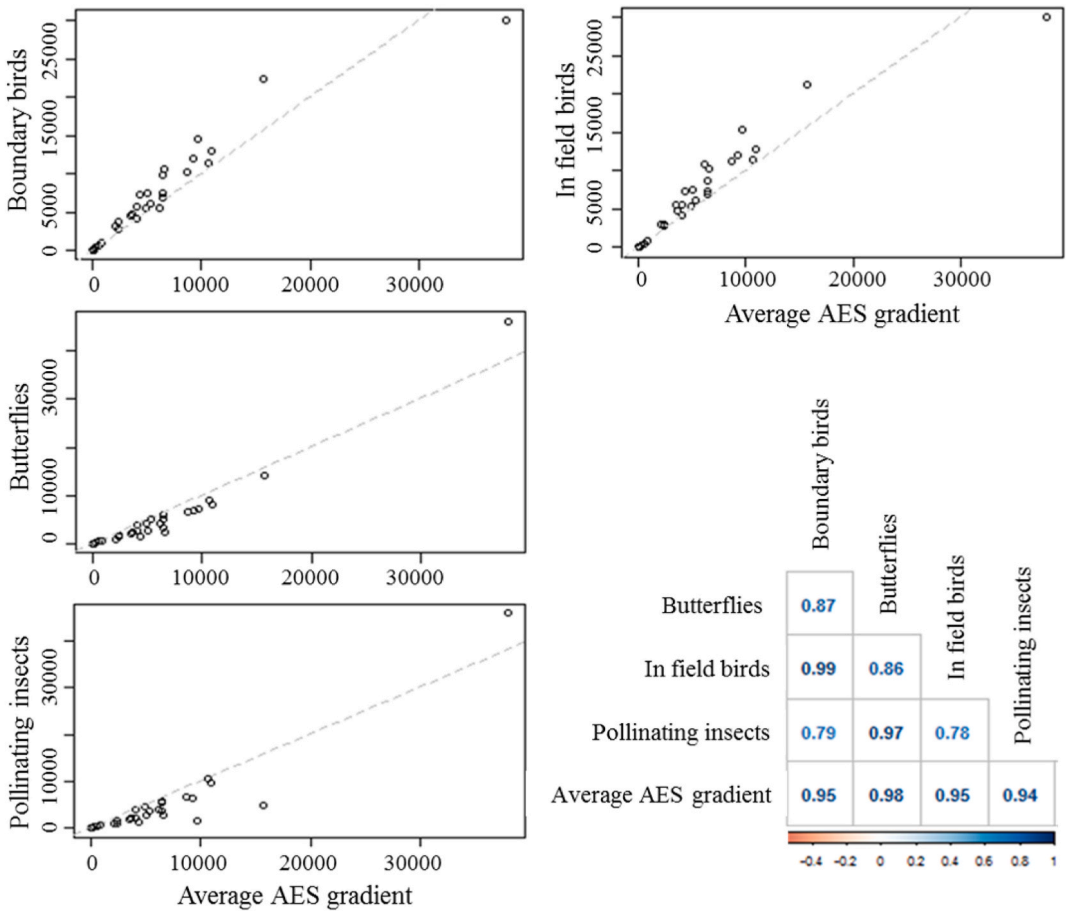

Fig. 5. Relationships between verified local AES gradients for each taxon/functional group. Plots show each taxon gradient calculated against the average gradient, correlations in bottom right. The dotted line indicates the 1:1 line.

Table 4
Coefficients (Spearman's) for correlations between validated AES gradients and broad habitat variables, both calculated using field-mapped data in the 1 km survey squares. Survey squares were grouped within regions with broadly homogenous background habitats (National Character Areas: NCA). N = number of survey squares. R = Spearman's correlation coefficient, P = probability. Broad habitat class data from Land Cover Map (2007) (Morton et al., 2011; https://www.ceh.ac.uk/services/land-cover-map-2007).

NCA	N	Arable		Semi-natural habitat		Habitat diversity	
		R	P	R	P	R	P
Dunsmore and Feldon	9	0.293	1	0.351	1	0.427	1
High Weald	9	0.678	0.268	0.017	1	0.119	1
South Suffolk and North Essex Clayland	9	0.083	1	0.350	1	−0.050	1
The Fens	9	−0.418	0.406	0.601	0.261	0.469	0.406
All NCAs	36	0.093	1	0.197	0.745	0.061	1

management on abundance of five bird species, potentially due to possible spill-over effects. The design developed and validated here would allow these to be explicitly tested.

We demonstrate that an integrated approach to quantifying relevant AES management interventions and selecting study sites can be used for four different taxa/functional groups. Average AES gradients correlated positively with each taxon-specific AES gradient, supporting the co-location of monitoring across birds, butterflies and pollinating insects. This will allow any variation shown between the responses of taxa to the AES gradients to be attributed to differences in their underlying ecology, rather than potentially being confounded with differences between survey sites, or with differing interpretations of landscape-scale effects used across several single-taxon studies. This co-location of monitoring allows a rounded assessment of AES effects on biodiversity, and the design here is the first practical method to achieve this, which has been validated through the mapping of AES options on the ground. Previous large-scale pseudo-experimental designs have selected sites along independent environmental gradients (e.g. gradients of floral resource availability and insecticide loadings; Gillespie et al., 2017), but not tested whether sites can be selected along contrasting gradients of a single environmental variable at different spatial scales.

The diversity of AES options at the higher end of the AES gradient scores reflects the deliberate design of gradients that could be applied across the range of agricultural habitats found in England. The breadth of the AES options that were included in the gradients allowed survey sites to be selected within regions that differed in dominant agricultural land use, including two regions dominated by arable land, and two with substantial proportions of both arable and pastoral farmland. Within the four regions (NCAs) surveyed, the AES gradients were shown not to relate to the area of arable land, area of SNH or habitat diversity, and thus are broadly independent of background habitat variables. By designing the study around blocks consisting of relatively homogenous areas of land, it was possible largely to avoid potentially confounding correlations with habitat variables. Using large-scale regions based on landscape characteristics as blocks in this way can add power to pseudo-experimental studies at landscape scales, increasing the chance of detecting and correctly attributing taxon responses to AES gradients.

While the responses of populations of butterflies and birds to AES have been assessed previously using citizen science monitoring schemes as outlined above, responses of populations of pollinating insects to AES have not been tested in this way. Insect pollinators provide a critical ecosystem service through pollination, and declines in wild pollinators have been recently highlighted (Powney et al., 2019). Senapathi et al. (2017) identify the dearth of temporal studies showing that AES can increase insect pollinator populations over time at the landscape scale, as a crucial knowledge gap in temperate pollinator conservation. Monitoring using this study design will help to fill this gap.

The context of this study is AES management, but the approach could be applied more broadly to other types of land management, for example to test the effects of woodland creation, or to AES management in other countries. Spatial data availability will be key to applying this approach in other countries and regions, or to other types of management. Whilst georeferenced data on AES uptake are not universally available at the level of individual options, permitting the scoring approach used here, such data are becoming more widely available for entire countries (or administrative regions thereof). Not all these datasets are openly accessible to researchers, but are held by government departments or the regional administrative bodies responsible for the design, monitoring and implementation of AES that may wish to deploy the approach to monitoring outlined in this paper. For example, European Union member states are required to report on land under AES with different target outcomes under the Rural Development Programmes. Even if data on individual AES options are not available in a study region, as long as some form of spatial data on AES uptake is available (e.g. total area of land under AES), it may be possible to construct suitable AES gradients.

Datasets on land cover at sufficiently fine spatial resolution to explore inter-correlations with AES uptake are increasingly widely available, either through existing access to continental (Pflugmacher et al., 2019) or global (Sulla-Menashe et al., 2019; Pérez-Hoyos et al., 2017) land cover maps, or the creation of bespoke maps through rapid processing of accessible data from satellite constellations (Carrasco et al., 2019). The use of NCAs or equivalent homogenous landscape regions could also be applied in other contexts, where there is a need to keep background habitat variables as constant as possible.

The design developed here is being used across England to collect data on the response of mobile species to the AES intervention gradients in survey squares within these NCAs for several taxa: butterflies, moths, pollinating insects (bees and hoverflies), birds and bats. Two additional upland NCAs were added to the study design after a first year of species data were collected. A four-year baseline survey is currently underway (Natural England project LM0465), with the aim of resurveying the same squares 8–10 years after the baseline, to quantify population change. We recommend that a similar design process could be considered in other regions that require a multi-scale, integrated approach to monitoring the impacts of land management interventions on target species at landscape scales.

Author contributions

JTS wrote the manuscript and led the project; JTS, RSO'C, JWR, GMS, SGJ, IGH, MSB, CC, SP and SMS collaboratively devised the study design; RSO'C and IGH conducted the taxa evidence review; NJ led the scoring of AES options; JWR carried out the spatial analysis and testing of AES gradients; MEM coordinated the survey; JC arranged survey access; KH collected habitat data; and SGJ did the validation analyses. All authors contributed critically to manuscript drafts and gave approval for publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112589.

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