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RESEARCH ARTICLE

Reversing declines in farmland birds: How much agri-environment provision is needed at farm and landscape scales?

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Abstract

1. Agri-environment schemes (AES) are the primary policy mechanism for addressing farmland biodiversity declines across Europe. Despite previous studies on the impacts of AES on biodiversity, there is little empirical evidence on the scale of provision required to reverse declines.
2. Across three regions of lowland England with contrasting farm systems (arable, pastoral, mixed), we estimated avian population growth rates (PGRs) on farmland with high AES provision ('higher-tier': average bird-friendly option cover = 7.4%), low AES provision ('lower-tier': 2.3%) and no bird-friendly AES ('no AES'). Ten-year PGRs were derived for 24 species and three multi-species groups comprising farmland-associated species ('farmland birds'), species of conservation concern ('priority birds') and species restricted to farmland ('specialist birds'). We used PGRs to simulate the proportion of the regional farmland landscape that would have to be assigned to higher- and lower-tier agreements to stabilise or increase populations.
3. In the arable and pastoral regions, 13/23 and 13/22 species, respectively, had more positive PGRs under higher-tier AES than on no AES farmland (none had more negative PGRs), compared to 4/22 (positive) and 1/22 (negative) in the mixed region. Only two to four species per region exhibited more positive PGRs under lower-tier AES compared to no AES farmland.
4. Multi-species PGRs in the arable and pastoral regions increased from no AES (strong decline), to lower-tier (decline or stability) to higher-tier (moderate or strong increase). There was no overall AES effect in the mixed region.
5. To increase regional farmland bird populations by 10% over 10 years, 47% and 26% of the farmed landscape would need to be devoted to higher-tier agreements in arable and pastoral landscapes respectively. This falls to 34% and 17% when higher-tier is targeted at localities supporting higher abundances of target

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species, and to 29% and 10% when 30% of the farmed landscape is also devoted to lower-tier. Priority and specialist birds require higher provision levels.

6. *Policy implications*. Where farmland bird recovery is an AES objective, farms should prioritise higher-tier agreement delivery over lower-tier. Farmland bird responses to AES provision are likely to vary regionally, but careful targeting will reduce the amount needed in the landscape.

KEYWORDS

common agricultural policy, conservation targeting, environmental stewardship scheme, farmland biodiversity, farmland bird index, landscape-scale conservation, rural development, sustainable farming

1 | INTRODUCTION

Agricultural intensification is a major driver of global biodiversity decline (Donald et al., 2001). In Europe, agri-environment schemes (AES)—where landowners are financially incentivised to implement environmentally beneficial measures—are the primary policy mechanism for addressing these declines (Batáry et al., 2015). Schemes outside of Europe, such as the Conservation Reserve Program in the United States (Evans et al., 2014), fulfil a similar function. There has been much debate over the effectiveness of AES, with evidence of mixed benefits for biodiversity generally (e.g. Kleijn et al., 2006; Kleijn & Sutherland, 2003) and for specific taxonomic groups (e.g. butterflies, Aviron et al., 2007; bats, Fuentes-Montemayor et al., 2011; and birds, Princé et al., 2012). However, well-targeted schemes deploying effective interventions have increased the abundance of target groups (Redhead et al., 2022; Walker et al., 2018; Zingg et al., 2019) and species (Bretagnolle et al., 2011; Peach et al., 2001). Despite the importance of these schemes, policy-makers lack empirical guidance on how much AES-type provision is needed to meet time-bound biodiversity targets.

Reviews suggest that AES efficacy is often moderated by landscape context, with the largest biodiversity gains where interventions provide the greatest contrast in limiting resources (Batáry et al., 2011; Scheper et al., 2013). Specifically, biodiversity responses to AES tend to be more positive when deployed in simpler landscapes lacking semi-natural habitats. Responses to AES interventions are also often weaker for specialist species with more complex requirements (Kleijn et al., 2006). Other factors affecting AES effectiveness include the availability of landowner advice (McCracken et al., 2015) and whether key resources are delivered at appropriate spatial and temporal scales for the target species (Siriwardena, 2010).

Most AES biodiversity evaluations have been conducted at the field or patch scale, with fewer at the farm or landscape scale. Some studies have explored the relationship between option quantity and species abundance (e.g. Meichtry-Stier et al., 2014), but very few have considered the impact of AES provision extent on abundance change. Therefore, whilst existing evidence identifies species groups, interventions and landscape contexts most likely to generate positive biodiversity outcomes, it does not address policy-relevant questions about how much AES provision is required, at the farm and landscape scales, to reverse population declines and meet quantitative biodiversity targets, such as the UK government's commitment to halt species abundance declines in England by 2030 (Environment Act, 2021). Similar time-bound EU targets are under discussion (EC, 2021). Here, we use data from a 10-year, multi-landscape AES study of farmland birds to determine how much bird-friendly AES provision is required at both these scales to meet potential policy objectives. Previous such assessments are restricted to single species (Perkins et al., 2011) or single provision levels (Walker et al., 2018). To address this knowledge gap, we extend the approach to multi-species groups and make quantitative predictions on the scale of AES required across a 'narrow-and-deep' higher-tier scheme and a 'broad-and-shallow' lower-tier scheme.

Many AES focus on farmland birds which have suffered population declines across Europe since the 1970s (Gregory et al., 2004). Many of the demographic and environmental causes of farmland bird declines are well known (Newton, 2004) and this has led to the development of a suite of conservation interventions, including infield fallow plots for ground nesting birds, and seed-rich and insect-rich foraging habitats (Wilson et al., 2009). Farmers are encouraged to adopt multiple interventions on the same land holding to meet the lifecycle requirements of the target species; however, empirical guidance as to how much provision is required to restore populations is sparse. An early attempt at such guidance—based on limited knowledge of the habitat requirements of a few species—suggested at least 7% of arable farmland within each land holding needs to be devoted to bird-friendly habitat (Winspear et al., 2010). From 2005, this provision level became the target for bird-focused higher-tier AES agreements under the English Environmental Stewardship (ES) scheme in localities known to support multiple priority species, with a similar target area adopted in the Swiss AES (Birrer et al., 2007). In addition to this competitive and targeted higher-tier, the English ES scheme also included a non-competitive and untargeted lower-tier with a more modest level of provision recommended (3%–4% of the farmed area, Winspear et al., 2010). The lower-tier scheme excluded some of the more demanding bird-friendly options and lacked the bespoke management advice available to landowners under the higher-tier.

In this study, we measured changes in the abundance of farmland birds on land managed under both higher- and lower-tier levels of AES provision across three contrasting lowland landscapes. We used population growth rates (PGRs) for contrasting provision levels to explore different farm- and landscape-level scenarios of AES deployment to meet potential policy objectives (Figure 1). At the farm scale, we explored the site-level effects of two levels of AES provision (typical of higher- and lower-tier schemes) on the PGRs of farmland birds. At the landscape scale, we asked what proportion of the wider farmed landscape would need to be subjected to different combinations of higher- and lower-tier agreements in order to stabilise or recover farmland bird populations across that landscape. As far as we know this is the first study to use PGRs associated with differing AES provision levels to predict the amount of landscape-scale AES deployment required to achieve potential policy objectives.

2 | MATERIALS AND METHODS

2.1 | Bird surveys on higher-tier farmland

PGRs of farmland birds under higher level AES provision were derived from surveys of 67 farms subject to Higher Level Stewardship agreements. The farms were selected according to their provision

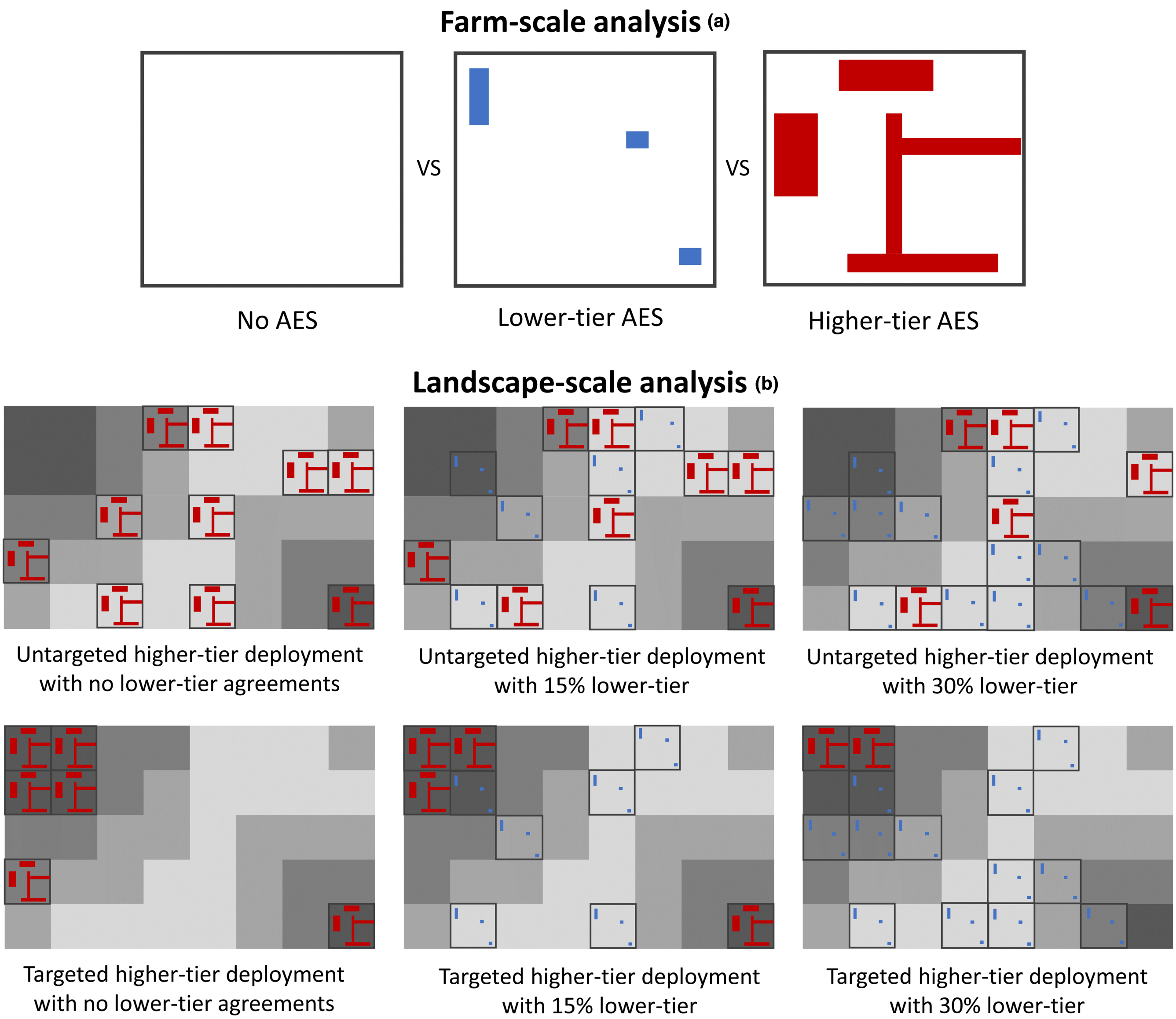

FIGURE 1 Schematic illustration of the two scales of AES provision considered by this study. The farm-scale analysis (a) compares the site-level effects of lower-tier (blue polygons) and higher-tier (red) AES provision on farmland bird population growth rates (polygons are not drawn to scale). The landscape-scale analysis (b) explores what proportion of the regional farmed landscape would need to be devoted to higher-tier agreements to stabilise or recover populations across six deployment scenarios: Geographically untargeted/targeted higher-tier deployment (with respect to initial farmland bird densities), with 0%, 15% or 30% of the landscape in lower-tier agreements. Squares represent hypothetical 1 km grids; shading denotes initial bird densities (light grey = low densities, dark grey = high densities); and polygons illustrate the amount of lower- and higher-tier deployment required to achieve stability.

of 'bird-friendly' measures and the presence of at least one of six target bird species (Walker et al., 2018). Most of the farms entered into higher-tier agreements in 2006 (51 farms) or 2007 (13), with one entering in each of 2008, 2011 and 2012. Bespoke pre-agreement advice to landowners was provided to help select, locate and manage options for farmland birds. The farms were spread across three regions of lowland England with contrasting farming systems and defined by National Character Areas (NCAs) (Figure 2): the arable-dominated 'East Anglia' (arable to grassland ratio: 1.0:0.2, see Figure S1), the pastoral-dominated 'West Midlands' (1.0:1.5) and the mixed-farming 'Oxfordshire' (1.0:0.9). In 2008, 2011, 2014 and 2017, a total of 63, 65, 67 and 45 farms, respectively, were surveyed for farmland birds (the pastoral region was not surveyed in 2017).

Bird abundance on higher-tier farms was measured using a complete area search (Walker et al., 2018) conducted twice annually (April–May and June–July) recording all bird species seen or heard within a tetrad, centred on the key bird-friendly AES options. We separated adults from juveniles where possible, and the maximum adult count (from the two visits) of each species at each tetrad in each year was the dependant variable in subsequent analyses. Nearly all (65) tetrads covered separate agreements; the remaining two covered two geographically separated blocks within the same agreement. On average, 65% of the AES agreement area fell within the tetrad (SD 22%, range 15%–100%); any land outside the agreement, but within the tetrad, was excluded. Every field boundary and parallel cross-field transects (50–70 m apart) were walked, excluding woodland. Surveys were undertaken between an hour after dawn and midday, avoiding poor visibility, rain or strong wind.

For most of the tetrads, areas of AES were mapped during field surveys, with reference to agreement maps, in each of 2011, 2014 and 2017; though 26 and 5 were only surveyed in two or one of these years respectively. Across 66 of the 67 farms (excluding one that only adopted wet grassland options) bird-friendly AES management—defined as the combined extent of seed-rich, insect-rich and in-field nesting options (Table S1) within each tetrad across the surveyed years—covered on average (median) 7.4% (SD 11.6%; range 1%–66%) of the farmed area (arable and pasture) (Table 1). This area of 'effective provision' involved multiplying the stubble area by 0.4 to convert to an equivalent area of Wild Bird Seed (WBS) crops (following Natural England, 2013). Including actual stubble area gives an average total area of 11.1% (SD 15.2%, 1%–66%; Table S2) (hereafter 'total provision'). Although some higher-tier sites had lower levels of bird-friendly AES provision (<4%), individual species showed no consistent directional pattern in response to their exclusion and the average (cross-species) effect of their removal on PGRs was either negative or small (Appendix S1). Most of the bird-friendly AES options were intended to benefit multiple species and can therefore be considered as generic measures. For Lapwing *Vanellus vanellus*, a slightly different set of AES options were considered (Table S1) and this covered an effective area of 9.3% (SD 13.9%; 1%–66%) and a total area of 13.4% (SD 16.6%, 1%–66%) across all 67 farms. Six farms with no bird-friendly

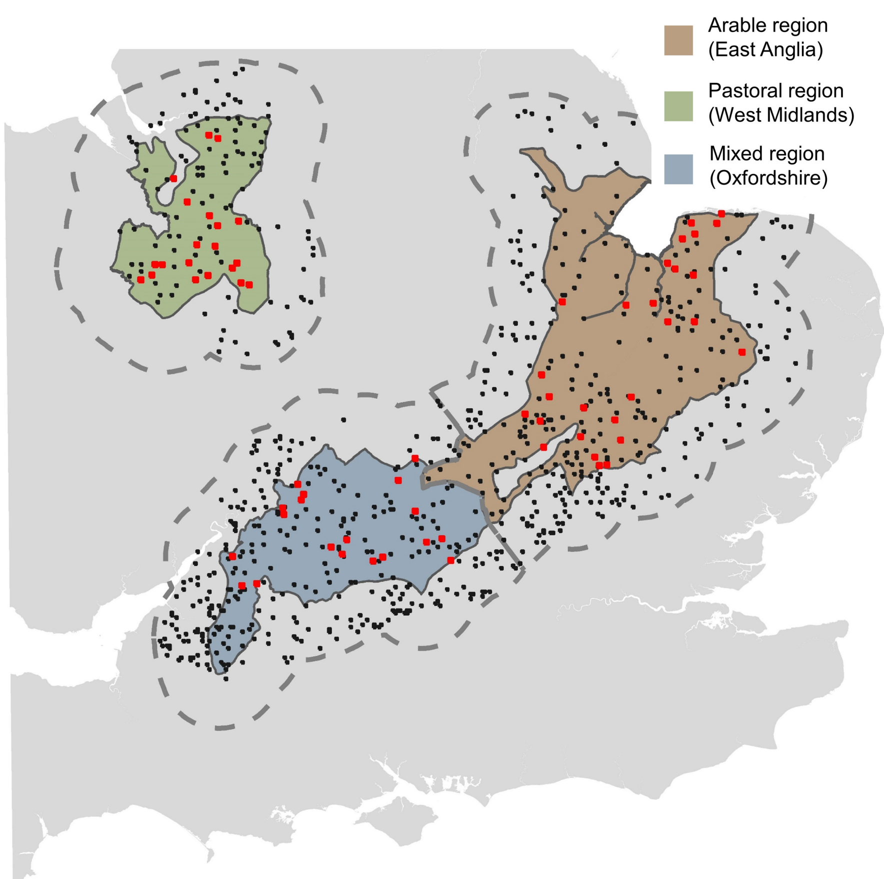

FIGURE 2 Location of the higher-tier farmland (red squares) and lower-tier/no AES BBS squares (black squares) across three regions in lowland England. BBS squares were also selected from a 20 km buffer around National Character Areas (NCAs, dashed line), but excluding adjacent NCAs with different landscape character.

TABLE 1 Number of higher-tier, lower-tier and no AES sites in East Anglia (EA), West Midlands (WM) and Oxfordshire (OX). For higher-tier and lower-tier, the median (±SD) % of AES habitat per square, relative to the total farmed area, is shown. Bird-friendly AES and the additional measure of Lapwing-friendly AES are reported separately. Effective provision includes all seed-rich, insect-rich and infield nesting habitat

AES status	Number of sites			Effective bird-friendly provision	Seed provision[a]	Insect provision	Infield provision[b]	Wet grassland provision
	EA	WM	OX					
Higher-tier AES	27	20	19	7.4% (±11.6)	3.1% (±4.6)	1.4% (±10.4)	0.2% (±2.6)	—
Higher-tier AES (Lapwing)	27	20	20	9.3% (±13.9)	3.1% (±4.6)	1.1% (±10.4)	0.0% (±2.4)	0.0% (±8.5)
Lower-tier AES	131	39	192	2.3% (±1.4)	1.2% (±1.0)	0.7% (±1.3)	0.0% (±0.5)	—
Lower-tier AES (Lapwing)	128	42	193	2.4% (±1.4)	1.1% (±1.0)	0.7% (±1.2)	0.0% (±0.7)	0.0% (±0.5)
No AES[c]	171	91	269	—	—	—	—	—
No AES (Lapwing)[c]	172	91	270	—	—	—	—	—

[a]Seed includes overwinter stubble habitat and wild bird seed crops (see Table S1 for the options). The effective area extent of this category was calculated by multiplying the area of stubbles by 0.4 (following Natural England, 2013) before adding this to the area of wild bird seed mixes. For Lapwing, rye-grass set seed was excluded.

[b]Infield includes Skylark plots and AES fallow plots for breeding birds (see Table S1 for the options). The area extent of this category was calculated by assuming that 1 Skylark plot contributed 0.05 ha (following Winspear et al., 2010) before adding this to the area of fallow plots. For Lapwing, Skylark plots were excluded.

[c]For the 'no-AES' category, BBS squares with more than 0.25% of seed ES provision across the farmed wider landscape (defined here as the closest 24 1 km squares, see Section 2.2) were excluded.

management in 2017 (expired agreements) were excluded from the analysis for this year. No licencing or permits were required for fieldwork and no ethical approval was required for the bird surveys.

2.2 | Bird surveys on lower-tier and no-AES farmland

Data from the UK Breeding Bird Survey (BBS) (Harris et al., 2020) were used to provide a counterfactual measure of PGRs across farmland with lower-tier levels of, or no, bird-friendly AES provision. The BBS involved two early morning visits to 1 km^2 squares in early April to mid-May, and mid-May to late June. Observers counted adults of all bird species along two parallel 1 km transects, each divided into five 200 m sections. Bird encounters 0–100 m from the transect were considered and in-flight registrations were excluded except for Skylark *Alauda arvensis* (which displays in flight) and Kestrel *Falco tinnunculus* (to capture foraging). Counts from transect sections without farmland, on at least one side, were excluded. Although some BBS transects will span multiple land holdings having potentially contrasting managements, this may introduce noise into square level counts but should not introduce systematic bias. BBS squares were selected to: (i) include at least one 'farmland' transect section; (ii) include at least 10% arable, semi-natural grassland or improved grassland habitats (hereafter 'farmed habitat') according to the UK Centre for Ecology and Hydrology Land Cover Map (LCM2015, Rowland et al., 2017); and (iii) fall within a 20-km buffer of an NCA with at least one higher-tier farm, but excluding adjacent NCAs with different geology or land use (Figure 2). BBS data were included from 2008 to 2017 (arable and mixed region) and 2008–2014 (pastoral region).

Spatial data containing agreement details from the ES scheme were used to quantify the amount of AES present in each BBS square in each year. Following Baker et al. (2012), the amount of each option per agreement and square was calculated by assuming that the quantity of each option, within each square, was proportional to the area of the agreement that fell within the square. Option category-specific areas (seed-rich, insect-rich, infield and wet grassland) were summed across all agreements within each square. To account for temporal variation in option provision, the mean annual area of each option category was calculated for the years that the square was subject to bird-friendly AES. Separate option area measures were calculated for Lapwing.

Across the selected BBS squares, AES provision estimates were used to generate 'no AES' and 'lower-tier AES' samples. For 'no AES', we selected squares that received no bird-friendly AES between 2008 and 2017, and square-years (specific years within a specific square) before bird-friendly AES commenced. To ensure that this sample was not contaminated by potentially suitable management from the more recent Countryside Stewardship Scheme (CS), all square-years with bird-friendly CS agreements (which were first introduced in 2016) were excluded (Table S1). To minimise any effects of seed-rich habitat in the surrounding landscape on 'no-AES' PGRs (as reported by Baker et al., 2012), we excluded from the analysis any BBS squares for which seed-rich habitat in the surrounding 5 km × 5 km exceeded 0.25% of the farmed area. Note, previous studies have demonstrated enhanced Skylark and Yellowhammer *Emberiza citronella* abundance when local overwinter-stubble provision exceeds 5% (Gillings et al., 2005), so this 0.25% cut-off is highly conservative. For 'lower-tier', BBS square-years having 1%–6% effective bird-friendly AES provision (relative to the farmed area) were selected, which gave a median effective provision of 2.3% (SD 1.4%, range 1%–6%) (total provision = 3.9%, SD 2.5%, range 1%–15%) (similar to the recommended lower-tier level, Winspear et al., 2010). This classification was repeated for Lapwing.

Whilst our selection ensured more than a threefold difference in average bird-friendly AES provision between the lower- and higher-tier samples, the composition of that provision (extent of seed-rich, insect-rich and infield habitat) was similar between the two tiers (Appendix S1). Although some 'high-quality' options were restricted to higher-tier agreements, empirical comparisons have failed to detect enhanced resource provision or bird usage of these options (Bright et al., 2014a, 2014b). Thus, our higher- and lower-tier comparison primarily reflects variation in option provision extent and bespoke landowner advice rather than provision composition or quality.

2.3 | Estimating the effects of AES provision on farmland bird populations at the farm scale

Generalised linear mixed models (GLMM) were used to estimate region- and species-specific PGRs for each AES status category. As AES status is partially confounded with survey methodology, our analysis assumes that temporal trends in avian abundance are comparable across methodologies, an assumption that has strong empirical support (Freeman et al., 2007) and has been made in previous conservation intervention assessments (Jellesmark et al., 2021; Redhead et al., 2022; Walker et al., 2018). Our analysis was restricted to higher-tier farms and lower-tier/no AES BBS squares (hereafter collectively 'sites') with at least two survey years and at least one encounter (from any year) of the species in question. Species encountered on fewer than six higher-tier, lower-tier or no AES sites per region were dropped, leaving 23 (arable) or 22 (pastoral or mixed) species for which PGRs were estimated (see Table S3 for sample sizes). Maximum annual adult count of each species, from the two visits, was the dependent variable. Analyses were carried out in R (R Core Team, 2015) and GLMMs were built using glmmTMB (Brooks et al., 2017).

Separately for each species in each region, a 'full' model was fitted with 'AES status' (categorical, three levels) and 'AES duration' (years since AES initiation, continuous; PGR) included as fixed effects, plus their interaction. Models were initially fitted with six error structures (Poisson, negative binomial, negative binomial with variance increasing greater than linearly with the mean or zero-inflated versions of each) and the structure with the lowest Akaike information criterion was selected. Since the average start year of higher-tier and lower-tier sites differed (Table S4), including 'AES duration' as a fixed effect—instead of 'calendar year'—controlled for this temporal variation. For 'no AES', the first survey year was set to zero. Note, 30% of sites initially classified as 'no AES' were reclassified as 'lower-tier AES' in subsequent years; here, 'AES duration' was reset to zero at the point of reclassification. Higher- or lower-tier sites were not reclassified to 'no AES' when agreements ended to avoid carryover effects; instead, these years were excluded. The natural logarithm of the farmland area surveyed was included as an offset (higher-tier mean = 1.37 km^2; BBS squares = 0.35 km^2), and 'site identity' and 'calendar year' were included as random effects to control for spatial and temporal non-independence (following Daskalova et al., 2019). Coefficient estimates from the full model were backtransformed to provide meaningful PGRs; for example, an estimate of 1.05 or 0.95 represented a 5% annual population increase or decrease respectively.

To test whether PGRs differed in relation to AES status, a likelihood ratio test was used to compare the 'full' model to a 'control' model with the 'AES status' × 'AES duration' interaction removed. Equivalent post hoc comparisons, restricted to two AES status levels, were used to determine where significant differences lay between PGRs. Using the full model, 95% CIs were derived for species-, region- and AES status-specific PGRs using a bootstrap involving 1000 replications. Because our sample for some species–region combinations was too low for a non-parametric approach, we used a parametric procedure which resampled from a multivariate normal distribution based on the fitted (full) model.

To provide an aggregate measure of abundance change, 'multi-species' PGRs were estimated for: (i) 19 farmland-associated species (hereafter 'farmland birds', as recognised by the UK Farmland Bird Index); (ii) 18 farmland-associated species of conservation concern ('priority birds'); and (iii) 12 species restricted to farmland ('specialist birds') (Table S5). For each group, multi-species PGRs were calculated as the geometric mean of all species-specific PGRs for each AES status and region combination. Next, the 950 bootstrapped PGR estimates that fell within the 95% CI range of each region-×species-specific PGR model were used to quantify error based on underlying model uncertainty. To do this, individual bootstrapped PGRs for each species were randomly assigned to a single 'iteration set' for each region × AES status category. For each multi-species group, a separate PGR geometric mean was estimated for each iteration set producing 950 higher-tier, lower-tier and no-AES multi-species PGR estimates, per region. The multi-species PGRs in the arable region were sensitive to the inclusion of Turtle Dove *Streptopelia turtur* which declined strongly across all three levels of AES provision. This range restricted species has specialised ecological requirements and has recently become the subject of a targeted AES package in England comprising habitat options tailored to the needs of Turtle Dove. We therefore explored the consequences for multi-species PGRs and predicted landscape provision of excluding Turtle Dove from our three species groupings in a separate supplementary analysis.

2.4 | Simulating landscape AES provision requirements for regional policy targets

Previous studies have used simple ratio calculations to estimate the proportional area of AES management needed in a landscape to offset continuing declines on non-AES farmland (Perkins et al., 2011; Walker et al., 2018). However, this approach fails to allow for spatial variation in the initial background density of the target populations (meaning the impact of conservation targeting cannot be assessed), and the uncertainty associated with the PGRs. To address these limitations, we developed a simulation framework, that incorporates initial background bird densities and multi-species PGR error, to estimate how much and what combinations of higher- and lower-tier AES—at the scale of 1 km squares—would be required in our study regions to achieve hypothetical region-level policy targets for farmland bird recovery (Figure S2 illustrates the analytical processes). To do this, our multi-species PGRs (above) were applied to baseline multi-species abundance scores derived at the 1-km square level. Abundance scores were derived using a five-stage process, fully described in Appendix S2. First, species- and habitat-specific detectability functions were calculated using all BBS data for Great Britain for the period 1994–2017. Second, these functions were used to convert farmland-specific BBS counts for the period 2015–2017 to farmland bird densities (see Appendix S2 for details). Third, these densities for all GB BBS squares were the dependent variables in species-specific generalised additive models (GAMs) which included a suite of environmental (e.g. land cover, tree cover and elevation) and spatial predictors. Fourth, these GAMs were used to predict bird densities on farmland for every 1-km square in our study regions, including the 20-km buffer. Finally, species-specific farmland densities for each square were combined into multi-species farmland abundance scores in which each species had equal weighting (Figures S3 and S4).

Having derived baseline regional abundance scores, a simulation process was developed that involved deploying differing quantities of higher- and lower-tier AES at the 1-km square level across each region to achieve two regional policy targets for the three species groupings: (1) population stability and (2) 10% population growth, both after 10 years. Because stability or growth is unachievable where PGRs in the absence of AES are less than 1.0, and higher-tier AES has no positive effect, multi-species group and region combinations where higher-tier PGR 95% CIs spanned or fell below 1 were not simulated. For each combination that met this criterion, six AES deployment 'scenarios' were examined: geographically untargeted or targeted higher-tier deployment, each with 0%, 15% or 30% lower-tier AES (Figure 1). The geographically untargeted scenario tested the impact of no spatial prioritisation by randomly allocating higher-tier management across the regional farmed landscape; the geographically targeted scenario tested the opposite by initially constraining higher-tier deployment to 1-km squares where the predicted abundance of specialist farmland birds was highest. Starting with the 'untargeted 0% lower-tier' scenario, 5000 simulation iterations were run for each multi-species group and region combination. For each iteration, a single no AES PGR (from 950) was randomly selected (with replacement) and applied to every regional farmland square, before calculating regional abundance, after 10 years, as:

$$\Sigma(As \times Rs\hat{\ }10).$$

where A is the multi-species abundance score of square S and R is the PGR of the same square. Next, a higher-tier PGR was randomly selected and applied to 1% of the squares selected at random (with the rest retained as 'no AES') before recalculating abundance. Using the same higher-tier PGR, this process was repeated at 1% increments until both policy targets were achieved. If all configurations failed to achieve either target, the iteration was deemed a 'failure' for the target(s) in question. For each target, all iterations were pooled to calculate: (i) the number of failed iterations; and (ii) the average amount of higher-tier AES required to achieve the target from the successful iterations.

For the 15% and 30% lower-tier AES scenarios, lower-tier PGRs were randomly selected and applied at random to 15% or 30% of the farmland squares at the onset of each iteration. When assigning higher-tier PGRs, deployment was initially constrained to 'no AES' squares; however, when none remained, deployment switched to lower-tier squares. For the 'targeted' scenarios, higher-tier deployment was initially constrained to regional farmland squares with a specialist bird abundance score in the top 25 percentile (first strata), followed by the top 25–50 percentile (second strata), and then the rest (third strata). Geographical targeting was based on this multi-species group because it closely matches the six farmland birds targeted for higher-tier AES in England (Table S5). For 'targeted' scenarios with lower-tier, higher-tier deployment was initially constrained to no AES squares, before switching to lower-tier squares in the same stratified order.

3 | RESULTS

3.1 | Effects of AES provision on farmland bird populations at the farm scale

In both the arable and pastoral regions, 13 of 23 (arable) or 22 (pastoral) species tested had more positive PGRs on higher-tier farmland compared to no AES farmland (Figure 3, Tables S3 and S6, the rest exhibited no significant change), whilst in the mixed region, only four species of 22 tested had more positive PGRs on higher-tier farmland (one was more negative, the others no different). Nine (arable), two (pastoral) and five (mixed) species had more positive PGRs on higher-tier than on lower-tier farmland, whilst in the mixed region, a further four species had more negative PGRs on higher-tier farmland. Only two to four species per region had more positive PGRs on lower-tier compared to no AES farmland.

In the arable and pastoral regions, all three multi-species PGRs exhibited positive growth (PGR >1.0) under higher-tier AES, stability or weak decline under lower-tier AES and strong decline (PGR <1.0) under no AES (Figure 4). The higher-tier effect was more positive in the pastoral region across all multi-species groups. In the mixed region, multi-species PGRs were lower under higher-tier, and higher under no AES, than in the other two regions. Across all multi-species groups, populations in the mixed region were generally stable under higher- and lower-tier, and exhibited a comparatively modest decline under no AES.

3.2 | Landscape AES provision requirements for regional policy targets

Our simulations of regional AES provision requirements were restricted to the arable and pastoral regions where higher-tier AES had

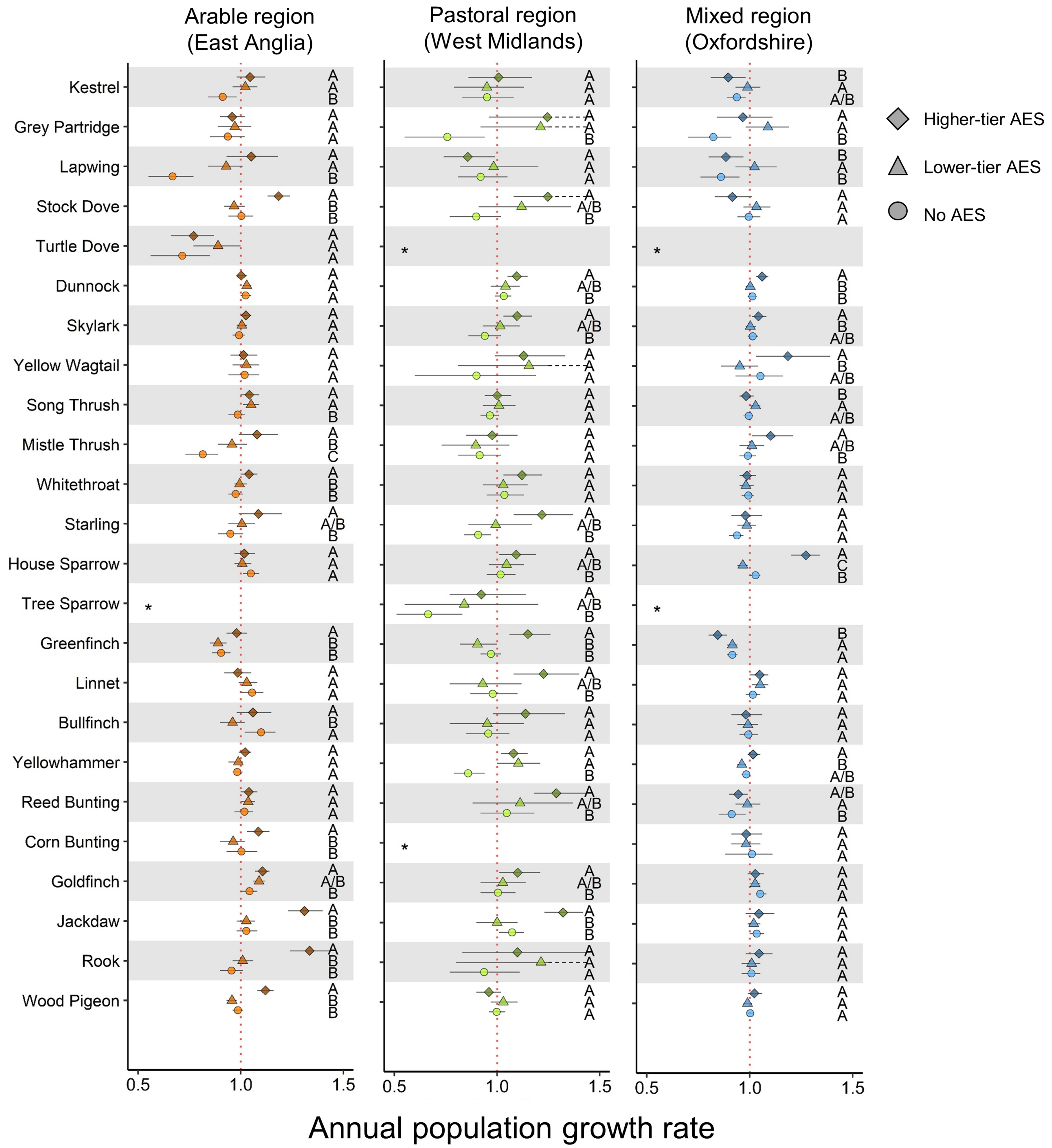

FIGURE 3 Predicted annual population growth rates (PGRs) of individual bird species across higher-tier, lower-tier and no AES farmland, across three regions in lowland England. Predictions are derived from generalised linear mixed models with an AES status and AES duration interaction (Table S3). PGR estimates that do not share a letter (A–C) differ significantly ($p > 0.05$). Asterix denotes species × region combinations that were excluded from analysis. PGRs to the left or right of the vertical dashed line indicate a declining or increasing population respectively. Bars show 95% CIs; dashed horizontal lines denote CIs that exceed 1.45.

clear positive impacts on multi-species PGRs; the same was not true of the mixed landscape, where higher-tier PGRs were less than or close to 1.0 (Figure 4).

For the farmland bird multi-species group all simulation iterations achieved both policy objectives in both regions. When higher-tier AES was geographically untargeted, with no lower-tier AES, 38%

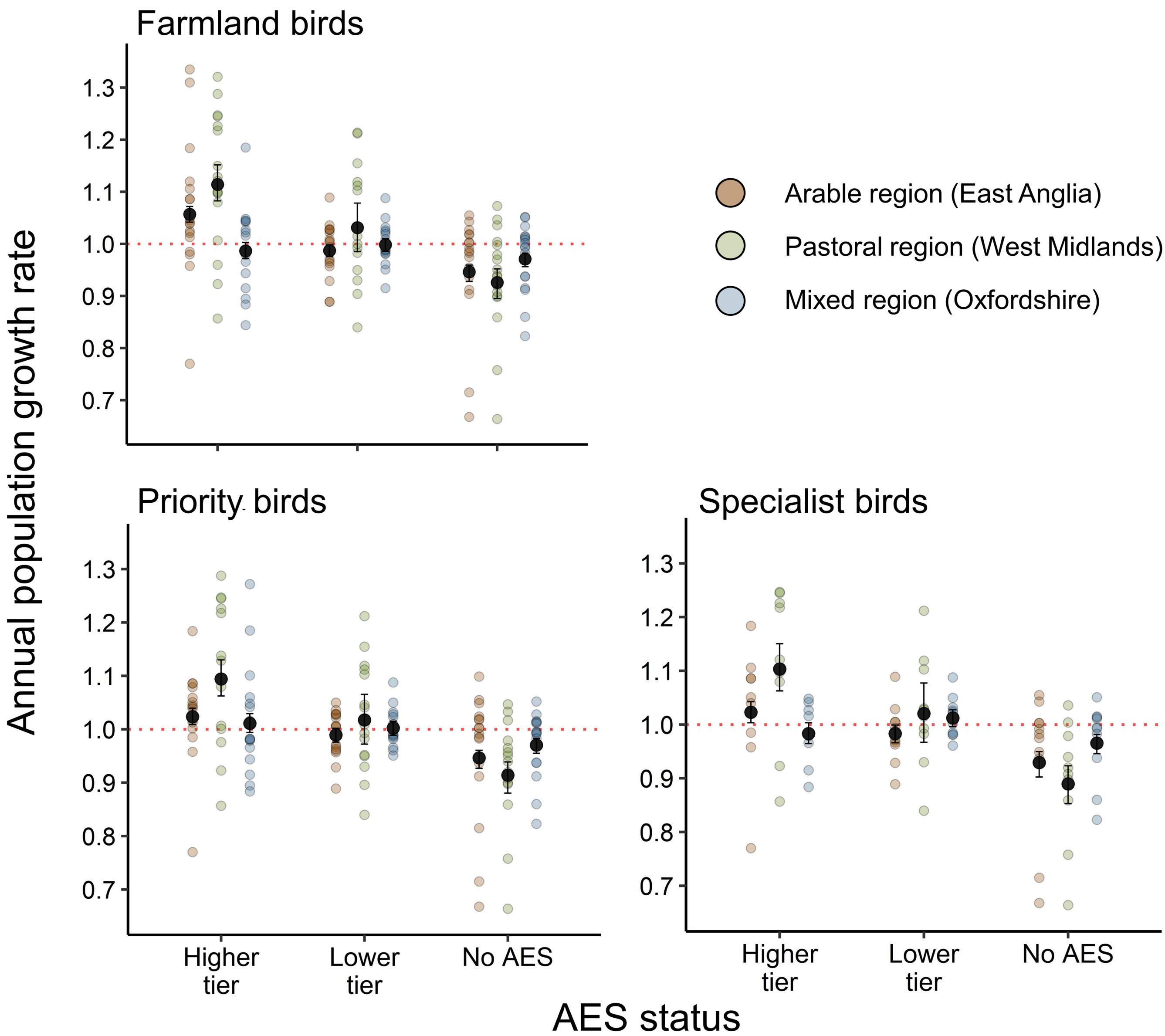

FIGURE 4 Annual multi-species population growth rate (PGR) estimates for farmland, priority and specialist birds (Table S5) in higher-tier, lower-tier and no AES farmland, across three regions in lowland England. Multi-species PGRs (black dots) show the average annual PGRs of each AES status × region combination, calculated as the geometric mean of all species-specific PGRs (coloured dots). Bars show the 95% CIs of 950 bootstrapped multi-species PGRs (Figure S6). PGRs below or above the dotted line indicate a declining or increasing population, respectively.

(95% CIs: 29%–48%; arable region) or 22% (14%–33%; pastoral) of the farmed landscape would need to be devoted to higher-tier agreements to achieve population stability (Figure 5, Table S7a), rising to 47% (37%–58%; arable) or 26% (17%–38%; pastoral) for 10% population growth. Given that approximately 10% of the farmed area of higher-tier farms was devoted to bird-friendly AES options, 47% (arable) and 26% (pastoral) of the farmed landscape subject to higher-tier agreements equates to bird-friendly AES option coverage of 4.7% and 2.6% of the landscape respectively. When higher-tier deployment was geographically targeted, required landscape provision was reduced to 27% (20%–35%; arable) or 14% (9%–21%; pastoral) for stability, and 34% (25%–43%; arable) or 17% (11%–25%; pastoral) for growth. When higher-tier deployment was targeted and lower-tier AES was present across 30% of the farmed landscape, the higher-tier requirement fell further to 21% (16%–28%; arable) or 7% (1%–13%; pastoral) for stability, and 29% (22%–38%; arable) or 10% (3%–17%; pastoral) for growth. In the arable region excluding Turtle Dove from the analysis increased average multi-species PGRs across all AES status levels and reduced landscape-scale higher-tier requirements across all scenarios (Appendix S3).

For the priority and specialist multi-species groups, 100% of the simulation iterations achieved both policy objectives in the pastoral region, though up to 10% failed in the arable region (Figure 5). Both groups required a much greater provision of higher-tier agreements to achieve policy targets, especially in the arable landscape; for example, to stabilise specialist birds with targeting but without

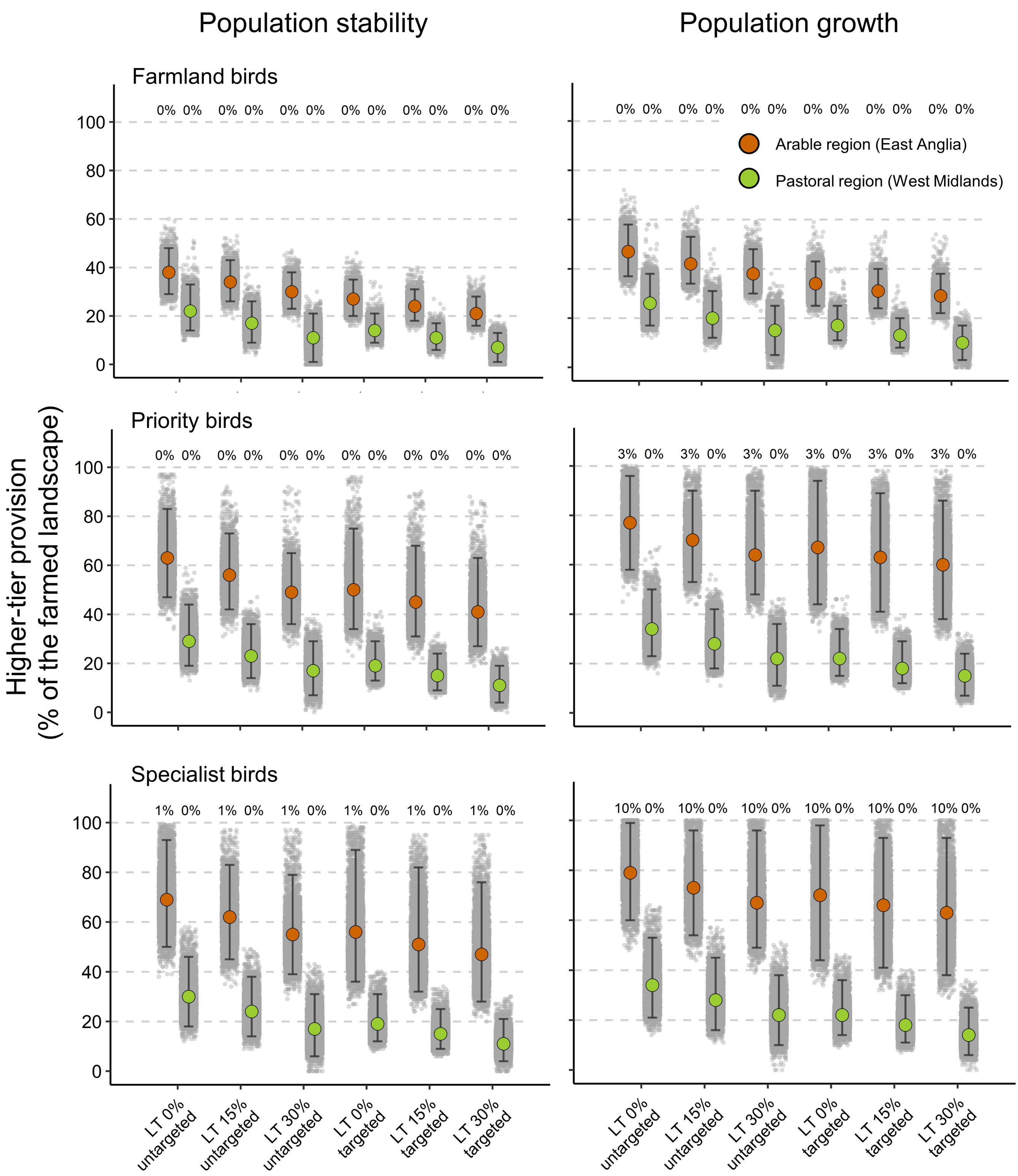

FIGURE 5 Estimated proportion of the farmed landscape that would need to be subject to higher-tier AES agreements to stabilise (stability) or increase populations by 10% (growth), over 10 years, for farmland, priority and specialist birds (Table S5). Results are reported for two regions in lowland England and six deployment scenarios: Geographically untargeted/targeted higher-tier deployment, with 0%, 15% or 30% lower-tier (LT) AES. Grey dots represent individual simulation iterations, coloured dots show the mean amount of higher-tier provision required to achieve stability or growth (bars show 95% CIs). The percentage of iterations that failed to meet each policy objective is reported above the bars.

lower-tier agreements would require 56% higher-tier compared to 19% in the pastoral region. Similar effects of targeting, lower-tier agreement provision and Turtle Dove exclusion (in the arable region) were observed.

4 | DISCUSSION

The key finding of this well-replicated 10-year study is that higher-tier provision had a strong positive effect on the abundance of many farmland birds in two of the three regions, where in the absence of AES provision, abundance was declining. AES provision had no consistent effect on farmland bird abundance in our mixed landscape. Lower-tier provision only affected the abundance of a few species. Our predictions of AES provision required to meet policy objectives vary between regions and highlight the importance of spatial targeting.

4.1 | Farm-scale AES provision

Our study demonstrates that higher-tier AES has a reasonable chance of enhancing farmland bird abundance. Our sample of 66 higher-tier agreements was characterised by an average area of 11.1% of farmland devoted to bird-friendly options and the provision of bespoke site-specific technical advice. This average option area falls to 7.4%, or rises to 12.1%, if all the seed-rich habitat provision, across our sample of higher-tier farms, were entirely comprised of WBS or stubbles, respectively (see Section 2.1); however, to benefit the widest suite of species, a combination of both is probably optimal. Although responses to lower-tier (2.3% effective provision; 3.9% total) were limited, it maintained multi-species PGRs at close to stability in all three regions, which in two of the regions were higher than under no AES (Figure 4). Therefore, although lower-tier AES did not enhance abundance, it mitigated ongoing declines. There was no obvious ecological distinction between species that responded to AES provision and those that did not. Indeed, only Turtle Dove, which has ecological requirements that may not be readily met by generic AES, failed to respond positively to AES in any region.

A key finding of this study is the pronounced regional variation in the response of farmland birds to higher-tier AES. Despite the extent and composition of higher-tier AES being similar in each region (Appendix S1), average responses were most positive in the pastoral region and weak or absent in the mixed. The abundance of seed-eating birds in pastoral landscapes is more sensitive to the provision of small areas of seed-rich arable habitats than in arable landscapes (Robinson et al., 2001) and this might explain the relatively strong response of several seed-eating species in this region. The weaker AES effect in the mixed landscape is more difficult to explain. AES effects are often weaker in landscapes with more semi-natural habitats (Batáry et al., 2011), but the mixed region contained only marginally more semi-natural land cover (Figure S5). It is also unlikely that a lack of an AES response is attributable to a density-dependent effect, as the initial densities of most species were similar across regions (Table S8). One factor that might explain the weaker apparent effectiveness of higher-tier AES in the mixed region is the much higher intensity of AES provision across that landscape (Appendix S4). Here, the average extent of bird-friendly AES options was 2.2–4.3 times greater than the other two regions. This could explain why PGRs under no AES were higher in the mixed region; birds breeding in 'no AES' areas would have had greater access to AES provision in surrounding areas, especially during winter when many resident species are more dispersive. A landscape rich in AES might also explain why PGRs on higher-tier farms were less positive if farmland birds are more evenly distributed across the landscape.

4.2 | Landscape-scale AES provision

The amount of higher-tier provision required to meet policy objectives varies between species groupings and regions, and in relation to spatial targeting and lower-tier provision. The strong effect of targeting is illustrated by the farmland bird group which required 47% and 26% of the farmed landscape to be managed under higher-tier agreements to increase population size by 10% over 10 years in the arable and pastoral regions, but 34% and 17%, respectively, when the provision was targeted to locations supporting the highest bird densities. Our higher-tier provision estimates in the arable region were sensitive to the inclusion of Turtle Dove. For example, the requirement for population growth under targeted higher-tier provision fell from 34% to 21% when Turtle Dove was excluded (Appendix S3). Given that the specialist ecological requirements of the Turtle Dove may render generic AES ineffectual as a conservation measure, it may be reasonable to exclude this species from assessments like this of generic AES provision requirements for England.

Density-dependant effects may moderate higher-tier efficacy in such a way that areas with higher initial densities may experience lower PGRs (Sutherland & Norris, 2002), which would affect our agreement provision estimates. Although we did not explicitly control for density dependence, we only explore how much AES is required to achieve a 10% population increase. Given the Farmland Bird Index—which is analogous of our farmland bird group—declined by 58% in England between 1970 and 2017, and by 12% between 2008 and 2017 (DEFRA, 2022), any density-dependant moderation is probably weak within our simulation limits.

Priority and specialist species require higher levels of AES agreement uptake in the arable, though not the pastoral, landscape, highlighting three further research requirements. First, to facilitate regional targeting, there is a need to better understand how AES effectiveness varies regionally and what factors are driving that variation. Second, for species that failed to respond, or only responded modestly, it may be necessary to develop new, bespoke options that better meet their requirements. Such bespoke measures can generate population growth when carefully designed and targeted (Bretagnolle et al., 2011; Peach et al., 2001). Third, it would be useful to re-visit some existing interventions to establish whether aspects of their design and deployment can be improved (Siriwardena, 2010).

5 | CONCLUSIONS

This study demonstrates that higher-tier AES (approximately 10% of the farmed area devoted to bird-friendly AES) can generate population growth for a range of priority farmland bird species. Lower-tier levels of AES provision (<4%) generally failed to enhance bird abundance but helped sustain populations. The amount of higher-tier AES required to achieve population stability or growth at the landscape-scale varies between regions, but this is reduced with careful higher-tier targeting and additional lower-tier management. Recovering priority and specialist species in arable regions may require better targeting or more effective options. Our findings have wider relevance to AES-type programmes including higher- and lower-tier components, but similar regionally explicit studies are needed to provide locally reliable guidance.

AUTHOR CONTRIBUTIONS

Elwyn Sharps, Will J. Peach, Dave L. Buckingham, Antony J. Morris, Robert W. Hawkes, Andrew J. Bladon and Philip V. Grice conceived the ideas; Elwyn Sharps, Robert W. Hawkes and Andrew J. Bladon conducted the analyses; Jennifer Border derived the baseline abundance scores; Robert W. Hawkes led the writing of the manuscript. All authors contributed critically to the drafts.

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CONFLICT OF INTEREST

There is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.p2ngf1vv8 (Hawkes et al., 2022).

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SUPPORTING INFORMATION

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