Received: 3 May 2021 | Accepted: 2 December 2021

DOI: 10.1111/1365-2664.14104

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Complex landscapes stabilize farm bird communities and their expected ecosystem services

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Funding information
School of Biological Sciences, Washington State University; National Institute of Food and Agriculture, Grant/Award Number: 2015-51300-24155, 2016-04538 and 2021-67012-35133

Handling Editor: Urs Kormann

Abstract

1. Birds play many roles within agroecosystems including as consumers of crops and pests, carriers of pathogens and beloved icons. Birds are also rapidly declining across North America, in part due to agricultural intensification. Thus, it is imperative to identify how to manage agroecosystems to best support birds for multifunctional outcomes (e.g. crop production and conservation). Both the average amounts of services/disservices provided and their temporal stability are important for effective farm planning.
2. Here, we conducted point count surveys for 4 years across 106 locations on 27 diversified farms in Washington and Oregon, USA. We classified birds as ecosystem service or disservice providers using indices spanning supporting, regulating, provisioning and cultural services/disservices. We then examined service/disservice index pairwise correlations and assessed the relative importance of local, farm and landscape complexity on the average and temporal stability of avian service/disservice provider indices.
3. Generally, service provider indices (production benefitting birds, grower appreciation and conservation scores) were positively correlated with each other. Foodborne pathogen risk, grower disapproval and identity/iconic value indices were also positively correlated with each other. However, the crop damaging bird index generally had low correlations with other indices.
4. Farms that implemented more conservation-friendly management practices generally had higher average service provider indices, but farm management did not impact disservice provider indices, except for grower disapproval. Average disservice provider indices were lower on farms in complex landscapes.

5. Local vertical vegetation complexity tended to increase the temporal stability of service provider indices but did not affect the disservice provider indices. Greater landscape complexity was generally associated with increased temporal stability of service and disservice provider indices. Increased landscape complexity may stabilize bird communities by increasing bird community evenness, which in turn, positively predicted temporal stability of all service/disservice provider indices.
6. *Policy implications*. Our results suggest that farmers can effectively manage their farms to harness ecosystem services from birds through farm diversification. Disservices provided by birds, however, appear to be most negatively impacted by landscape-level complexity. Thus, greater incentives for farmers to increase semi-natural cover at the landscape scale are likely necessary to achieve multi-functional outcomes for conservation and agriculture.

KEYWORDS
Campylobacter, ecosystem services, evenness, landscape, multi-functional landscapes, stability, sustainable agriculture, wild birds

1 | INTRODUCTION

Birds play many roles within human societies, from voracious consumers of crippling crop pests, to haulers of pathogens, to symbols of peace, love and strength (Karp et al., 2013; Smith et al., 2020; Whelan et al., 2008). Birds are also rapidly declining, largely in response to accelerating levels of habitat loss and land use intensification (Rosenberg et al., 2019). The rapid loss of birds is likely to have severe consequences for the functioning of coupled human-natural systems by compromising important ecosystem services (Echeverri et al., 2021; Şekercioğlu et al., 2004; Whelan et al., 2008). The ecosystem services (benefits that nature provides to humans) and disservices (harmful effects of nature to human well-being) that birds provide to people are varied. These services and disservices include a variety of supporting (e.g. biodiversity), regulating (e.g. pathogen spread or disease regulation, insect control and pollination), provisioning (e.g. consumption of crops) and cultural (e.g. spiritual enrichment and positive or negative aesthetics) services/disservices (Figure 1a; Echeverri et al., 2021; Şekercioğlu et al., 2004). This is especially true in agricultural systems where the functional roles of birds can either enhance or reduce farmer livelihoods (Anderson et al., 2013; Gardner et al., 2011; Karp et al., 2013). In turn, agricultural management can impact bird communities, which could generate feedback loops that alter the net effects of birds on farmer livelihoods and broader society as a whole (Pejchar et al., 2018; Smith, Kennedy, et al., 2020; Smith, Taylor, et al., 2021).

Management of birds within agroecosystems can be a highly contentious issue, impacting a wide range of stakeholders beyond individual farmers (Table S1) (Baur, 2020; Olimpi et al., 2019). A notable example is the pressure to exclude wildlife from farms for fear that they may carry foodborne pathogens (e.g. Shiga-toxin producing *E. coli*, *Salmonella* spp., or *Campylobacter* spp.) versus the pressure to diversify farms for conservation and environmental benefits (Beretti & Stuart, 2008; Olimpi et al., 2019; Smith, Edworthy, et al., 2020). Farmers may also wish to deter birds due to their consumption of crops or wish to promote birds for suppression of insect and vertebrate pests (Smith, Taylor, et al., 2021). Indeed, birds can improve crop yields via pest control services but can also cause large crop losses through direct consumption (Anderson et al., 2013; Karp et al., 2013; Kross et al., 2012). The average amount and relative balance of services to disservices have important environmental and social implications and are likely to shift across farming contexts (Olimpi et al., 2020; Smith, Taylor, et al., 2021).

The stability of avian services and disservices is also important for effective farm management. One reason is that many farmers are risk averse and operate within tight financial margins (Gong et al., 2016; Liu & Huang, 2013). For example, if birds occasionally damage crops, or inconsistently control key pest arthropods, then farmers may hedge their bets, increasing pesticide application rates to avoid the potential of an outbreak causing crop failure (Zhang et al., 2018). Stability in ecosystem service provisioning may also help stabilize crop yields, allowing for more consistent returns to be realized each year (Bommarco et al., 2013). Thus, better understanding the factors contributing to temporal fluctuations of service and disservice providers can improve farmer decisions and their ability to effectively harness ecosystem services and decrease yield fluctuations.

Increasing species diversity and/or community evenness may reduce temporal fluctuations in service provider abundances, thereby delivering more consistent service provisioning. For example, because many species fluctuate asynchronously in abundance over time, enhanced community diversity increases biomass stability through the portfolio effect (Blüthgen et al., 2016; Ives & Carpenter, 2007; Schindler et al., 2015). Additionally, more diverse communities are more likely to contain at least a few service providers that can weather any given disturbance (i.e. more response diversity), as well as competitors that rapidly assume the functional roles of declining species (i.e. density compensation; Ives &

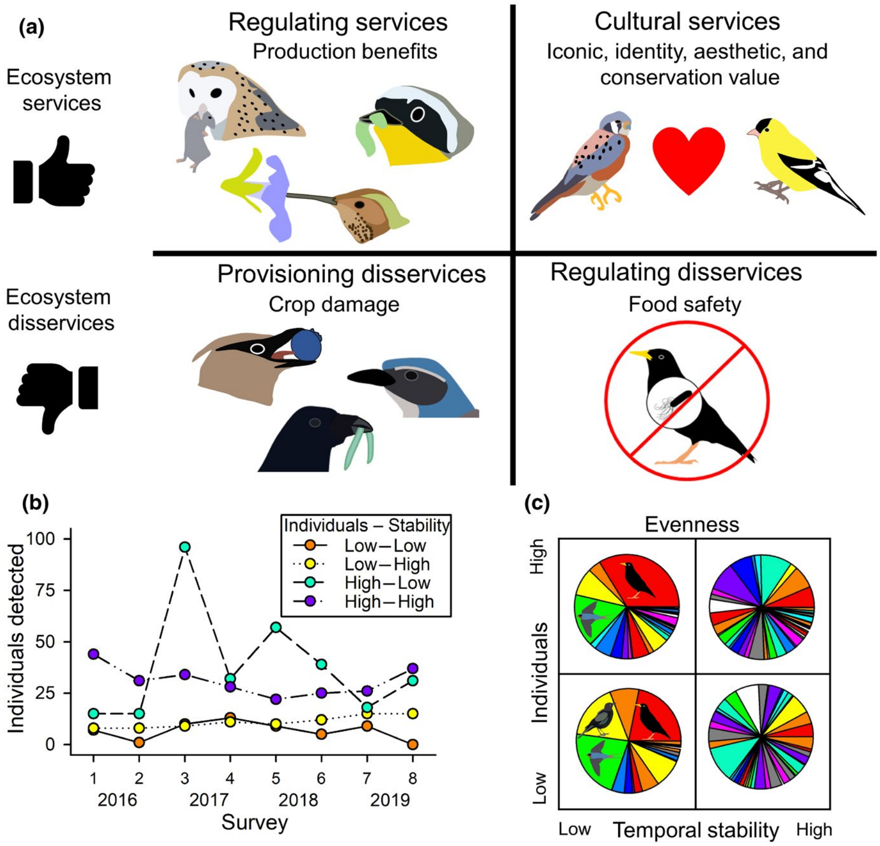

FIGURE 1 (a) Birds in agroecosystems provide services and disservices. (b) Point count survey locations within farms can have high or low numbers of individual birds detected that can have high or low stability (variability over time). The figure displays an example of number of detections over time at four point count locations from this study. (c) Pie charts showing species relative abundances at the four farms represented in (b). Each colour and 'pie slice' represents a different species. Pies with single-coloured slices that dominate represent communities with lower evenness, hypothesized to be linked to lower temporal stability. Birds displayed in (a): regulating services = barn owl *Tyto alba* consuming a rodent, common yellowthroat *Geothlypis trichas* consuming a caterpillar, and rufous hummingbird *Selasphorus rufus* consuming nectar; cultural services = American kestrel *Falco sparverius* and American goldfinch *Spinus tristis*; provisioning disservices = cedar waxwing *Bombycilla cedrorum* consuming a bluberry, California scrub-jay *Aphelocoma californica* and common raven *Corvus corax* pulling out a plantlet; regulating disservices = European starling *Sturnus vulgaris* with a foodborne pathogen. Birds displayed over their 'pie slice' in (c) barn swallow *Hirundo rustica*, Brewer's blackbird *Euphagus cyanocephalus*, and European starling

Carpenter, 2007; Hillebrand et al., 2008; Karp et al., 2011; Blüthgen et al., 2016). Similarly, increasing the diversity and complexity of habitats, in natural ecosystems or agroecosystems, is thought to increase stability (Levin, 1992) by reducing the risk that any given habitat dominates and is unsuitable for most species in the community (Schindler et al., 2015; Tscharntke et al., 2012).

Thus, local, farm and landscape factors that promote bird species diversity may also increase service stability. First, at the local scale, greater vertical vegetation complexity may promote and retain a greater diversity of species (Heath et al., 2017). Second, at the farm scale, greater habitat complexity could provide greater continuity of resources to promote greater temporal stability of ecosystem services (Smith et al., 2019). That is, the shocks caused by tillage, harvest, application of pesticides or other farm management actions may be buffered in more diversified and complex systems if resources are available nearby the disturbed area (Tscharntke et al., 2012). Third, the landscape scale may impact temporal stability by shifting bird community composition and supporting a more even, diverse community of species (Smith, Edworthy, et al., 2020; Smith, Kennedy, et al., 2020).

Here, we conducted avian point count surveys across 106 point count locations on 27 farms (Figure S1); classified birds as ecosystem service or disservice providers using metrics spanning supporting, regulating, provisioning and cultural services/disservices; created ecosystem-service-and-disservice-weighted abundance indices (Figure 1a; Table S1); and classified point-level local vertical vegetation complexity, overall farm conservation value by modifying the High Nature Value index, and per cent semi-natural land cover in the landscape. We used these data to ask (a) Do avian-mediated services and disservices coincide on farms or are they independent? (b) What is the relative importance of local, farm and landscape complexity on the quantity and temporal stability of avian service- and disservice provisioning? While stability has many definitions (Ives & Carpenter, 2007), here we use stability to refer to fluctuations in abundance over temporal replicates (Figure 1b). (c) What local and/or landscape contexts have the best joint outcomes to promote services and dissuade disservices? Our central goal was to identify aspects of agroecosystems that best support birds for multi-functional outcomes, considering both the average and temporal stability of service/disservice provider indices.

2 | MATERIALS AND METHODS

2.1 | Study system

Across 4 years (2016–2019), we surveyed bird communities on a total of 27 farms in Oregon (n = 15) and Washington (n = 12; Figure 2; Figure S1) states, USA. We obtained permission to conduct surveys on all farms from the farm owners and/or managers. All farms fell into the Northern Pacific Rainforest Bird Conservation Region. Farms were highly diversified, largely used organic practices (20 were certified), and grew a range of crops (no monocultures; mean = 46.5 ± 19.8 (*SD*) crops grown per farm) including cereals, vegetables and melons, fruits and nuts, oilseed crops, roots, spice crops, beverage crops, medicinal crops, commercial flowers, and grasses and fodder crops, among others. Livestock were integrated into farming operations for at least 1 year of the study on 18 of these farms in a variety of forms. Farms spanned a range of landscape contexts, from intensified agriculture to primarily semi-natural (e.g. Figure 2; Figure S1; range: 2.19%–95.7% semi-natural).

2.2 | Bird point count surveys

Bird surveys were conducted twice per farm each year between 20 May and 8 August 2016–2019 to coincide with peak produce production in the region. We moved along a south to north transect among farms (Figure S1a) for each of the two annual survey periods. Survey one each year roughly corresponded with the nesting season along the south to north transect, while survey two roughly corresponded with the fledging and flocking periods for gregarious species. One point count location ('point') with a 100-m radius was surveyed for every 4 ha of farmed land to maintain a consistent point density. Points were systematically stratified to capture the range of land uses present on farms (e.g. Figure 2c,d; Smith, Kennedy, et al., 2020). Point count centres were at least 200 m apart to avoid double counting individuals. In total, 106 points were surveyed across the 27 farms included in this analysis (mean per farm: 3.9 ± 3.3 (*SD*); range = 1–14).

At each point, the observer recorded the number of unique individuals per species seen or heard within a 100-m radius during a 10 min period. Surveys were conducted between sunrise and 10:45 a.m., only in the absence of heavy rain, by the same skilled observer (OMS) to eliminate biases due to observer differences. Additionally, points within farms were surveyed in a different order each visit to reduce detection biases due to time-of-day effects (Smith, Kennedy, et al., 2020). If structures interfered with visual detectability of birds, the observer moved within points to see around structures

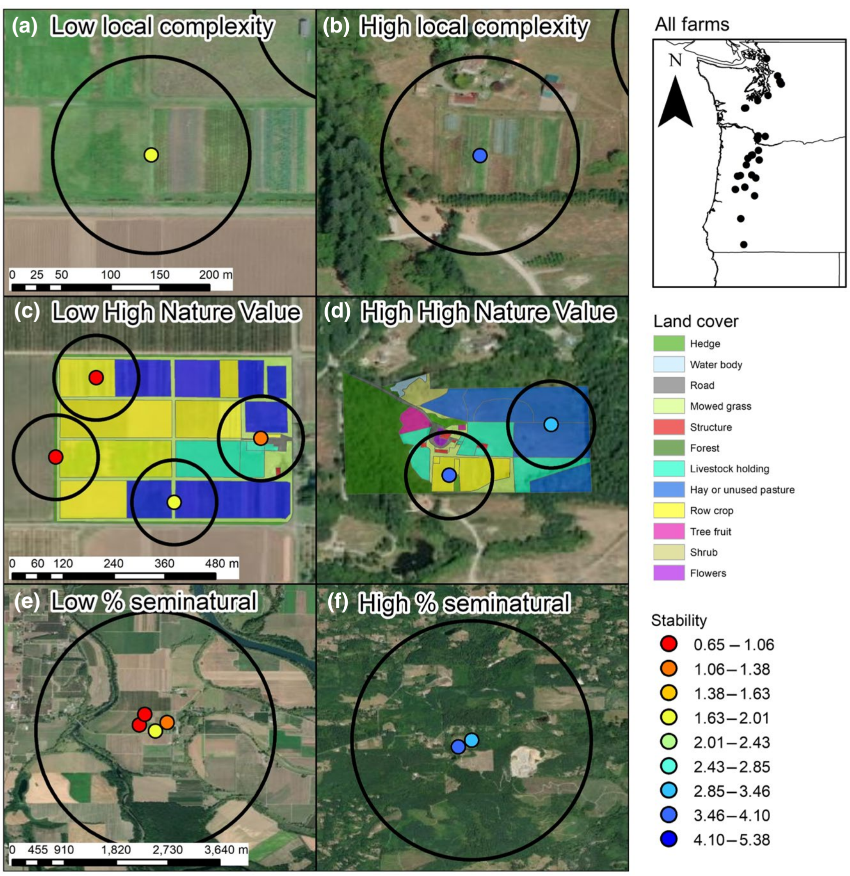

FIGURE 2 Schematic of scales examined including at the (a, b) local survey point level, (c, d) farm scale, and (e, f) landscape scale. (a, c, e) shows an example farm with (a) low local vertical complexity, (c) low farm-wide High Nature Value score and (e) low % semi-natural in the landscape. (b, d, f) shows an example farm with (b) high local vertical complexity, (d) high farm-wide High Nature Value score, and (f) high % semi-natural in the landscape. Stability of total abundances at points displayed in circles from low stability (red) to high stability (blue). Map of all farm locations shown in top right inset

(Šálek et al., 2017). Because our study traded geographic breadth for within-season temporal replication, we were unable to account for detection probability in our analyses. Thus, detection probability was assumed to be constant during each survey period across farms. For conciseness, we use the term 'abundance' in the article to refer to the number of individuals detected, but it should be noted that we may have missed individuals. Our research was conducted with the approval of Washington State University's Institutional Animal Care and Use Committee (ACC protocol ASAF #04760). This manuscript uses point count data (which only requires passive observation of birds) and weights the point count estimates by foodborne pathogen prevalence estimates derived from mist-netting birds reported previously (Smith, Edworthy, et al., 2020; Smith et al., in press).

2.3 | Ecosystem service and disservice provider classification

We calculated several metrics spanning supporting, regulating, provisioning and cultural ecosystem services and disservices provided by birds (Figure 1a; Table S1). We acknowledge that all service and disservice proxies have limitations, which we note for each proxy used in Table S1. We used abundance (total number of individuals detected during each point count survey) as a metric of supporting services.

To estimate the risk of foodborne pathogen delivery to crops (regulating disservice), we generated a foodborne pathogen risk index. To do so, each bird observed was weighted by its species' estimated *Campylobacter* spp. prevalence and crop contacts/survey point from Smith et al. (in press). Briefly, Smith et al. (in press) estimated *Campylobacter* spp. prevalence and number of crop contacts/survey point for 139 bird species by examining which of 11 species traits were most predictive of each. They then used the best-supported models to predict *Campylobacter* spp. prevalence and number of crop contacts/survey point for understudied bird species. Our analyses used the estimated prevalence of *Campylobacter* spp. because it is the most common foodborne pathogen found in birds (Smith, Edworthy, et al., 2020; Smith, Snyder, et al., 2020). The crop contact score represents the estimated number of individuals of that species in crop fields per survey point. We accounted for both the estimated *Campylobacter* spp. prevalence and estimated crop contact rate because the probability that an individual will deposit pathogens on crops is the joint probability that it will carry the pathogen, enter crop fields and defecate on produce (Smith, Edworthy, et al., 2020; Smith, Snyder, et al., 2020).

We calculated a per point estimate of food safety risk as (Equation 1):

$$\text{Per-point foodborne pathogen risk index} = \sum \text{species}'(\text{estimated } \textit{Campylobacter} \text{ spp. prevalence} \times \text{crop contacts} \times \text{number of individuals detected}). \tag{1}$$

To generate a proxy for regulating services (pest consumption and pollination) and provisioning disservices (full or partial consumption of crops), all bird species detected were assigned to a diet guild following the protocol outlined in Smith, Kennedy, et al. (2020) and Smith, Taylor, et al. (2021) (Data S1 in Smith, Kennedy, et al., 2021). Wilman et al. (2014) assigned species to diet guilds when the diet was ≥50% that item, and we followed this definition to assign species to guilds based on the majority items in the diet (if ≤50% in any category, the species was considered omnivorous). We then assigned insectivorous, carnivorous and nectivorous species as 'production benefiters' (species potentially provide pest control or pollination services); and frugivorous, granivorous and herbivorous species as 'crop damagers' (species potentially inflict crop damage/loss through foraging on fruits, grains, seeds or vegetation of crop plants; Peisley et al., 2015; Smith, Taylor, et al., 2021). To calculate per survey point estimates of production benefit services (Equation 2) and crop damage disservices (Equation 3), we calculated the abundance of birds falling into each guild and weighted those abundances by the summed proportion of the diet in those categories from Elton Traits 1.0 (Wilman et al., 2014).

$$\text{Per-point production benefitting bird index} = \sum \left[(\text{number of individuals from insectivorous, carnivorous or nectivorous species}) \times (\text{Total per cent of the species' diet composed of invertebrates, endothermic vertebrates, carrion, plus nectar}) \right]. \tag{2}$$

$$\text{Per-point crop damaging bird index} = \sum \left[(\text{number of individuals from granivorous, herbivorous and frugivorous species}) \times (\text{Total per cent of the species' diet composed of fruits, seeds, plus plants}) \right] \tag{3}$$

We then considered several metrics of cultural ecosystem services (Table S1). We first estimated identity and iconic value to the US population as a whole using the popularity score of 'celebrity' birds (Schuetz & Johnston, 2019). We created subsets of all species to include those that were ranked as 'celebrity' (n = 37), which are those that have above average national interest when considering national-level encounter rates ('popularity') and have low geographic alignment in interest, or interest outside of where they are found ('low congruence'). This is because prior work has demonstrated that people may only perceive a subset of birds around them (Belaire et al., 2015). Therefore, low popularity scores likely indicate lack of awareness rather than a disservice per se. Thus, we used weighted abundances of 'celebrity' species by weighting observed abundances by the species' continuous popularity scores (Equation 4).

$$\text{Per-point identity and iconic value index} = \sum \text{celebrity species}' (\text{number of individuals detected} \times \text{continuous popularity score}). \tag{4}$$

We then generated a metric of cultural ecosystem service provisioning to the growers whose farms we surveyed using data from Smith, Taylor, et al. (2021). Smith, Taylor, et al. (2021) distributed a grower questionnaire survey to 54 farmers, including the 27 who managed farms included in this study alongside more farmers who managed similar farms in California, USA. These questionnaire surveys were conducted under the Washington State University Office of Research Assurances Institutional Review Board (IRB) that deemed it exempt from the need for IRB review (certification number 16610-001). Farmers provided open-ended responses to questions asking which species were considered beneficial or harmful to the farm and why, as well as which species farmers were attempting to attract/repel and why. Based on these open-ended data, we generated a metric of cultural ecosystem service provisioning to the farmers by first calculating a salience/interest metric similar to Schuetz and Johnston (2019) and then conducting a sentiment analysis (Lennox et al., 2019). See Supplementary Methods, Figure S2, and Data S2 in Smith, Kennedy, et al., 2021 for full details. We then generated an index of grower appreciation using species with positive averaged sentiment values and an index of grower disapproval using species with negative averaged sentiment values. For each, we first summed the abundance of individuals from each bird taxonomic family per survey point. We then multiplied each family's abundance by its interest/salience score and by its sentiment score. For the service (Equation 5) and disservice (Equation 6) indices, we summed the weighted abundances across species with positive and negative sentiments respectively.

$$\text{Per-point grower appreciation index} = \sum_{\text{families with positive averaged sentiments}} (\text{number of individuals detected} \times \text{positive sentiment} \times \text{interest/salience}). \tag{5}$$

$$\text{Per-point grower disapproval index} = \sum_{\text{families with negative averaged sentiments}} (\text{number of individuals detected} \times \text{negative sentiment} \times \text{interest/salience}). \tag{6}$$

Finally, we estimated conservation value using the maximum Combined Conservation Score from the North American Bird Conservation Initiative State of North America's Birds (2016). We considered 'conservation need' as a cultural ecosystem service in itself because of the greater value people assign to species in need of conservation (Schuetz & Johnston, 2019). We used the Combined Conservation Score instead of species' binary listing because only 3% of total observations were of species listed as at least sensitive at the state level (Data S1 in Smith, Kennedy, et al., 2021), precluding analyses. To calculate the per point conservation value index, we weighted abundances of each species that had Moderate (9–13) or High (14–20) Combined Conservation Scores by its Maximum Combined Conservation Score (CCSmax). We then summed across species' weighted abundances for each point for each survey for the conservation value index (Equation 7).

$$\text{Per-point conservation value index (combined conservation score index)} = \sum_{\text{species with moderate to high CCSmax}} (\text{CCSmax} \times \text{number of individuals detected}). \tag{7}$$

We repeated analyses using all species weighted by their CCSmax, which yielded similar results. Therefore, we refer the reader to Tables S2–S5 and Figure S3 for results from analyses using all species.

2.4 | Local, farm and landscape complexity

2.4.1 | Local complexity

To capture the structural complexity of each survey point, we estimated the per cent cover of ground herbaceous vegetation (0–0.5-m height class), low shrubs/crops (0.5–2 m), tall shrubs/crops (2–6 m) and trees (>6 m) within a 10-m radius of each point count location's centre (Figure S4a). We divided the 10-m radius circles into four equal quadrants divided along the four cardinal directions (Kennedy et al., 2010). During each survey, we estimated the per cent vegetative cover in each height class for each of the four quadrants. We then averaged estimates across the four cardinal directions for each height group to estimate per cent cover by vertical strata. Vegetation surveys were conducted at each bird point count location at each bird survey occasion. Finally, we averaged the ground, shrub, tall shrub and tree cover estimates across the eight surveys (4 years × 2 repetitions per year) for each point, giving us 106 averaged values for each of the four vertical strata to estimate the local complexity.

To obtain a single estimate of local vertical vegetation complexity for each survey point location, we conducted a principal components analysis using the 'prcomp' function in the 'STATS' package in R version 3.6.3 (R Core Team, 2020). First, we standardized values by calculating a z-score for each. The first two principal components (PCs) combined accounted for 67.5% of the variation (Figure S4b). Increasing values of PC1 ('local vertical vegetation complexity'; 41.0% of the variation) were associated with increased fullness of the shrub, tall shrub and tree layer. Increasing values of PC2 ('ground cover'; 26.5% of the variation) were primarily associated with increased cover in the ground layer. We used PC1 in subsequent models because we were interested in local vertical vegetation complexity.

2.4.2 | Farm-wide High Nature Value index

We measured farm intensification/extensification, or conservation-friendly management practices, by modifying the High Nature Value index (Pointereau et al., 2010; Smith, Taylor, et al., 2021). In brief, the High Nature Value index is a continuous metric from 1 (lowest conservation value/most intensive) to 30 (highest conservation value/most extensive). Farms are classified using three sub-component indices ('diversity of crops', 'extensive/intensive practices' and 'landscape elements'), which each get equal weight (10 points max). Farms that score highest on the 'diversity of crops' indicator are typically small with high crop diversity and/or integrate livestock. Farms that score high on 'extensive/intensive practices' typically use few inputs, are certified organic, and maintain low stocking densities of livestock. Farms that score high on 'landscape elements' incorporate semi-natural elements within their farms, such as hedges or wet grassland. See Smith, Taylor , et al. (2021) for full details on our modification. Each farm had one High Nature Value score to represent management across years.

2.4.3 | Landscape complexity

To characterize landscape context, we calculated the per cent semi-natural land cover based on the 2016 National Land Cover Database (Dewitz, 2019) using a 2.1 km radius buffer from each point count location (Figure 2e,f) using R and FRAGSTATS 4.1 (McGarigal & Marks, 1995; R Core Team, 2020). Semi-natural land cover included forest (deciduous, evergreen and mixed), scrubland (dwarf scrub and shrub/scrub), herbaceous (grassland/herbaceous, sedge/herbaceous, lichens and moss) and wetland categories (woody and emergent herbaceous wetlands). Categories not included in semi-natural land cover were water, ice/snow, developed, barren, pasture/hay and cultivated crop classes. We used a 2.1 km radius as the biologically relevant landscape scale (Jackson & Fahrig, 2015) because it was the estimated weighted average home range size for birds detected on our farms (Smith, Kennedy, et al., 2020).

2.5 | Statistical analysis

We first estimated ecosystem-service-and-disservice-weighted abundance indices for each point per survey per year (which we label 'average ecosystem-service-and-disservice-weighted abundance indices'). Then, we calculated the coefficient of variation for each of the indices per survey point across the eight temporal replicates as an estimate of temporal variability. The coefficient of variation is calculated by dividing the standard deviation by the mean (CV = σ/μ). Stability is the inverse of the coefficient of variation (1/CV) (Blüthgen et al., 2016), which is the metric we used in temporal stability analyses. We then examined Pearson's pairwise correlations (Pearson's *r*) across the average and stability of ecosystem-service-and-disservice-weighted abundance indices at the survey point level. We used the mean of the eight temporal replicates for average ecosystem-service-and-disservice-weighted abundance indices for the Pearson's pairwise correlations, which we described on a continuous scale.

We then examined the potential single, additive and interactive effects of local, farm and landscape complexity on the average and stability of the ecosystem-service-and-disservice-weighted abundance indices using a series of nested generalized linear mixed effects models fit in the R package 'GLMMTMB' (Brooks et al., 2017) (Table S6). Models used negative binomial distributions (average ecosystem-service-and-disservice-weighted abundance indices) and Gaussian distributions (stability of ecosystem-service-and-disservice-weighted abundance indices). Model assumptions were checked in the 'DHARMA' package in R (Hartig, 2021). We determined the optimal random effects structures on the global model for each model set for our average ecosystem-service-and-disservice-weighted abundance indices by constructing models with all combinations of farm, survey point, year and survey number (survey replicate 1–8). We then selected the optimal random effects structure by comparing the AIC_c values. All models that examined the average ecosystem-service-and-disservice-weighted abundance indices included point nested within farm and survey number as random effects. All models that examined temporal stability of ecosystem-service-and-disservice-weighted abundance indices included farm as random effects.

We then ranked models to examine the relative importance of our fixed effects based on AIC_c in the 'BBMLE' package in R (Bolker, 2020) and identified those that were most supported ($\Delta AIC_c < 2.0$) (Burnham & Anderson, 2002). We assessed multicollinearity for candidate models using the 'PERFORMANCE' package in R (Ludecke et al., 2020) and found it not to be an issue in our models (VIF < 5). We then estimated covariate effects by model averaging among the best-supported models (within 2 ΔAIC_c of the best-supported model) in the 'MuMIn' package in R (Barton, 2020; Burnham & Anderson, 2002). We considered variables important if their conditional 95% confidence intervals did not overlap zero.

Our results suggested that landscape context was important in promoting temporal stability. We hypothesized that this was due to a shift away from dominant, highly nomadic species (i.e. an identity or selection effect; Figure 1c). Therefore, we conducted analyses examining the relative importance of local, farm and landscape complexity on evenness of the overall bird community at each survey point. We averaged the evenness values across the eight surveys and repeated our analyses described above used to examine temporal stability. We then examined the influence of evenness as a predictor of temporal stability on each of the ecosystem-service-and-disservice-weighted abundance indices examined.

3 | RESULTS

We observed 15,684 individuals from 111 species across our 106 survey points (Data S1 and Data S3 in Smith, Kennedy, et al., 2021). The species with the most individuals observed across sites were European starling (*Sturnus vulgaris* (n = 2,093), American robin *Turdus migratorius* (n = 1,293) and barn swallow *Hirundo rustica* (n = 1,276). European starling, American robin and violet-green swallow *Tachycineta thalassina* were observed on all farms (n = 27) at least once, while other species were observed on 26 or fewer farms.

3.1 | Trade-offs and synergies between ecosystem-service-and-disservice-weighted abundance indices

The average and temporal stability of an individual ecosystem-service/disservice-weighted abundance index were not often highly correlated (Figure 3). Within the same service/disservice index, an equal number of metrics had positive (n = 4) and negative (n = 4) correlations between their average value and their temporal stability. Across metrics, there was a mixture of positive (n = 25) and negative (n = 39) correlations between average value indices and temporal stability indices. Between average ecosystem-service-and-disservice-weighted abundance indices, the production benefitting bird index was positively correlated with higher grower appreciation indices (Pearson's r = 0.76) and combined conservation score indices (Pearson's r = 0.79). The foodborne pathogen risk index was positively correlated with higher grower disapproval indices (Pearson's r = 0.70) and higher identity and iconic value indices (Pearson's r = 0.88), which were also positively correlated with each other (Pearson's r = 0.74). The crop damaging bird index generally had low correlations with other service/disservice provider indices (highest Pearson's r = 0.42). The temporal stability of ecosystem-service-and-disservice-weighted abundance indices exhibited similar patterns to the average indices. However, the temporal stability of grower disapproval indices had higher correlation with the temporal stability of the production benefitting bird index (Pearson's r = 0.51) compared to correlations between the indices' average values (Pearson's r = 0.19).

3.2 | Impacts of local, farm and landscape complexity on average ecosystem-service-and-disservice-weighted abundance indices

We found weak relationships between local (point-level) vertical vegetation complexity and average ecosystem-service-and-disservice-weighted abundance indices (Figure 4a; Table 1; Figures S5 and S6; Tables S7–S22). Farm-level High Nature Value scores were, however, strong predictors of increased overall bird abundances (Figure 4b; Tables S7 and S8), production benefitting bird indices (Tables S9 and S10), identity and iconic value indices (Tables S11 and S12), grower appreciation indices (Tables S13 and S14) and grower disapproval indices (Tables S15 and S16). However, High Nature Value scores did not strongly impact foodborne pathogen risk indices (Tables S17 and

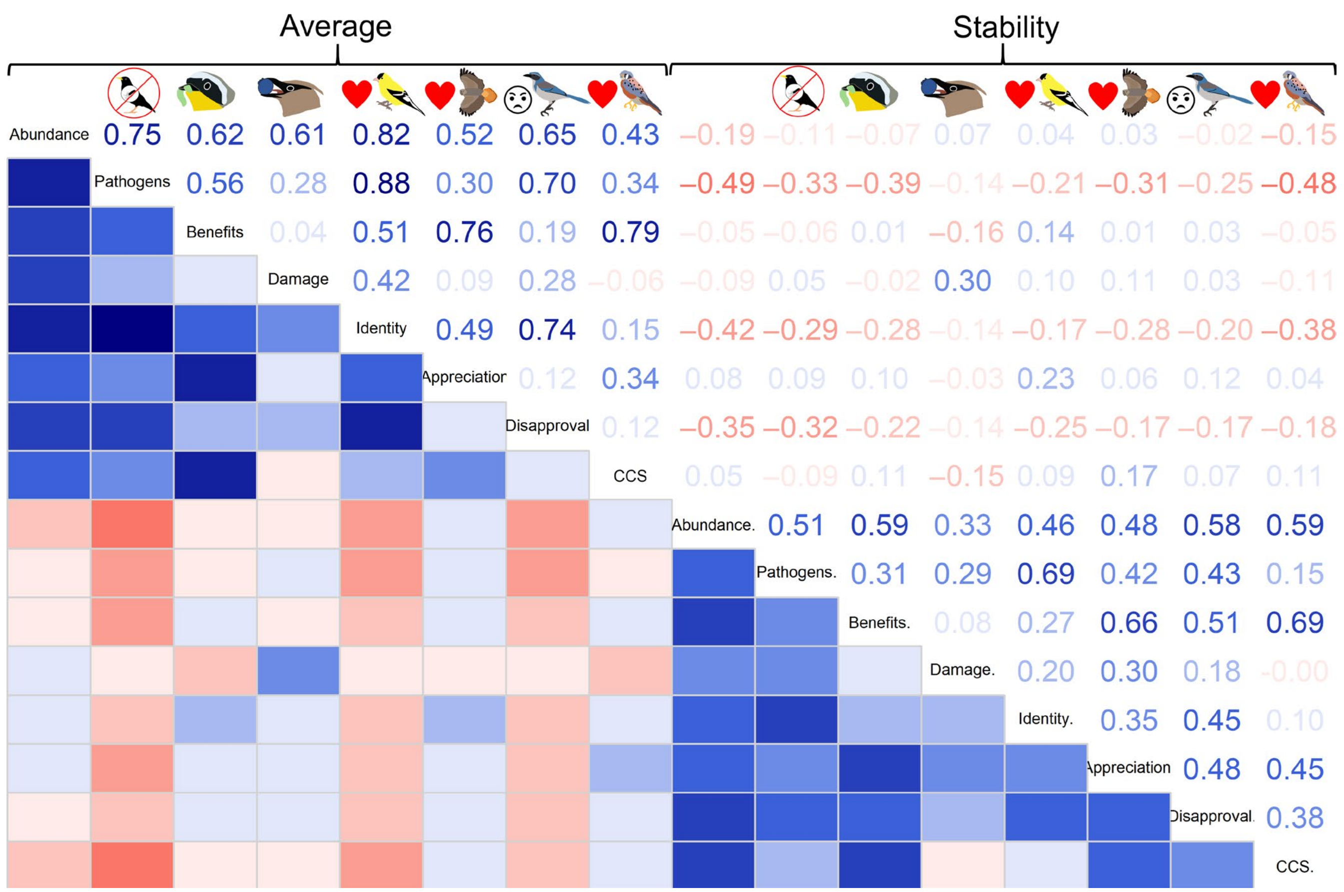

FIGURE 3 Pearson's pairwise correlation coefficients between average ecosystem service (ES) and disservice (DES) indices and temporal stability of ecosystem service and disservice indices. Colour shading (i.e. light to dark colours) corresponds to increasing correlation coefficients. Average indices and stability of indices shown for total abundance (ES), pathogens = foodborne pathogen risk index (DES; European starling *Sturnus vulgaris* displayed); benefits = production benefitting bird indices (ES; common yellowthroat *Geothlypis trichas* displayed); damage = crop damaging bird indices (DES; cedar waxwing *Bombycilla cedrorum* displayed); identity = identity/iconic value index (ES; American goldfinch *Spinus tristis* displayed); appreciation = grower appreciation index derived from farmer data (ES; red-tailed hawk *Buteo jamaicensis* displayed); disapproval = grower disapproval index derived from farmer data (DES; California scrub-jay *Aphelocoma californica* displayed); and CCS = combined conservation scores for species with moderate or high conservation scores (ES; American kestrel *Falco sparverius* displayed)

S18), crop damaging bird indices (Tables S19 and S20) or combined conservation scores (Tables S21 and S22).

Increased landscape complexity was a strong predictor of decreases in all disservice indices: food safety risk, crop damage and grower disapproval (Figure 4c; Figures S5 and S6; Tables S15–S20). Farms in more complex landscapes also had reduced identity and iconic value indices (Figure 4c; Figure S6; Tables S11 and S12). No metrics examined were strong predictors of average values of our combined conservation score index (Figure 4; Figure S6; Tables S21 and S22).

3.3 | Impacts of local, farm and landscape complexity on temporal stability of ecosystem-service-and-disservice-weighted abundance indices

Local vertical vegetation complexity was a good predictor of increased temporal stability of three of four service provider indices but none of the disservice provider indices (Figure 4d; Table 1; Figures S7 and S8; Tables S23–S38). That is, increased local vertical vegetation complexity was associated with increased temporal stability of the production benefitting bird index (Tables S25 and S26), grower appreciation index (Tables S27 and S28) and combined conservation score index (Tables S29 and S30).

We generally detected weak relationships between farm-wide High Nature Value and the temporal stability of our ecosystem-service-and-disservice-weighted abundance indices (Figure 4e) with the exception of the grower appreciation index (Figure S8; Tables S27 and S28). We also detected an interaction between farm-wide High Nature Value and landscape complexity in mediating overall abundance and the production benefitting bird index (Figure 5; Tables S23 and S25). That is, farms in complex landscapes had greater temporal stability of overall abundances when they had low High Nature Value, but the benefit of landscape complexity was diminished on farms with High Nature Value.

Finally, we found strong support that landscape complexity increased temporal stability of the foodborne pathogen risk index, identity and iconic value index, grower disapproval index and combined conservation score index (Figure 4f; Figures S7 and S8; Tables S29–S36). However, we found weak relationships between all variables examined and temporal stability of the crop damaging bird index (Figure 4; Figure S7; Tables S37 and S38).

3.4 | Evenness as a mediator of temporal stability

We found strong support that increased landscape complexity was associated with greater average bird species evenness at point count locations (Tables S39 and S40; Figure S9). In contrast, we found weak relationships between evenness and local vertical vegetation complexity or farm-wide High Nature Value. Greater bird species evenness at point count locations, in turn, was a strong, positive predictor of temporal stability for all service/disservice indices examined (Figure 6; Table S41).

4 | DISCUSSION

Our study sought to identify how agroecosystems can be managed to best support birds for multi-functional and stable outcomes. Assessments of costs and benefits of biodiversity to agriculture are generally done in isolation (Peisley et al., 2015). This limits our ability to holistically manage farming systems to meet multi-stakeholder needs that are often thought to be in opposition (Baur, 2020). Collectively, our results suggest that farm diversification may increase services without large disservice costs (Figure 4b,e). However, increasing landscape complexity is needed to suppress the average level of avian-mediated disservice provisioning and to enhance the temporal stability of both service and disservice provisioning.

Contention between stakeholders has risen in recent decades over whether farmers should attract birds to their farms (Baur, 2020; Olimpi et al., 2019). On the one hand, many farmers are concerned that birds may cause foodborne illness and/or cause economic losses through consumption of crops (Anderson et al., 2013; Baur, 2020; Olimpi et al., 2019; Smith, Taylor, et al., 2021). However, others advocate for conserving birds on farms, both because they are in rapid decline (Rosenberg et al., 2019) and because some farmers want to leverage their pest control services (Smith, Taylor, et al., 2021). Our findings that service and disservice provider indices are correlated among themselves via their responses to land use (Figure 4; Table 1) suggest that farmers may be able to harness services through local diversification without strongly impacting disservices. That is, service provider indices generally responded similarly to each other to land use factors examined, while disservice provider indices generally responded similarly to each other (but differently from service provider indices) to factors examined (Figure 4). These distinct responses suggest a path forward towards holistic agroecosystem management.

We found low overall impacts of local vertical vegetation complexity on average ecosystem-service-and-disservice-weighted abundance indices. This contrasts with prior work conducted in California that showed dense field margins strongly increased the abundance, richness and evenness of bird communities (Heath et al., 2017). We may not have seen a similar impact of local vertical vegetation complexity in our study because our PCA approach did not distinguish the effects of different types of vegetation cover, which could have varying effects on different bird guilds. We did, however, detect a stabilizing effect of local vertical vegetation complexity on beneficial bird indices. This suggests that farmers wishing to harness biocontrol services may benefit by planting crops vulnerable to arthropod and rodent pest damage alongside hedges that are attractive to beneficial birds. However, in some systems, pests may benefit from hedges, limiting the efficacy of this approach (Tscharntke et al., 2016).

Increased farm-wide High Nature Value indices were generally associated with increased average ecosystem-service-, but not disservice-, weighted abundance indices (Figure 4b,e). The exception was that farms with larger High Nature Value indices also had higher average grower disapproval indices (Figure 4b). Our results suggest

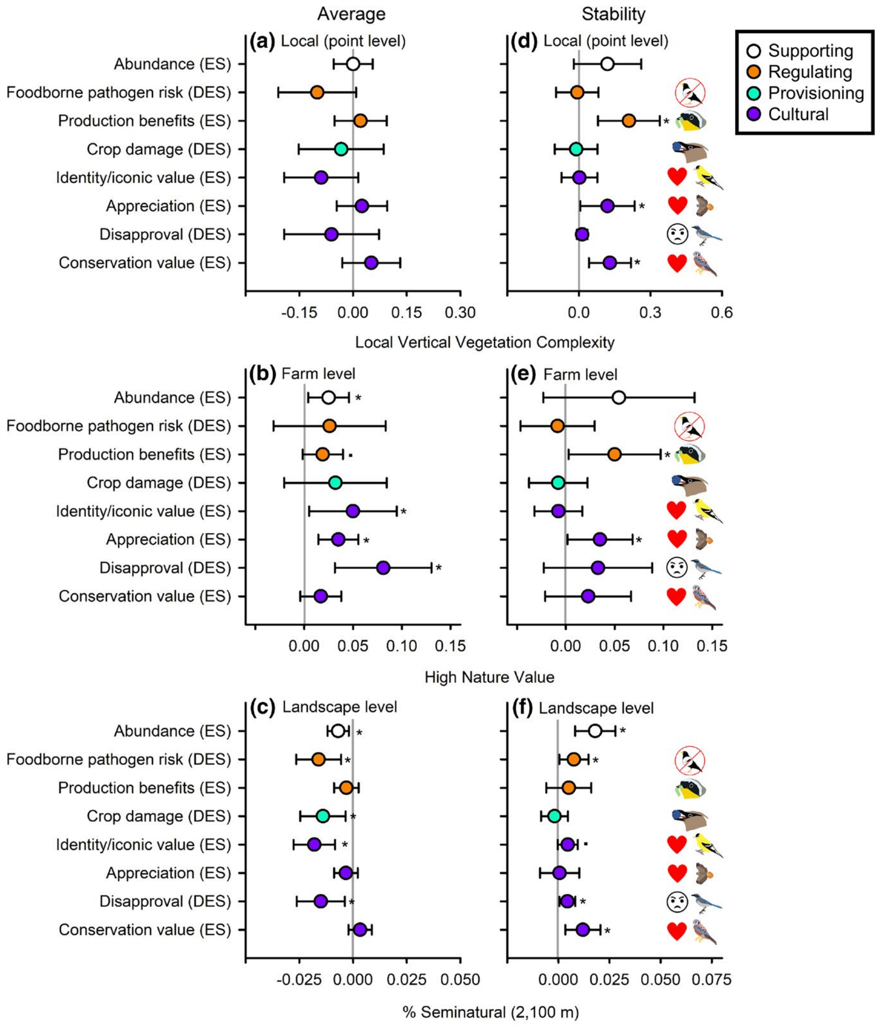

FIGURE 4 Impacts of (a, d) local vertical vegetation complexity, (b, c) farm-wide High Nature Value index, and (c, f) % semi-natural in the landscape on (a–c) average-ecosystem-service-and-disservice indices and (d–f) temporal stability of ecosystem-service-and-disservice indices. Graphs display model-averaged 95% confidence intervals from models within 2 ΔAIC_c of the best-supported models. *95% confidence intervals do not overlap zero; ·90% confidence intervals do not overlap zero. ES, ecosystem service; DES, ecosystem disservice. See Figure 3 for species icon codes

that farmers wishing to diversify their farms should generally experience increases in beneficial, but not harmful, birds. However, greater High Nature Value indices were also associated with a disruption in the stabilizing effect of landscape complexity on overall bird abundance indices (Figure 5). The intermediate landscape complexity hypothesis, which posits that the effectiveness of local conservation management is highest in structurally simple rather than in cleared or in complex landscapes, may explain this finding (Tscharntke et al., 2012). Additionally, farms in our study with greater High Nature Value indices likely had greater rotationality because they were more likely to integrate livestock (Pearson's $r = 0.48$). Crop-livestock farms may also have decreased stability because they have increased densities of nonnative birds (Smith, Kennedy, et al., 2020). Nonnative birds and native birds with similar life-history traits have large daily movements and may be more ephemeral, tracking resources as they are available throughout the annual cycle (Billerman et al., 2020; Fischl & Caccamise, 1985). Thus, farming with livestock may destabilize local bird communities by shifting the community towards species like European starlings that are highly ephemeral (Smith, Kennedy, et al., 2020).

Farms in complex landscapes generally had lower average ecosystem-disservice-weighted abundance indices without changes in their average service provider indices (Figure 4). Our results align with recent work demonstrating that farms embedded in more semi-natural landscapes had reduced damage from birds to strawberry production (Olimpi et al., 2020). Other recent work in this system demonstrated that farms embedded in more semi-natural landscapes had reduced food safety risks from birds (Smith, Edworthy, et al., 2020). Here, we found that farms embedded in complex landscapes not only experience lower food safety risk scores but also have *stably* low concentrations of risky birds (Figure 4c,f). Landscape complexity was also associated with increased temporal stability of grower disapproval indices (Figure 4f). The increase in temporal stability of disservice indices is important because farmers are risk averse and can have their livelihoods impacted by variable income from fluctuating crop yields (Gong et al., 2016; Liu & Huang, 2013). Thus, understanding the factors affecting the stability of service and disservice provisioning makes it easier for farmers to reliably and accurately plan to accentuate birds' beneficial, or mitigate birds' harmful, effects.

Increasing landscape complexity is often argued as important for promoting overall biodiversity and ecosystem services (Benton et al., 2003). Thus, the negative response of overall abundance and identity/iconic value indices to increasing semi-natural cover

TABLE 1 Summary of number of positive and negative responses to local vertical vegetation complexity, farm-wide High Nature Value and % semi-natural cover (2,100-m) of ecosystem-service- and disservice-weighted abundance indices examined in this study. (+) or (−) included if model averaged 95% confidence intervals did not overlap zero, and (+) indicates a positive response while (−) indicates a negative response

	Average ecosystem service/disservice index			Stability of ecosystem service/disservice index		
Group	Local vertical vegetation complexity	High Nature Value	% Semi-natural	Local vertical vegetation complexity	High Nature Value	% Semi-natural
Overall abundance (1 metric)		(+)	(−)			(+)
Services (5 metrics; production benefits, identity/iconic value, grower appreciation, conservation (medium to high concern), conservation (all birds))		(+) (+)	(−)	(+) (+) (+) (+)	(+)	(+) (+)
Disservices (3 metrics; foodborne pathogen risk, crop damage, grower disapproval)		(+)	(−) (−) (−)			(+) (+)

is seemingly counterintuitive. It may be that increasing the amount of semi-natural cover decreases overall abundances because of community composition shifts (Smith, Edworthy, et al., 2020). Farms in our study embedded in less semi-natural landscapes often have large flocks of gregarious species such as European starlings and native blackbirds (Figure S10). Therefore, increased overall abundance of birds on farms in less semi-natural landscapes may not be due to increases in species that provide ecosystem services (Smith, Taylor, et al., 2021). Additionally, the increase in the identity/iconic value indices in less semi-natural landscapes may be due to an increase in species that the general public values, which can differ from those that farmers and conservationists value (Echeverri et al., 2019). For example, it is possible that people prefer more abundant or common species because of peoples' greater familiarity and frequent interactions with these species (Echeverri et al., 2017; Gaston, 2011; Gaston et al., 2018). On the other hand, our result may be due to a limitation from using the 'celebrity species' database (Schuetz & Johnston, 2019), which is based on Google searches that fail to capture peoples' attitudes (positive or negative) towards a species.

Farms embedded in more complex landscapes may have greater temporal stability of ecosystem-service-and-disservice-weighted abundance indices via increased bird community evenness (Figure 6, Figure S9). There generally exists a positive relationship between species diversity and community stability (MacArthur, 1955). The stabilizing effect of evenness may be due to the portfolio effect (Karp et al., 2011), species' asynchrony in environmental responses and their dynamics (Blüthgen et al., 2016), or a selection/identity effect wherein stability is driven by a single or a few dominant species (Hillebrand et al., 2008). If the dominant species have high fluctuations in abundances, then communities with low evenness would have lower stability.

4.1 | Management and policy recommendations

Our results suggest that management strategies and environmental policies that enhance habitat restoration at the landscape scale and diversification at the farm scale will promote ecosystem services and minimize disservices. Although individual farmers may realize economic benefits through avian ecosystem services (Karp et al., 2013), diversification practices remain poorly adopted world-wide (Pretty et al., 2018), indicating that stronger policy incentives are needed. Yet, less than 40% of countries globally have any requirement for maintaining native habitats within working landscapes—despite wide recognition that doing so is urgently needed to achieve national commitments like the UN Convention on Biological Diversity and Sustainable Development Goals (Garibaldi et al., 2021). Although not widely adopted, there are some policies in place in certain regions that can promote landscape-scale restoration and management that could also benefit birds and their ecosystem services, for example, landscape-wide implementation of agri-environment schemes

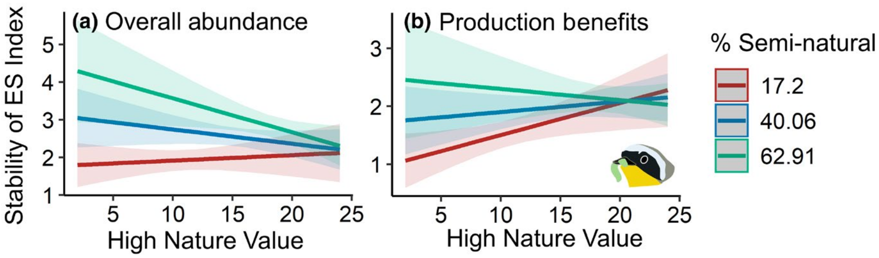

FIGURE 5 Interaction between % semi-natural land cover in a 2,100-m radius and farm-wide High Nature Value index on (a) temporal stability of overall abundance and (b) the production benefits index. % semi-natural in the figure is divided at the mean value as well as one standard deviation below and above the mean. Common yellowthroat *Geothlypis trichas* displayed as insectivore example

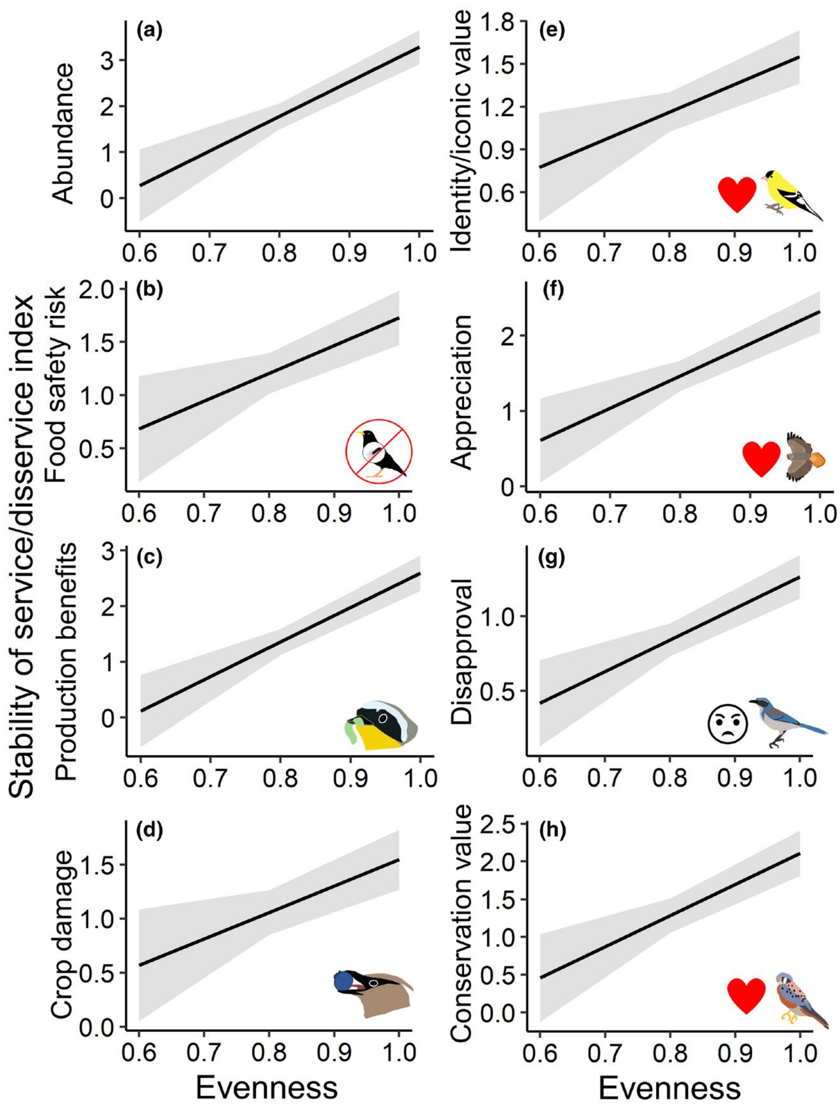

FIGURE 6 Point count locations with greater species evenness have greater temporal stability of (a) overall abundances, (b) foodborne pathogen delivery risk indices, (c) production benefitting bird indices, (d) crop damaging bird indices, (e) idenity/iconic value indices, (f) grower appreciation indices, (g) grower disapproval indices and (h) combined conservation score indices for species moderate to high risk. See Figure 3 for species icon codes

and a collaborative implementation of Common Agricultural Policy in Europe (Dallimer et al., 2010; Santos et al., 2021). Additionally, farmers may be incentivized to adopt diversification practices when enrolled in private-sector or NGO-led eco-certification programs (e.g. Audubon Certified Grazed on BirdFriendly Land) that enable their commodifies to be sold at a price premium (Biggs et al., 2021).

4.2 | Limitations and caveats

Several limitations should be considered when interpreting the findings of our study. Our service and disservice provider indices are proxies rather than direct quantifications, each with limitations (detailed in Table S1). Here we highlight several of these shortcomings. First, realized pest control services and crop damage disservices may vary depending on factors such as species-specific crop contact rates; bird body size; crop type and crop vulnerability to bird, insect and rodent damage; and seasonal variation (Karp et al., 2013; Pejchar et al., 2018). For example, many granivorous species provision their young with insects and thus could control pests during chick rearing but shift towards consuming crops later in the season (Pejchar et al., 2018; Whelan et al., 2008). Second, placement of birds into diet guilds ignores intraguild predation that may decrease overall pest control services (Olimpi et al., 2020; Pejchar et al., 2018).

Additionally, we focused on highly diversified farms. Thus, our results may not fully extend to conventional, large-scale agriculture or other production systems (e.g. orchard or vineyard monocultures), or to other regions. In particular, we may have detected greater densities of birds than would be found in more intensified (e.g. large fields, high mechanization or high pesticide use) or specialized systems (i.e. monocultures; Gonthier et al., 2019; Smith, Kennedy, et al., 2020; Smith, Taylor, et al., 2021). Additionally, specialized, monocultural systems may experience greater variance in net impacts of birds depending on how vulnerable (or invulnerable) their single-crop species are to bird or other pest damage. For example, tree fruit farmers may experience large, direct negative impacts from passerine birds' fruit consumption (Anderson et al., 2013), while coffee producers may experience large indirect benefits from passerine birds' pest control services (Karp et al., 2013). Finally, although service and disservice provider indices generally responded most strongly to complexity at different scales in our study, in some contexts, it may be hard to manage them separately.

5 | CONCLUSIONS

Birds are rapidly declining across North America, largely due to habitat loss and land use intensification (Rosenberg et al., 2019). These rapid bird declines are concerning because they may compromise vital ecosystem services including the regulating (e.g. pest control) and cultural (e.g. conservation) services birds provide (Echeverri et al., 2021; Şekercioğlu et al., 2004). Here, we found evidence that farmers can generally promote higher abundances of beneficial birds through whole-scale farm diversification without increasing disservices. Increasing local vertical vegetation complexity via hedges, paddock trees or live fencerows may also stabilize service provisioning. In contrast, disservices, such as foodborne pathogen delivery, appear most strongly associated with landscape-level features but were relatively unaffected by farm-level diversification. That is, farms embedded in landscapes with more semi-natural land cover generally had reduced average amounts of disservices alongside greater temporal stability of both services and disservices. This suggests need for greater public policy and farmer incentives for landscape-scale planning to promote maintenance of semi-natural cover at landscape scales.

ACKNOWLEDGEMENTS

We are grateful to the many growers who allowed us access to their farms and took time out of their incredibly busy schedules to facilitate this research, esp. V. Alexander. This work was supported by USDA-NIFA-OREI grant 2015-51300-24155 awarded to W.E.S., J.P.O., C.M.K. and E.E.W-R., the USDA NIFA Predoctoral Fellowship 2016-04538 awarded to O.M.S., the USDA NIFA Postdoctoral Fellowship 2021-67012-35133 awarded to O.M.S., and the Carl H. Elling Endowment in the School of Biological Sciences awarded to O.M.S. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the U.S. Department of Agriculture. C. Blubaugh and H.S. Burns assisted with project development. G.H. Ow, A. Tormanen and M. Edworthy provided field work logistical support. S. Knutie provided the federal master banding permit that made our food safety risk score assessment possible. Finally, we thank the reviewers of our article (one anonymous and one self-revealed, Matthias Tschumi) that significantly improved its quality.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors conceived the ideas; O.M.S. collected the point count, farm, landscape and service/disservice provider classification data, analysed the data and created the figures and led the writing of the manuscript; O.M.S., J.M.T. and A.E. collected the grower-focused cultural service index data. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.wm37pvmpn (Smith, Kennedy, et al., 2021).

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How to cite this article: Smith, O. M., Kennedy, C. M., Echeverri, A., Karp, D. S., Latimer, C. E., Taylor, J. M., Wilson-Rankin, E. E., Owen, J. P., & Snyder, W. E. (2022). Complex landscapes stabilize farm bird communities and their expected ecosystem services. *Journal of Applied Ecology*, 00, 1–15. https://doi.org/10.1111/1365-2664.14104