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Defining specialism and functional species groups in birds: First steps toward a farmland bird indicator

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ABSTRACT

Although farmland birds are used extensively in Europe as an indicator group to assess agricultural impacts on ecosystems, no such group has been formally identified in North America. Here we present a hierarchical framework to identify a suite of farmland bird species in Ontario, Canada by consolidating and validating classifications derived from literature review and empirical modelling. First, we reviewed literature to compile candidate farmland bird species in Ontario and assigned species to four guilds (row crop specialists, pasture specialists, farmstead specialists, and farmland edge generalists). Second, we used regression trees (RTs) to test whether these species could be classified into the same literature-based guilds or different guilds, based on modelled relationships between breeding bird atlas abundance data and Census of Agriculture statistics. We consolidated both classifications using a decision tree into a final list of 45 farmland bird species, comprising 11 farmstead specialists, 13 pasture specialists, 5 row crop specialists, 12 farmland edge generalists, and 4 farmland generalists flagged for classification uncertainty. To validate the distinctness of the assigned farmland bird guilds, we used pairwise permANOVA to test for differences in species composition among guilds, based on 34 species with sufficient occurrence data. We found significant compositional differences between almost all guilds, except for the farmstead specialist and row crop specialist guilds which could not be differentiated. We also validated species' guild assignments using canonical analysis of principal coordinates (CAP) to group 35 species according to ecological resemblance which were then compared to our proposed guild classifications. CAP validated guild assignments for 78.2% of the evaluated farmland specialists, particularly for farmstead specialists and pasture specialists, while 50% of evaluated farmland edge generalists were grouped differently than our final classification. Each final classification was associated with low, moderate, or high uncertainty according to concordance between classification methods and support from CAP groupings to highlight species with uncertainly assigned guilds. For some such species, mismatches between their literature-based and empirically-derived classifications might be due to the predictor variables being measured at too large a scale to reflect associations between their abundance distributions and agricultural landscape characteristics. We recommend that these farmland bird species be further verified using statistical models of bird count data, satellite imagery, and climate variables, and a trait-based approach to bolster confidence in the proposed list. When confirmed and expanded, this list can be used to inform a farmland bird indicator to monitor agroecosystem health in Ontario, and perhaps elsewhere in eastern North America.

1. Introduction

Considering the importance of agricultural landscapes for biodiversity conservation and the well-documented avian biodiversity declines in farmed land (Donald et al., 2001; Gregory et al., 2004; Inger et al., 2015), it is remarkable that no suite of farmland bird species has been formally developed for North America. In this respect, Canada and the United States have lagged behind Europe, where the Farmland Bird Indicator (FBI, or Farmland Bird Index) is one of 28 Agri-Environmental Indicators used by the European Union to monitor the structure and

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ecological sustainability of farmland ecosystems (Butler et al., 2010; Gregory and van Strien, 2010; PECBMS, 2017). This lag may be attributed to a historical preoccupation with patches of native or semi-natural features within the agricultural mosaic in North America (Martin et al., 2012), which has driven the reticence of avian ecologists to embrace the ecological value of farmland, defined here as the area under production in agricultural landscapes, for birds in that continent (but see Peterjohn, 2003). A second reason is that agriculture in North America has a much shorter history than it does in Europe, where traditional agriculture has been valued for biodiversity conservation for hundreds of years (Dieterich and Van der Straaten, 2004; O'Connor and Shrubb, 1990).

As a group, birds serve as an excellent indicator of non-avian farmland biodiversity for a variety of reasons (Burel et al., 1998; Devictor and Jiguet, 2007; Donald et al., 2002; Gaston and Fuller, 2007; Gregory et al., 2005; Lemoine et al., 2007; Sauberer et al., 2004). First, there is a broader and richer knowledge base about their ecology than any other taxa. Second, a large number of species (up to 200 in North America) with diverse habitat requirements and life history characteristics can be monitored using rapid, extensive, standardized, and often volunteer-based, point count surveys (Hutto, 1998) and now also autonomous recording units (ARUs; Shonfield and Bayne, 2017). Third, bird indicator information is statistically robust, cost-effective, relatively easy to update, and complementary to other biodiversity indicators (Padoa-Schioppa et al., 2006). Fourth, many bird species respond relatively rapidly to environmental changes that are difficult to measure directly (Furness and Greenwood, 1993; Thingstad, 1997). Fifth, migratory species and species at risk are legally protected and are flagships commanding media, public, and policy maker attention. Sixth, they perform ecosystem services that carry economic benefits in farmland (see Kirk et al., 1996; Whelan et al., 2016 for reviews). As a result, they are often selected as focal species in agricultural landscapes at local and landscape extents, usually on the basis of threatening processes (e.g., pesticide use) or acting as surrogates for other species (Brooker and Lefroy, 2004; Morelli et al., 2014; Padoa-Schioppa et al., 2006; Szymkowiak et al., 2014).

A farmland bird indicator could also be used to evaluate the efficacy of policy and management actions, such as agri-environmental schemes, designed to conserve avian biodiversity in agricultural landscapes (Gamero et al., 2017). For example, monitoring population trends of farmland birds—a functional group that would include all birds that use farmland—would track varying impacts of agricultural activities on biodiversity. Although traditionally pooled according to land cover type or nesting substrate (e.g., grassland, wetland, shrub, woodland, cavity-users, etc.), this group's key commonality is that they are all under the direct or indirect influence of farming-related human activities (Quinn et al., 2017). These activities can influence landscape composition and structure (Benton et al., 2003), and include the clearance of woodlands or edge vegetation (e.g., hedgerows, shelterbelts, riparian areas) to enlarge fields (Flinn et al., 2005) or to remove (sometimes alleged) crop pests and pathogens (Karp et al., 2016). Some farming practices, such as pesticide use, impact the flora and fauna of local agricultural fields, as well as adjacent hedgerows and field margins through spray-drift (Boutin et al., 2014; de Jong et al., 2008; de Snoo, 1999; Freemark and Boutin, 1995). A farmland bird indicator would therefore be an accessible and sensitive tool to monitor the outcomes of management strategies aimed at reducing or mitigating the detrimental impacts of these agricultural activities.

Despite the benefits of a farmland bird indicator, farmland birds have been largely overlooked in North American avian ecology and conservation. For instance, although grassland birds have shown steep declines in North America (National Audubon Society, 2014; Rosenberg et al., 2019), species that use farmland (including both crop and non-crop land cover) were not explicitly considered as a separate group. Likewise, the North American Breeding Bird Survey (BBS) has not treated farmland birds separately, though trend analyses have been carried out for groups such as grassland, early successional, and shrub-associated birds (Sauer et al., 2017). Separation into these groups was also done previously for the Canadian BBS trend analyses, but the practice has been discontinued (Smith et al., 2019). While Murphy (2003) analyzed population trends for avian guilds in agricultural landscapes in the eastern and central United States, only grassland and shrubland breeding birds with differing migratory status were explicitly grouped. One notable exception is a recent analysis of population trends in 'farmland-associated' birds in North America based on the BBS (Stanton et al., 2018), which adopted 'grassland' birds from the BBS and added other 'farmland-dependent' species from Murphy (2003). Quinn et al. (2014) also emphasized the value of examining conservation of grassland birds within anthromes (farmland). Moving forward, formally recognizing farmland birds in the North American roster of functional bird groups would add key insights into avian population and distributional trends in the often neglected, yet ubiquitous agricultural landscapes.

A first step in identifying a suite of bird species as indicators of environmental change in North American farmland is to ask 'what is a farmland bird?' and investigate specialism and functional groups. However, this question has yet to be addressed in North America: potential candidate farmland bird species for Ontario were listed by Boutin et al. (1999a,b), Freemark and Kirk (2001); Kirk et al. (2001) and Kirk et al. (2011), and for North America by Rodenhouse et al. (1995), and Stanton et al. (2018). However, none of these studies explicitly evaluated suites of farmland bird species. Although Hvenegaard (2011) did explore bird diversity as an indicator of change in farmland in North America, birds were not categorized with respect to their association with agricultural landscapes.

In this paper, we propose a list of "farmland birds" that could be used to construct a Farmland Bird Indicator in Ontario agroecosystems, with the intention of expanding this list for Canada as a whole in future studies. Specifically, we ask: 1) Which bird species are associated with farmlands in Ontario, and can these be classified into meaningful functional guilds according to their association with agricultural landscape characteristics? 2) How uncertain is our classification of these farmland bird species into guilds, and which species require further investigation to bolster confidence in our list? To examine these questions, we used a combination of expert opinion, scientific literature, and empirical evidence based on bird distributional and agricultural land cover data to identify a list of farmland bird species, and subdivide them into functional guilds. We first used expert opinion and scientific literature to discern candidate farmland bird species, which we then sorted into four functional guilds according to agricultural habitat preferences: farmstead specialists, pasture specialists, row crop specialists, and farmland edge generalists. For species with sufficient data, we then used regression trees (RTs) to classify each species into one of these four guilds according to the most important agricultural landscape predictors shaping their abundance across 176 agricultural subdivisions in Ontario. To evaluate the uncertainty of our classification, we compared guild classifications resulting from the expert opinion and literature survey and the regression tree approach using a decision tree, and highlighted species with discordant classifications as requiring further investigation. We also used: 1) permutational multivariate analysis of variance to compare species composition among guilds; 2) canonical analysis of principal coordinates to ordinate species into guilds according to ecological resemblances (i.e., the resemblance or similarity between objects, usually sites, and the variables describing them, usually 'species'), among and within groupings; and 3) tested for inconsistent composition of guilds compared to our farmland bird list to further flag uncertain classifications. We propose and demonstrate this hierarchical classification framework to identify farmland birds in Ontario, with the ultimate goal of informing a farmland bird indicator that monitors agricultural impacts on biodiversity at the landscape extent in North America.

2. Materials and methods

2.1. Literature-based candidate list of farmland species

We first conducted a web-based literature review to compile and characterize a candidate list of farmland birds for North America (Canada and the United States) as in Gregory and van Strien (2010) (see Supplementary Material 1). Based on a literature review of studies in five Canadian provinces and 18 states in the USA, we identified 159 species associated with agricultural landscapes (Kreuzberg, 2011). We modified this list by cross-checking the species recorded in the Ontario Breeding Bird Atlas (OBBA; Cadman et al., 2007) as occurring in grassland (166 species) and pasture (159 species), giving an additional 12 candidate species to the 159 obtained from the literature review (171 species). Of the 171 breeding species identified above, we excluded 93 species that use farmland incidentally, including vegetation that is usually adjacent to native remnants within agricultural landscapes. Our final candidate list of farmland birds retained a total of 78 species (Supplementary Table 2).

2.2. Literature-based classification of farmland birds

We categorized species according to the European Bird Conservation Council guidelines as 'farmland specialists' and 'farmland generalists' (EBCC, 2018). 'Farmland specialists' included species that rely heavily on land that is under production or managed as part of a farming regime (e.g., row crop, pasture, and farmstead), and typically required specific types of farmland vegetation for nesting or foraging. 'Farmland generalists' included species that use a variety of land cover types — native remnants (shrubs, trees, woods, grasslands, wetlands or their edges) and semi-natural features (hedgerows, grassy vegetation), in addition to those that are completely human-modified (row crop, pasture and farmstead). We then divided this initial classification into four 'guilds': row crop specialists (RCS), pasture specialists (PSS), farmstead specialists (FSS), and farmland edge generalists (FEG). Row crop specialists are species primarily associated with crops, pasture specialists with natural or semi-natural grassland and farmstead specialists are associated with farm buildings. Farmland edge generalists (FEG) are strongly associated with native remnants and semi-natural features which covered relatively small areas in farmed landscapes. It is important to note that these classifications are not absolute, because many species are widely distributed across a variety of land cover types and have expanded their ranges to cover newly created agricultural land areas (Brennan and Kuvlesky, 2005). This list was then verified by expert opinion from avian ecologists in Ontario (D. Bert, E. Cheskey, J. Girard, P. Mineau, L. Olson, S. Overington and A. Smith, pers. comm.).

2.3. Bird abundance and agricultural landscape data

We used point counts for birds collected for the second OBBA between 2001 and 2005 (Cadman et al., 2007) to characterize bird species' distributions across agricultural subdivisions in Ontario (obtained from bsc-eoc.org/birdmon/default/datasets.jsp?code=OBBA2PC). OBBA observers recorded all birds seen or heard during a five minute period at 25 point count sites within each 10 × 10 km atlas square in Ontario (n = 582). Each square was located randomly along roadsides (excluding provincial highways) at least 500 m apart, and each site was surveyed once during the breeding season (May 24 – July 10) between dawn and five hours thereafter (Cadman et al., 2007). To ensure that all vegetation types were given proportional representation, the roadside sample's vegetation type was evaluated against the vegetation type distribution for the rest of the atlas square. If certain vegetation types were under-represented, off-road points were added for under-sampled vegetation types.

Agricultural landscape predictors were obtained from the 2006 Census of Agriculture (Statistics Canada, 2011) at the agricultural subdivision level, as this provided the closest temporal overlap with the OBBA's temporal coverage (obtained from www150.statcan.gc.ca/n1/ca-ra2006/index-eng.htm). We selected 181 (of 269) subdivisions that contained from 5 to 94% farmland (average 53% ± 22.0 SD), representing 84% of all farmland area in Ontario. Subdivision area varied widely around a mean of 48,214 ha, ranging from 7000 to 347,000 ha (± 42,690 SD). We omitted subdivisions that did not overlap with OBBA point count data, leaving a total of 176 subdivisions.

We selected four groups of variables from the Census of Agriculture: 1) farmland composition (area in row crop—which designates all annual crops mechanically harvested on a large scale, including what are usually termed 'field crops', such as grains—as well as natural pasture, seeded pasture, summer fallow, farmstead, natural remnants); 2) farmland heterogeneity (Shannon diversity index of the six farmland composition variables and Shannon crop diversity based on 21 crop types); 3) farmland configuration (average farm size, average row crop acreage per farm); and 4) farming practices (livestock grazing, pesticide use, fertilizer use, farm machinery). See Supplementary Table 1 for further details.

We retained all OBBA point counts from survey locations within the Statistics Canada agricultural subdivisions (Fig. 1). We omitted subdivisions with less than one point count per 500 ha, leaving a total of 29,114 point counts. We retained only point counts associated with crop and pasture according to the Ontario land cover classification (Ontario Ministry of Natural Resources, 2007), to obtain the relative species abundance per point count in subdivisions (22,862 points, n = 176 subdivisions). The resulting abundance value used for each species was the mean number of birds for the unlimited distance counts

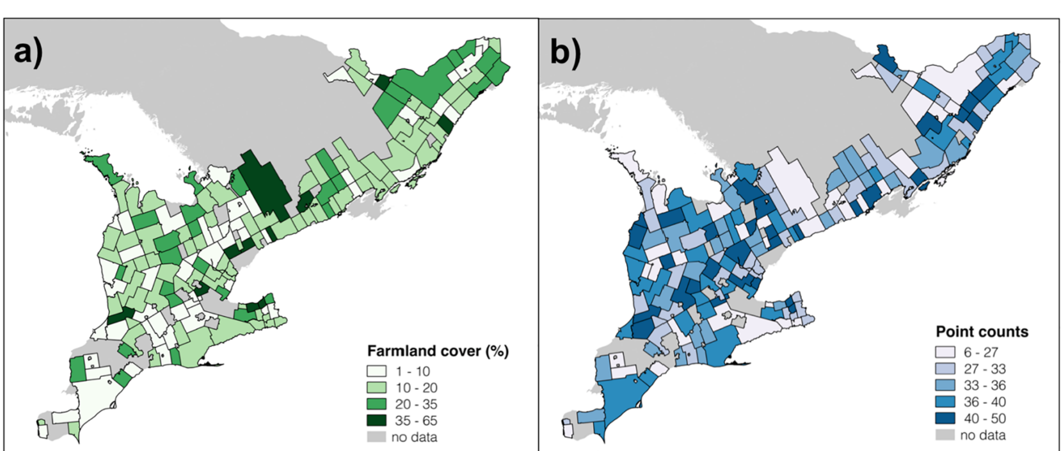

Fig. 1. (a) Proportion of farmland cover and **(b)** number of bird point counts per agricultural subdivision in Ontario.

across all points within each subdivision (176 subdivisions × 66 species).

Of the 78 specialist or generalist farmland birds identified through our literature survey (Supplementary Table 2), 66 species breed in the portion of Ontario covered by the Census of Agriculture, and 55 species had sufficient abundance data for regression tree analysis. We could not model some species because: 1) they were not detected at all in the 176 subdivisions (n = 3 species; Yellow-breasted Chat, Western Meadowlark and Dickcissel); 2) they were species at risk with restricted data access (n = 3 species; Barn Owl, Loggerhead Shrike, Henslow's Sparrow); 3) they occurred at too few point counts for analysis (n = 4 species; Northern Pintail, Great-horned Owl, Short-eared Owl, Brewer's Blackbird); and/or 4) they were flocking species not well suited to the model platform we used (n = 3 species; Bank Swallow, Northern Rough-winged Swallow, Chimney Swift). Note that eight farmland specialist species (one row crop specialist, Northern Bobwhite, and five pasture specialists, four of which are species at risk, Barn Owl, Short-eared Owl, Loggerhead Shrike, Henslow's Sparrow, and Dickcissel) also had insufficient point counts for analysis, but we retained them in the candidate list of 78 species (Supplementary Table 2) because they are of conservation concern.

2.4. Empirical classification of farmland birds

For each of the 55 farmland bird species with sufficient abundance data, we used RTs to identify key variables structuring their abundance across 176 Ontario agricultural subdivisions in a way that accounts for nonlinear relationships and that is easy to visually interpret (De'Ath and Fabricius, 2000). RTs are binary decision trees that are recursively partitioned into successively smaller groups of sample sites and observations. Relatively homogenous groups of observations are represented by a 'leaf' or 'terminal node'. The splits (or internal nodes) are made according to values of a single variable and minimize within-group variance.

Before fitting the RTs, we tested for positive spatial autocorrelation in each species' count distributions across agricultural subdivisions using a Moran's I test. We found positive spatial autocorrelation for Red-tailed Hawk abundance (see Supplementary Table 3), and therefore included spatial coordinates in the full candidate model RT for this species. For all other species, the full candidate model included all aforementioned agricultural predictors. Each tree was fit using Poisson regression, and was limited to a maximum depth of two for simplicity, as we aimed to identify a manageable number of key variables. Each tree's R^2 was assessed through cross-validation across subsets of the bird count dataset. All RTs were built using the R package *rpart* (Therneau et al., 2019). R scripts to compute Moran's I, RTs, and related visualizations are available at github.com/katherinehebert/FarmlandBirds.

To classify species empirically, we defined *a priori* expectations of abundance responses to each agricultural predictor for each guild (Table 1), based on their predicted habitat preferences. For example, we expected that more occurrences and/or higher abundances in sites with more natural and seeded pasture area would be indicative of pasture specialists, while strong associations with row crops would signal row crop specialists (Table 1). We then compared the 'key' variables identified through the RT (i.e., the agricultural predictors chosen through cross-validation to split the tree) to these expectations and classified each species according to the concordance between the two response 'profiles'.

2.5. Consolidation of the literature-based and empirical classifications

Of the 78 farmland bird species identified in our candidate list, 23 species could not be classified empirically due to data limitations, and were therefore classified based on the literature survey alone. For each of the 55 remaining farmland bird species, we followed a decision tree (Fig. 2) to consolidate the literature-based and empirically derived classifications. When a species' guild affiliation matched between the two classification methods, we assigned this guild as the final classification. When there was a mismatch between methods, we selected the guild derived from the regression tree if its R^2 was above a threshold of $R^2 = 0.15$. This threshold was determined as the approximate midpoint of the range of R^2 values across all species, which varied between 0.043 and 0.348. Otherwise, we assigned the literature-derived guild as a final classification. In both cases, this mismatch was considered when evaluating the classification uncertainty during the following validation process.

Table 1
Expected relationships between occurrence/abundance of farmland bird functional groups/guilds and agricultural land cover covariates derived and adapted from Statistics Canada's 2006 Census of Agriculture.

Category	Predictor	Acronym	RCS	PSS	FSS	FEG	FG
Farmland composition	Row crop	CROP	+	−	+	−	+
	Natural pasture	NPP	0	+	0	+	+
	Seeded pasture	TSPP	0	+	0	+	+
	Summer fallow	SFALP	+	−	0	0	+
	Farm area	FARM	+	0	+	+	+
	Natural remnants	TWWP	0	+	+	+	+
	Farmstead and roads	URP	−	−	−	+	+
Farmland configuration	Average farm size	AVFS	+	0	0	0	+
	Average rowcrop acreage per farm	AVCRS	+	−	0	−	+
Farmland heterogeneity	Shannon-Wiener diversity index	SWDIFR	0	+	+	+	0
	Crop Shannon-Wiener diversity index	SWDICR	+	0	0	+	0
Farming practices	Livestock grazing	CTPHA	0	+	+	0	+
	Pesticides	PESTIN	0	−	−	0	0
	Fertilizer	FERTIN	0	−	−	0	0
	Machinery	AMPF	+	−	+	0	0

2.6. Validation of farmland bird guild composition

With the aim of validating whether the assigned guilds represent ecologically similar groupings of species, we deployed permutational multivariate analysis of variance (permANOVA) to compare allocation of species between farmland bird guilds as a fixed effect based on a species × species resemblance matrix and conducted *post-hoc* pairwise tests between categories. Species resemblance was measured as the 'index of association' (previously Whitaker's Coefficient; Clarke and Gorley, 2014), which is computed as the Bray-Curtis resemblance between species' proportional abundances. Because this method is sensitive to species with low frequency of occurrence, we removed species that occurred in fewer than 18 subdivisions (10%), leaving a total of 34 species for analysis. Statistically significant differences among all categories and between all category pairs would confirm that the assigned groupings are ecologically distinct, and therefore provide an appropriate representation of separate functional guilds. All permANOVA and *post-hoc* tests were performed using PERMANOVA+ (Anderson et al., 2008).

We used canonical analysis of principal coordinates (CAP; Anderson et al., 2008) to validate species' classifications within the farmland bird guilds, and to determine the coherence between species groupings based on species resemblance and groupings based on the guilds derived from the literature-based and empirical approaches. CAP determines axes through multivariate data clouds to predict *a priori* groups, and the model is assessed using a leave-one-out misclassification error (or residual SS). Here, we attempted to predict *a priori* groupings derived from our bird guild classification methodology based on the species resemblance matrix, and assessed the frequency of

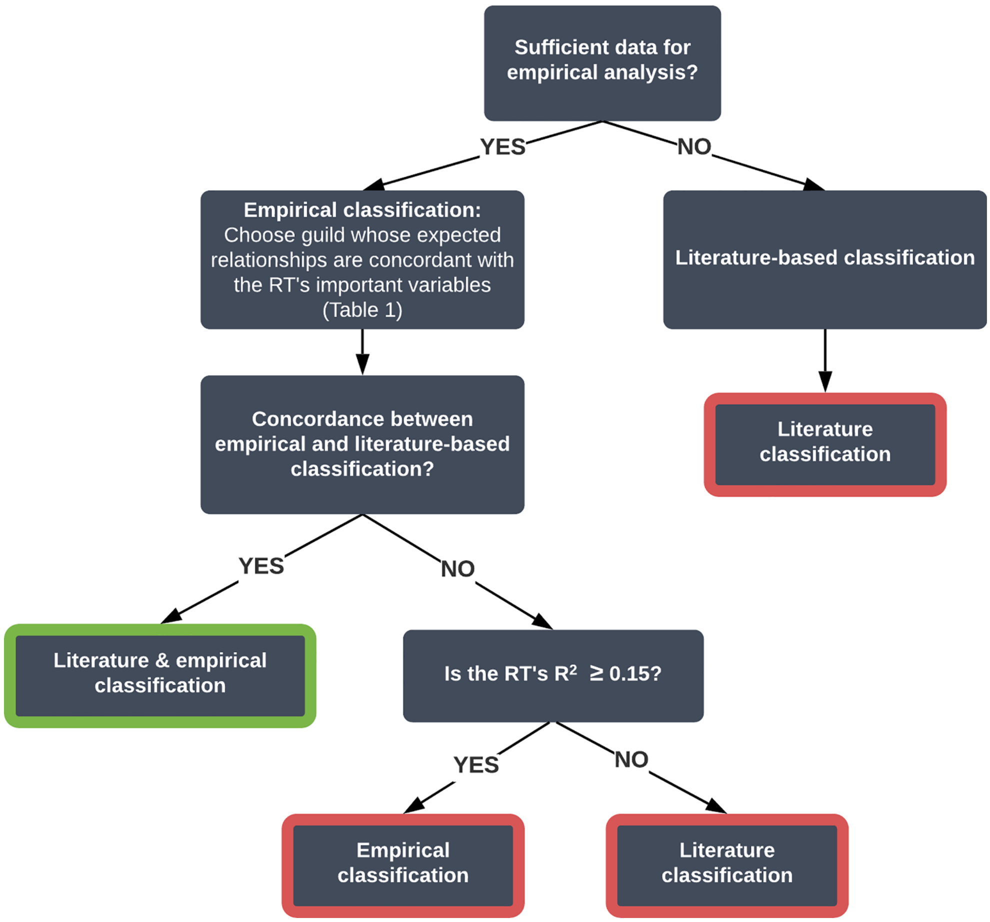

Fig. 2. Decision tree to consolidate the literature-based and empirically-derived classifications.

successful prediction. If prediction success is high, the species compositions of our farmland bird guilds successfully constitute ecologically similar species groupings. Of the 55 classified species, 35 had sufficient data to perform the CAP, including the Ring-necked Pheasant (RCS) which was an outlier with undue influence and was therefore removed, though later reinserted (see Supplementary Fig. 2). CAP was performed in PERMANOVA+ (Anderson et al., 2008).

For each species assessed using our classification scheme, we evaluated three certainty levels in our final guild classification: high, when there was concordance between the literature and empirical classifications and this final classification was supported by the CAP groupings; moderate, when there was discordance between classifications but the final classification was supported by the CAP groupings, or vice-versa; and low, when there was discordance across classifications and the final classification was not supported by CAP groupings.

3. Results

3.1. Literature-based classification of farmland birds

Of the 78 farmland bird species retained in our candidate list, 42 species were classified as specialists, including 5 introduced species, and 36 species were classified as farmland generalists (Supplementary Table 2). We further evaluated habitat preferences of 34 farmland specialist species and 27 farmland generalist species when this information was available, and sorted them into guilds. According to the evaluated literature, we identified 6 row crop specialists, 16 pasture specialists, 12 farmstead specialists, and 11 farmland edge generalists, while the remaining 16 species were categorized as farmland generalists.

3.2. Empirical classification of farmland birds

RTs for the 55 species with sufficient point count data varied in goodness-of-fit, ranging from an R^2 of 0.05 to 0.30 (detailed RT results are in Supplementary Material 2). The highest average R^2 values were for species empirically identified as pasture specialists (0.14 ± SE 0.02), followed by those categorized as row crop specialists (0.11 ± SE 0.03), as farmstead specialists (0.10 ± SE 0.03), as farmland edge generalists (0.09 ± SE 0.01), and as farmland generalists (0.08 ± SE 0.01).

Overall, species varied widely in their responses to most agricultural landscape predictors (Fig. 3a, b; Table 2). Average crop area (AVCRS; Fig. 3a, b) was the most generally important variable across the evaluated species, being chosen as the root node variable in the final cross-validated RTs for 22 species, including 1 row crop specialist (20% of modelled species within the guild), 7 pasture specialists (63.6%), 2 farmstead specialists (16.7%), 8 farmland edge generalists (72.7%), and 3 farmland generalists (18.8%).

Many RTs were informative, but relationships with apparently ‘key’ variables at the subdivision level were not always biologically meaningful. For example, in the case of the Horned Lark, a row crop specialist, the importance of farm machinery (AMPF) could be related to bare ground and cropland, but the relationship between its occurrence and natural remnants (TWWP) (albeit very low levels) is somewhat counterintuitive (declines in Horned Larks have occurred in Ontario because of reforestation of farmland). On the other hand, the RT results for the Turkey Vulture demonstrated this species’ well-known associations with natural pasture and livestock (Supplementary Material 2).

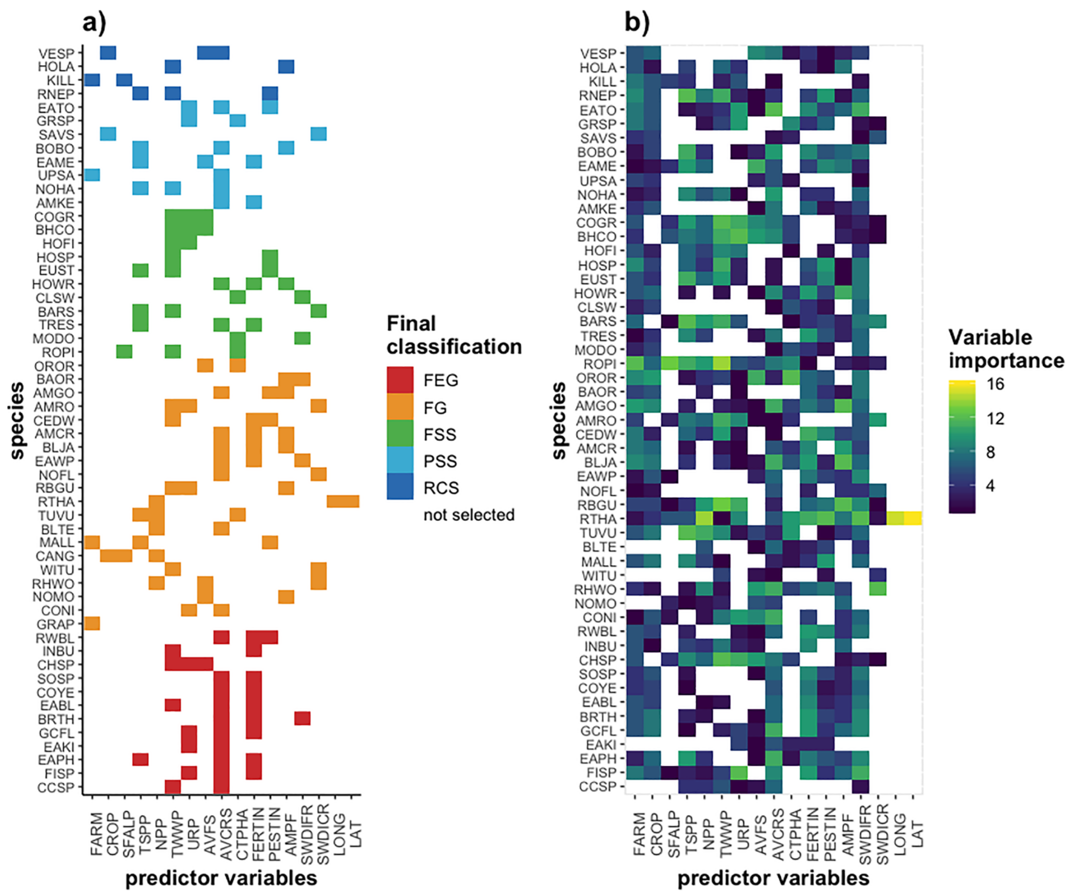

Fig. 3. (a) Variables selected and **(b)** variable importance of agricultural landscape predictors in univariate regression trees built for each bird species, with a maximum depth of 2. In (a), filled tiles show variables that were selected in each tree, and are coloured by each species' final classification, indicated as: RCS = row crop specialists, PSS = pasture specialists, FSS = farmstead specialists, FG = farmland generalists, FEG = farmland edge generalists. In (b), variable importance is ranked across variables selected during tree construction. See Table 1 for a description of agricultural predictors (further details in Supplementary Table 1). See species acronyms in Table 2.

3.3. Consolidation of literature-based and empirical classifications

Guild classifications derived from the RTs for the 55 species with sufficient point count data were often concordant with the literature-based classifications for farmland generalists, but were generally mismatched in the case of farmland specialists (Table 2).

Complete concordance between the literature-based and empirical classifications (RT and CAP) supported a highly certain guild assignment for 24 species of the 55 species evaluated, consisting of 14 farmland generalists (Wild Turkey, Mallard, Blue-winged Teal, Red-tailed Hawk, Ring-billed Gull, Northern Flicker, Eastern Wood-pewee, Blue Jay, American Crow, Cedar Waxwing, American Robin, American Goldfinch, Baltimore Oriole, Orchard Oriole), 3 farmland edge generalists (Great Crested Flycatcher, Brown Thrasher, Indigo Bunting), 2 row crop specialists (Horned Lark, Vesper Sparrow), and 4 pasture specialists (Northern Harrier, Eastern Meadowlark, Bobolink, Grasshopper Sparrow; Table 2). No farmstead specialists were classified with certainty. We suggest omitting Eastern Wood-pewee from the final list, because it is a forest species according to the literature review and expert opinion although our classification method identified it as a farmland generalist.

We classified a total of 23 species into guilds with low certainty (Table 2). These include 6 data-limited species whose guild assignments were based on the literature-search method alone, including 1 row crop specialist (Northern Bobwhite) and 5 pasture specialists (Barn Owl, Short-eared Owl, Loggerhead Strike, Henslow's Sparrow, Dickcissel; Table 2). An additional 15 species were classified with low certainty according to our decision tree, namely due to inconsistencies between the two classification methods and/or with the CAP grouping validation results. The Gray Partridge, the Common Nighthawk, the Northern Mockingbird, and the Red-headed Woodpecker were each classified as farmland generalists according to their respective regression trees, but with low certainty. Because the literature-based approach assigned them more specialized guilds (Table 2), we suggest further investigation into their habitat preferences before excluding them from the final proposed list of farmland birds. We classified the remaining 21 species into guilds with moderate certainty, indicating mismatched classifications or a lack of validation support from CAP groupings (Table 2). We excluded all farmland generalists classified with high certainty from the final list, as well as the Canada Goose which was identified in the literature as a farmland generalist though this was not supported by the regression tree (low certainty).

The final proposed list of farmland birds for Ontario included a total of 45 species assigned into four guilds, including 29 farmland specialists (5 row crop specialists, 13 pasture specialists, 11 farmstead specialists), 12 farmland edge generalists, and the 4 low-certainty farmland generalists mentioned above (Table 2).

3.4. Validation of farmland bird guild composition

Permutational multivariate ANOVA demonstrated a significant difference in ecological similarity among all farmland bird groups (pseudo $F = 2.326$, $P = 0.0012$), confirming that the distribution of species' abundances in Ontario subdivisions differed more greatly between literature-based groupings, then within groupings. Pairwise tests indicated significant differences between pasture specialists and farmstead specialists (t = 1.84, p = 0.0002), between pasture specialists and farmland edge generalists (t = 1.37, p = 0.0186), between pasture specialists and row crop specialists (t = 1.41, p = 0.0377), between farmstead specialists and farmland edge generalists (t = 1.55, p = 0.0028), and between farmland edge generalists and row crop specialists (t = 1.64, p = 0.0135). However, pairwise tests showed no support for differences between farmstead specialists and row crop specialists (t = 1.06, p = 0.2507).

Canonical analysis of principal components (CAP) revealed clusters of ecologically similar species (Fig. 4) that generally reflected our final guild classification (Table 2). Of the 35 species whose guilds were validated using CAP, 68.6% (24 species) were grouped into ecologically similar "guilds" that supported our final classification. CAP groupings supported the classification of 18 of the 23 (78.2%) species identified as specialists in our final classification, validating the guilds assigned to 3 of the 4 (75%) evaluated row crop specialists, 6 of the 8 (75%)

Table 2
List of 45 farmland bird species for Ontario with their final guild classification, consolidated from literature review and regression trees (RT) and validated using canonical analysis of principal coordinates (CAP).

Farmland bird species	Classification				Validation		
	Literature	RT	Match	Final	CAP	Support	Certainty
Northern Bobwhite* (NOBO)	RCS	–	–	RCS	–	–	low
Ring-necked Pheasant (RNEP)	**RCS**	FEG	N	RCS	RCS**	Y	moderate
Gray Partridge (GRAP)	RCS	**FG**	N	FG	–	–	low
Killdeer (KILL)	RCS	RCS	Y	RCS	FSS	N	moderate
Horned Lark (HOLA)	RCS	RCS	Y	RCS	RCS	Y	high
Vesper Sparrow* (VESP)	RCS	RCS	Y	RCS	RCS	Y	high
American Kestrel* (AMKE)	**PSS**	FG	N	PSS	PSS	Y	moderate
Northern Harrier* (NOHA)	PSS	PSS/FEG	Y	PSS	PSS	Y	high
Upland Sandpiper (UPSA)	**PSS**	FG	N	PSS	PSS	Y	moderate
Barn Owl* (BAOW)	PSS	–	–	PSS	–	–	low
Short-eared Owl* (SEOW)	PSS	–	–	PSS	–	–	low
Common Nighthawk* (CONI)	PSS	**FG**	N	FG	–	–	low
Loggerhead Shrike* (LOSH)	PSS	–	–	PSS	–	–	low
Eastern Meadowlark* (EAME)	PSS	FG/PSS	Y	PSS	PSS	Y	high
Bobolink* (BOBO)	PSS	PSS	Y	PSS	PSS	Y	high
Savannah Sparrow (SAVS)	**PSS**	FG	N	PSS	FSS	N	low
Grasshopper Sparrow* (GRSP)	PSS	PSS	Y	PSS	PSS	Y	high
Henslow's Sparrow* (HESP)	PSS	–	–	PSS	–	–	low
Clay-colored Sparrow (CCSP)	PSS	**FEG**	N	FEG	PSS	N	moderate
Field Sparrow* (FISP)	**PSS**	FEG	N	FEG	FEG	Y	moderate
Eastern Towhee* (EATO)	**PSS**	FG	N	PSS	FG	N	moderate
Dickcissel* (DICK)	PSS	–	–	PSS	–	–	low
Rock Pigeon (ROPI)	**FSS**	FG	N	FSS	FSS	Y	moderate
Mourning Dove (MODO)	**FSS**	FEG	N	FSS	FSS	Y	moderate
Tree Swallow (TRES)	**FSS**	PSS/FG	N	FSS	FEG	N	low
Barn Swallow* (BARS)	**FSS**	PSS/FEG	N	FSS	FSS	Y	moderate
Cliff Swallow (CLSW)	**FSS**	PSS	N	FSS	FSS	Y	moderate
House Wren (HOWR)	**FSS**	FG	N	FSS	FEG	N	low
Northern Mockingbird (NOMO)	FSS	**FG**	N	FG	FSS	N	moderate
European Starling (EUST)	**FSS**	FG	N	FSS	FSS	Y	moderate
House Sparrow (HOSP)	**FSS**	FG	N	FSS	FSS	Y	moderate
House Finch (HOFI)	**FSS**	FEG/FG	N	FSS	FSS	Y	moderate
Brown-headed Cowbird (BHCO)	**FSS**	FEG/FG	N	FSS	FSS	Y	moderate
Common Grackle (COGR)	**FSS**	FG	N	FSS	FSS	Y	moderate
Red-headed Woodpecker *(RHWO)	FEG	**FG**	N	FG	–	–	low
Eastern Phoebe (EAPH)	**FEG**	FG	N	FEG	FEG	Y	moderate
Eastern Kingbird* (EAKI)	**FEG**	FG	N	FEG	PSS	N	low
Great Crested Flycatcher (GCFL)	FEG	FG/FEG	Y	FEG	FEG	Y	high
Brown Thrasher* (BRTH)	FEG	FEG	Y	FEG	FEG	Y	high
Eastern Bluebird (EABL)	FEG	FG/FEG	Y	FEG	PSS	N	moderate
Common Yellowthroat (COYE)	**FEG**	FG	N	FEG	FEG	Y	moderate
Song Sparrow (SOSP)	**FEG**	FG	N	FEG	FSS	N	low
Chipping Sparrow (CHSP)	FEG	FG/FEG	Y	FEG	FSS	N	moderate
Indigo Bunting (INBU)	FEG	FEG	Y	FEG	FEG	Y	high
Red-winged Blackbird (RWBL)	FEG	FEG	Y	FEG	FSS	N	moderate
Wild Turkey (WITU)	FG	FEG/FG	Y	FG	–	–	high
Canada Goose (CANG)	**FG**	RCS/PSS	N	FG	–	–	low
Mallard (MALL)	FG	FG	Y	FG	–	–	high
Blue-winged Teal (BLTE)	FG	FG	Y	FG	–	–	high
Turkey Vulture (TUVU)	FG	PSS	FG	FG	–	–	low
Red-tailed Hawk (RTHA)	FG	FG	Y	FG	–	–	high
Ring-billed Gull (RBGU)	**FG**	FEG	N	FG	–	–	high
Northern Flicker (NOFL)*	FG	FEG/FG	Y	FG	–	–	high
Eastern Wood-pewee (EAWP)	FG	FEG/FG	Y	FG	–	–	high
Blue Jay (BLJA)	FG	FG	Y	FG	–	–	high
American Crow (AMCR)	FG	FG	Y	FG	–	–	high
Cedar Waxwing (CEDW)	FG	FEG/FG	Y	FG	–	–	high
American Robin (AMRO)	FG	FEG/FG	Y	FG	–	–	high

(*continued on next page*)

Table 2 (*continued*)

Farmland bird species	Classification				Validation		
	Literature	RT	Match	Final	CAP	Support	Certainty
American Goldfinch (AMGO)	FG	FG	Y	FG	–	–	high
Baltimore Oriole (BAOR)*	FG	FG	Y	FG	–	–	high
Orchard Oriole (OROR)	FG	FG	Y	FG	–	–	high

Species scientific names shown in Supplementary Table 2.
Species in italics are farmland generalists (16 species) to be excluded from a farmland bird indicator.
*Priority species in Bird Conservation Region 13 (Lower Great Lakes/St. Lawrence Plain) in Ontario.
Guild acronyms: RCS = row crop specialists, PSS = pasture specialists, FSS = farmstead specialists, FEG = farmland edge generalists, FG = farmland generalists.
Dashes indicate lack of empirical evidence, namely due to data limitations.
Final classifications were obtained using the decision tree.
Classifications chosen following discordance between the literature-based and regression tree (RT) classifications according to the decision tree (Fig. 2) are bolded.
Matches between the literature and RT classifications are indicated as: Y = yes (match), N = no (mismatch).
Groupings derived from ecological resemblances via canonical analysis of principal coordinates (CAP) were used to validate the final classification, and their support of the final classifications are indicated as: Y = yes (supported), N = no (not supported).
Uncertainty levels were assigned according to concordance between the literature and RT classifications and support from CAP groupings (high), lack of classification concordance or lack of support from CAP (moderate), and lack of classification concordance and lack of support from CAP groupings (low).

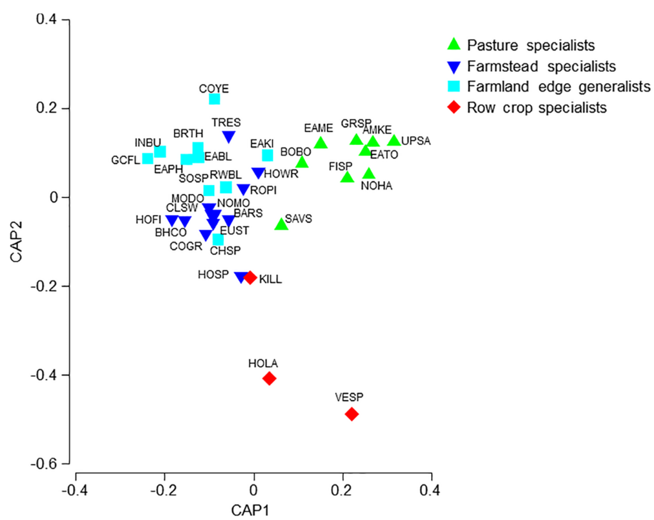

Fig. 4. Species' ecological resemblances in ordination space, as determined by Canonical Analysis of Principal Coordinates (CAP), where proximity between points reflects closer ecological similarity. Point shape and colour reflect each species' literature-based classification. Acronyms are in Table 2 and Supplementary Table 2.

evaluated pasture specialists, and 9 of the 11 (81.8%) evaluated farmstead specialists. The farmland edge generalist group was the most frequently misclassified group (6 of 12 evaluated species; 50%), and received the least support from the CAP groupings, which validated the guilds assigned to only 6 of the 11 (54.5%) evaluated species in this category. Of the 12 species termed farmland edge generalists in our final classification, 3 species (Chipping Sparrow, Red-winged Blackbird, and Song Sparrow) were classified as farmstead specialists and 2 species (Eastern Bluebird and Eastern Kingbird) were classified as pasture specialists in the CAP groupings. The Northern Mockingbird was the only species classified as farmland generalist included in the CAP validation, but its guild assignment was not supported by its CAP grouping (farmstead specialist; Table 2). Because this species was also identified as a farmstead specialist during the literature review (Table 2), we recommend further study of its habitat preferences before confirming its categorization as a generalist.

4. Discussion

Despite their long-standing effectiveness in Europe, "farmland birds" have yet to be formally embraced as an indicator group of agricultural impacts on ecosystems in North America. To take our first steps towards a North American farmland bird indicator, we developed a list of farmland-associated bird species for North America using existing literature and bird survey information, and sub-categorized these species into guilds as in Europe, to provide greater insight into species' differing responses to agricultural activities. We derived our classification through a hierarchical approach based on a consolidation of literature review and modelled landscape-scale responses to farmland composition, heterogeneity, configuration, and farming practices at the species level (Julliard et al., 2006). Our final classification was then validated against groupings shaped by ecological similarities between species. We present this framework and a list of farmland birds for Ontario with the ultimate goal of implementing a farmland bird indicator in North America to monitor the landscape-level impacts of agricultural activity on farmland birds' distributions and abundances, and thus on ecosystems as a whole.

Our full list of farmland birds includes 45 species, comprised of 26 farmland specialists and 16 farmland generalists. Farmland specialists mostly consisted of species that historically inhabited grasslands, as well as 5 species introduced by Euro-American settlers (and currently categorized in the EU as farmland birds; PECBMS, 2017). Farmland generalists included species associated historically with a variety of land cover types, including woods, grasslands, shrub, wetlands, and edge vegetation. Specialists and generalists were each broken down into sub-guilds according to their responses to different land cover types. Our final suite of specialist farmland birds for Ontario was comparable in size to the list developed in the European Union (36 specialists, compared to our 29). Of the 29 farmland specialists, five species were row crop specialists (RCS), 13 were pasture specialists (PSS), and 11 were farmstead specialists (FSS). We also present 16 farmland generalists in our list, which were categorized as farmland edge generalists (FEG; 12 species), or as farmland generalists (FG 4 species). As in Stanton et al. (2018), we suggest excluding wetland obligate species from consideration as farmland-associated birds, although some Anseriformes were categorized as farmland generalists, and some could even be classified as specialists based on the models.

Classifying species as specialists or generalists was challenging both in our study, and more generally, due to a lack of standardized criteria or definition of these two categories. This ambiguity is problematic, as this classification directly informs the choice of management approach that would be most appropriate for species of current and future conservation concern. For example, as in our study, Ahnström et al. (2008) classified Swedish farmland bird species that are dependent on human habitations for breeding as specialists. In contrast, based on the breadth of their habitat use (farmstead and urban species), Clavel et al. (2011) would classify these species as generalists. Although the farmstead specialists we identified in Ontario also occur in urban and suburban habitats, they are distinguished by their strong relationships with farmland structural variables according to literature review and expert opinion. Moreover, Clavel et al. (2011) may classify our edge generalists as edge specialists, given their preferential use of natural feature edges. However, in our study many 'farmstead specialists' and 'farmland edge generalists' were positively correlated with a number of non-crop farmland cover types, illustrating the wide breadth of vegetation types used. In addition, the lack of strong covariate descriptors for farmsteads made model interpretation challenging. Because these inconsistencies are difficult to resolve, it is essential to maintain transparency about the classification process when assigning species into such categories. In presenting our hierarchical classification framework in a transparent way, we aim to redress the lack of standardized approach to farmland bird classification and to encourage the use of a farmland bird indicator at broader scales.

Discrepancies between the literature-based and empirically derived classifications suggest that: 1) our environmental covariates were not sufficiently fine-scale to derive some of the functional groups (e.g., farmstead specialists, as above); or more likely 2) classifying species into functional groups is fundamentally problematic because birds are mobile and use multiple land cover types and resources in farmland landscapes. A particularly complex example is that of the Barn Swallow, a species which uses farm buildings for nesting, and is associated with livestock (manure) and pasture for foraging, as well as farmland heterogeneity (temporally and spatially variable; Turner, 2012). This species was classified as a farmstead specialist by literature review in agreement with expert opinion, but showed positive relationships with tame and seeded pasture in its regression tree model.

Employing a hierarchical classification framework ensures that the list of species is validated multiple times via a variety of methods, which each provide different levels of information. Reviewing the literature and consulting expert opinion was an informative first step to determine a candidate list of farmland birds, and to propose guilds based on previous knowledge of species' associations with agricultural landscape characteristics. This approach was particularly useful to assign guilds for less abundant species, for which data limitations would have otherwise prevented their inclusion in our final list.

Using RTs to model species' responses to agricultural landscape variables provided empirical evidence of species' habitat preferences. Although a detailed interpretation of the regression trees for each species is not possible here (and is presented in Supplementary Material 2), the RTs are a simple way to visualize and identify agricultural predictors that most strongly impact each species. This can ultimately inform interpretations of species' trends in terms of their expected responses to specific agricultural land cover or activities.

When possible, consolidating the literature-based guilds with empirically derived groups allowed us to assess classification uncertainty, and flag species that require further study before being used in the context of a farmland bird indicator. When CAP validation and permANOVA were also possible, we were able to add another layer of information regarding whether the composition of our proposed guilds, as well as the distinction between them, were supported by ecological resemblances among species. As such, we were able to quantify uncertainty in the classification of species into specific guilds, including row crop specialists. We therefore caution that row crop specialists should potentially not be treated as a distinct group from other specialists, if assessing farmland bird trends at the sub-guild level.

Although empirical classification is a key component of our process, it is important to note that empirical methods are subject to the limitations of available agricultural landscape data and bird species abundance information, including issues of missing predictors, sample size, and scale. First, we averaged bird point count data at the level of subdivisions in Ontario to match the sub-divisional agricultural census data. Because birds respond to land cover at multiple spatial extents, our agricultural covariates might be measured at a scale that is too large to detect bird responses, which could be at extents of, for example, 100 m or 1000 m. Taking an average for the response variable at the sub-divisional level, however, should mitigate these anomalies to some extent. In addition, inspecting species' abundance responses to agricultural predictors at the scale of agricultural subdivisions does not take into account the multi-scale response of birds to land cover (Thogmartin et al., 2006) and may not be ideal to identify species' smaller-scale habitat preferences, such as vegetation composition, which are equally important. Second, we used agricultural statistics that were readily available from the Census of Agriculture. However, these data were not necessarily the best descriptors for bird species distribution and abundances, and some were correlated. For example, the variable used to describe farmsteads included not only farmsteads, but also roads, and birds are likely to respond differently to these two features. This might explain why we identified fewer farmstead specialists when using our empirical classification.

As such, certain relationships deemed important in our RTs might be attributable to predictor correlations with unmeasured variables, rather than cause and effect. For example, the apparently positive relationship between abundances of some species and pesticide use is likely due to unmeasured variables, as pesticide use is a broadly defined variable which does not distinguish pesticide toxicity, and which could be associated with other farmland characteristics like crop area. In addition, rare species had low sample sizes by definition, making it impossible to parameterise RTs for an empirical classification. This is potentially problematic, as rare species are more likely to be strongly affected by agricultural activity, and monitoring their populations might showcase early reactions to certain agricultural activities (Pywell et al., 2012; see Supplementary Discussion for the relevance of our classification to declining farmland and grassland bird species).

Our results suggested that using a combination of literature review and expert opinion (which may be subject to bias) and empirical models (which are subject to data limitations) may be the best approach; see Gregory et al., 2019. In our study, relying on empirical models alone would have been inadvisable as many results were not interpretable biologically. However, with more robust models could be built using finer resolution species data and satellite imagery, as well as machine-learning platforms such as boosted regression trees or Random Forest (Elith et al., 2008; Evans et al., 2011; Regos et al., 2018). We also caution that agricultural land cover is dynamic and can change considerably between breeding bird atlases, and that species' associations with farmland land cover can also change over time. Therefore, in moving forward to build empirical models contemporary data is needed for both bird species and environmental predictors. In the case of rare species, data will always be limited and empirical models not feasible. While literature review and expert opinion can be used in these cases it is important to note that population trends often cannot be developed for these species.

Importantly, our study also highlighted the need to consider variation in species' habitat preferences within farmland. For example, row crop specialists and pasture specialists were mainly associated with row crop and pasture land cover, respectively. On the other hand, farmstead specialists and edge farmland generalists require heterogeneous landscapes containing a juxtaposition of several farmland cover types. Some species occupied a specific ecological niche, requiring that breeding structures (e.g., farmstead) be of close proximity to vegetation for foraging (e.g., fields). Defining and analyzing distinct farmland bird species groups is therefore essential to accurately assess the status of the full breadth of farmland birds, which have a diversity of ecological requirements and habitat requirements.

We have proposed a hierarchical classification framework to identify farmland birds in Ontario, with the ultimate aim of informing a farmland bird indicator to monitor agricultural impacts on biodiversity at the landscape scale in North America. Two important next steps are to: 1) refine our models using bird species data from individual point counts derived from the OBBA overlaid with Landsat satellite imagery and climate data, and 2) employ a trait-based approach in order to develop a farmland bird indicator for Ontario and North America as a whole, as recently developed in Europe (Butler et al., 2012). However, establishing a transparent framework to identify farmland bird species represents an important first step toward developing a farmland bird indicator in North America, which has the potential to be an essential tool for monitoring ecosystem responses to agricultural management schemes across the continent.

CRediT authorship contribution statement

David Anthony Kirk: Conceptualization, Formal analysis, Investigation, Project administration, Supervision, Writing - original draft, Writing - review & editing. **Katherine Hébert:** Formal analysis, Investigation, Validation, Visualization, Writing - review & editing. **Kathryn Freemark Lindsay:** Conceptualization, Investigation, Supervision, Funding acquisition, Writing - original draft. **Elena Kreuzberg:** Conceptualization, Data curation, Formal analysis, Investigation, Writing - original draft.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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References

Ahnström, J., Berg, Å., Söderlund, H., 2008. Birds on farmsteads – Effects of landscape and farming characteristics. Ornis Fenn. 85, 98–108.
Anderson, M.J., Gorley, R.N., Clarke, K.R., 2008. PERMANOVA+ for PRIMER, Guide to software and statistical methods. PRIMER-E Ltd., Plymouth, UK. Plymouth, United Kingdom.
Benton, T.G., Vickery, J.A., Wilson, J.D., 2003. Farmland biodiversity: Is habitat heterogeneity the key? Trends Ecol. Evol. 18, 182–188. https://doi.org/10.1016/S0169-5347(03)00011-9.
Boutin, C., Freemark, K.E., Kirk, D., 1999a. Farmland birds in southern Ontario: Field use, activity patterns and vulnerability to pesticide use. Agric. Ecosyst. Environ. 72, 239–254.
Boutin, C., Freemark, K.E., Kirk, D.A., 1999b. Spatial and temporal patterns of bird use of farmland in southern Ontario. Can. Field-Naturalist 113, 430–460.
Boutin, C., Strandberg, B., Carpenter, D., Mathiassen, S.K., Thomas, P.J., 2014. Herbicide impact on non-target plant reproduction: What are the toxicological and ecological implications? Environ. Pollut. 185, 295–306. https://doi.org/10.1016/j.envpol.2013.10.009.
Brennan, L.A., Kuvlesky, W.P., 2005. North American grassland birds: An unfolding conservation crisis? J. Wildl. Manage. 69, 1–13. https://doi.org/10.2193/0022-541X(2005) 069<0001:NAGBAU>2.0.CO;2.
Brooker, L., Lefroy, T., 2004. Testing approaches to landscape design in cropping lands: Habitat neighbourhoods for conserving viable populations of birds. Final Report for Land and Water Australia Project CSE 9 Affiliation: CSIRO Sustainable Ecosystems, Wembley, WA.
Burel, F., Baudry, J., Butet, A., Clergeau, Ph., Delettre, Y., Le Coeur, D., Dubs, F., Morvan, N., Paillat, G., Petit, S., Thenail, C., Brunel, E., Lefeuvre, J.-C., 1998. Comparative biodiversity along a gradient of agricultural landscapes. Acta Oecologica 19, 47–60.
Butler, S.J., Boccaccio, L., Gregory, R.D., Vorisek, P., Norris, K., 2010. Quantifying the impact of land-use change to European farmland bird populations. Agric. Ecosyst. Environ. 137, 348–357. https://doi.org/10.1016/j.agee.2010.03.005.
Butler, S.J., Freckleton, R.P., Renwick, A.R., Norris, K., 2012. An objective, niche-based approach to indicator species selection. Methods Ecol. Evol. 3, 317–326. https://doi.org/10.1111/j.2041-210X.2011.00173.x.
Cadman, M.D., Sutherland, D.A., Beck, G.G., Lepage, D., Couturier, A.R., 2007. Atlas of the Breeding Birds of Ontario 2001-2005. Bird Studies Canada, Ontario Ministry of Natural Resources and Ontario Nature.
Clarke, K.R., Gorley, R.N., 2014. Primer v7: User manual/tutorial. Primer-E, Plymouth, United Kingdom.
Clavel, J., Julliard, R., Devictor, V., 2011. Worldwide decline of specialist species: Toward a global functional homogenization? Front. Ecol. Environ. 9, 222–228. https://doi.org/10.1890/080216.
De'Ath, G., Fabricius, K.E., 2000. Classification and regression trees: A powerful yet simple technique for ecological data analysis. Ecology 81, 3178–3192. https://doi.org/10.1890/0012-9658(2000)081[3178:CARTAP]2.0.CO;2.
de Jong, F.M.W., de Snoo, G.R., van de, J.C., 2008. Estimated nationwide effects of pesticide spray drift on terrestrial habitats in the Netherlands. J. Environ. Manage. 86, 721–730.
de Snoo, G.R., 1999. Unsprayed field margins: Effects on environment, biodiversity and agricultural practice. Landsc. Urban Plan. 46, 151–160.
Devictor, V., Jiguet, F., 2007. Community richness and stability in agricultural landscapes: The importance of surrounding habitats. Agric. Ecosyst. Environ. 120, 179–184. https://doi.org/10.1016/j.agee.2006.08.013.
Dieterich, M., Van der Straaten, J., 2004. Cultural Landscapes and Land Use: The Nature Conservation-Society Interface. Kluwer Academic Publisher, Dordrecht, The Netherlands.
Donald, P.F., Pisano, G., Rayment, M.D., Pain, D.J., 2002. The common agricultural policy: EU enlargement and the conservation of Europe's farmland birds. Agric. Ecosyst. Environ. 89, 167–182.
Donald, P.F., Green, R.E., Heath, M.F., 2001. Agricultural intensification and the collapse of Europe's farmland bird populations. Proc. R. Soc. B Biol. Sci. 268, 25–29. https://doi.org/10.1098/rspb.2000.1325.
Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecol. 77, 802–813. https://doi.org/10.1111/j.1365-2656.2008.01390.x.
EBCC, 2018. https://www.ebcc.info/european-wild-bird-indicators-and-trends-of-common-birds-in-europe-2018-update/ (accessed 30 January 2020).
Evans, J.S., Murphy, M.A., Holden, Z.A., Cushman, S.A., 2011. Modeling species distribution and change using Random Forest. In: Drew, C.A., Wiersma, Y.F., Huettmann, F. (Eds.), Predictive Species and Habitat Modeling in Landscape Ecology: Concepts and Applications. Springer Science and Business Media, pp. 1–313. https://doi.org/10.1007/978-1-4419-7390-0.
Flinn, K.M., Vellend, M., Marks, P.L., 2005. Environmental causes and consequences of forest clearance and agricultural abandonment in central New York, USA. J. Biogeogr. 32, 439–452. https://doi.org/10.1111/j.1365-2699.2004.01198.x.
Freemark, K., Boutin, C., 1995. Impacts of agricultural herbicide use on terrestrial wildlife in temperate landscapes: A review with special reference to North America. Agric. Ecosyst. Environ. 52, 67–91. https://doi.org/10.1016/0167-8809(94)00534-L.
Freemark, K.E., Kirk, D.A., 2001. Birds on organic and conventional farms in Ontario:Partitioning effects of habitat and practices on species composition and abundance. Biol. Conserv. 101, 337–350.
Furness, R.W., Greenwood, J.J.D., 1993. Birds as Monitors of Environmental Change. Chapman and Hall, New York.
Gamero, A., Brotons, L., Brunner, A., Foppen, R., Fornasari, L., Gregory, R.D., Herrando, S., Hořák, D., Jiguet, F., Kmecl, P., Lehikoinen, A., Lindström, Å., Paquet, J.Y., Reif,

J., Sirkiä, P.M., Škorpilová, J., van Strien, A., Szép, T., Telenský, T., Teufelbauer, N., Trautmann, S., van Turnhout, C.A.M., Vermouzek, Z., Vikstrøm, T., Voříšek, P., 2017. Tracking progress toward EU biodiversity strategy targets: EU policy effects in preserving its common farmland birds. Conserv. Lett. 10, 394–401. https://doi.org/10.1111/conl.12292.

Gaston, K.J., Fuller, R.A., 2007. Biodiversity and extinction: Losing the common and the widespread. Prog. Phys. Geogr. 31, 213–225. https://doi.org/10.1177/0309133307076488.

Gregory, R.D., Noble, D.G., Custance, J., 2004. The state of play of farmland birds: Population trends and conservation status of lowland farmland birds in the United Kingdom. Ibis (Lond. 1859). 146, 1–13. https://doi.org/10.1111/j.1474-919X.2004.00358.x.

Gregory, R.D., Skorpilova, J., Vorisek, P., Butler, S., 2019. An analysis of trends, uncertainty and species selection shows contrasting trends of widespread forest and farmland birds in Europe. Ecol. Ind. 103, 676–687. https://doi.org/10.1016/j.ecolind.2019.04.064.

Gregory, R.D., van Strien, A., 2010. Wild bird indicators: Using composite population trends of birds as measures of environmental health. Ornithol. Sci. 9, 3–22. https://doi.org/10.2326/osj.9.3.

Gregory, R.D., van Strien, A., Vorisek, P., Gmelig Meyling, A.W., Noble, D.G., Foppen, R.P.B., Gibbons, D.W., 2005. Developing indicators for European birds. Philos. Trans. R. Soc. B Biol. Sci. 360, 269–288. https://doi.org/10.1098/rstb.2004.1602.

Hutto, R.L., 1998. Using landbirds as an indicator species group. In: Marzluff, J.M., Sallabanks, R. (Eds.), Avian Conservation Research and Management. Island Press, Washington, D. C, pp. 75–92.

Hvenegaard, G.T., 2011. Validating bird diversity indicators on farmland in east-central Alberta. Canada. Ecol. Indic. 11, 741–744. https://doi.org/10.1016/j.ecolind.2010.06.018.

Inger, R., Gregory, R., Duffy, J.P., Stott, I., Voříšek, P., Gaston, K.J., 2015. Common European birds are declining rapidly while less abundant species' numbers are rising. Ecol. Lett. 18, 28–36. https://doi.org/10.1111/ele.12387.

Julliard, R., Clavel, J., Devictor, V., Jiguet, F., Couvet, D., 2006. Spatial segregation of specialists and generalists in bird communities. Ecol. Lett. 9, 1237–1244. https://doi.org/10.1111/j.1461-0248.2006.00977.x.

Karp, D.S., Moses, R., Gennet, S., Jones, M.S., Joseph, S., M'Gonigle, L.K., Ponisio, L.C., Snyder, W.E., Kremen, C., 2016. Agricultural practices for food safety threaten pest control services for fresh produce. J. Appl. Ecol. 53, 1402–1412. https://doi.org/10.1111/1365-2664.12707.

Kirk, D.A., Boutin, C., Freemark, K.E., 2001. A multivariate analysis of bird species composition and abundance between crop types and seasons in southern Ontario, Canada. Ecoscience 8, 173–184.

Kirk, D.A., Evenden, M.D., Mineau, P., 1996. Past and current attempts to evaluate the role of birds as predators of insect pests in temperate agriculture. Curr. Ornithol. 13, 175–269. https://doi.org/10.1007/978-1-4615-5881-1_5.

Kirk, D.A., Lindsay, K.E., Brook, R.W., 2011. Risk of agricultural practices and habitat change to farmland birds. Avian Conserv. Ecol. 6, 1–58. https://doi.org/10.5751/ACE-00446-060105.

Kreuzberg, E., 2011. Effects of Landscape Structure and Agricultural Practices on Farmland Birds in Ontario. M.Sc Thesis. Carleton University, Ottawa, Canada.

Lemoine, N., Bauer, H.-G., Peintinger, M., Bohning-Gauser, K., 2007. Effect of climate and land-use change on bird abundance in a central European bird community. Conserv. Biol. 21, 495–503.

Martin, J.-L., Drapeau, P., Fahrig, L., Freemark Lindsay, K., Kirk, D.A., Villard, M.-A., 2012. Birds in cultural landscapes: Actual and perceived differences between northeastern North America and western Europe. In: Fuller, R.J. (Ed.), Birds and Habitat. Cambridge University Press, Cambridge, U.K, pp. 481–515.

Morelli, F., Jerzak, L., Tryjanowski, P., 2014. Birds as useful indicators of high nature value (HNV) farmland in Central Italy. Ecol. Indic. 38, 236–242. https://doi.org/10.1016/j.ecolind.2013.11.016.

Murphy, M.T., 2003. Avian population trends within the evolving agricultural landscape of eastern and central United States. Auk 120, 20–34. https://doi.org/10.1642/0004-8038(2003) 120[0020:aptwte]2.0.co;2.

O'Connor, R.J., Shrubb, M., 1990. Farming and Birds, Second ed. Cambridge University Press, Cambridge, UK.

National Audubon Society, 2014. State of the Birds 2014 report. [WWW document] https://archive.stateofthebirds.org/state-of-the-birds-2014-report/ (accessed 6 February 2020).

Ontario Ministry of Natural Resources, 2007. Southern Ontario Land Resource Information System (2000-2002) Version 1.1: Including Accuracy Assessment Report. Geospatial Data. Peterborough, Ontario.

Padoa-Schioppa, E., Baietto, M., Massa, R., Bottoni, L., 2006. Bird communities as bioindicators: The focal species concept in agricultural landscapes. Ecol. Ind. 6, 83–93. https://doi.org/10.1016/j.ecolind.2005.08.006.

PECBMS, 2017. European Wild Bird Indicator, 2017 update [WWW Document]. URL https://www.ebcc.info/index.php?ID=632 (accessed 31 August 2018).

Peterjohn, B.G., 2003. Agricultural landscapes: Can they support healthy bird populations as well as farm products? Auk 120, 14. https://doi.org/10.1642/0004-8038(2003)120[0014:ALCTSH]2.0.CO;2.

Pywell, R.F., Heard, M.S., Bradbury, R.B., Hinsley, S., Nowakowski, M., Walker, K.J., Bullock, J.M., 2012. Wildlife-friendly farming benefits rare birds, bees and plants. Biol. Lett. 8, 772–775. https://doi.org/10.1098/rsbl.2012.0367.

Quinn, J.E., Awada, T., Trindade, F., Fulginiti, L., Perrin, R., 2017. Combining habitat loss and agricultural intensification improves our understanding of drivers of change in avian abundance in a North American cropland anthrome. Ecol. Evol. 7, 803–814. https://doi.org/10.1002/ece3.2670.

Quinn, J.E., Johnson, R.J., Brandle, J.R., 2014. Identifying opportunities for conservation embedded in cropland anthromes. Landsc. Ecol. 29, 1811–1819. https://doi.org/10.1007/s10980-014-0098-8.

Regos, A., Imbeau, L., Desrochers, M., Leduc, A., Robert, M., Jobin, B., Brotons, L., Drapeau, P., 2018. Hindcasting the impacts of land-use changes on bird communities with species distribution models of Bird Atlas data. Ecol. Appl. 28, 1867–1883. https://doi.org/10.1002/eap.1784.

Rodenhouse, N.L., Best, L.B., O'Connor, R.J., 1995. Effects of agricultural practices and farmland structures. In: Martin, T.E., Finch, D.M. (Eds.), Ecology and Management of Neotropical Migratory Birds: A Synthesis and Review of Critical Issues. Oxford University Press, New York, pp. 269–293.

Rosenberg, K.V., Dokter, A.M., Blancher, P.J., Sauer, J.R., Smith, A.C., Smith, P.A., Marra, P.P., 2019. Decline of the North American avifauna. Science 366 (6461), 120–124. https://doi.org/10.1126/science.aaw1313.

Sauberer, N., Zulka, K.P., Abensperg-Traun, M., Berg, H.M., Bieringer, G., Milasowszky, N., Moser, D., Plutzar, C., Pollheimer, M., Storch, C., Tröstl, R., Zechmeister, H., Grabherr, G., 2004. Surrogate taxa for biodiversity in agricultural landscapes of eastern Austria. Biol. Conserv. 117, 181–190. https://doi.org/10.1016/S0006-3207(03)00291-X.

Sauer, J.R., Niven, D.K., Hines, J.E., Ziolkowski, D.J., Jr., Pardieck, K.L., Fallon, J.E., and Link, W.A., 2017. [WWW document] The North American Breeding Bird Survey, Results and Analysis 1966–2015. Laurel, MD, USA. https://www.mbr-pwrc.usgs.gov/bbs/bbs2015.html (accessed 7 February 2017).

Shonfield, J., Bayne, E.M., 2017. Autonomous recording units in avian ecological research: current use and future applications. Avian Conserv. Ecol. 12. https://doi.org/10.5751/ace-00974-120114.

Smith, A., Hudson, M.-A.R., Aponte, V., Francis, C.M., 2019. North American Breeding Bird Survey - Canadian Trends Website, Data-version 2017. Environment and Climate Change Canada, Gatineau, Quebec, K1A 0H3. Environ. Clim. Chang. Canada. https://open.canada.ca/data/en/dataset/2cc215a2-f010-4083-bff2-ee9f028a6b69 (accessed 6 February 2020).

Stanton, R.L., Morrissey, C.A., Clark, R.G., 2018. Analysis of trends and agricultural drivers of farmland bird declines in North America: A review. Agric. Ecosyst. Environ. 254, 244–254. https://doi.org/10.1016/j.agee.2017.11.028.

Statistics Canada. 2011. Census of Agriculture 2006. [WWW Document]. URL https://www.statcan.gc.ca/ca-ra2006/index-eng.htm (accessed 5 July 2019).

Szymkowiak, J., Skierczyński, M., Kuczyński, L., 2014. Are buntings good indicators of agricultural intensity? Agric. Ecosyst. Environ. 188, 192–197. https://doi.org/10.1016/j.agee.2014.02.037.

Therneau, T., Atkinson, B., Ripley, B., 2019. Package ' rpart.' https://cran.r-project.org/web/packages/rpart/rpart.pdf.

Thingstad, G., 1997. Challenges to conservation of biological diversity in boreal forestry landscape; a case study using bird guilds as environmental indicators. Fauna Norv. Ser. C Cinclus 20, 49–68.

Thogmartin, W.E., Knutson, M.G., Sauer, J.R., 2006. Predicting regional abundance of rare grassland birds with a hierarchical spatial count model. Condor 108, 25–46.

Turner, A., 2012. The Barn Swallow, Third. ed. T. & A. D. Poyser, London, UK.

Whelan, C.J., Şekercioğlu, Ç.H., Wenny, D.G., 2016. Bird Ecosystem Services: Economic Ornithology for the 21st century. In: Şekercioğlu, Ç.H., Wenny, D.G., Whelan, C.J. (Eds.), Why Birds Matter: Avian Ecological Function and Ecosystem Services. University of Chicago Press, Chicago, pp. 1–26.

Further reading

Scholefield, P., Firbank, L., Butler, S., Norris, K., Jones, L.M., Petit, S., 2011. Modelling the European Farmland Bird Indicator in response to forecast land-use change in Europe. Ecol. Ind. 11, 46–51. https://doi.org/10.1016/j.ecolind.2009.09.008.