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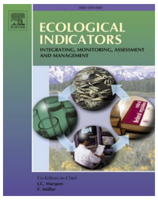

Review

Landscape metrics as indicators of avian community structures – A state of the art review

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ABSTRACT

In this state-of-the-art review, we investigate the use of landscape metrics in landscape ecology studies to predict structure of avian communities. We reviewed papers published in international peer-reviewed journals indexed by Web of Science Core, from January 2010 to December 2021. We give an overview of the study methods used in the past twelve years, the type of landscapes investigated, and the most important landscape metrics that show a significant influence on the ecological parameters of bird community distribution. We demonstrate that study designs are highly variable and thus only comparable to a limited extent. We identify multiple factors of spatial data usage that are important in determining the characterisation of landscape pattern and affect the outcome of analysis in landscape ecology that need to be standardised to allow simplification and generalization of results. Few empirical studies exist which describe the indicator value of landscape metrics comprehensively, taking into account different spatial scales, thematic resolution, landscapes and species, and the need for conducting such surveys in order to be able to use landscape metrics as a biodiversity monitoring tool in a targeted way.

1. Introduction

1.1. *Use of landscape metrics - current state of knowledge*

Most landscape metrics are generated from remote sensing (RS) data or data derived from RS data and are used to describe spatial arrangements of landscape types represented by cover classes (Sinha et al., 2016). These metrics are used in ecological research to describe landscape structure numerically, which takes not only the composition and percentage of area but also the spatial arrangement of landscape elements into account (Zanella et al., 2012; Fahrig 2003).

Birds are good indicators of habitat quality. Many studies show that birds respond more to habitat composition, represented by land-cover classes, than to configuration, represented by the spatial arrangement of landscape features (Uuemaa et al., 2009; Lustig et al., 2015). Most studies also illustrate that the spatial configuration of landscape structure elements can play an important role in the habitat suitability of a landscape (Barbaro et al., 2007). Being able to describe the landscape numerically enables researchers to examine different landscapes for specific configurational properties, to determine important differences, and to draw conclusions about ecological functions, such as biodiversity or animal population abundance (Saura and Martinez-Millan 2001), resulting from these arrangements (Turner 1990). As a tool for nature conservation, these statistically calculable factors are especially useful in determining current problems and possible future effects of various influencing factors on ecosystem and landscape functions and services. Ultimately, the derivation of necessary changes in the landscape to achieve sustainable landscape change is an important application of landscape metrics that should be of particular interest to practitioners (Zanella et al., 2012).

1.2. *Selection of landscape metrics*

Over the past 20 years, various landscape metrics have been developed to describe and compare not only the composition or proportion of different landscape components, but also their configuration, connection, and diversity (Fahrig 2003; Read and Lam, 2002). Hundreds of metrics at a patch-, class- and landscape-level are easily calculated (McGarigal and Marks 1995) in a variety of tools to quantify landscapes, such as "FRAGSTATS" (McGarigal and Marks 1995) and Patch Analyst (Fardila et al., 2017; Rempel 1999). Despite the ease of generating metrics due to the easy availability of geospatial data, this plethora of options also makes it difficult to select the "right" metrics for the problem at hand (Cushman et al., 2008). The high number of correlated

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metrics and the very different recommendations of metrics that are particularly suitable for a variety of research aims contribute to this problem in many ways (Cushman et al., 2008). In order to avoid the use of many redundant metrics, which is especially problematic for small samples, a preselection of landscape metrics is often necessary (Dormann et al., 2013). Different methods are also available for selecting the right metrics (depending on the question). Schindler et al. (2015) examined the performance of six of these selection methods. These include methods that are regularly used in the selection of landscape metrics, like expert decision, decision trees, PCA (principal components analysis), PC regressions, but also a method that requires both high computing power and an extensive mathematical and statistical knowledge: to calculate all possible combinations of sets. None of the commonly used methods performed significantly better than a random set of metrics (Schindler et al., 2015). Many metrics are fundamentally suitable for analysing the structure and patterns of the landscape (Uuemaa et al., 2011). Over the past 25 years, quite a few studies have been concerned with finding a fundamentally suitable set of metrics and have repeatedly defined different sets as particularly suitable (e.g., (Schindler et al., 2015; Lustig et al., 2015; McGarigal and McComb 1995; Griffith et al., 2000; Lausch and Herzog 2002; Cushman et al., 2008; Schindler et al., 2008). Schindler et al. (2015) concluded that the best method (to calculate all possible combinations of sets) to find the optimal set of landscape metrics is not a feasible option for applied studies.

1.3. *Spatial scale (resolution and extent) of remote sensing data*

Landscape metrics are fundamentally dependent on the remote sensing data from which they are generated. Their behaviour and informative value are affected by grain, extent, and resolution of the land cover data used (Schindler et al., 2015; Schindler et al., 2013). In most studies, remotely sensed data are used at one spatial scale - comprising two components: resolution and extent (Bar-Massada et al., 2012). Resolution, in this context, is defined as "*the typical order of magnitude at which the technique is able to resolve differences between objects*" (Kool et al., 2013, p. 36). Scientists often use the resolution that is available in the selected geodata. However, considering the effects spatial resolution can have on the species-habitat relationship, it is obvious that this limits the effectiveness of the results obtained (Wu 2004; Bar-Massada et al., 2012). When studying different species or species groups, the extent of the study area also plays a significant role (Bar-Massada et al., 2012). The spatial extent can be defined as "*the total area of the map being considered*" (Saura and Martinez-Millan 2001, p. 1027). There are quite a lot of studies that have already investigated the impact of different extents on the occurrence, abundance, and diversity of bird species and groups (Sinha et al., 2016; Cushman et al., 2008; Bar-Massada et al., 2012). Depending on the question, different extents may be relevant to investigate the relationship between species and their environment (Fahrig et al., 2011). If these relationships at different scales have not already been investigated, or if the relationships to be investigated occur at different levels, it is necessary to use different extents to calculate metrics (Fahrig et al., 2011). Culbert et al. (2012), with their research on the theory stated by Hutto (1985), confirm that small and medium extents are particularly relevant for investigating the effect of habitat structure on species richness, while large extents are more important for the relationship between habitat type and species richness (Culbert et al., 2012; Hutto 1985).

1.4. *Cover classes*

The most common method to classify landscapes in landscape ecology is to divide the landscape into patches of habitats surrounded by species-specific non-habitat (Lechner et al., 2012) to represent functional landscape heterogeneity for the species investigated (Fahrig et al., 2011). However, many studies use more classifications by categorising landscape types into more than two cover classes (Culbert et al., 2012; Pedersen and Krøgli 2017). However, several studies show that a more detailed classification does not necessarily lead to better results. Bailey et al. (2007) found that a classification of 14 cover classes produced statistical models with stronger relationships to farmland biodiversity than statistical models based on a classification of 47 cover types. Coinciding with these results, a Norwegian study found that a less detailed maps (6–7 cover classes) best explained abundance patterns of farmland birds (Pedersen and Krøgli 2017). On the other hand, Pedersen and Krøgli (2017) showed that a detailed cover type map (102 types) explained more of the variation in the farmland bird species richness data collected then a less detailed classification.

1.5. *Resulting research questions*

In this context, it seems to be a largely unresolved question of which - preferably fewer, but more meaningful - landscape metrics can be used to assess the importance of landscape metrics for bird communities. As stated by Uuemaa et al. (2009), most studies published show that compositional factors of the landscape play a stronger role for bird species than the configuration. Even though numerous studies describe relationships between landscape structure and ecological processes, variables of structure usually have far less explanatory value than variables of composition (Bailey et al., 2007; Uuemaa et al., 2013). Moreover, the results of some studies even contradict each other and thus are hardly generalizable (Lausch et al., 2015) and hardly usable for practice.

In this review, we analyse studies investigating the effects of different landscape types (e.g., forest, agriculture, grassland, water, urban) and structure (landscape metrics) on bird communities (abundance, richness, diversity). We give an overview of the study methods used in the past ten years, to answer the following questions:

1. Is there a "correct" spatial scale/study design for investigating the influence of configuration metrics on bird species richness and their habitat preferences?
2. How does composition and configuration influence the occurrence of certain bird species/groups? Can specific landscape metrics be derived from previous research that are particularly relevant for bird communities?
3. Are landscape metrics fundamentally suitable to use in practical landscape planning or nature conservation?

2. Materials and methods

We reviewed papers published in international peer-reviewed journals indexed by Web of Science Core Collection (last accessed on 22 December 2021), from January 2010 to December 2021. The review focuses on articles investigating the effects of different landscapes (e.g., forest, agriculture, grassland, water, urban) on bird data (abundance, richness, diversity). We conducted a keyword literature review and used the search terms from Uuemaa et al. (2013) "landscape metrics", "landscape indexes", and "landscape indices" (linked by "or") to include all commonly used names for landscape-metrics-type-analysis in combination with the term "birds" "((“LANDSCAPE METRICS” OR “LANDSCAPE INDEXES” OR “LANDSCAPE INDICES”) AND (“BIRDS”))".[1] This review was limited to research on birds and included English language-based, international peer-reviewed articles. Our focus was mainly on landscape metrics introduced by McGarigal et al. (2002) and FRAGSTATS, as well as similar landscape metrics related programs. The search provided 112 results. We evaluated each search result for relevance (Fig. 1). This review is not necessarily exhaustive but should be

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[1] Web of Science Core Collection (last accessed on 22 December 2021): https://www.webofscience.com/wos/woscc/summary/e3aa00bc-a358-4c7c-91ac-4931b1215d38-157b98a7/relevance/1.

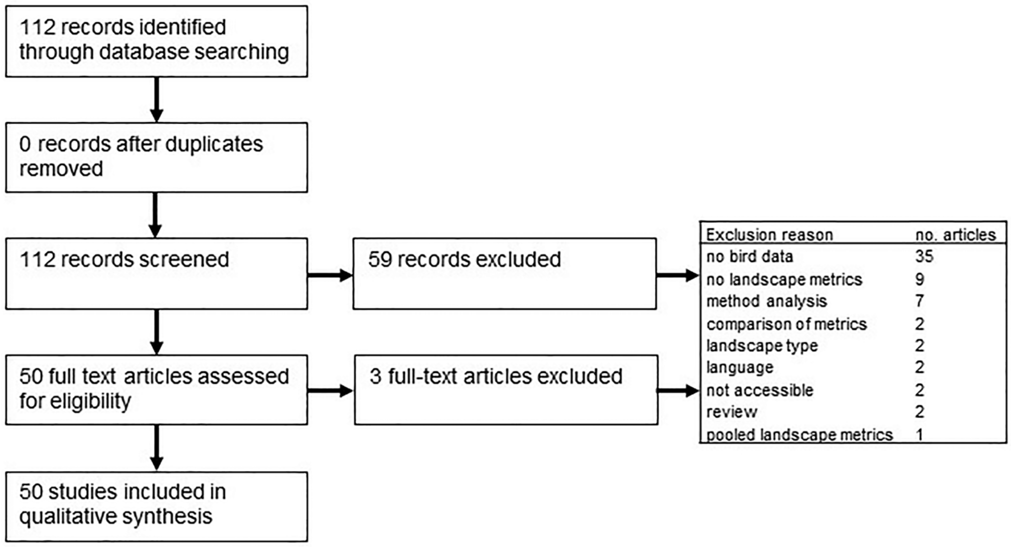

Fig. 1. Flow of information through the different phases of this systematic review. Adapted from (Moher et al., 2009).

sufficient to summarize recent literature on the use of and results for landscape metrics as an indicator for bird habitat quality.

3. Results

3.1. Reviewed literature

After abstract review and exclusion of non-relevant articles out of the 112 identified articles on landscape metrics influence on bird distribution data, we identified 50 articles relevant for our research aim. Since 2010, an average of four articles per year were published (Fig. 2) in international peer-reviewed journals. Uuemaa et al. (2013) described three articles per year from 2000 to 2010 for the category biodiversity and habitat analysis effecting birds. The quantity of publications seems to be relatively constant over the past 12 years. The leading countries in using landscape metrics to investigate bird data are countries in Europe (n = 18) and North American (n = 10) followed by South American (n = 8) and Asian (n = 5) countries. The articles covered a broad range of landscapes, types and spatial scales.

3.2. Spatial scale

Most of the studies were performed using remote sensing data, some analysed the changes in landscapes during the past years. Only one (Coulon et al., 2010) of 50 reviewed studies used vector based data not derived from RS data. The results of the spatial analysis depend highly on the classification and the pixel size. Nevertheless, in almost half of the articles (45%) the resolution was not indicated. The land use/cover categories selected varied severely between 2 and 34 classes with an even greater variety of classes in different detailing investigated. 24% of studies used a binary system of habitat/non-habitat to classify the landscape, 58% <10 types of classification and 18% choose to differentiate between>10 cover classes (Table 1). As previously stated by Bar-Massada et al. (2012) we detected that almost half (48%) of all articles measured at a single spatial scale to investigate the effect of landscape metrics on bird community structures. A third (32%) of the studies

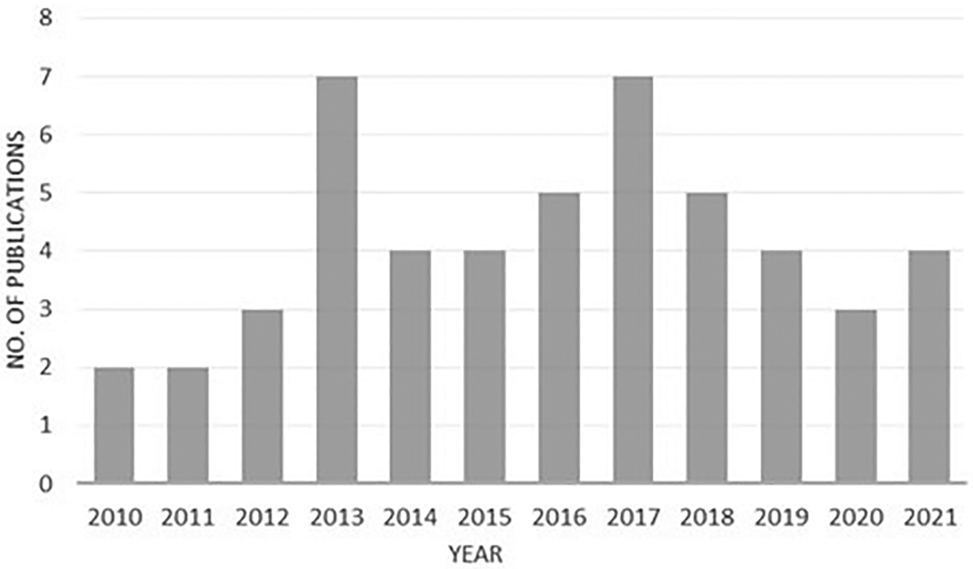

Fig. 2. No. of publications on biodiversity and habitat analysis with landscape metrics effecting birds in international peer-reviewed scientific papers by year.

Table 1
Summary of spatial data use (sum exceeds 50; use of multiple resolutions).

Review category	total	percentage
No. of landcover categories (n = 50)		
Binary	12	24
Multi-class < 10	29	58
Multi-class > 10	9	18
Extents investigated (n = 50)		
1	24	48
<10	16	32
>10	8	16
N/A	2	4
Resolution Spatial data (n = 51)		
<10 m	9	18
10 m	6	12
>10 m/<30 m	4	8
30 m	7	14
>30 m	2	4
N/A	23	45

examined <10 extents and 16% used >10 different extents to test for effects (see Table 1). Almost half of the studies did not state the resolution of the geodata used. The most commonly used resolution sizes were < 10 m (18%), 30 m (14%) and 10 m (12%) (see Table 1). This variation in categorisation and spatial scale of landscape data makes the comparison of the results and the interpretation of these results difficult.

The selection process for landscape metrics used were not described in 42% of the studies and is therefore not applicable (N/A) for this evaluation. The most commonly used methods for selecting subsets of indicator variables are a selection from previous studies (30%), the author's expert selection (16%) and statistical analysis (12%) (Pearson's correlation, decision tree, generalised additive model).

3.3. Bird data

Most studies evaluated matrix effects on community (72%) or population (28%) characteristics. Effects on communities included community-structure (richness, diversity, composition and detectability) and population-structure (genetic diversity, population de-/increase, post-fledging movements and survival) variables. The most common dependent variables were species richness (35%), presence/absence (33%) followed by abundance (22%) and diversity (10%) of birds. Some studies used more than one dependent variable. Bird categories investigated were quite heterogeneous. Most articles used different habitat guilds (n = 15) to categorise birds or investigated the influence of landscape metrics on a single species (n = 14). No effect on one single species was represented more than once in all 50 studies reviewed.

3.4. Landscape metrics used

3.4.1. Overall use

In the evaluated articles 44 different types of landscape metrics introduced by McGarigal et al. (2002) and 19 either pooled or completely newly developed metrics were used. Area metrics were applied most commonly (56%). We separated PLAND (percentage of landscape comprised of a particular patch type) as a variable from other AREA metrics to distinguish between compositional and configurational metrics (Table 2). PLAND was a selected variable in 52% of all studies and showed a significant relationship with bird community structure in 85% of cases. Metrics groups including SUBDIVISION, DIVERSITY, SHAPE and ISOLATION metrics (for Acronym definition see Table 3) were used in less than half of the literature (48, 42, 40, 36%, respectively). EDGE metrics were considered in only 32% of study designs but had a significant influence on bird data in 64% of studies.

Overall certain metrics such as AREA, PLAND, SHAPE, ED, PD, SHDI, ENN, PROX, NP and LSI are commonly selected in studies investigating landscape metrics used to predict or accommodate avian communities (see Table 3).

Table 2
Landscape metrics groups (previously defined by McGarigal 2017) used in reviewed literature with influence on bird variables and without, sorted by decreasing influence on bird variables (for Acronym definition, see Table 3).

Landscape metrics group	used (n)	influence on bird variables (n)	no influence on bird variables (n)	influence on bird variables (%)
PLAND	26	22	4	85
EDGE	22	14	8	64
AREA	39	22	17	56
SHAPE	47	26	21	55
SUBDIVISION	32	16	16	50
DIVERSITY	32	16	16	50
AGGREGATION	41	19	22	46
ISOLATION	29	11	18	38
CORE AREA	6	2	4	33
CONTRAST	9	3	6	33

3.4.2. Forest and agricultural landscapes

The most commonly studied landscape types are agricultural and forest areas with one third (n = 17) conducted studies in each landscape type. Another third of the reviewed studies investigated landscape structure influence on bird communities in wetland (n = 7), mixed landscapes (n = 5), grassland (n = 3), urban areas (n = 1), and shrubland (n = 1). Seventy-one per cent of the 17 studies in forest areas took place in America (North 24% & South America 47%). In Southern American countries, landscape metrics are often used in forest studies, as deforestation is a major issue (Uuemaa et al., 2013). Agricultural areas are predominantly studied in the Europe (65%). Tables 3 and 4 show the evaluated papers separately for forest and agricultural landscapes with regard to location, extend, windows, bird data measurements, guilds, and the significance of the analysed landscape metrics.

In both landscape types (forest and agricultural), PLAND has frequently a significant influence on the bird community. In forest areas, the use of this variable led to a significant result in 71% of cases, and in the agricultural context in 91% of cases (Fig. 3). To create a simplified overview of landscape metrics used and the explanatory value for bird communities we grouped landscape metrics by the aspect of landscape pattern as previously described by McGarigal (2017). Commonly selected in forest areas are landscape metrics in the group of AREA, SHAPE and ISOLATION and based on the results of this study generate in up to 50, 45 and 44% (respectively) of cases a significant influence on bird communities. In agricultural areas explanatory values of EDGE, SHAPE, DIVERSITY (90, 89, 71%, respectively) metrics groups have generated significant effects (see Table 4 and Table 5 for more detailed results).

4. Discussion

In 1988, Magurran described species diversity indices as follows: "A quick dip into the literature on diversity reveals a bewildering range of indices. Each of these indices seeks to characterize the diversity of a sample or community by a single number. To add yet more confusion an index may be known by more than one name and written in a variety of notations using a range of log bases. The diversity of diversity indices has arisen because, for a number of years, it was standard practice for an author to review existing indices, denounce them as useless, and promptly invent a new index" (Magurran 1988, p. 7). This description could hardly be more apt for the current state and development of landscape metrics. From 2010 to 2021, an annual average of four international peer-reviewed journals were published on the topic of effects of different landscape types and structures (landscape metrics) on bird

Table 3

Landscape metrics used in reviewed articles (n = 50) with significant influence on bird data. (nl: non-linear, us: unspecified influence). Distribution statistics (mean, area-weighted mean, median, range, standard deviation, coefficient of variation) are pooled. For complete descriptions of landscape metrics, see McGarigal and Marks (1995).

Landscape metric Acronym	Landscape metric (LM) name	LM group	Metrics used (total)	positive influence (total)	negative influence (total)	no influence (total)	nl/us influence (total)
AREA	Patch area	AREA	35	16	7	12	2
PLAND	percentage of landscape	PLAND	30	17	9	4	4
SHAPE	Shape index	SHAPE	18	6	5	7	1
ED	edge density	EDGE	16	6	5	5	2
PD	patch density	SUBDIVISION	15	5	5	5	1
SHDI	Shannon’s diversity index	DIVERSITY	12	6	2	4	3
ENN	Euclidean nearest neighbour distance	ISOLATION	10	2	2	6	1
PROX	Proximity index	ISOLATION	9	5	1	3	0
LSI	Landscape shape index	AGGREGATION	8	3	2	3	0
NP	Number of patches	SUBDIVISION	8	3	1	4	2
FRAC	Fractal dimension index	SHAPE	7	2	2	3	0
LPI	Largest patch index	AREA	6	1	3	2	0
PARA	Perimeter-area ratio	SHAPE	6	2	2	2	0
CONTIG	Contiguity index	SHAPE	5	2	2	1	0
IJI	Interspersion and juxtaposition index	AGGREGATION	5	1	0	4	0
PLADJ	Percentage of like adjacencies	AGGREGATION	5	1	1	3	0
AI	Aggregation index	AGGREGATION	5	3	1	1	0
COHESION	Patch cohesion index	AGGREGATION	5	1	1	3	0
PAFRAC	Perimeter-area fractal dimension	SHAPE	4	1	0	3	0
CONTAG	Contagion index	AGGREGATION	4	1	0	3	0
DIVISION	Landscape division index	SUBDIVISION	4	1	0	3	0
PR	Patch richness	DIVERSITY	4	1	0	3	0
SIDI	Simpson’s diversity index	DIVERSITY	4	2	1	1	0
TE	Total edge	EDGE	3	1	1	1	0
CORE	Patch core area	CORE	3	2	0	1	0
ECON	Edge contrast index	CONTRAST	3	1	1	1	0
SPLIT	Splitting index	SUBDIVISION	3	0	0	3	0
CONNECT	Connectance index	ISOLATION	3	2	0	1	0
GYRATE	Patch radius of gyration	AREA	2	0	0	2	1
CA	Class area	AREA	2	1	0	1	0
CAI	Core area index	CORE	2	0	0	2	0
CWED	Contrast-weighted edge density	CONTRAST	2	0	0	2	0
TECI	total edge contrast index	CONTRAST	2	0	1	1	0
CLUMPY	Clumpiness index	AGGREGATION	2	0	1	1	0
SIMI	Similarity index	ISOLATION	2	0	0	2	0
PRD	Patch richness density	DIVERSITY	2	0	0	2	0
ltd/LCD	Land type diversity	DIVERSITY	2	1	0	1	0
MESH	Effective mesh size	SUBDIVISION	1	0	0	1	0
RPR	Relative patch richness	DIVERSITY	1	0	0	1	0
SHEI	Shannon’s evenness index	DIVERSITY	1	0	0	1	0
SIEI	Simpson’s evenness index	DIVERSITY	1	0	0	1	0
MSIEI	Modified Simpson’s Evenness Index	DIVERSITY	1	0	0	1	0
MSIDI	Modified Simpson’s Diversity Index	DIVERSITY	1	0	0	1	0
HIX	Heterogeneity index	DIVERSITY	1	1	0	0	0
OTHER			16	9	4	3	7

communities. Landscape metrics are used for many fields of application (e.g., evaluating of land use / cover changes, landscape functions, regulation functions, ecosystem services, etc.); in the ecology research field they are commonly used for the investigation of structural influences on animal communities (Uuemaa et al., 2013). However, there is hardly any comprehensive research giving an appropriate combination of metrics that are particularly relevant for certain fields of study, a standardised procedure for selecting them (Sinha et al., 2016), or a standardised use of the geodata from which they are derived (Lechner et al., 2012).

1. Is there a “correct” spatial scale/study design for investigating the influence of configuration metrics on bird species richness and their habitat preferences?

All reviewed studies used a single resolution in their research design, except one that specifically addressed scale issues by conducting a multi-scale study (Bar-Massada et al., 2012). Almost half of the studies did not state the resolution of the geodata used. The most commonly used resolution sizes were < 10 m, 30 m, and 10 m. Similar to the findings of Lechner et al. (2012), this use of similar resolution sizes suggest that researchers did not actively choose a resolution but were driven by the availability of data. The study investigating the effect of different resolutions on the relationships between landscape metrics and field-based bird biodiversity measures (Bailey et al., 2007; Bar-Massada et al., 2012; Duro et al., 2014) found a significant impact of changing the resolution, and stated that the effect of scale has received insufficient research attention. In a comparison between a finer and a coarser resolution, the results suggest that a finer resolution (10 m) should be used

Table 4

Forest: Articles with significant relationships between bird-community measurements and landscape metrics in forest dominated landscapes.

Author(s)	Location	Extent min. – max. (km^{2})	Window	Bird data measurements					bird guilds	Significant landscape metrics
				abundance	richness	diversity	presence/ absence	other		(+positive, - negative, ^{2} quadratic, ^{nl} nonlinear, ~unimodal)
Aurélio-Silva et al. (2016)	Amazonas, South America	314 – 125.664	N/A		●				all species	(+AREA)forest
Banks-Leite et al. (2013)	Sao Paulo, Brazil South America	2.827 – 53.093	circular buffer	●	●				understorey birds	(+AREA)forest, (-SHAPE) forest, (+DISTANCE TO EDGE)forest
Bar-Massada et al. (2012)	Wisconsin, North America	0,00021 – 0,00051	square cells		●				all species	(^{2}PLAND)woodyhabitat, (^{nl}EDGE)woodyhabitat, (^{nl}PD)woodyhabitat, (^{2}S0MCSPAs)woodyhabitat, (^{nl}S1MCSPAs)woodyhabitat
Becker et al. (2012)	West Virginia, North America	34; 2.827	circular buffer, Forest area				●		single species	(+PLAND)mature mixed forest, (-PLAND)heavy partial harvests, (+PLAND)light partial harvest, (+SHDI)all
Benchimol & Peres (2015)	Brazil, South America	0,0055 – 31,416	circular buffer + cut off patches				●		terrestrial bird species	(+AREA)forest, (+PROX) forest
Blank (2013)	Maryland, Delaware, US	7.854	circular buffer				●		single species	(+PLAND)crop
Cunningham and Johnson (2011)	North Dakota; New York, North America	314 – 125.664	circular buffer				●		woodland species	(+PLAND)tree cover
Kati et al. (2010)	Greece, Europe	0,05 – 0,2	square cells		●				terrestrial bird species	(+SHAPE)all, (+ECON)all, (+SIDI)all
Martínez-Ruiz et al. (2020)	Mexico, South America	11 – 33	circular buffer	●	●	●			raptors	(+/-PLAND)forest, (+/-PD) all, (+/-MATRIX HARDNESS) all
Michalski & Peres (2017)	Brazil, South America	0,47 – 13,551	Forest area		●			●	large body gamebirds	(+AREA)forest, (+PLAND) closed-canopy, (+PLAND) semi-open forest
Moulatlet et al. (2021)	Ecuador, South America	1	square cells				●		understorey birds	(+AREA)forest, (-AREA) forest, (+SHAPE)forest, (+SHAPE)all, (+/-PLADJ) forest, (+/-LSI)forest, (+/-fragindex)forest
Pagaldai et al. (2021)	Spain, Europe	1; 25	square cells	●				●	single species	(-PLAND)urban, (^{2}PLAND) forest, (-PLAND)forest^{2}, (-SHAPE)urban, (-CLUMPY) urban, (+NP)urban, (-ENN) urban
Ritter et al. (2021)	Brazil, South America	785.398	circular buffer					●	neotropical bird species	(+PROX)sampling patch
Santamaria-Rivero et al. (2016)	Yucatan Mexico, South America	1	square cells	●	●				feeding guilds	(-ED), (-SHAPE)forest, (+PROX)forest
Schindler et al. (2013)	Greece, Europe	0,2; 0,5; 1, 2; 5	circular buffer		●				small terrestrial birds	(+AREA)all, (+PARA)all, (+FRAC)all, (-FRAC)all, (+SHAPE)all, (+ENN)all
Song & Kim (2016)	South Korea, Asia	0.000356 – 42	forest patches				●		single species	(+AREA)forest, (-SHAPE) forest, (+CONNECT), (+PROX), (+TREE RATE), (+PATCH BETWEENNESS)
Touihri et al. (2017)	north-western Tunisia, Africa	5.027; 31.416	circular buffer				●		woodpecker species	(+AREA)forest (+AREA)high scrub, (-AREA)low scrub, (+PROX)forest

for the relationship between habitat heterogeneity and species occurrence. Data calculated with a coarser resolution (30 m) produces good predictors for gradual observation factors resulting from habitat selected by the presence of habitat type under investigation (Bar-Massada et al., 2012). One problem of too coarse a resolution can be the differentiation of small-scale and linear landscape elements (Lausch and Menz 1999). Linear elements such as roads, railways and streams are important factors for habitat fragmentation and can be difficult if not impossible to differentiation from surrounding structures if the resolution of the RS data is too coarse (Lausch and Menz 1999; Wickham and Rhtters 1995). More research is required to address spatial resolutions influence of the characterisation of landscape structure metrics. The complexity of processing and classifying geodata imagery and a lack of standardisation makes the interpretation and comparability of these results difficult (Lechner et al., 2012; Sinha et al., 2016).

We detected that almost half of all articles used a single extent to investigate the effect of landscape metrics on bird community structures. Given that bird species in particular are likely to interact at multiple spatial scales in their habitat (Lawler and Edwards 2006), and landscape metrics are highly influenced by spatial scale (Marja et al., 2013), addressing diverse factors is necessary. Accordingly, it is important to determine the best extents for the environmental data considered to improve the prediction of bird community structures (Morelli et al., 2013).

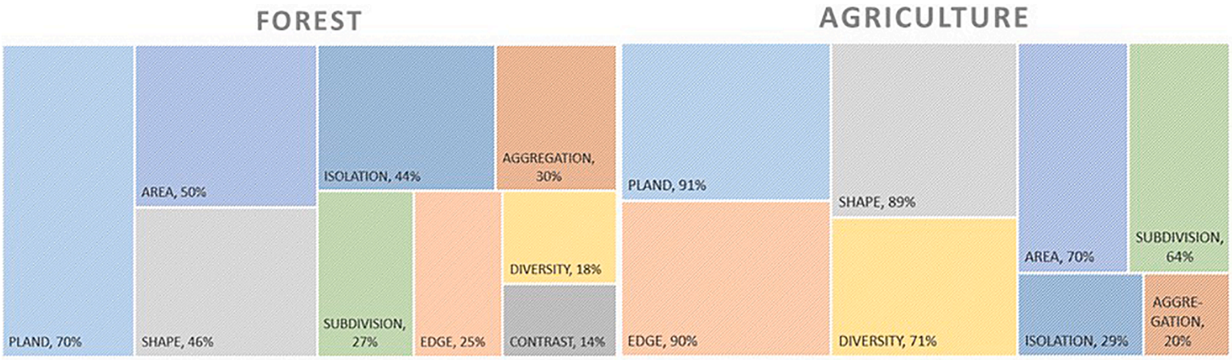

Fig. 3. Percentual Influence (pooled positive and negative) of different landscape metric groups on bird data in landscapes dominated by forest (left) and agriculture (right). Percentages describe the significant influence of the variable depending on the frequency of use.

Different studies come to different conclusions on which spatial extent is the most suitable to address particular research questions. Marja et al. (2013) state that a larger study area yields the best results in explaining the variance between landscape metrics (patch density, edge density, and Shannon's diversity index) and bird species richness. Although Marja et al. (2013) states that under 50 m is not precise enough, other studies say that small extents (Fuller et al., 1994: radius 125 m; Morelli et al., 2013: 125–250 m) improve the predictive power of landscape metrics for modelling bird species richness (Schindler et al., 2013; Morelli et al., 2013; Fuller et al., 1994). Banks-Leite et al. (2013) state that there is no "right" scale to use landscape metrics as predictors of species richness and species' abundances and call for a new indicator, independent of scale.

The land use/cover classes selected varied greatly between 2 and 34 classes, with an even greater variety of classes in different detailing investigated. This shows that spatial scale is an important consideration in species analyses (Miller et al., 2019). Thematic resolution (land cover classes) is another factor worth considering when correlating landscape metrics with biodiversity data. One study investigating the relation between landscape metrics and biodiversity, whilst checking for the role of thematic resolution, concludes that different class levels should be considered for different metrics (Bailey et al., 2007). In a previous survey, Bailey et al. (2006) found that some metrics (e.g., grain and dominance) better describe landscapes which were classified into fewer land cover classes. Landscapes classified into many land cover classes are better represented by using shape, configuration, and diversity metrics. These findings are supported by a study in Norway, investigating the effect of different land type diversities on farmland birds (Pedersen and Krøgli 2017). Their results implicate that a more detailed classification of landscape types explained more of the variation in bird species richness but a less detailed classification was more suitable for the prediction of bird abundance (Pedersen and Krøgli 2017).

A general problem in the classification of landscape types is possible classification error (Lechner et al., 2012). Very few studies describe or consider this source of error (Lechner et al., 2012). In view of the results described by Langford et al. (2006), that classification error can have a significant effect on the error rate of the calculated landscape metrics, the use of continuous information instead of discrete land cover classifications can be considered. The use of continuous information could be preferable to the use of discrete land cover classifications because the latter can cause an inherent level of error and generalisation (Duro et al., 2014). It is important to consider the above-stated issues carefully in advance of selecting spatial scale / study design for investigating the influence of configuration metrics on bird species richness and their habitat preferences. This overview corroborates the recognized notion that there is no single scale for characterizing spatial heterogeneity to determine species community structures. The comparison between studies and landscapes using landscape metrics should be based on the same spatial scale (Wu 2004) which, by the diversity of study designs (reviewed in this article), is quite difficult to achieve.

2. How does composition and configuration influence the occurrence of certain bird species/groups? Can specific landscape metrics be derived from previous research that are particularly relevant for bird communities?

The most common methods of metrics selection are based on a selection from previous studies, the author's expert selection and a statistical analysis. None of these commonly used methods performs significantly better than a randomly selected set of metrics (Schindler et al., 2013). For bird species richness, the expert selection of metrics even performed significantly worse than a randomly chosen set of metrics (Schindler et al., 2015). Quite a few studies have defined different sets as particularly suitable (e.g., (Schindler et al., 2015; Lustig et al., 2015; McGarigal and McComb 1995; Griffith et al., 2000; Lausch and Herzog 2002; Cushman et al., 2008; Schindler et al., 2008)). More and more authors acknowledge that metric selection should be based on the specific research question at hand and should fit the landscape context of the targeted taxon and the ecological process under investigation (Bailey et al., 2007; Cushman et al., 2008; Fahrig 2003; Walz 2011; Schindler et al., 2013). Despite the ease of generating metrics in the absence of prior knowledge of multiple factors of the studied landscapes, the selection of metrics to test is quite challenging for scientists and near impossible for practitioners (Walz 2011).

As described by Uuemaa et al. (2013), it can be shown here that bird species react strongly to the composition of the landscape (here in the form of the PLAND index), both in the overall consideration of all studies ($n = 50$) and in the consideration of the two landscape types of forest and agriculture. In forest areas, metric categories AREA, SHAPE, and ISOLATION provide metrics with frequently higher explanatory values. From the literature reviewed here, the following landscape metrics produced significant correlation results in forest-dominated landscapes: PLAND (significant result in 22% of studies $n = 17$), AREA (17%), SHAPE (14%), PROX (9%). In agricultural areas, metric categories EDGE, SHAPE, and DIVERSITY provide metrics with frequently higher explanatory values. Similar to Fauth et al. (2000) in a study on neotropical migrant birds in forest landscapes, our results show a correlation between bird community and fragment size (AREA) in forest habitats. AREA explained the variation of birds in 17% of studies. Large forest fragments provide habitat for more stenotic species that are absent in small fragments or marginal areas (Fauth et al., 2000). The following landscape metrics produced significant correlation results in agricultural-dominated landscapes: AREA (29%), SHDI (7%), ED (6%). Bird species are very different in their habitat requirements and respond very differently to landscape heterogeneity (Maskell et al., 2019). Other studies have come to similar conclusions: for example, heterogeneity

Table 5
Agriculture: Articles with significant relationships between bird-community measurements and landscape metrics in agricultural dominated landscapes.

Author(s)	Location	Extent min. – max. (km^2)	Window	Bird data measurements					bird guilds/ groups	Significant landscape metrics
				abundance	richness	diversity	presence/ absence	other		(+positive, - negative, ^{2} quadratic, ^{nl} nonlinear, ~unimodal)
Bonthoux et al. (2017)	France, Europe	N/A	regions		●		●		diet- &, migration strategy	(+PLAND)woodland, (-PLAND) hedges, (+SHDI)all
(Borges et al., 2017)	Germany, Europe	1.963	circular buffer	●				●	breeding birds	(+/-ED)all, (-LPI)all, (-CONTIG)all, (+/-SHAPE)all, (-PD)all, (+/-SIDI) all
(Csikós and Szilassi, 2021)	Hungary, Europe	11.310	circular buffer	●					single species	(+AREA)arable land, open sand steppes, closed grassland patches, (-AREA)built-up land, green urban areas, complex cultivation pat., forests, wetlands, water surfaces, (+FRAC)all, (-SHDI)all
(Decaëns et al., 2018)	Uttarakhand, India	50	square cell		●				all species	(+PLAND)forest(undisturbed), (-PLAND)agricultural land
Duro et al. (2014)	Ontario, North America	3	square cell	●		●			farmland birds	(-SHDI)all
(Fang et al., 2016)	Taiwan, Asia	10.000	circular buffer			●		●	all species	(+AREA)agricultural, (-AREA) all, ponds, (CA-)all, (+PARA)all, ponds, (-PARA)all, agriculture, (+CONTIG)agriculture,(-CONTIG) all, (+CAI)agriculture, (-CAI)all, ponds, (+CORE)all, (-CORE)ponds
(Griffin et al., 2017)	New Mexico, South America	11.310	circular buffer					●	single species	(+AREA) agriculture, (+NP)all
(Harmange et al., 2019)	France, Europe	0,0002	moving window				●		single species	(^{2}PLAND)cereal, (^{2}ENN)woodland, (^{2}ENN)building
(Lockhart and Koper, 2018)	Manitoba, North America	180.956	circular buffer	●	●				songbirds	(+PLAND)grassland, (-LSI)all
Marja et al. (2013)	Estonia, Europe	1 – 314	circular buffer, square cell	●		●			all species	(+EDGE)all, (+PD)all, (+SHDI)all
Maskell et al. (2019)	UK, Europe	1	square cell		●				species by habitat type	(+AREA) habitat, impr. Grassland, semi-natural habitat, (-AREA) habitat, impr. Grassland, semi-natural habitat, (~AREA) habitat, semi-natural habitat, (+SHDI) habitat, (+/-LINEAR FEATURES), (+/-/~PROBABILITY OF CONNECTIVITY)
Miller et al. (2019)	Oklahoma, North America	4 8, 50, 96	square cell				●		single species	(-AREA)pasture/rangeland, (-AREA) cropland, (+AREA) woodland, (-PLAND)cropland, (+PLAND)woody, (-ED)pasture/ rangeland, (+ED) cropland, (+ED) woody, (-LPI)woodland, (-LPI) cropland
(Morelli and Tryjanowski, 2014)	Italy, Europe	1.963	circular buffer				●		farmland birds	(=PLAND)urban, cultivated, vineyard, forest, grassland, uncultivated, badland, water, (=NP)all, (=SHDI)all, (=LAND USE NUMBER)all
Morelli et al. (2015)	Italy, Europe	314	circular buffer				●		all birds	(+/-AREA)Roads, (=ED)all, (=NP) all, (=SHDI)all, (=LAND USE NUMBER)all
Pedersen & Krøgli (2017)	Norway, Europe	1	square cell	●	●				farmland breeding birds	(+CA)cultivated), (-ltd)all, (+HIX) all
(Rüdisser et al., 2015)	Austria, Europe	314 – 785.398	circular buffer		●				species by habitat type	(+AREA)forest, (-AREA)farm, (+PD)forest, other, (-PD)farm, (+/-D2N)all
(Syrbe et al., 2013)	Germany, Europe	1	square cell					●	red list species	(+AREA)wetlands, (+ED) wetlands, (^{2}SHAPE)all

(represented by SHDI and ED) is considered an important variable for bird communities by representing marginal habitats, and providing nesting habitat as well as ecological corridors for different species (Siriwardena et al., 2012; Maskell et al., 2019; Morelli et al., 2015; Bonthoux et al., 2017) and can explain the distributions of some bird species and overall species richness (Bonthoux et al., 2017).

The comparability of the studies compiled here is very limited. Studies differ greatly in their research design, which makes a generalised statement on landscape metrics explaining variation in bird community data very difficult. The studies reviewed here all aim to investigate the structural properties of the landscape represented by the use of landscape metrics on avian communities. However, they differ in spatial scale, extents, research area windows, dependent variables (bird data), number and type of land cover classes, and finally the landscape metrics chosen for the study to test for explanatory value.

3. Are landscape metrics fundamentally suitable to use in practical landscape planning or nature conservation?

As stated by Uuemaa et al. (2009), most studies published show that compositional factors of the landscape play a stronger role for bird species than the configuration. Even though numerous studies have found relationships between landscape structure and ecological processes, many variables of structure usually have far less explanatory value than variables of composition (Bailey et al., 2007; Uuemaa et al., 2013). Moreover, the results of some studies even contradict each other and are, by the lack of comparability, hardly generalizable (Lausch et al., 2015; Walz 2011) and thus hardly usable in practice. However, collecting actual data on bird communities, like most biodiversity monitoring, is still expensive and time consuming (Bailey et al., 2007), whereas the generating of large-scale landscape metrics, given by the availability of geospatial data and freeware tools for calculation, is easy and cost efficient (Sinha et al., 2016). For many metrics, the literature repeatedly shows that they can produce constant values despite a wide variety of influencing factors, such as extents (Schindler et al., 2013), resolution (Sinha et al., 2016), or landscape types (Cushman et al., 2008). Our state-of-the-art analysis shows that it is difficult to compile the "right" metrics for certain research questions. Statistical compilation is not only very demanding for researchers but also for the technology, and other methods are so far not very efficient (Schindler et al., 2013). Considering our very specific focus on compiling landscape metrics to describe avian communities in different landscape types, our sample size is relatively small (n = 50) and yet the study designs are highly variable and thus only comparable to a limited extent. In consensus with existing research, we conclude that few empirical studies exist which describe the indicator value of landscape metrics comprehensively, taking into account different spatial scales, thematic resolution, landscapes, and species (Schindler et al., 2013; Uuemaa et al., 2009; Walz 2011) and the need for conducting such studies in order to be able to use landscape metrics as a biodiversity monitoring tool in a targeted way is apparent.

5. Conclusion

In our study we reviewed methods used in the past twelve years, the type of landscapes investigated, and the most important landscape metrics that show a significant influence on the ecological parameters of bird community distribution using international peer-reviewed journals indexed by Web of Science Core Collection. We discovered that bird species react strongest to the composition of the landscape (PLAND), both in the overall consideration of all studies and in the consideration of the two landscape types of forest and agriculture. Landscape metrics PLAND, AREA, SHAPE and PROX repeatedly produced significant results in articles investigating forest-dominated landscapes. AREA, SHDI, ED frequently produced significant results in agricultural-dominated landscapes. These metrics should be considered in future studies investigating bird species in forest or agricultural dominated areas.

We suggest that future studies should be more transparent and always specify data properties influencing metrics in detail. Few empirical studies exist which describe the indicator value of landscape metrics comprehensively, taking into account different spatial scales, thematic resolution, landscapes, and species and the need for conducting such studies in order to be able to use landscape metrics as a biodiversity monitoring tool in a targeted way is apparent.

In order to be able to use landscape structure measures as a standardisable, practical instrument for biodiversity monitoring, and as target indicators for sustainable landscape development and nature conservation goals, further scientific research is required. The spatial scale and resolution of the sensor data, landscape types, and species groups considered should be varied as a matter of priority in a systematic study design. We propose focussing on bird data in relation to landscape structure measures; this is because birds are particularly well suited as target or keystone species for nature conservation due to their spatial demands, differentiated structural and habitat requirements, and ease of detection. In addition to the quality of occurring individual species (Red Lists, habitat and structural references), different guilds must also be considered in particular in order to derive more differentiated nature conservation assessment criteria. The main objective should be to determine suitable structural measures, for the configuration of the landscape and not only its composition. Our comparative analysis has at least provided clear indications of which measures are more meaningful than others for this purpose.

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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Data availability

Data will be made available on request.

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