



Original Research Paper/Review Paper

Machine Learning Analysis of Seasonal Bird Communities Along Urbanization Gradients

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Key Words

Urbanization gradient,
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Machine learning,
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Landscape ecology.

Abstract

Introduction: Urbanization is among the strongest factors of land cover alteration and affects bird communities in terms of vegetation cover, food supply, noise environment and nest-building substrates from natural or agricultural areas towards cities. The study of changes of species composition and diversity parameters at such gradients and over seasons usually relied on field sampling and identification of calls manually. Methodology: In the present paper we discuss theoretically the use of machine learning algorithms for analysis of seasonal data about bird communities recorded along urbanization gradients. Supervised classifiers, unsupervised clustering techniques and deep learning models for acoustic data are considered, along with a proposed conceptual framework of analysis based on the combination of remote-sensing derived gradient variables, field survey data, features building and modelling of classification into diversity outcomes. Results: From the literature review, it is clear that the ensembles and deep learning classifiers usually perform better than simple classifiers, given high richness and high background noises; that seasonality affects the performance of the classification system; and that including habitat gradient covariates in addition to acoustic features results in an effective separation between the urban-tolerant and urban-avoiding species. Conclusion: Machine learning provides a scalable concept for studying bird community seasonal dynamics in fragmented and urbanized environments, taking into consideration data imbalance, seasonality, and covariates.

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Introduction

One of the most influential and permanent types of land-use changes is urbanization, which transforms agriculture and wildlife habitats into impervious surfaces, buildings, and green spaces. With the progression of such transformation, bird species change their composition along an observed gradient, moving from rural or agricultural areas to suburban and then urbanized ones. Birds with requirements for the constant presence of the canopy, nesting on the ground and feeding on insects tend to decrease their populations along the gradient, while some generalist species, which can be considered omnivores, or nesters in cavities and buildings, tend to increase in number. Because of different timing throughout the year, migration, breeding period, and wintering periods influence species' compositions.

Traditional evaluation of such patterns involves regular field observations, point counting surveys, and manual species identification based on either visual or acoustic characteristics; this method is accurate but difficult to implement over large, fragmented areas and across different seasons. The application of ML allows for such scaling through automation of species classification from survey and acoustic data and association of community-level results with the landscape covariates describing the urbanization gradient (Clavijo-López et al., 2024). This paper represents a theoretical approach to the subject: it neither introduces empirical data nor fits any equation nor calculates model parameters. It is a synthesis of current research on urban ecology of

birds and automated bird species identification using machine learning and discusses the organization of the synthesized theoretical framework for analyzing seasonal bird communities in fragmented agricultural-to-urban gradients (Babu et al., 2026).

Review of Literature

The early research in ecology revealed that bird communities changed predictably as a function of the type of urban land use. It was shown that richness and Shannon diversity were highest at moderately disturbed habitats within an urban gradient, while native species were replaced by invasive and exotic species towards the commercial center of the gradient. This investigation has been continued through the association between nesting success and life history characteristics, including nest heights and brooding habits, with the location on the continuum of urbanization in southwest Ohio, where it was found that proportionally more low-nesters and multi-brooders were present in the urban environment (Jennings et al., 2025). In (Leveau, 2013), the exploratory factor analysis has been used to categorize fifteen biological characters into four functional categories, indicating that the associations between combinations of variables can better explain bird assemblage differentiation.

A related research stream has explored the use of unsupervised and supervised machine learning techniques on bird communities and bioacoustics data sets. (Li et al., 2025) employed an unsupervised self-organizing map to categorize breeding bird communities in Seongnam City, South Korea, using impervious surface,

vegetation, and deadwood attributes, and showed that neural clustering was capable of generating meaningful clusters without any labeled data. In bioacoustics literature, (Kahl et al., 2017; Salamon et al., 2017) have independently shown that convolutional neural networks trained on spectrograms of audio recordings of field recordings can accurately classify many bird species based on flight call and song data, while (Zhong et al., 2020) showed how transfer learning and pseudo-labeling can help lower the need for labeled data in multispecies bioacoustic classification in the wild. (Gupta et al., 2021) benchmarked recurrent and convolutional models using a large, multi-species acoustic dataset and pointed out that there is information contained in the temporal component of bird sounds that visual spectrograms cannot capture. In summary, this body of literature reveals that ecology across urbanization gradients is well understood, and machine learning algorithms, especially those employing ensembles and deep learning techniques, have the potential to automate classification of organisms at the species level from both acoustics and surveys; however, there exists a gap in the theoretical framing of how these literatures might be integrated to study communities along gradients seasonally.

Paper Organization and Key Contributions

The rest of the paper is structured as follows. The Methodology section will include an analytic methodology, which involves landscape gradients and seasonal survey data being related to classification by machine learning and

outputting communities through a diagram that does not use equations. The Results and Discussion section will include the summarization of the strength and weaknesses of each of the main machine learning approaches in the field, presented in the form of a comparative table.

The major contributions of this study are as follows: (i) development of a unified conceptual framework based on the integration of ecology and machine learning research on bird communities along urbanization gradients; (ii) a straightforward analytical process that does not require mathematical equations and that can be used to guide future studies involving gradient variables measured through remote sensing combined with seasonal acoustics; (iii) comparison and assessment of clustering, ensemble, and deep learning methods in this area; and (iv) the importance of seasonal detectability and imbalanced training datasets for future work.

Methodology

This work uses the theoretical, review-based method, and no empirical data or fitting of models has been conducted. Based on literature, the conceptual workflow used in the analysis involves four consecutive steps, as shown in Figure 1 below. Step one involves gathering data about each surveyed area in terms of its landscape gradients, for example, land cover types, percentage of impervious surfaces, and vegetation indices acquired through remote sensing, which helps place each surveyed site on the agriculture to urban gradient. Step two involves gathering seasonal field surveys data, which include point counts and acoustic data

gathered during the breeding, post-breeding, and wintering seasons.

Stage three, Feature construction, involves combining the habitat features derived from gradient analysis with the acoustic/visual features derived from survey data, resulting in the inputs required for classification. Stage four involves using a machine learning classification strategy based on the categories developed from

the literature review – unsupervised clustering, tree-based ensemble, support vector machine and convolutional neural networks – to derive the classifications and the community level output metrics such as richness, evenness and gradient associations. Given that this is a theoretical paper, there is no training of a particular algorithm at this point but rather, the process is provided as a template.

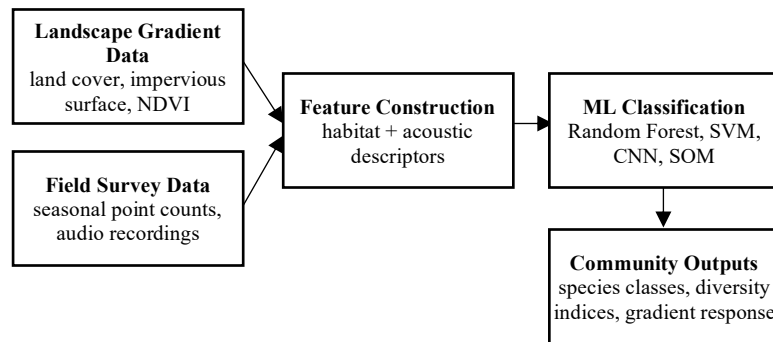


Figure 1: Conceptual Workflow for Machine-Learning-Based Analysis of Seasonal Bird Community Data

Results and Discussion

Since this essay is based on theory, the “results” found here are a compilation of results found through the analysis of the literature. Table

1 below gives the nature of the input data, strengths, and weaknesses associated with each group of machine learning techniques in use for classifying species of birds and their communities.

Table 1: Comparative Overview of Machine Learning Approaches Reported for Avian Community Analysis

Approach	Typical Input Data	Reported Strength	Reported Limitation
Unsupervised clustering (e.g., self-organizing maps)	Habitat/land-cover variables across gradient sites	Reveals assembly patterns without labelled data	Groups are descriptive; limited predictive classification
Tree-based ensembles (e.g., Random Forest)	Tabular habitat and gradient covariates	Robust to mixed variable types; interpretable feature ranking	Performance drops with highly imbalanced rare-species classes
Support vector machines	Extracted acoustic or spectral features	Effective with moderate sample sizes	Requires careful feature engineering and tuning
Convolutional neural networks	Spectrograms from seasonal audio recordings	High accuracy on large, multi-species datasets	Needs large labelled training sets and compute resources

There are a few recurring themes from this synthesis. One theme is that unsupervised techniques like self-organizing maps work very well as a discovery tool during an exploratory phase of analysis for finding ecologically coherent groups without labels along the urbanization gradient, but they do not constitute a predictive classifier for future locations or seasons. Another theme is that tree ensembles work well for habitat and gradient covariates in tabular format, providing variable importance ranks, which is important when it comes to identifying the gradient covariates that influence communities, although their performance can be hampered when rare or seasonally absent species are poorly represented in the training data. Third, deep learning techniques, especially convolutional neural networks using spectrograms, have shown the highest classification accuracy when applied to large datasets containing recordings of multiple species in acoustic classification studies due to their ability to automatically discover discriminative features within the raw signal, albeit at the expense of needing extensive labeled data and computation power, which may not always be feasible in fragmented landscapes.

Seasonality exacerbates such issues. Vocalization rates and consequently the strength of the acoustic signal used in the classification process are considerably higher during breeding seasons compared to migrations and winter seasons. Thus, a classifier created on data from the breeding season can work poorly when dealing with data recorded at other times of the year unless some changes are made. The effect of

gradient position described in (Silvetti et al., 2023; Leveau, 2013) shows that the link between environmental covariates and community structure cannot be considered linear along the entire urban-to-rural gradient, which makes it necessary to include gradient variables in the model explicitly.

Conclusion

Bird communities exhibit systematic responses to urbanization that vary not only by spatial location along an agricultural-urban gradient but also by time of year. In addition, the body of literature on birds and urbanization and the body of literature on machine-learning approaches to bioacoustics and habitat classification have each evolved independently. This paper has, from a theoretical perspective, made the case for the integration of these two bodies of research into a unified workflow. Harnessing the power of such models in reality will entail consideration of seasonal detectability, training data imbalance of rare or gradient-sensitive species, as well as the inclusion of gradient covariates in model development, which is a natural path of inquiry for future empirical work using this proposed framework.

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