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Identification of dialects and individuals of globally threatened yellow cardinals using neural networks

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Highlights

- Deep learning reinforces results of statistically different Yellow Cardinal songs among regions.
- Deep learning audio-based methods enable the recognition of individual vocal signatures.
- Confusion between individuals was more frequent within regions, as indicative of dialects.

Abstract

Audio-based analysis of bird songs has proven to be a valuable practice for the growth of knowledge in the fields of ethology and ecology. In recent years, machine learning techniques applied to audio field recordings of bird calls have yielded successful results in studying population distributions and identification of individuals for their monitoring in a variety of bird species. This offers promising possibilities in the study of social behavior, biodiversity, and conservation strategies for birds. In this work, we trained deep learning models, directly from the sonograms of audio field recordings, to investigate the statistical properties of vocalizations in an endangered bird species, the Yellow Cardinal, *Gubernatrix cristata*. This research marks the first successful application of this method to an endangered species. Our results indicate the presence of vocal signatures that reflect similarities in songs of individuals that inhabit the same region, determining dialects, but which also show differences between individuals.

These differences can be exploited by a deep learning classifier to discriminate the bird identities through their songs. Models trained with data labeled by regions showed a good performance in the recognition of dialects with a mean accuracy of 0.84 ± 0.04, significantly higher than the accuracy obtained by chance. Precision and recall values also reflected the classifier's ability to find alike vocal patterns in the songs of neighboring individuals. Models trained with data labeled by individuals showed an accuracy of 0.63 ± 0.03, significantly higher than that obtained by chance. However, the individual discrimination model showed greater confusion with neighboring individuals. This reflects a hierarchical structure in the characteristics of the Yellow Cardinal's vocalization, where the intra-individual variability is lower than the inter-individual variability, but it is even lower than the variability obtained when individuals inhabit different regions, providing evidence of the existence of dialects. This reinforces the results of previous works but also offers an automated method for characterizing cultural units within the species. Along with genetic data, this method could help better define management units, thereby benefiting the success of reintroduction of individuals of Yellow Cardinal recovered from the illegal trade. Moreover, the novelty of individual discrimination using neural networks for the Yellow Cardinal, which has limited data availability, shows promise for non-invasive acoustic monitoring strategies with potentially relevant implications for its conservation.

Introduction

The Yellow Cardinal, *Gubernatrix cristata*, is currently listed as an endangered species according to the International Union for Conservation of Nature (IUCN) Red List (BirdLife International, 2018). This passerine bird belonging to the Thraupidae family (Barker et al., 2013), is endemic to the southern regions of South America (Ridgely and Tudor, 1989), including the south of Brazil (Beier et al., 2017; Beier and Fontana, 2019; Bülau et al., 2021), Uruguay (Azpiroz et al., 2012; Domínguez et al., 2017), and central Argentina, where the largest populations have been found (Domínguez et al., 2017, Domínguez et al., 2020). The global population is estimated to be between 1000 and 2000 mature individuals, distributed in small and fragmented populations (Collar et al., 1997), which has led to categorizing the species as endangered (BirdLife International, 2018). Current studies show that the Yellow Cardinal has suffered a drastic and persistent population decline throughout its range (Domínguez et al., 2020; Reales et al., 2019). This is attributed to the loss of natural habitat and to the capture of birds for illegal trade and mascotism (Domínguez et al., 2020; Pessino and Tittarelli, 2006; Segura et al., 2019). Because bird trapping is focused on the extraction of males for use as cage birds (Pessino and Tittarelli, 2006), probably due to the richer vocalizations of males and the conspicuousness of male's plumage (Chebez, 1994; Collar et al., 1992; Ridgely and Tudor, 1989), a lack of males is assumed in Yellow Cardinal populations (Segura et al., 2019). This lack of males could be the cause of the hybridization with the Common Diuca, *Diucadiuca*, in some regions (Bertonatti and López Guerra, 1997; Domínguez et al., 2016), as well as observed breeding anomalies like polygyny

(Segura et al., 2019) that hinder reproductive success. Additionally, another factor affecting the reproduction of the species is the impact of both Shiny Cowbird, *Molothrus bonariensis*, and botfly parasitism, *Philornis* spp., resulting in brood reduction and often in nest abandonment (Azpiroz, 2015; Domínguez et al., 2015), which has been shown to even lead to zero recruitment in a breeding season for this species (Atencio et al., 2022). As a result, the Yellow Cardinal has seen its populations decline at an alarming rate and the status of this endangered species becomes more worrying every day. The urgent need for conservation is palpable, and yet traditional methods of monitoring can be invasive and costly. Furthermore, traditional methods might not scale well, given the vast terrains and reduced visibility of these species.

The motivation of the study then stems from the need to find an alternative non-invasive method of monitoring. Bird song offers a promising avenue, and acoustic monitoring is a cost-effective method. It is also timely, as in the last years regular releases of confiscated Yellow Cardinals are being carried out by governmental authorities (Atencio et al., 2022; Domínguez et al., 2019) with the need of post-release monitoring to evaluate their success. For this purpose, trustworthy monitoring is the backbone of successful conservation and research, as it provides reliable data for informed decision-making, effective resource allocation, and early detection of threats or population shifts, enabling timely interventions. In this way, the exploitation of computational techniques, such as audio-based analysis of bird songs from field

recordings, could be very helpful for effective non-invasive monitoring and conservation planning.

In the last decade, the analyses of animal vocalizations from audio recordings, improved by the application of computational methods from data science and deep learning (LeCun et al., 2015), have become prominent techniques for addressing multiple animal behavior questions. The most visible precedent is the BirdCLEF contest (Goëau et al., 2014) in which several advances in the recognition of bird species were achieved through their songs extracted from audio data collected by the crescent Xeno-Canto initiative (Vellinga and Planqué, 2015). Publications related to these competitions have shown successful approaches for that task, allowing progress in the study of biodiversity (Goëau et al., 2016), particularly since convolutional neural networks started to be used as models trained from images representing the temporal evolution of acoustic features (Piczak, 2016; Sprengel et al., 2016; Tóth and Czeba, 2016). This approach has become the main one for bird species recognition and, although large amounts of data are often used, in many cases data augmentation techniques analogous to those used for visual tasks are applied (Kahl et al., 2017). Recently, deep learning techniques started to be applied for the identification of individual birds through their songs (Bedoya and Molles, 2021; Bistel et al., 2022a, Bistel et al., 2022b; Martin et al., 2022; Tubaro and Mindlin, 2019). The vocal recognition to track individuals within a population requires that bird call features show lower within- than between-individual variation and that this variation is stable over the course of an individual's life (Budka

et al., 2015). This could be useful for monitoring the social behavior of a small population, which may be particularly relevant in the case of threatened bird species, where songs play a fundamental role in a variety of social interactions, from territorial defense to partner selection (Bistel et al., 2022a). More generally, the recognition capacity of these models is conditioned to the statistical properties of data in such a way that among class variability must be higher than within class variability, and a classifier must be able to capture and exploit these differences.

Since imitative vocal learning allows for the generation and rapid transmission of new patterns of vocal structure (Slabbekoorn and Smith, 2002; Slater, 1989), it is plausible to find differences in songs between populations of the same species (Catchpole and Slater, 2008) that inhabit different geographical regions. This results in the presence of local songs, often described as dialects (Lemon, 1975), which occur when a group of conspecific males share vocal characteristics that differ slightly from those of other groups (Baker and Cunningham, 1985). It is hypothesized that these geographical variations could be caused by the interaction between learning and isolation mechanisms and influenced by the effects of cultural drift, genetic drift, cultural selection, natural selection, and sexual selection (Catchpole and Slater, 2008; Podos et al., 2004; Podos and Warren, 2007). Due to the fragmentation of the environment and the isolation of the populations of Yellow Cardinals (Domínguez et al., 2020), the presence of song dialects is expected. In fact, previous studies have reported evidence of dialects in the songs of the Yellow Cardinal (Domínguez et al.,

2016), and males of the Yellow Cardinal species can recognize these dialects since they respond more strongly to local songs than to foreign ones in playback experiments (Fracas et al., 2023). This could potentially affect reproductive behavior in the Yellow Cardinal and highlights the need to understand the properties of cultural units, which is a sensitive issue for developing better strategies for the reintroduction of individuals of threatened species.

Here we used deep learning models to build sonogram-based classifiers for the study of audio field recordings of Yellow Cardinal vocalizations in individuals-labeled data from four geographical regions. We first trained a model to detect from which region a vocalization is, by assigning a unique label to all audios from individual birds that inhabit the same region. Therefore, this classifier is oriented to the study of the conformation of dialects in Yellow Cardinal songs, to reinforce the results obtained in previous works (Domínguez et al., 2016; Fracas et al., 2023), but from a deep learning techniques perspective. Then, we trained a model to discriminate individuals, from audio labeled with bird identities. The aim of this work is to use deep learning techniques that allow the identification of dialects and individuals and contribute to a non-invasive monitoring and conservation planning of the species.

Section snippets

Data

Audio data reported in a previous work was used (Domínguez et al., 2016), acquired during four breeding seasons (September–January 2011–14) in four different populations covering most of the known distribution of the Yellow Cardinal in Argentina and Uruguay: Corrientes (Co), San Luis (SL), Rio Negro (RN) and Uruguay (U) (Fig. 1). Differences among these regions were found in terms of genetics (Domínguez et al., 2017) and in song dialects (Domínguez et al., 2016). Recordings were obtained using…

Dialects

We obtained classifier accuracies of 0.84 ± 0.04 and compared accuracy values distribution with that obtained by chance 0.30 ± 0.02. A paired sample *t*-test showed significant differences between distributions (*p*-value=2.82e-11), reflecting significantly higher accuracies for the model than those obtained after random permutation of labels (Fig. 3.a; Table 2).

The model showed good performances in prediction for most classes according to ROC curves (Fig. 3.b) and confusion matrix

(Fig. 3.c),…

Discussion

Models trained using data labeled by regions and individuals had a better-than-chance performance in recognizing dialects and individuals, respectively. This indicates that deep learning classifiers can achieve relatively high accuracy even for an endangered species with limited data availability due to a small number of individuals and songs. Our main finding is that the intra-individual variability in Yellow Cardinal songs is lower than the inter-individual variability, which has not been…

Conclusions

Our study is the first to successfully employ deep learning models on sonograms from audio field recordings of an endangered species. We have identified compelling evidence of vocal signatures of Yellow Cardinal, which enables discrimination between dialects and individuals. Both the dialect classifier and the individual classifier demonstrated good general performance for most populations and individuals, with the latter showing some confusion with neighboring individuals. These results…

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CRediT authorship contribution statement

Hernan Bocaccio: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization. **Marisol Domínguez:** Conceptualization, Investigation, Data curation, Writing – review & editing. **Bettina Mahler:** Investigation, Writing – review & editing. **Juan C. Reboreda:** Investigation, Writing – review & editing. **Gabriel Mindlin:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Visualization.…

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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