Analysis of Aviary Specialization Changes in the Montreal Metropolitan Community

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Abstract

Migration is an essential ecological process highly influenced by anthropogenic factors, spatiotemporal pressures and climate change; studying migratory species is thus of conservatory importance. Urban development is often considered one of the largest threats to wildlife through environmental disturbances such as habitat loss and fragmentation. Here, we analyzed the effects of urbanization on natural populations through the temporal study of bird dynamics in the Montreal Metropolitan Community between 1990 and 2016. Data from 344 species over 82 municipalities was collected from the eBird database in order to measure changes in Community Specialization Index (CSI) and observe which types of habitats exhibit stronger biotic homogenization. Presence-absence data, seasonal migratory patterns and population compositions with time did not present evidence of a decrease in CSI over the study period. In fact, it increased in the beginning, which was most likely due to a greater number of recorded observations and sampled municipalities. However, almost all regions showed a decrease in average Species Specialization Index (SSI) values with time, suggesting that urbanization plays a role in homogenizing biological communities. Overall, this type of study can be useful to the assembly of human biodiversity indices and to the conservation of endangered species in more populated areas. These results also highlight the importance of citizen science, which allows the public to directly contribute to data collection and to the monitoring of threats to certain species, the state of ecosystems and conservation responses.

Introduction

Across the globe, urban areas are much more populated than rural ones; these regions pose many challenges to sustainable advancements, especially since they expand very rapidly (Isaksson, 2016). Urbanization is known for posing many threats to ecological communities, as it alters both biotic and abiotic environments in a panoply of ways. This growth bestows novel challenges to native species by modifying ecosystems, exposing wildlife to man-made stress and acting as a selective force, thereby altering animal community composition (Marzluff & Ewing, 2001). For example, species that cannot adapt to urban environments must move elsewhere in order to thrive, while those that cannot migrate faster than urbanization's expansion rate are led to extinction. On the other hand, other species are driven into areas of higher density by food abundance and a lack of predators (Fischer et al., 2012). Urbanization therefore acts by filtering communities; this may result in huge ecological impacts on wildlife populations profiles at an international scale, likely presenting a major menace to biodiversity.

The Montreal Metropolitan Community (CMM) comprises of three principal types of habitats with varying geographical distributions (CMM, 2011). The rural ones occupy village or agricultural environments over vast grounds, comprise of dwellings distant from one another, have limited community services, and are mainly located over thirty kilometers from downtown Montreal. The suburbs isolate their residents from the inherent nuisances in urban

life (such as noise, traffic and air pollution), encompass a homogeneity of functions and densities and are characterized by structured and hierarchical road networks. They occupy a vast territory, including all the urbanized areas of Laval, Longueuil, the North shore and the South shore. Finally, urban habitats are multifunctional and animated, involve major residential projects and industrial buildings and contain a much higher population density and heterogeneity. They mainly comprise the central part of the island, with overflows in certain areas of Laval and Longueuil. These types of habitats would therefore be expected to impact diversity in their own distinctive manners, where higher-density areas could destroy natural environments, drive species away and homogenize the remaining communities.

There is a clear gap in knowledge of the mechanisms and effects of urbanization on natural populations. However, a good place to start is through the study of bird dynamics. They react quickly to environmental changes, making them good indicators of local biodiversity (Viellard, 2000). Studying seasonal migratory patterns and population compositions with time can allow for a better understanding of the impacts of urban development on native species, thus allowing us to help animals survive in the vicinity of metropolitan areas.

Measuring bird specialization indices allows for the study of many dimensions of their ecological niches. In fact, a central theme in ecology is based on the coexistence of specialist and generalist species, where the former tolerates a more restricted range of resources than the latter (Mills et al., 2019). Specialists experience greater difficulties adapting to environmental changes, and thus suffer more populational disturbances. Therefore, invasions and extinction lead to an increase in genetic, taxonomic and functional similarity (Olden et al., 2004). This results in community homogenization (McKinney and Lockwood, 1999), an important form of biotic impoverishment that has negative impacts on communities such as hindered species expansion and genetic bottlenecks (Olden et al., 2004).

The French Bird Breeding Survey (FBBS) is a participatory science initiative through which any citizen can contribute by voluntarily collecting bird observations in order to improve united knowledge about biodiversity. Similarly, eBird is an online, free-to-use database from the ornithology laboratory at Cornell University (2013). It also employs citizen science, namely observations from both amateur and professional ornithologists. This database allows for the study of the abundance and distribution of bird observations at various spatial and temporal scales.

The goal of this study was to analyze the relationship between common bird species' specialization degree and urbanization in the Greater Montreal region using eBird data on 344 species. The strategy was to apply methods inspired from the FBBS research to the CMM ecosystem. This permits the quantification of temporal changes in the Community Specialization Index (CSI) between 1990 and 2016 in order to measure biotic homogenization, allowing us to analyze whether some types of habitats exhibit stronger pressures than others. The theory suggests that urbanization leads to functional homogenization, resulting in specialist populations' instability (Devictor et al., 2007). In fact, measuring this would allow us to evaluate the effect of landscape modification, and therefore to further contribute to biodiversity indicators and sustainable urbanism.

Methodology

Data collection

To begin, we obtained geo-referenced data on 83 municipalities on the CMM website (Statistics Canada, 2016). From this, we were able to calculate the housing density in each (in number of lodgings per hectare) in order to sort them into one of the three types of habitats; rural ones were characterized by values strictly inferior to 1, suburban ones by the range of 1-6 and urban ones by values over 6. Then, we obtained the polygons and municipality vectors from the Montreal Metropolitan Community (CMM, 2018), allowing us to use this GIS data to classify data points in the various environments.

We downloaded eBird data in the greater Montreal area, notably 1.66 million observations between January 1st, 1990 and December 31st, 2016. We then classified each observation in its respective municipality using their geographical coordinates. The spatiotemporal presence-absence data of each species allowed for the study of their distributions through the entire period using the following metrics.

Measures of ecological diversity

Two important variables we took into account in this analysis were species richness and beta diversity. Species richness is the number of distinct species found in a given area. It is simply a count, and it does not allow for species abundances or their relative abundance distributions. It is however highly affected by the ecosystem heterogeneity, notably through environmental gradients (Yang et al., 2015).

Moreover, the beta (β) diversity is defined as the ratio between gamma (regional) and alpha (local) diversities; it quantifies the number of different communities in the studied region, informing us about the degree of differentiation among biological communities (Whittaker, 1960). This is because alpha and gamma diversities are different if and only if the biological communities within the region are different. Although several indices allow for its spatial quantification, we may temporally measure the beta diversity $\beta_{x,y}$ in a given community between a pair of adjoining time windows x and y through:

$$\beta_{x,y} = \frac{\{S_x\} + \{S_y\}}{2\{S_x + S_y\}}$$

Where S_x and S_y respectively characterise the species independently found in windows x and y, and $\{\}$ represents the set of unique species, i.e. community richness. This can be used to contrast the distribution of species in a given area for windows of the same size and using the same overlap ("window shift") for every pair-wise comparison. This relative index ranges from 0.5 to 1; values at 0.5 represent no overlap while values of 1 denote identical species. Therefore, a higher $\beta_{x,y}$ characterizes higher similarity between both windows.

Measures of temporal community specialization

We could thereafter compute the Species Specialization Index (SSI), a measure of territory specificity, through the presence and absence of species in each habitat. Its values range from more generalist species (i.e. who reside in many habitat classes) to more specialist ones (i.e. who reside in few habitat classes). A bigger SSI thus symbolizes a more specialized

species, whereas an SSI of 1 signifies a species present in exactly half the available habitat classes. It assumes equal densities in occupied habitats and a null density in unoccupied ones, independent of surface area (Julliard et al., 2006). For this study, habitat classes are defined by the municipalities since most political biodiversity-related decisions by the Montreal Metropolitan Community are made at that level (Boudreau et al., 2006; ICLEI, 2010). For each of the 344 species, the SSI is calculated in each window by:

$$SSI_{i,j} = \left(\frac{H}{h_{i,j}} - 1\right)^{1/2}$$

Where $SSI_{i,j}$ represents the specialization index of species i at period j, $h_{i,j}$ represents the number of habitats in which species i is present at period j and H represents the number of possible habitat classes. SSI can range from 0 to $\sqrt{H-1}$, a value of 0 represents all habitats occupied by a species (i.e. a generalist) while a high value represents a very specialized species. The CMM comprises of 83 municipalities; however, Kanesatake was excluded from this study through lack of observational and anthropogenic data from that municipality. Therefore, it was not used when calculating SSI values for each species.

The density-independent Community Specialization Index (CSI) comprises of the average SSI from all species in the community. It is calculated through:

$$CSI_{j,p} = \frac{\sum_{i=1}^{s_{j,p}} SSI_{i,j}}{s_{j,p}}$$

Where $SSI_{i,j}$ is the Species Specialization Index of species i at period j and $s_{j,p}$ is the number of species at point p in period j. Its values follow the same logic, where index is directly related to the community specialization.

Using the above equations, we quantified the changes in community richness and CSI in the CMM between 1990 and 2016 using 981 periods of 60 days with 10-day window shifts. Beta diversity was computed between 980 adjoining pairs of these same windows. We then compared temporal trends in the CSI to quantify biotic homogenization.

Since this study ranges from 1990 to 2016, which involves large technological advancements and a surprising increase in urban sprawl in the Montreal region (Nazarnia et al., 2016), the number of eBird observations as well as the number of municipalities sampled was expected to increase in this period, potentially hinting at higher community richness, beta diversity and CSI. Also, since migration plays an important role in the number of species observed throughout the year, data was expected to fluctuate between the summer and winter seasons; a study of these oscillations should show stable periodicities in the absence of disruptions. We thus conducted a wavelet analysis of ecological time series from the data following an approach presented by Cazelles et al. (2008), revealing the power spectrum of each signal to confirm these migration patterns in the eBird observations.

<u>Quantifying biotic homogenization by municipality</u>

Finally, in order to discern whether some types of habitats exhibit stronger functional homogenization, we plotted the average SSI values in each municipality at five three-year periods respectively averaging 1995, 2000, 2005, 2010 and 2015. The values were corrected for the number of observations by defining the total number of habitat classes as the sampled municipalities in each window. This was done using the geographic information system software QGIS 3.4 by loading a shapefile delimiting each municipality and joining its layer to the average SSI values of all observations computed in each period. This would visually display the changes in specialization with time across various habitat types, allowing us to identify homogenization trends and correlate them to urbanization.

Results

From all the recorded data from the Greater Montreal area obtained from eBird (2013), we acquired 1,664,650 observations in total between 1990 and 2016. When classifying each observation into its corresponding municipality through its coordinates, 296,79 did not strictly fall into any of the 82 municipalities; we were therefore left with a total of 1,634,971 properly classified data points within the geographical limits of the CMM.

We first observed a very pronounced increase in the numbers of observations and municipalities sampled between January 1990 and December 2016, as both the Internet and citizen science became more popular and accessible. As depicted in Fig. 1A, the recorded observations increased in an exponential manner. Fig. 1B also shows that a greater proportion of the total municipalities in the community were sampled with time, thereby covering a wider spatial range. The fluctuations observed in both graphs result from seasonality; interestingly, the numbers reach bi-yearly local maxima due to migration and mating season. In A), local maxima are in May and October, while local minima occur in July and November. In B), local minima occur bi-yearly, around the months of February and October.
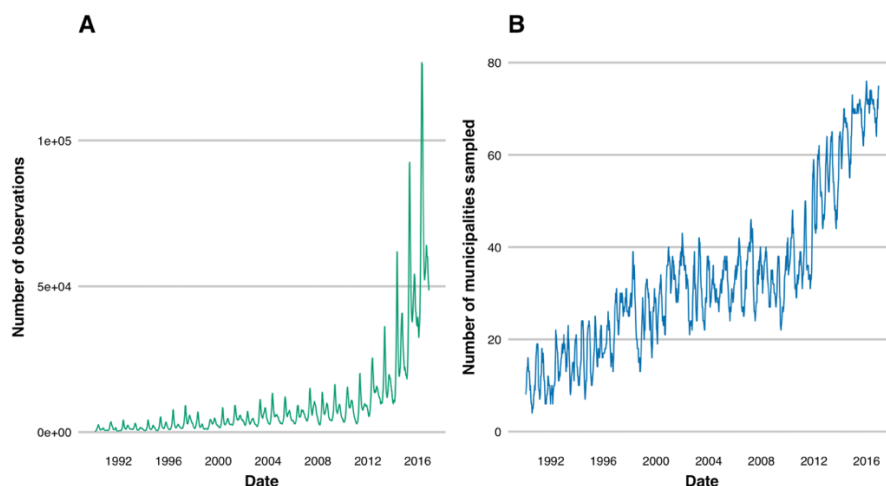

Fig. 1 eBird statistics in the Montreal Metropolitan Community between 1990 and 2016. The **A)** number of eBird observations recorded and **B)** municipalities sampled were computed through 982 windows of 60 days, with 10-day shifts between the beginning of each one and its adjoining one. In the range of this study, there is an exponential increase both in the number of observations and the number of sampled municipalities. There is a total of 83 municipalities in the community, including Kanesatake.

With regards to ecological measures, there was an increase in the number of species observed throughout this study, as shown in Fig. 2; this agreed with the greater number of observations in the database. Local peaks in A) occur every year due to mating season and migration. The yearly fluctuations also result from seasonality; as many species migrate South for the winter, the numbers decrease around October and increase once again around March. They reach a local minimum every July/August. For B), the beta diversity ranged from [0.81, 0.998] and remained stable over the years, averaging at a value of 0.952 ± 0.278. Local minima occur periodically in the spring due to migration.
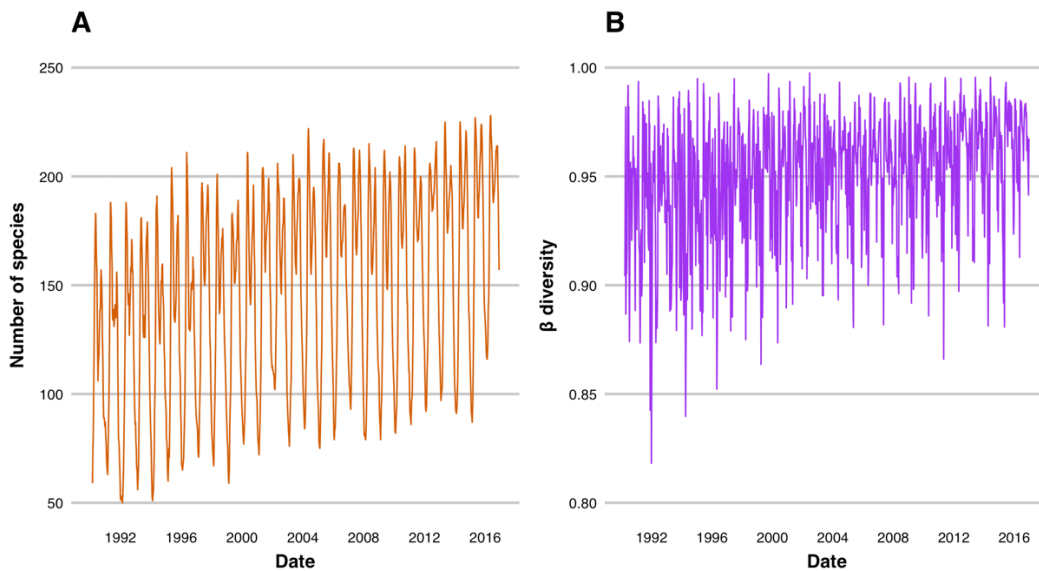

Fig. 2 Ecological diversity measures of the aviary population in the Montreal Metropolitan Community between 1990 and 2016. Like in Fig. 1, the **A)** community richness and **B)** β-diversity were computed using data from 982 windows of 60 days, with 10-day window shifts. There is a noticeable increase in richness with time, whereas the beta diversity follows a more stable pattern. Yearly fluctuations result from seasonality, especially migration.

In the range of this study, an initial increase in CSI was observed between 1990 and 1998 (as shown in Fig. 3) likely due to a greater number of observations and sampled municipalities depicted in Fig. 1. The CSI eventually reached stable temporal oscillations, showing little change between 1998 and 2016. Since 82 municipalities used to measure these indexes, the CSI values may range from 0 to 9; the values found here fluctuated around a mean of 2.92 ± 0.355 once stabilized after 1998, meaning that the average species occupied 8.61 (10.50%) of the municipalities in the CMM. The peaks and throughs respectively occur during the winter and summer seasons.
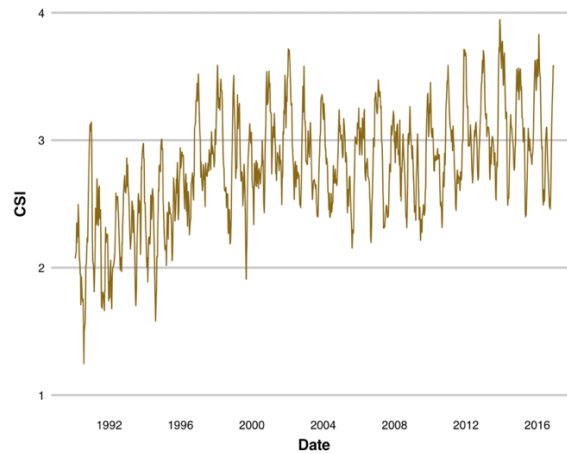
Fig. 3 Temporal variations in the Community Specialization Index (CSI) in the Montreal Metropolitan Community between 1990 and 2016. This data is calculated by using both SSI and CSI equations in the same windows of 60 days used in the previous figures. Yearly fluctuations occur due to seasonality, where winter periods exhibit greater CSI values than the summer ones.

When comparing variations in observational data at five different three-year periods between 1995 and 2015 (Fig. 4), we observed an increase in the number of sampled municipalities, which agrees with Fig. 1. We also observed that the average SSI values are lower than the CSI (Fig. 3), since the former echoes the same values in different environments in correlation to each species' distribution. Finally, we observed a comparable decrease in the average SSI values in all regions of the CMM, although center municipalities display lower values than those on the peripheries.
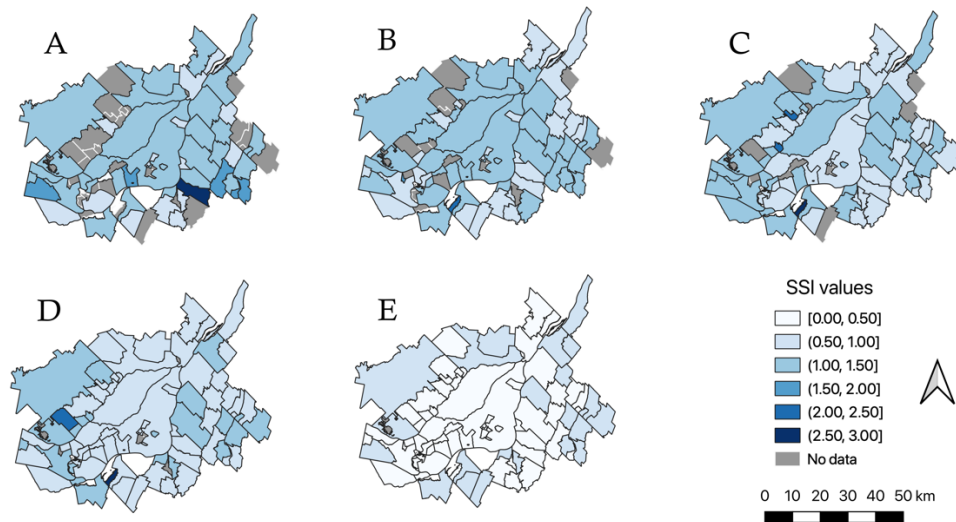

Fig. 4 Maps of the average SSI in each municipality of the Montreal Metropolitan Community. The geographical distribution of the average SSI in each municipality in three-year periods around **A)** 1995; **B)** 2000; **C)** 2005; **D)** 2010; **E)** 2015. Darker shades of blue symbolize higher SSI values, while the municipalities in grey denote a lack of data. As more distinct municipalities report observations with time (Fig. 1), a greater proportion of them are filled in. There is also a visible decrease in the average SSI values across all regions between 1995 and 2015.

In order to properly study the fluctuations in Fig. 2 and 3, we conducted a wavelet analysis of ecological time series, displaying a wavelet power spectrum of each signal shown in Fig. 4. This allowed for a local time-scale signal decomposition (i.e. the estimation of its spectral characteristics with time). Panel A shows very strong periodicity in community richness every 6 and 12 months; panel B displays beta-diversity periodicity every 4 months and weaker yearly ones. Finally, panel C shows unstable CSI periodicities between 1990 and 1998; afterwards, they stabilized and followed strong patterns at one-year intervals with weaker ones every 3 and 6 months.
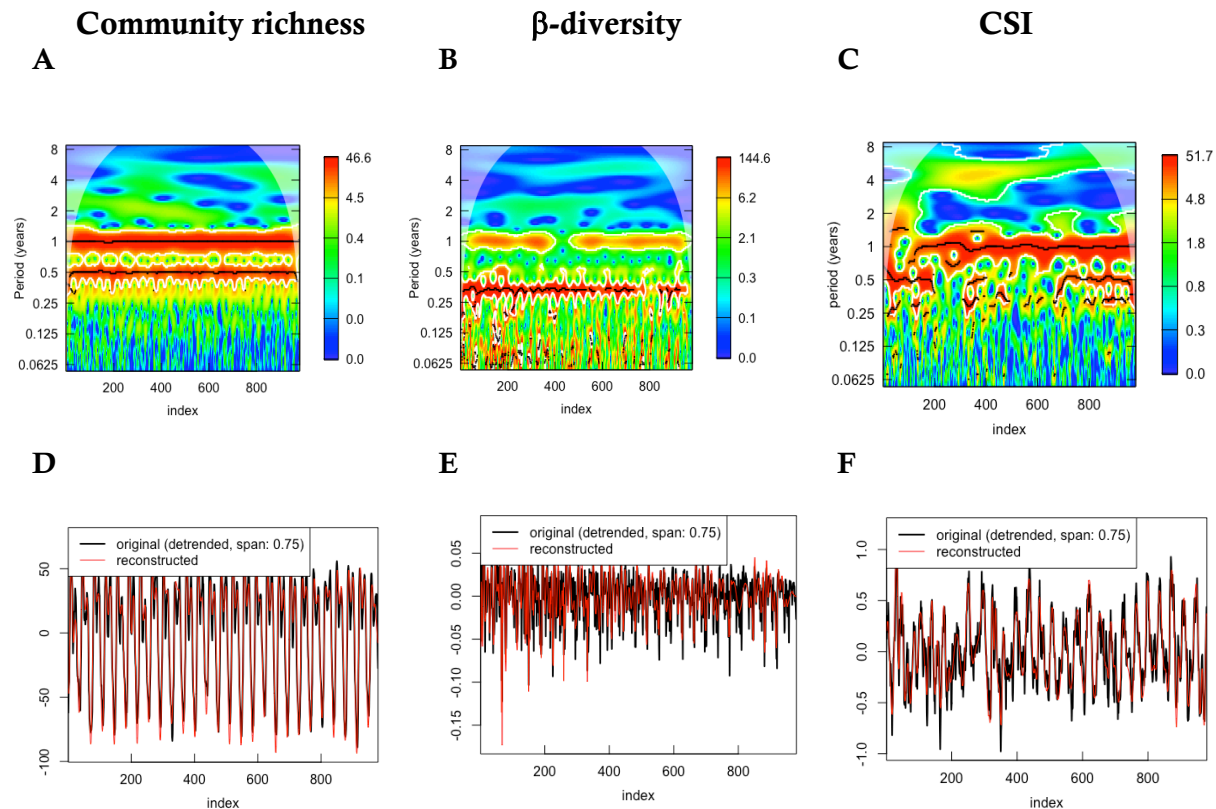

Fig. 5 Periodicity analyses of community richness, β-diversity and CSI data. The top row shows the strength and length of the periodicities, whereas the bottom row shows the original signal overlaid with its reconstruction. The colors code for power values from dark blue (low values) to dark red (high values). White lines represent the maxima of the undulations and the upper opaque zones designate the cone of influence, delimiting the region not influenced by edge effects.

Discussion

Citizen science relates communal citizenship involvement and pedagogy through action, generating vast open-access observation databases with high statistical power. Through eBird data, we used this kind of research to classify 1.63 million geo-referenced observations into 82 municipalities of the CMM. Both the number of observations and the proportions of the total number of sampled municipalities increased with time, showing a wider spatial range of study as citizen science became more popular. Species richness by observation steadily increased, whereas beta diversity oscillated around similar averages and showed no visible

similarity change in time. Periodicity analyses of community richness, β-diversity and CSI showed stable fluctuations for the bird communities according to the eBird database. Little interference to their populations and migration patterns were observed with regards to community richness and beta diversity.

Urbanisation is known for imposing pressures on biodiversity and driving community changes through the replacement of specialist with generalist species, leading to biotic homogenization (Conceptión et al., 2015). However, as shown in Fig. 3, our findings show no evidence of CSI decrease in the Montreal Metropolitan Community between 1990 and 2016. An increase was observed between 1990 and 1998, which is most likely due to increase in the numbers of observations and sampled municipalities. After this, no matter the rise in both variables, the Community Specialization Index reached stable oscillations at a yearly period. This is supported by the periodicity analysis shown in Fig. 5C, where fluctuations near the beginning of this study were less stable - possibly due to habitat disturbances or sampling effort - and became steadier with time, presenting very strong periodicity at one-year intervals. CSI values repeatedly peaked during winter and dipped during summer from migration, which is exhibited by the majority of bird species found in Canada (Ministry of Justice, 1994). In fact, more species are present and dispersed throughout the summer, showing a more generalized average, whereas species present in the winter are not only in lesser numbers but those still present are often less distributed across the CMM. For example, comparing the observed distributions of three different migratory species in summer 2014 and in the following winter showed that they were more spread out in the former, thereby each resulting in a lower SSI (see Appendix A). This agrees with the evidence that migratory birds are more likely to occur in urban areas during periods of migration (Zuckerberg et al., 2016).

When comparing spatiotemporal variations in Fig. 4 and Fig. B1, we observed biotic homogenization throughout the entire territory, as the average SSI decreased with time. We can support this by comparing the values by urban, suburban and rural groups (Table B1), showing that all three types of habitats exhibited a decrease at a similar rate. However, the center regions of the CMM revealed housing more generalist species than those on the outskirts (Fig. 4). These findings suggest that high-density metropolitan areas such as Montreal, which has been quickly expanding in the recent decades (Nazarnia et al., 2016), are more prone to impoverishing biological diversity with time.

Previous models have shown that human population size, land cover and city age were found to be "better predictors than geographical, climatic, and topographic factors typically identified as important predictors of global patterns of diversity (Aronson et al., 2014). This emphasizes the fundamentality of anthropogenic drivers in defining patterns of urban diversity, thus highlighting the importance of proper urban planning. For example, it has been found that patches of intact vegetation within urban areas retain macroecological patterns similar to those found outside (Pautasso et al., 2011) while large and interconnected patches are critical to upholding urban bird diversity (Beninde et al, 2015). Thus, parks as well as landscapes with private terrains and gardens take precedence as key socio-ecological factors for bird conservation (Goddard et al., 2017). The management of both private and public wildlife-friendly habitats by individuals and civic authorities could play a significant role in preserving vulnerable species and maintaining diversity in residential areas.

The goal was to relate temporal SSI and CSI trends to recent urban changes in the Montreal Metropolitan Community in order to better understand the impacts of urbanization on avian fauna, since it serves as a model biodiversity indicator. Other studies have done similar studies using bird monitoring programmes. For example, Barnagaud et al. (2001) used the FBBS to test whether species specialization varied over a short period of time; they assessed whether variations in specialization influenced community-level biotic homogenization in France. They found that out of the 94 observed species, 35 of them experienced decreased specialization and the resulting CSI decreased with a slope of -0.048 per year through a mixed-effect linear model. This emphasizes the importance of geographical scale and the metrics used, as their study was made at a national level, involved environmental habitats instead of geopolitical ones and incorporated specialization indexes strongly affected by density. Broader ranges, more sensitive indexes as well as mixed models taking other factors into account could thus lead to more accurate estimations, allowing a better monitoring of changes in the aviary Community Specialization Index in the future. An increase in the number of observations and in the number of municipalities sampled (notably including areas such as Kanesatake) would also be beneficial.

An important aspect of eBird is that each observation has an exact date and location, allowing to link them with covariate data such as weather, climate, habitat, and anthropomorphic variables. While protocol standards are encouraged, users have the flexibility to enter records in a variety of other ways, thereby encouraging participation in spite of a reduction in systematic uniformity (e.g. historic data often can only be entered at the county or region level, which may decrease its analytical value) (Wood et al., 2011). However, statistical models can aid in filling gaps by producing predictions at unsampled locations and times. For example, these data have been related to numerous environmental descriptors such as remotely sensed habitat data from the National Land Cover Database (Munson et al., 2009). This data can be used to estimate species distributions with the SpatioTemporal Exploratory Model, designed to utilize both the broad extent and fine resolution information collected by eBird (Fink et al., 2010). This has been used to estimate year-round distributions of bird species with a wide variety of distinct migration pathways and local habitat associations (NABCI, 2011). With these findings, eco-evo researchers can thus better identify, monitor and prioritize preservation programs across widespread territories.

Finally, this type of study highlights the power of citizen science for enlightening the general population and allowing individuals to directly contribute to research on a voluntary basis in order to benefit society. Recent years have shown a rapid and sustained growth in participation from the birding community (Wood et al., 2011). It is a form of simultaneous learning and knowledge making; encouraging this mutualistic approach could be useful to the assembly of human biodiversity indices and to the conservation of endangered species in more populated areas. For example, anthropogenic light pollution has been shown to be detrimental to nocturnal bird migration patterns (Van Doren et al., 2017); monitoring such behavioural plasticity while accounting for temporal variations in species specialization can aid our understanding of the effects of global changes on community dynamics.

Transparency Declaration

The author has no conflict of interest to declare and affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Data Availability Statement

All datasets and code used to produce this study are archived on the Open Science Framework and available via the following link: https://osf.io/vxrg7/.

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