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COMMENTARY

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Using citizen science data to define and track restoration targets in urban areas

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Abstract

1. Habitat fragmentation and land degradation, directly and indirectly caused by urbanization, are drastically altering the world's ecosystems and are therefore driving an imperative for ecological restoration within the world's cities. Current methods for the implementation and monitoring of restoration are limited. Restoration ecology needs cost-effective and repeatable tools for tracking changes at global scales, but with local relevance.
2. We propose the Urban Greenspace Integrity Index—a locally relevant measure of an urban greenspace's response to urbanization, derived from widely accessible citizen science data. Unlike classical measurements of biodiversity (e.g. species richness, species diversity), this index measures species-specific responses to continuous measures of urbanization.
3. Increases in this index are evidence of a successful urban restoration project; that is, restoration results in a community shift that favours urban-sensitive species. Importantly, data for this index are easily and efficiently collected by citizen scientists, providing long-term repeatable data. This urban index, calculated from greenspace surveys, correlates with and complements traditional biodiversity metrics.
4. *Synthesis and applications*. Policymakers and practitioners can use the index—a measure of the urbanness of the local bird community—to define and track restoration of urban ecosystems, effectively measuring changes in biodiversity in response to urbanization: measuring whether the urbanness of the bird community changes through time. Importantly, this index can be calculated using citizen science data, providing a potentially long-term monitoring effort of restoration projects.

KEYWORDS
alpha diversity, beta diversity, bird surveys, citizen science, gamma diversity, restoration, urban birds, urbanization

1 | INTRODUCTION

Ecological restoration is the process of assisting in the recovery of a degraded ecosystem and requires data to define "targets", followed by monitoring to assess the success of the restoration. These targets are essential for tracking ecosystem change, but are seldom adequately monitored, often due to budgetary reasons unrelated to biology (Lake, Bond, & Reich, 2007). As a result, restoration projects frequently fail to consider the long-lasting effects on wildlife (Block, Franklin, Ward, Ganey, & White, 2001). We increasingly need practical tools to measure ecosystem change (Hobbs & Harris, 2001), that are globally applicable, but have local relevance.

In an era of big biodiversity data (La Sorte, Lepczyk, Burnett, et al., 2018), citizen scientists have massively expanded the temporal and spatial scale of ecological data (Dickinson et al., 2012; Silvertown, 2009). These data have some drawbacks (Boakes et al., 2010), but their utility for understanding broad-scale biodiversity is increasing, particularly given the improving quality of citizen science data (Aceves-Bueno et al., 2017). Further, these data are relevant at spatial scales from the global to the local, with the latter frequently being neglected by global-scale projects (but see Sullivan et al., 2017). Restoration is one of these local scale applications (Lake et al., 2007), with small-scale projects generally more feasible because funding frequently derives from local governments and non-governmental organizations.

Increasing urbanization is having massive and global ecological impacts on ecosystems: By 2050, 68% of humanity is expected to live in cities (United Nations, 2018). Urbanization severely alters ecosystems through biotic (McKinney, 2006), phylogenetic (La Sorte, Lepczyk, Aronson, et al., 2018) or functional (Devictor, Julliard, Couvet, Lee, & Jiguet, 2007) homogenization. Importantly, humans also derive benefits from urban biodiversity (e.g. Luederitz et al., 2015), driving increased interest in restoration and protection of urban ecosystems, globally (Elmqvist et al., 2015). Consequently, decision-makers need targets for restoration of ecosystems within cities.

Conveniently, citizen science data are disproportionately collected near urban areas, offering great potential for their use in future management of urban biodiversity. Moreover, integrating citizen scientists into locally managed projects has the added benefit of improving scientific literacy (Evans et al., 2005; Trumbull, Bonney, Bascom, & Cabral, 2000), while instilling a sense of accomplishment in restoration projects by local residents (Keough & Blahna, 2006). We propose that ecological restoration, particularly in urban ecosystems, could benefit from integrating the use of already-collected citizen science data into restoration projects. We demonstrate how these data can be used to define and subsequently track restoration targets in urban greenspaces. To do this, we introduce an Urban Greenspace Integrity Index (UGII), derived by combining citizen science data with ecological restoration theory and community ecology theory. This index is broadly applicable across taxa and does not necessarily rely on citizen science data. Nevertheless, we use birds as a focal taxon, given their rich history of citizen science involvement (e.g. Sauer, Hines, Fallon, & Pardieck, 1966) and precedent as sentinels of environmental change (Temple & Wiens, 1989), relying on the eBird citizen science project (Sullivan et al., 2014). We (a) highlight the necessity for such an index, (b) demonstrate how the index is calculated, (c) provide evidence for the validity of the index, (d) demonstrate how the index can be used for quantifying restoration and (e) discuss implications for future use of the index.

2 | MOTIVATIONS FOR AN UGII

Many biodiversity metrics currently used to monitor environmental change adequately measure species diversity, and sometimes species composition, but lack the ability to weight "desired species" (particularly vulnerable to anthropogenic disturbances). Consider two urban greenspaces in the same city, each with their own ecological avian community (Figure 1). Community A consists of nine rock pigeon (*Columba livia*), three superb fairywren (*Malurus cyaneus*), two eastern yellow robin (*Eopsaltria australis*) and three Australian raven (*Corvus coronoides*). Community B consists of nine rock pigeon, three common myna (*Acridotheres tristis*), two noisy miner (*Manorina melanocephala*) and three Australian raven. The "difference" between the communities is that superb fairywren in greenspace A is replaced by common myna in greenspace B and eastern yellow robin by noisy miner. If we compare these communities using classic community ecology metrics, such as Shannon entropy (Jost, 2007) or species richness, these communities are "equal" (Figure 1). However, local knowledge tells us that both noisy miner and common myna are common urban park inhabitants negatively impacting other species—common myna is a non-native species in Australia and noisy miner is a despotic native species. In other words, eastern yellow robin and superb fairywren are "desired species" when viewed in the context of how they respond to urbanization.

Generally, restoration projects aim to preserve or, ideally, increase species richness (or another diversity index). Often, measurement takes the form of beta diversity—defined as the ratio between regional and local species diversity (Tuomisto, 2010; Whittaker, 1960). Beta diversity is important for conservation because it allows comparisons among disparate locations, by standardizing for the regional species pool (Socolar, Gilroy, Kunin, & Edwards, 2016). Returning to our example, imagine that Community B represents Community A 3 years after a restoration project. Both species richness and Shannon entropy remain equal, even after 3 years. However, we know that the community has been significantly altered. Hence, if classic beta diversity metrics are the only measure of restoration, it would not be deemed a success because no "difference" was detected. Urban greenspaces rarely have a species composition "reference" state to compare to, making methods that track or measure progression towards reference states difficult to implement. This is our motivation for determining a measure by which to judge whether urban restoration efforts are transitioning towards

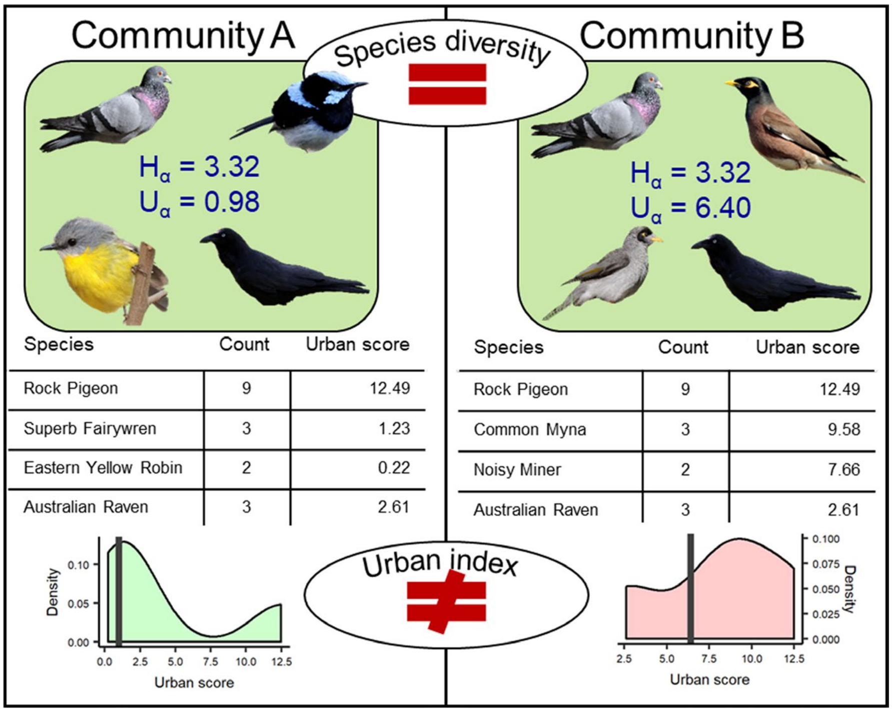

FIGURE 1 Theoretical bird communities A and B, demonstrating how species richness and species diversity (H_α) can be equal, while the two communities are unequal, revealed by the urban indices (U_α). The graphs along the bottom represent a distribution of U_s on a theoretical local-level sampling unit, shown with a simplistic kernel density estimation to represent the distribution, where "density" represents the kernel density estimation of U_s at a given point along that distribution. The curve in the bottom left-hand-side corner (shown in green) represents the distribution of U_s for Community A, while the curve in the bottom right-hand-side corner (shown in red) represents the distribution of U_s for Community B, and for each, the respective U_α (the 0.25 quantile of the shown distribution) is demarcated by the dark grey line

an improved ecosystem, without the need for an a priori reference state. Our simple method quantifies "improved diversity", incorporating whether "desired species" reenter the community. This works by incorporating local information into a conceptual framework built on broad-scale data.

3 | CALCULATING THE UGII

Calculation of UGII relies on two distinct steps: (a) calculation of continental-scale urban scores and (b) community-level metrics, relying on these urban scores. In our demonstration, both of these rely on the same set of eBird data, but with biases impacting these differently. We treat these in turn.

3.1 | Calculation of continental-scale, species-specific urban scores

To assign species-specific urban scores, relative to one another, we needed a continuous measure of urbanization (Evans, Chamberlain, Hatchwell, Gregory, & Gaston, 2011). Different potential metrics can be used (e.g. human population density, built-up area). However, we used night-time lights (Elvidge, Baugh, Zhizhin, Hsu, & Ghosh, 2017) as a continuous measure of urbanization intensity, calculated at a continental scale. There is strong support for the use of night-time lights as a proxy for urbanization (Zhang & Seto, 2013), with publicly accessible data for the world, making this approach generalizable and tractable (Elvidge et al., 2017).

We then integrated the remotely sensed map of night-time lights (Elvidge et al., 2017) with eBird data (Sullivan et al., 2014). eBird is a large citizen science project hosted by the Cornell Lab of Ornithology with >600 million global bird observations contributed by >400,000 participants, with data freely accessible to researchers and practitioners (https://ebird.org/data/download). It has a semi-structured citizen science protocol, relying on volunteer birdwatchers submitting "checklists" of birds. Each checklist documents the time, date, location, distance travelled, duration and whether it is complete—where all birds identified visually and/or audibly are recorded. Observations which fall outside predetermined spatiotemporal filters of the expected bird species and species' counts are reviewed by regional experts. For our approach, we filtered the overall pool of potential eBird checklists/observations based on the following criteria (for full details regarding the treatment of eBird data and calculation of urban scores, see Callaghan et al., 2019b and Appendix S1):

1. Included only eBird checklists from mainland Australia (Appendix S2);
2. Included only complete eBird checklists;
3. Included only eBird checklists which followed the travelling, random, stationary, area or BirdLife Australia protocols;
4. Included only eBird checklists which recorded birds between 5 and 240 min;
5. Included only eBird checklists which travelled <5 km or <500 Ha;
6. Any checklists shared among multiple observers were randomly subsampled, to avoid duplication;
7. Seabirds were omitted from the potential suite of species, given our focus on terrestrial bird species.

A species-specific urban score was defined as the median of a species' distributional response to the continuous measure of urbanization. It was calculated by assigning a continuous measure of urbanization to each bird observation, using Google Earth Engine (Gorelick et al., 2017), comprising the mean VIIRS night-time lights value within a 5-km buffer of the observation. The 5-km buffer was used to account for potential spatial mismatch between where the birds were recorded and where the spatial coordinates are located (Callaghan et al., 2019b). The assignment of urban scores was robust to the buffer size used (Appendix S3). A species needed a minimum of 100 observations to be included in the potential suite of species, and this resulted in a total of 581 species with a resulting urban score derived using this methodology (Appendix S4). We also compared the use of night-time lights to assign urban scores with human population density, and the two different measurements of urbanization showed strong agreement (Appendix S5). Further, these urban scores appear robust to the biases associated with individual eBird checklists, demonstrated by subsampling random eBird checklists irrespective of the distance travelled or time spent surveying and then re-calculating the species-specific urban scores (Appendix S6).

3.2 | Defining UGII

Our approach to defining UGII is analogous to that of a classical community ecology approach. To measure the urbanness of a bird community (i.e. UGII), we first measure the local-level urbanness, averaged among the local-level sampling units, followed by the overall urbanness of the regional pool of species, which provides us with a measure of a community-level urbanness which is the proportion of the local-level urbanness and the regional-level urbanness. This is most analogous to beta diversity (Whittaker, 1960), the proportion of regional diversity and local diversity (Anderson et al., 2011; Jost, 2007): $\beta_{SHANNON} = H_\gamma / H_\alpha$, where H represents effective diversity (Jost, 2007) for the regional (i.e. γ) and local (i.e. α) level and H_α is the average of the effective diversity values for all local-level sampling units.

Each species-specific urban score (U_s) is associated with a species observed on a local-level survey (i.e. in our instance, we used an eBird checklist). The list of species on this local survey can then be visualized as a distribution of U_s on that local survey (Figures 1 and 2a), representing the cumulative "urbanness" of that local-level sampling unit. The extent to which an individual local-level sampling unit (i.e. eBird checklist) reflected the urban adaptation of the local bird community (U_{α_i}) was calculated by listing the species-specific urban scores (U_s) for every species observed on the local-level survey. U_{α_i} was defined as the 0.25 quantile score of this list (i.e. distribution) to encompass a minimum level of "less urban birds", based on the distribution of U_s. The distribution of urban scores has the potential to vary greatly, making more conventional measures of a distribution of U_s (e.g. mean and median) inappropriate as the same score could be obtained for quite different local-level surveys. Thus, U_α is the average of all U_{α_i} within the local level—an urban greenspace. The regional urban score (i.e. U_γ) is the 0.25 quantile of the distribution of U_s across all species observed in a 50-km buffer (i.e. the species' pool). It follows that $\text{UGII} = U_\beta = U_\gamma / U_\alpha$.

For U_α, the average urban indices among all checklists in a greenspace, we also accounted for known sampling biases, typical of citizen science data (Appendix S7). We fitted generalized additive models, adjusting the urban indices to the "average" urban index on a checklist for a given greenspace (see Appendix S7 for details). To calculate U_γ, we extracted all eBird checklists within a 50-km buffer surrounding each greenspace (Figure 2a) and the overall species pool was defined as the terrestrial and freshwater species with >100 total observations in the eBird database (Appendix S4), occurring on at least 2.5% of checklists within the buffer. This regional species pool was subjective and could

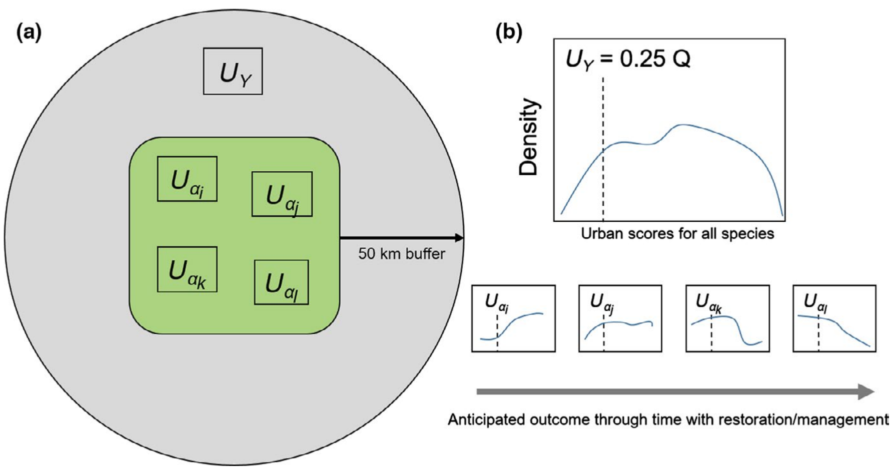

FIGURE 2 The theoretical workflow of Urban Greenspace Integrity Index (U_β). (a) A local greenspace (represented by the green square) within a theoretical city (represented by the grey circle) would be repetitively sampled, in our case using eBird checklists. Each species on an eBird checklist already has an assigned species-specific urban score (U_s), and thus, each checklist (i.e. where each U_{α_i} represents a unique and independent local-level sampling unit in the figure) receives an urban index (U_{α_i}). At the same time, U_γ represents the species pool in a 50-km buffer. (b) Through time, if restoration projects within a greenspace are successful, we would anticipate a shifting distribution (shown by the four graphs along the bottom) whereby the local-level community measure (U_α) is becoming less urban. Simultaneously, though time, the distribution at a greenspace would better approximate U_γ—calculated as the 0.25 quantile of the urban scores, for all species in the regional species pool

be varied across taxa and research goals, similar to regional species pools used in community ecology (Dupré, 2000). We used 50 km as a reasonable estimate of the landscape for birds and to illustrate the application of UGII. Alternatively, a biogeographical feature could be used. The key here, however, is to provide a regional scaler for the urbanness of a local community, hence the parallel with Whittaker's (1960) definition of beta diversity. This scaler allows for comparison of urban greenspaces throughout the world. A greenspace with UGII <1 should aim to shift their UGII to 1, and conversely, an urban greenspace with UGII >1 is doing exceptionally well. Within a specific city, we expect U_α to perform similarly with U_β. But, in order to make U_β comparable across greenspaces in different parts of the world, the regional scaler (U_γ) is necessary.

4 | PROPERTIES OF THE URBAN INDEX (U_α)

While H_{α_i} is not tied to U_{α_i} statistically (see Figure 1), there is an empirical correlation. To demonstrate this, we focused on the local-level sampling unit (i.e. an eBird checklist) and (a) filtered the data following the aforementioned protocols (Appendixes S1 and S7); (b) plotted the raw data relationships; (c) fitted models, adjusting the values for known sampling biases which impact diversity metrics on a checklist (Appendix S7); and (d) plotted the adjusted relationships.

Shannon entropy (Figure 3a) and species richness (Figure 3c) on a checklist were negatively correlated with the urban index of a checklist. After accounting for biases, the relationship became more evident (i.e. consistent) for both measures (Figure 3b,d). We present these results (Figure 3) independent of season, as analyses showed a minimal effect of season among greenspaces (Appendix S8). Checklists with high diversity (i.e. Shannon entropy and species richness) tended to have low urban indices and vice versa. Furthermore, we extracted all eBird checklists, meeting our filtering criteria (Appendixes S1 and S7), within 100 kilometres from Melbourne (N = 38,111), Sydney (N = 26,467) and Brisbane (N = 37,212). As expected for the response of a bird community to an urbanization gradient, as the distance from the city centre increased, the urban index on a checklist decreased (Figure 4), demonstrating the behaviour of the urban index (U_α).

5 | APPLICATION OF THE UGII TO MEASURE BIODIVERSITY CHANGE

Restoration at a small scale can take many forms, depending on the goals of the restoration. Restoration projects in urban greenspaces

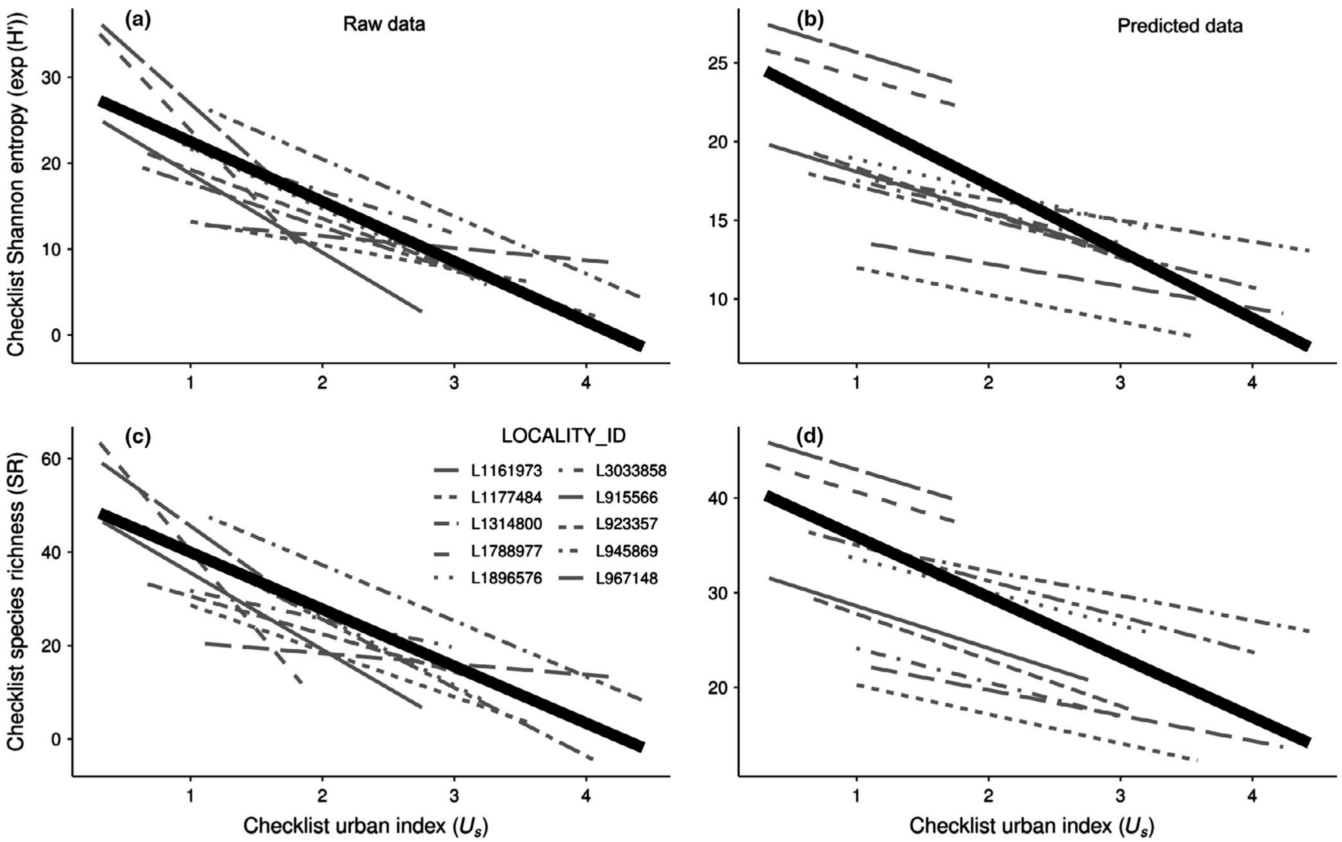

FIGURE 3 The relationship between raw Shannon entropy (a) and species richness (c), and urban index for a checklist, for 10 urban greenspaces. The relationship was strengthened after modelling to account for known sampling biases, predicting the relationship based on an average checklist at each greenspace (i.e. average time and distance travelled) for Shannon entropy (b) and species richness (d). The thick line in each panel represents the cumulative relationship of all greenspaces, with different grey lines individual greenspaces, and all relationships shown with a linear model fit

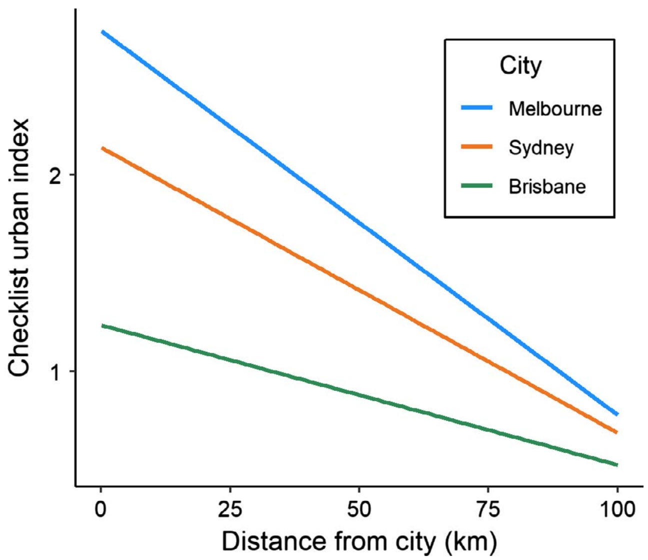

FIGURE 4 The relationship between the urban index on a checklist (U_{α_i}) and distance from city centre, based on all eBird checklists which met our filtering criteria, within 100 km of Melbourne (*N* = 38,111), Sydney (*N* = 26,467) and Brisbane (*N* = 37,212), showing linear model fits of the data

can include revegetating native habitats, installing nest boxes for hollow-nesting species or modifying hydrology to create habitat for waterbirds. A shared goal often includes increasing the local-species pool, by attracting those species which are "least-urban" and native, ultimately aiming to combat biotic homogenization (McKinney, 2006).

Our objective here is not to dictate *how* a local greenspace should implement change, but rather provide a repeatable procedure for defining and monitoring targets. Our index allows simple monitoring of success or failure, while incorporating local expertise regarding restoration options (e.g. habitat feasibility). Restoration of ecosystems is increasingly adaptive, involving public value management (Hodge & Adams, 2016) and UGII is a useful tool in these cases, relying on publicly collected data. For example, in an adaptive scheme of management, if there is an opportunity to adjust the hydrology of a greenspace, using UGII to identify target waterbird species is a good first step. Ultimately, we are hopeful that setting up habitat for slightly less urban species than are present may create the necessary conditions for recolonization by other species, both avian and otherwise.

6 | IMPLEMENTATION IN AN URBAN GREENSPACE

Accumulation of citizen science data in urban ecosystems is rapid and extensive across the world (e.g. eBird), and this is likely to provide new opportunities for historically undersampled countries (e.g. tropical, developing countries). Our framework (Figure 5a) could be simply applied to any urban greenspace with adequate eBird data. Step 1 involves downloading the data and calculating UGII (U_β) = U_γ / U_α. Steps 2 and 3 involve investigating and identifying the suite of species most feasible for local recolonization, which are dependent on the type of habitat features that can be targeted. These steps require at least some local expertise. It then follows (step 4) that the restoration process can be monitored through the same means by which it was defined. At this step, local governments could encourage greater participation of citizen science by their community through targeted campaigns, increasing data collection. We envision this as a cyclical framework, whereby restoration takes place for a small set of targeted species, followed by further restoration for the next set of species (Figure 2b), continuously shifting the local species index (U_α) towards the regional index (U_γ).

6.1 | A case study

To illustrate how a greenspace manager would implement this framework (Figure 5a), we provide a fictional case study (Figure 5b), taking Centennial Park, in Sydney, Australia, as our example greenspace—given our local understanding (Callaghan, Martin, Major, & Kingsford, 2018). Centennial Park receives 30 million visitors a year, representing a typical heavily visited greenspace, also known for its biodiversity.

- **Step 1**: $U_\gamma = 0.76$ (regional index), and $U_\alpha = 2.27$ (local index), thus UGII (U_β) = 0.33. For simplicity, and because season has minimal impact in this instance (Appendix S8), we collapsed seasonal derivations to a single value. This may not be applicable for regions with a strong seasonal climate and associated seasonal variations in bird diversity.
- **Step 2**: To calculate U_γ, we retrieved the species' pool; 101 species based on our criteria. We identified species lower than our calculated U_α, but not necessarily lower than U_γ. It was critical to choose species relevant for a hypothetical restoration in terms of the functionality of the habitat. We identified two small-bodied bird species with relatively low U_s, which are thought to respond to enhanced understory: Red-browed firetail (*Neochmia temporalis*) with a U_s of 0.88 and grey fantail (*Rhipidura albiscapa*) with a U_s of 0.66. Note that these values can be between U_α and U_γ. Both species could already exist in low abundance (i.e. occur on a small proportion of checklists from that site), but increasing the abundance of these species would result in increased probability of detection on a checklist, decreasing U_α and the overall "urbanness" of the avian community.
- **Step 3**: While delineating the species to target (Step 2 above), local knowledge of habitat functionality and the link with bird species was critical. Indeed, Red-browed firetail and grey fantail were chosen because we know these small-bodied birds rely on large amounts of understory shrubs for cover, and thus, our identified recommendation for this restoration project would be to increase the amount of understory at Centennial Park (Figure 5b).
- **Step 4**: eBird submissions are rapidly increasing for Centennial Park (Callaghan et al., 2018), and the utility of these could be improved with a clear restoration goal, using local birding groups

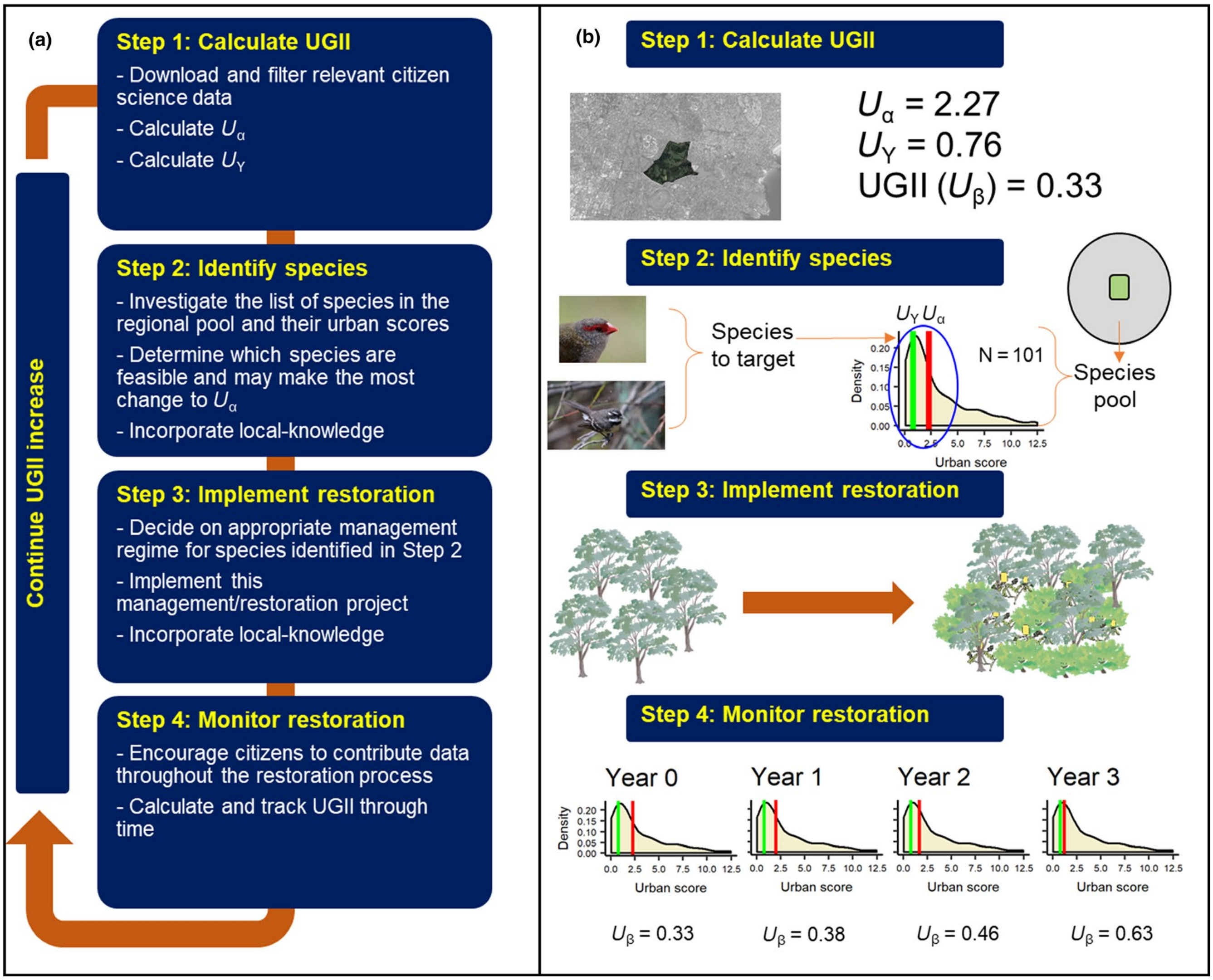

FIGURE 5 (a) Application of the Urban Greenspace Integrity Index (UGII) in urban greenspace management, with (b) a worked example from Centennial Park, Sydney, NSW, Australia, demonstrating how UGII can track potential restoration. Image credit for map: © Google

and social media platforms at little cost to managers. Restoration progress could be tracked through time, by recalculating UGII. Restoration, if successful, would be reflected in a lowered U_α and increased UGII (U_β). This process can progressively incorporate different species, related to specific habitat improvements, continually increasing UGII (Figure 5b).

7 | FUTURE DIRECTIONS

Following classical community ecology (Anderson et al., 2011), UGII is comparable across greenspaces, because it is the *proportion* of the urban index of the regional community (U_γ) represented in the local community (U_{α_i}). As such, UGII is meant to be a measure by which greenspaces can be compared, complementary to classical community metrics. For instance, studies could be conducted to elucidate patterns of UGII in response to various habitat attributes (e.g. Figure 4). UGII is also robust to spatial scale, meaning that different spatial scales can be used, depending on local influences, restoration goals, funding, and logistical constraints. We restricted our application to urban greenspaces, but large-scale restoration projects over entire cities (e.g. regreening a city by planting millions of trees) could be tracked with this conceptual framework. At the city scale, all relevant checklists would be sampling units for that city (e.g. Figure 4), and a larger catchment (i.e. >50 km buffer) of birds could then be defined as the regional pool of species, although additional modelling steps (e.g. spatial autocorrelation) would need to be considered. Moreover, we present this framework with the notion of tracking restoration, but similarly, land degradation or destruction could be tracked using our framework. Our framework is adaptable to different temporal scales, allowing for testing of changes where there are strong seasonal effects (e.g. migratory systems). Finally, we focused on urban greenspaces because of the large amounts of available citizen science data within urban areas, but we further envision a broader approach where other species-specific "scores" can be calculated based on continuous measures of response to forms of human (e.g. agricultural intensity) and natural (e.g. forest density) land cover types.

8 | CONCLUSIONS

Here, we show how the era of "big data" in ecology (La Sorte, Lepczyk, Burnett, et al., 2018) provides considerable opportunities to track changes in biodiversity, using urbanization impacts on birds as an example. Although big data means many ecological questions at large spatial and long temporal scales can be addressed, we stress the importance of considering applications at the local scale. And integrating local citizens with restoration projects in their "backyards" has the added benefit of increasing awareness of biodiversity issues both generally and politically (McKinley et al., 2017). We provide the conceptual basis for collecting and analysing data globally, but acting locally.

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AUTHORS' CONTRIBUTIONS

All authors contributed to conception, analyses and drafting and writing of the final manuscript and give approval for publication.

DATA AVAILABILITY STATEMENT

Data and R scripts used to produce the analyses and figures in this manuscript, via the Zenodo Repository https://doi.org/10.5281/zenodo.2698340 (Callaghan et al., 2019a).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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