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Estimating changes in distribution trend of alien birds in urban areas using citizen science data

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Abstract
Urban ecosystems are suitable for the introduction and spread of alien bird species, and early detection of their establishment and expansion is crucial to reduce potential negative impacts. In this context, the use of opportunistic citizen science data can have considerable advantages in relation to conventional scientific approaches. We gathered records of parakeets and parrots (Psittaciformes) and mynas and starlings (Sturnidae) for the urban area of Lisbon (Portugal) from the eBird database. We used this opportunistic citizen science data to document the establishment and expansion and to estimate distribution trends of alien bird species in urban ecosystems. In the last decade there has been a considerable increase in the amount of opportunistic citizen science data available in eBird for our study area. The probability of presence of the Senegal parrot, rose-ringed parakeet, blue-crowned parakeet, and crested myna was positively influenced by the number of lists. For the rose-ringed parakeet, blue-crowned parakeet, and crested myna, the year positively influenced the probability of presence, suggesting an increase in distribution range. We observed that spatio-temporal variations in effort associated to opportunistic citizen science data sources may generate bias in trend estimates, and therefore we recommend the effort should always be accounted for. Our approach agreed with the documented expansion of alien bird species in the study area, supporting the potential usefulness of opportunistic citizen science in providing early detection on biological invasions in urban ecosystems, particularly where this is the best or the only source of information available.

Keywords Community science · Distribution range trend · Early detection · eBird · Exotic parrots · Invasive bird species

Introduction

Urban sprawl across the world has caused profound impacts on biodiversity, with future scenarios suggesting alarming biodiversity losses (Li et al. 2022; Simkin et al. 2022). However, cities also create opportunities for some species to thrive, including native and alien species (Concepción et al. 2016; Zisenis 2015), and thus, a better understanding of urban biodiversity communities is still needed (Swan et al. 2021).

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Many bird species have been introduced worldwide across different ecosystems, with several of these alien species assuming an invasive status (Menchetti and Mori 2014; Carboneras et al. 2018). Urban ecosystems are often suitable for the introduction and spread of alien bird species, since these environments may offer less resistance to the proliferation of invaders than natural habitats (Sol et al. 2017; Cardador and Blackburn 2019; Ascensão et al. 2020). This may be due, for instance, to the depletion of native species and potential competitors in urban areas (e.g., as a consequence of habitat destruction and conversion in built areas), the lower abundance of natural predators and parasites, and the increased likelihood of alien species to find a favourable niche to occupy (Hernández-Brito et al. 2014; Sol et al. 2017; González-Lagos et al. 2021). Urban environments can provide new opportunities and niches to alien bird species, which are seldom explored by native species, e.g., nesting sites in man-made structures and food supplies, such as artificial feeders and human waste (Shochat et al. 2010; Minor et al. 2012; Sol et al. 2017; Cohen et al. 2019).

Early detection of the establishment and expansion of invasive species is among the most crucial aspects to reduce the negative impacts of biological invasions worldwide (Hulme 2009; Reaser et al. 2020). The use of new approaches and technologies can improve the detection and monitoring of biological invasions (Courchamp et al. 2017; Kamenova et al. 2017; Martínez et al. 2020; Morisette et al. 2020; Hernández-Brito et al. 2022). Citizen science (also referred to as community science) is a potentially valuable emerging tool to attain early detection of invasive species (Crall et al. 2010; Maistrello et al. 2016; Larson et al. 2020). Open access observational data can be considered a form of opportunistic citizen science (van Strien et al. 2013; Bradter et al. 2018; Soroye et al. 2018), and the amount of available information for birds is nowadays enormous due to sources such as eBird (Sullivan et al. 2009, 2014; www.ebird.org). Accordingly, opportunistic citizen science data from eBird has been successfully used for many purposes in bird monitoring and conservation (Davis et al. 2014; Callaghan and Gawlik 2015; Sullivan et al. 2017; Vall-llosera et al. 2017; Walker et al. 2017; Horns et al. 2018).

The use of opportunistic citizen science data can complement conventional scientific approaches, having several strengths, namely when studying invasive bird species in urban environments (Cooper et al. 2007; Aceves-Bueno et al. 2015; Wright et al. 2015; Luna et al. 2018): 1) most potential participants live in the area of interest (i.e. cities), have good experience in species identification, and supply a large amount of data (Tulloch and Szabo 2012; Randler et al. 2021); 2) the involvement of non-professional participants provides awareness to the general public to influence decision making-processes; and 3) this approach offers a cost-effective solution, in which volunteers contribute to active conservation. However, opportunistic citizen science data can also have some shortfalls, mostly related to considerable variation in observer's experience and behaviour, and spatial and temporal bias in data coverage resulting from the absence of observations and/or uneven sampling effort (Tulloch and Szabo 2012; Kelling et al. 2015; La Sorte and Somveille 2020; Neate-Clegg et al. 2020). Considering the potential biases, modelling approaches that do not account for the effort should be avoided when using opportunistic citizen science data to estimate species distributions and their potential changes (Isaac et al. 2014; Johnston et al. 2021). Opportunistic citizen science data has been used to determine changes and trends in population and distribution of several animal groups under different scenarios and employing different modelling approaches, therefore having varying data inputs and degrees of complexity (van Strien et al. 2013; Kamp et al. 2016; Dennis et al. 2017; Walker and Taylor 2017; Horns et al. 2018; Johnston et al. 2021; Hernández-Brito et al. 2022). However, documenting early detection of establishment and invasion by alien birds and estimating distribution trends using opportunistic citizen science data can present additional challenges. The number of records in early stages of invasive species establishment is generally small, limiting the robustness of statistical analysis. In addition, alien bird records in opportunistic databases are often incidental records, having no effort-related parameters associated to the list (e.g., observation time, number of species detected).

The urban area of Lisbon (Portugal) has been successfully occupied by several alien bird species along the past three decades (Costa et al. 1997; Matias 2002, 2008; Saavedra et al. 2015; Luna et al. 2016; Keller et al. 2020; Equipa Atlas 2022). Despite the clear establishment and increase for some of these alien bird species, when this process started and how it developed along time and space is not known with detail. Therefore, this case study seems suitable to develop our main objective of checking if the opportunistic citizen science data can document the process of introduction and establishment and provide distribution trend estimates of alien birds in urban ecosystems within a relatively broad time frame. We expected that opportunistic citizen science should be capable to provide some hints on distribution changes in an urban area, despite the potential biases caused by spatial and temporal variations in the amount of data input (i.e., effort).

Methods

Study area

The study area overlaps in great part with the Lisbon Metropolitan area and corresponds to 18 municipalities belonging to the districts of Lisbon, Santarém, and Setúbal (Portugal; Fig. 1). It includes the country's capital, Lisbon, and its satellite and nearby cities, holding about 2.81 million people (population density between 57 and 7210 inhabitants/km2; mean ± SD = 1998.5 ± 2153.6 inhabitants/km2; 2021 census: https://www.pordata.pt/censos/resultados/emdestaque-portugal-361). The area is delimited westwards and southwards by the Atlantic Ocean, and it includes the estuary of the river Tagus. The climate is typically Mediterranean with mean annual temperatures ranging between 15–17.5 ºC and mean annual rainfall ranging between 500–800 mm; while topography is mainly flat or slightly undulating with altitudes mostly below 200 m a.s.l. (APAmbiente 2020). The study area is partly dominated by an urban matrix, more continuous in the northern margin of the Tagus. Older areas of Lisbon and its satellite cities have several eighteenth century gardens embedded in the built area, which are rich in tropical trees. In the uppermost part of the Tagus estuary and eastwards (south of Tagus river), the study area is comprised mostly by a mixed landscape with woodland patches

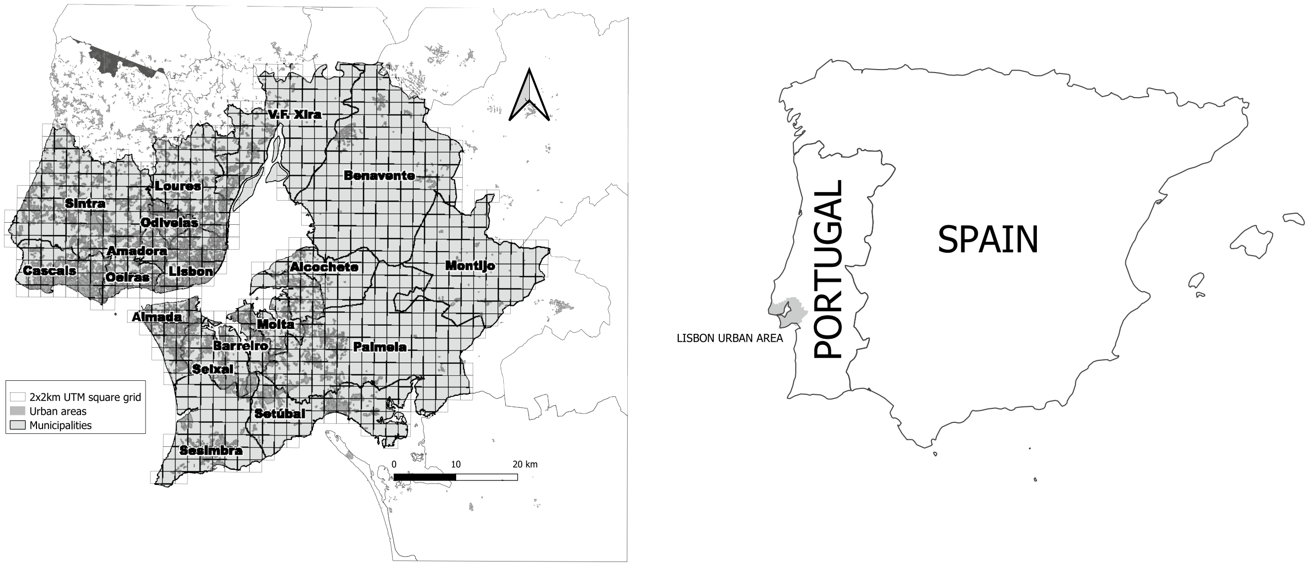

Fig. 1 Municipalities included in the study area, coinciding mostly with the Lisbon Metropolitan area (excluding Mafra and including Benavente), the sampling grid (2×2 km UTM squares), and the urban areas (dark grey)

(mainly oak and pine woods), agricultural fields, and more scattered urban areas. The region has been popular among birdwatchers and bird photographers, particularly in the last two decades (Moore et al. 2014). We used as sampling units a total of 841 squares of the 2×2 km UTM reference grid.

Collection of opportunistic citizen science data

We focused on two groups of alien bird species: (1) parrots and parakeets (order Psittaciformes); and (2) mynas and starlings (family Sturnidae, order Passeriformes). The choice took into consideration the existence of previous records in the study area (Matias 2002; Equipa Atlas 2008) and the knowledge of the potential negative impacts of these bird groups (e.g., Menchetti and Mori 2014; Dyer et al. 2017). In addition, most species in these groups have medium body size and conspicuous phenotypic traits (namely plumage, behaviour, and voice), which facilitate their detection and identification by a wide range of observers.

In a preliminary step, we wanted to determine if eBird was the most comprehensive open source of data on alien bird species for the study area. Therefore, beside retrieving records of alien bird species from eBird, we also searched for records on: 1) non-scientific literature reporting bird observations (Portuguese Ornithological Yearbooks and Ornithological News compiled by the Portuguese Society for the Study of Birds – SPEA); 2) three online databases that compile bird observations and/or photographs; 3) eight personal websites reporting bird observations; and 4) books and reports in Portuguese that include alien bird records (Table S1 in ESM1). We gathered 21,079 records for 24 species from order Psittaciformes and 6 species from family Sturnidae in a timespan between 1984 and 2022 (Tables S2 and S3 in ESM1; 1984 was the first year with alien records). The number of records retrieved from eBird (n = 19,454; 92%) largely exceeded the number of records obtained from other sources (n = 1625; 8%; Tables S1 and S2 in ESM1). Five alien species were not recorded in eBird, despite being mentioned in the other data sources. Nevertheless, these species were just sporadically detected in the study area. Accordingly, we used exclusively the information from eBird in the analysis of the distribution trend of alien bird species. eBird (Sullivan et al. 2009, 2014) was launched in 2002 for USA only, being available globally only in June 2010, including Portugal. In 2015, eBird provided its own smartphone app, and in the same year started a partnership with Macaulay Library to upload photos, videos and sounds to checklists.

All the analyses of spatio-temporal trends were based on two datasets collected from eBird: one including all the alien bird records available for the study area (hereafter "alien dataset"), and other with all the records of native birds for the same region (hereafter "control dataset"). The alien dataset included records from 1992 up to 2022. We focused the analyses on six alien species – monk parakeet *Myiopsitta monachus*, Senegal parrot *Poicephalus senegalus*, rose-ringed parakeet *Psittacula krameri*, blue-crowned parakeet *Thectocercus acuticaudatus*, crested myna *Acridotheres cristatellus*, and common myna *Acridotheres tristis* (see species description in Table S4 in ESM1). This choice considered, simultaneously, the species with more records, more years with records (see Tables S2 and S3 in ESM1) and known invasive ability and impact in Europe (Carboneras et al. 2018; White et al. 2019; Keller et al. 2020). Despite the import of wild-caught alien birds was prohibited in Europe after 2005, all six alien species have been popular in the pet market for the last two decades, existing several recorded events of intentional releases and/or captivity escapes, leading to the observation of free-living individuals outside their natural range (Butler 2005; Chiron et al. 2010; Martin-Albarracin et al. 2015; Cardador et al. 2017; Reino et al. 2017; see also Table S5 in ESM1). Each record was assigned to a 2 × 2 km UTM square and included the date. Presence in each square was considered both when the number of individuals observed was specified or not provided ("X" code in eBird).

The control dataset was used as a surrogate of sampling effort in order to assess potential biases and gaps in spatio-temporal coverage that could compromise the suitability of opportunistic citizen science data to estimate trends. The eBird database is organized in a structure of bird lists, each consisting in a sampling unit that assembles the information of each observation event (i.e., date, observation site, eBird survey protocol, and species presence or individual count). Our dataset included all lists (i.e., both "complete lists", which have the starting time and total duration of each observation event, and the distance/area sampled; and "incomplete lists", i.e., occasional observations that might not have effort specification), registered in the study area between 1992 and 2022. To avoid oversampling and analytical bias, we removed: 1) duplicated lists (several observers birding together and sharing the same list); 2) birds that were not identified to the species level; 3) hybrid individuals; 4) domestic and ornamental birds (e.g. ducks, geese and swans in city parks); 5) sea birds; 6) vagrant bird species that need the homologation of the Portuguese Rarities Committee; 7) all the bird records not validated by the eBird regional reviewers; and 8) all alien bird species (to ensure the independence of the two datasets).

Data analysis

To have an indicator of the potential establishment of the six focal alien bird species, we focused our analysis on the spatio-temporal trend of each species across the study area, using the 841 2 × 2 km squares as sampling units. Only data between 1999 and 2022 was used, since the number of alien bird records for prior years was too limited for modelling purposes. We used Generalized Estimating Equations models (GEE; Liang and Zeger 1986; Halekoh et al. 2006; Zuur et al. 2009), which are often employed to estimate population trends in birds (TRIM, Pannekoek et al. 2018; Lehikoinen et al. 2013). The GEEs implement marginal generalized linear models to clustered data, e.g., longitudinal data and repeated measures, being a valuable tool in ecology (Zuur et al. 2009; Pekár and Brabec 2017).

Our response variables corresponded to the presence/absence of each species in the 2 × 2 km squares per year, therefore the GEE models followed a binomial distribution with a logistic link ("logit"). For each GEE model, we considered only the squares where each species was detected at least once. We used "year" and "effort" as explanatory variables. The variable year is the main descriptor of the temporal trend. The variable effort was used to control for potential bias associated to large differences in the number of lists introduced each year in eBird. This variable consisted in the logarithm of the number of complete lists in eBird (control dataset) per 2 × 2 square per year. The number of lists was log-transformed to improve linearity of the model and reduce the effect of outliers. For all six alien species, the collinearity between the variables "year" and "effort" was below the threshold of ± 0.7 (Pearson correlation: monk parakeet $r = 0.37$; Senegal parrot $r = 0.37$; rose-ringed parakeet $r = 0.31$; blue-crowned parakeet $r = 0.48$; crested myna $r = 0.30$; common myna $r = 0.29$). The models used the unique ID of each 2 × 2 km square as grouping variable (clusters) and applied an autoregressive correlation structure ("ar1"), which considers the correlation as a function of the distance (here time) between observations from the same cluster (here each 2 × 2 km square).

Models were validated by checking the plots of residuals. Data were analysed using the statistical software R 4.3.2 (R Core Team 2023) with the package geepack (Halekoh et al. 2006). Statistical significance was set as $p < 0.05$.

Results

Spatio-temporal coverage of opportunistic citizen science data

Between 1992 and 2022, there was a considerable increase in the amount of opportunistic citizen science data available in eBird for our study area. This was evident when considering the total number of lists per year and the total number of records per year, which have increased exponentially after 2010 (Fig. 2). The total number of lists per year in the study area varied from a minimum of 53 in 1996 to a maximum of 14,241 in 2022. Likewise, the total number of records varied from 491 in 1996 to 250,538 in 2022.

The proportion of squares with bird records per year is an indicator of the growth in spatial coverage along the study period. This proportion ranged between 4 and 9% during the period from 1992 to 2003, and then started to increase 2004 onwards to reach the maximum coverage of 58% of the squares with records in 2022 (Fig. 2). There was a considerable variation in the total number of lists per

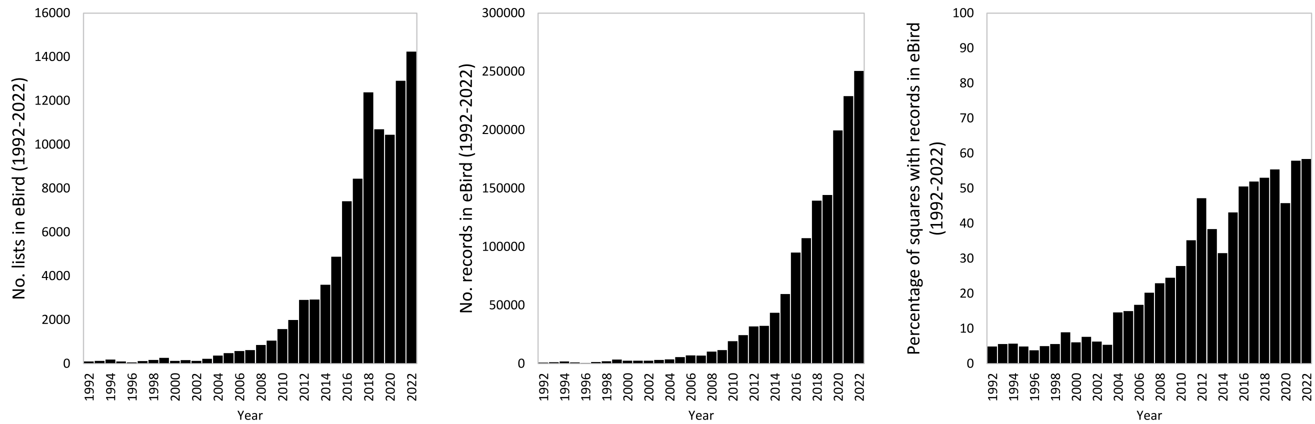

Fig. 2 Total number of lists per year (left), total number of records of birds per year (centre), and proportion of 2×2 km UTM squares with bird records per year in eBird for the period 1992–2022 (right)

2×2 km square across the study area. The squares with a greater number of lists were predominantly those located in the most human populated areas (Fig. 3). Twenty-three squares (3%) had more than 1,000 lists (maximum 5,485), whereas 153 squares (18%) had between 100 and 999 lists, 307 squares (37%) had between 10 and 99 lists, 283 squares (34%) had between 1 and 9 lists, and 76 squares (9%) had no lists in eBird.

Estimates of spatio-temporal trends of alien species

Between 1999 and 2022, the presence of at least one of the six alien bird species was detected in a total of 184 2×2 km squares (22% of the total squares in the study area). The crested myna was detected in a total of 178 squares (21%), the rose-ringed parakeet in 161 squares (19%), the blue-crowned parakeet in 57 squares (7%), the Senegal parrot in

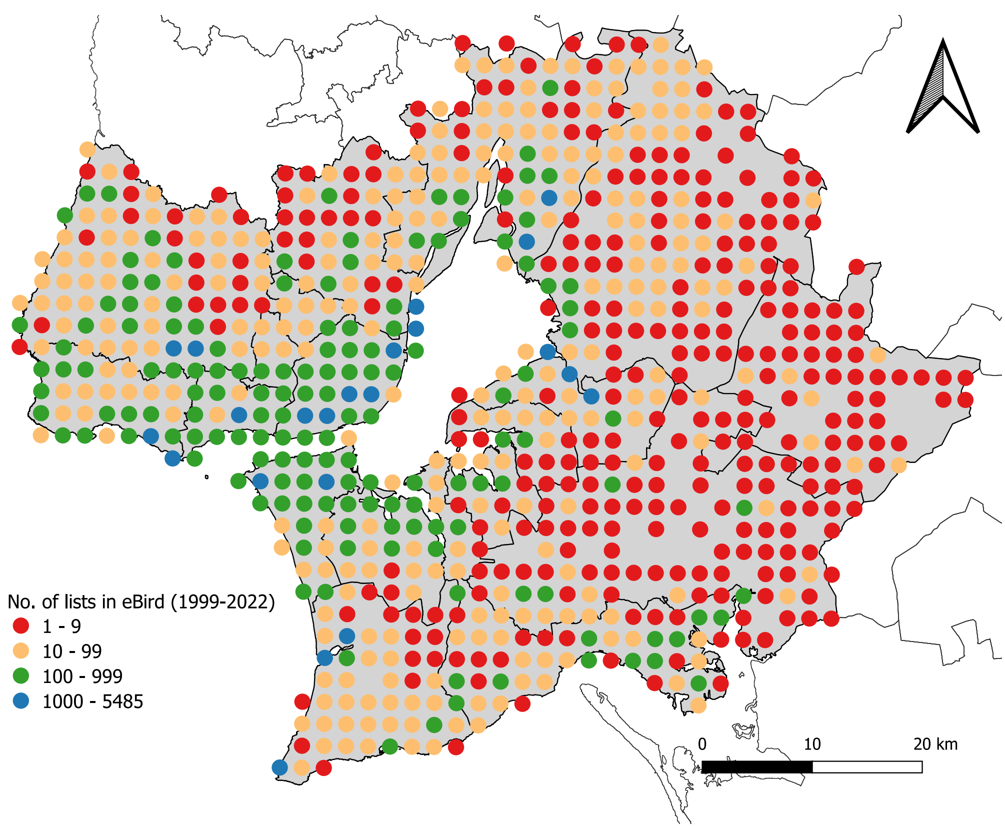

Fig. 3 Spatial pattern in the number of lists in eBird for each 2×2 km UTM square for the period 1999–2022

17 squares (2%), the monk parakeet in 14 squares (2%), and the common myna in 10 squares (1%). The proportion of squares with presence of crested myna and the rose-ringed parakeet in each year (from the total of squares with presence during the whole period) showed an increasing pattern, reaching a maximum of 18% for the crested myna in 2018 and 17% for the rose-ringed parakeet in 2019 (Fig. 4). The proportion of squares with presence of blue-crowned parakeet showed a smaller increase, reaching a maximum of 7% in 2018. The monk parakeet, Senegal parakeet, and common myna showed a constantly low proportion of presences along the years.

When considering the presence of the six alien bird species in the 2 × 2 km squares in two temporal intervals (1999–2010 and 2011–2022), it is evident, for four of these species, that most presences occurred only in the latter period (Fig. 5): rose-ringed parakeet (81% of overall presences), blue-crowned parakeet (95%), Senegal parrot (65%), and crested myna (88%). The common myna and the monk parakeet both had respectively 20% and 36% of the overall presences in the first period only (Fig. 5).

The results of the GEE models showed that the probability of presence was positively influenced by the number of lists in four species – Senegal parrot, rose-ringed parakeet, blue-crowned parakeet, and crested myna (Table 1). For three of these species, the year was also found to positively influence the probability of presence – rose-ringed parakeet, blue-crowned parakeet, and crested myna. On the contrary, the common myna showed a negative relationship between the probability of presence and the year. Accordingly, we assume that the increasing number of lists in eBird along the study period (1999–2022) has the potential to generate bias in assessing trends in the distribution range when using this source of opportunistic citizen science data. Nevertheless, even considering the effort effect (i.e., the number of lists), the GEE approach still suggested that between 1999 and 2022 there was a considerable increase in the number of 2 × 2 km squares registering the presence of the rose-ringed parakeet, blue-crowned parakeet, and crested myna. These results indicate that these three alien bird species have increased their distribution range during the last two decades, most likely as a consequence of a population growth

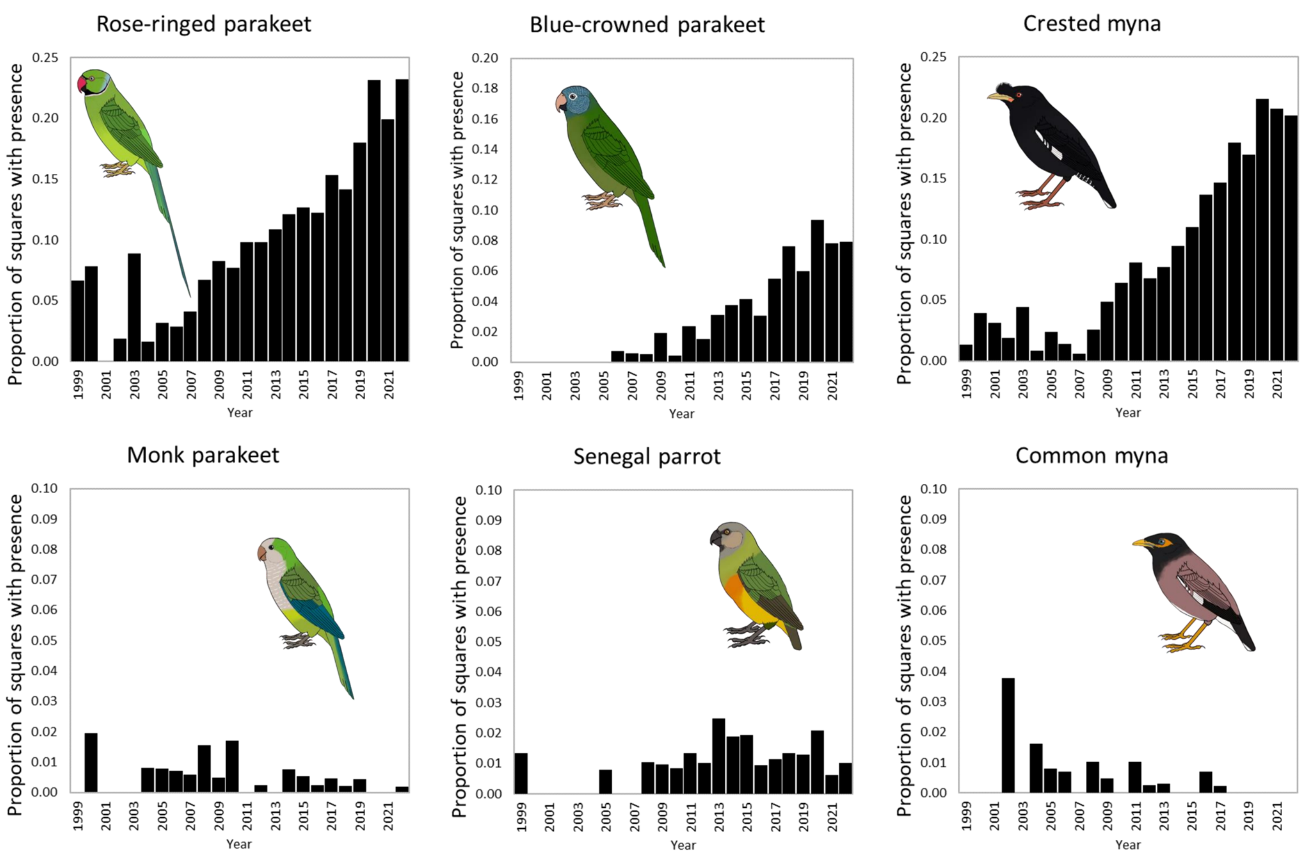

Fig. 4 Proportion of 2 × 2 km UTM squares with presence of each alien bird per year in relation to the total number of squares the species was detected between 1999 and 2022 (rose-ringed parakeet = 161 squares; blue-crowned parakeet = 57 squares; crested myna = 178 squares; monk parakeet = 14 squares; Senegal parrot = 17 squares; common myna = 10 squares)

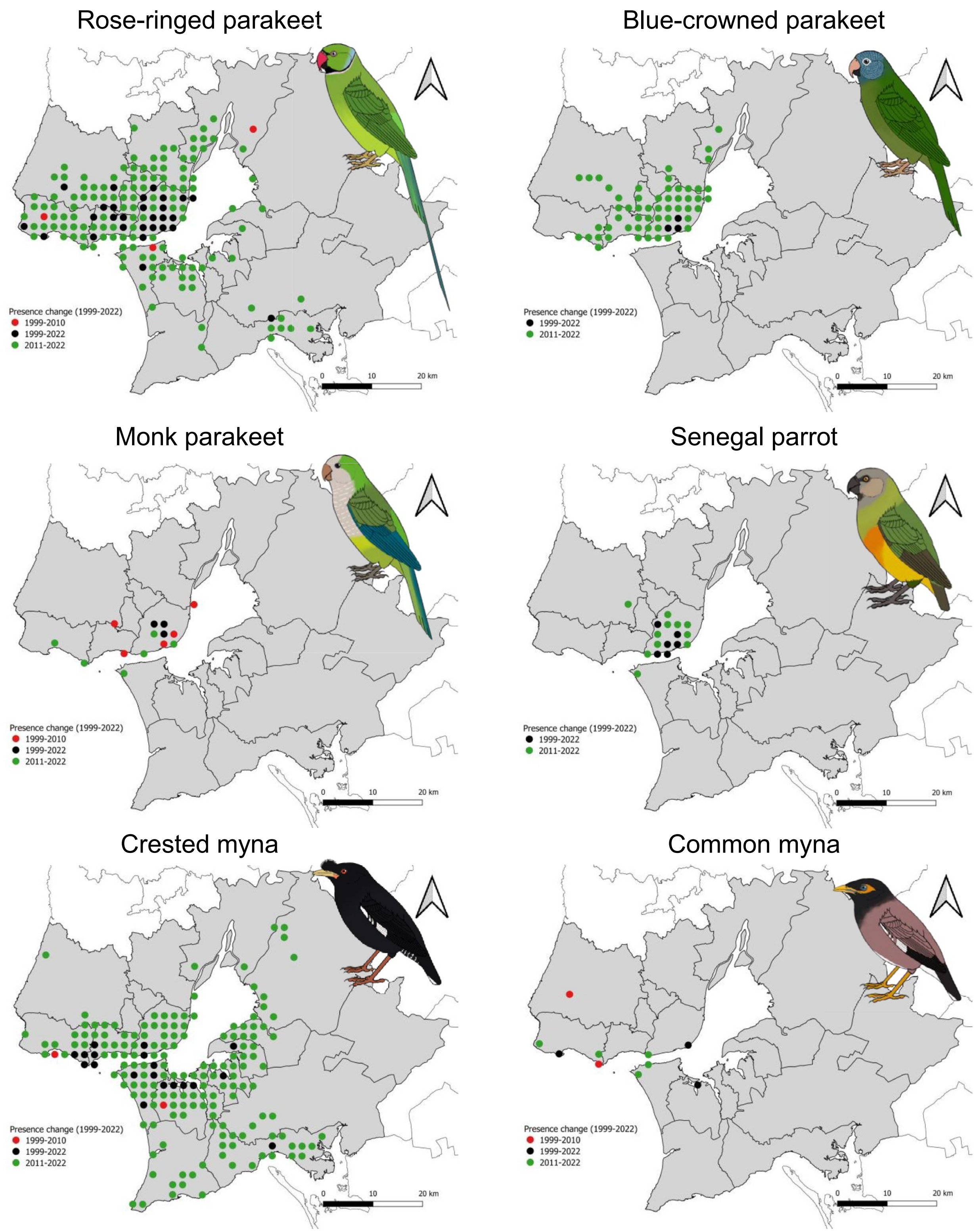

Fig. 5 Presence of the six alien bird species in the 2×2 km UTM squares in two periods (1999–2010 and 2011–2022). Red circles – presence only in 1999–2010; green circles – presence only in 2011–2022; black circles – presence in both periods. Rose-ringed parakeet *Psittacula krameri*; blue-crowned parakeet *Thectocercus acuticaudatus*; monk parakeet *Myiopsitta monachus*; Senegal parrot *Poicephalus senegalus*; crested myna *Acridotheres cristatellus*; common myna *Acridotheres tristis*

Table 1 Results of the Generalized Estimating Equations (GEE) models to analyse the spatio-temporal pattern (1999–2022) of the presence of six alien birds (presence/absence of each species used as response variables). Year and number of lists (logarithm of the number of lists per year in eBird as surrogate of effort) were used as explanatory variables. P – p value; SE – Standard Error

Species	Year		Number of lists		Sample size (no. 2×2 km squares)
	Estimate (SE)	P	Estimate (SE)	P	
Monk parakeet *Myiopsitta monachus*	0.018 (0.047)	0.70	0.043 (0.195)	0.83	14
Senegal parrot *Poicephalus senegalus*	-0.028 (0.042)	0.50	0.597 (0.136)	< 0.001	17
Rose-ringed parakeet *Psittacula krameri*	0.116 (0.019)	< 0.001	0.705 (0.073)	< 0.001	161
Blue-crowned parakeet *Thectocercus acuticaudatus*	0.204 (0.046)	< 0.001	0.697 (0.099)	< 0.001	57
Crested myna *Acridotheres cristatellus*	0.150 (0.020)	< 0.001	0.646 (0.070)	< 0.001	178
Common myna *Acridotheres tristis*	-0.092 (0.032)	0.004	0.361 (0.218)	0.10	10

and not just because of an increase in annual amount of citizen science data. The results on the common myna suggest that this species may have declined after an initial establishment in the study area, with no obvious influence of the effort in the trend.

Discussion

The increasing volume of information being uploaded to databases, such as eBird (Sullivan et al. 2014; Hochachka et al. 2021), along with our results, suggests that opportunistic citizen science data has the potential to be a powerful tool to detect the establishment of alien bird species. The currently available data, particularly for urban areas, also has the potential to provide good insight of the distribution trend of alien birds along a relatively large time span. Advantages are clearer in large urban areas, which generally hold a considerable number of active birdwatchers. In areas that are seldom visited, opportunistic citizen science data has some limitations in rendering reliable monitoring data (Johnston et al. 2020; La Sorte and Somveille 2020). Nevertheless, before drawing any conclusions about the trends and establishment of alien bird species using opportunistic citizen science data, we strongly reinforce the importance of considering spatial and temporal variation in effort (i.e., number of visits and their duration), which generate coverage biases (Horns et al. 2018; Johnston et al. 2021).

Like in many other countries, the amount of opportunistic citizen science data in Portugal has registered an increasing trend in the last decades (Hochachka et al. 2021). This pattern was clear in the urban area of Lisbon. Although our dataset covered a period of around 30 years, the most visible increase in data availability only started in 2005. This is of course related to the development of internet-based online websites and platforms that allow reporting bird observations. The available dataset was nonetheless sufficient to cover most of the first known records of alien bird escape events in the region, some occurring in the 1990's (as reported in: Matias 2002; Equipa Atlas 2008; Catry et al. 2010). Our study area is the most populated region in Portugal, with a corresponding large number of birdwatchers and bird records. Despite this fact, the spatial coverage of the opportunistic citizen science data was clearly biased: urban areas and favourite birdwatching sites had a considerably greater number of lists in eBird. Therefore, an eventual replication of this study in a less populated area, may not yield sufficient data from opportunistic citizen science in order to detect the establishment of alien bird species. We stress the fact that, although the occurrence of alien bird species is most often associated to urban areas (Cardador and Blackburn 2019; Ascensão et al. 2020), it is not exclusive of urban areas for some species, e.g., wetlands and native forests (Sanz-Aguilar et al. 2014; Pereira et al. 2020).

Despite of eBird being available in Portugal since 2010, its boost of popularity in Portugal began when the former initiative PortugalAves (started in 2009 and hosted in WorldBirds) was transferred to eBird in 2015. These systems of data-sharing may have contributed to change the behaviour of Portuguese birdwatchers in terms of location and duration of their observation events. These potential changes may create differences in the quantity and quality of data available in eBird before and after the arrival of these initiatives, and consequently, generate biases when using long temporal series, as in our case study. Some changes in birdwatchers' behaviour may be assessed from the data and then considered in modelling analysis as effort covariates (Johnston et al. 2021). However, other behavioural changes may be suspected but hardly assessed, and thus not possible to control for their effect. The first case (known effects) includes the variables related to effort, either directly inferred from information given by the observer about the observation event (e.g., duration, distance), but also indirect indicators of effort such as number of lists and proportion of complete lists. The second case (non-controllable effects) includes changes in: (1) the availability of information to correctly identify alien bird species (e.g., birds guides, online resources); (2) the willingness of birdwatchers to retrospectively insert bird observations in eBird (recorded in personal paper notebooks); (3) the willingness to report alien birds, namely those species that can be considered occasional escapes; and (4) the temporal variation of filters created by local eBird reviewers for alien bird species validation. These effects can generate increased data variability, being harder to assess distribution and population trends, but this intrinsic limitation must be accepted in order to benefit from the many advantages of citizen science data.

Our modelling approach evidenced that in the four species with most records (Senegal parrot, rose-ringed parakeet, blue-crowned parakeet, and crested myna), the probability of presence in the sampling units each year was positively influenced by the corresponding number of lists (i.e., effort covariate). Despite this, the results also suggested that three of these species (rose-ringed parakeet, blue-crowned parakeet, and crested myna) showed an increasing spatio-temporal trend in the study area. These positive trends are visible in the increasing proportion of squares with presence for the three species. Therefore, despite the intrinsic limitations of the data and the clear effect of observation effort, the increase in distribution range of the most common species still seems to emerge.

The use of opportunistic citizen science data to estimate the population and distribution trends of alien species can be a reliable alternative to structured monitoring schemes, and it may also work as a complementary way of filling information gaps (Dickinson et al. 2010; Aceves-Bueno et al. 2015; Klemann-Junior et al. 2017). Even if unable to provide completely reliable trend estimates, it may still be worthwhile using this source of data for early warning of the introduction of alien species (Vall-llosera et al. 2017). For this purpose, it is relevant to include all available records and not only those from complete lists. However, when the alien bird species is already established and relatively common, it may be better to use only data from complete lists along with more complex methods in order to obtain more robust trend estimates (Horns et al. 2018; Johnston et al. 2021).

For our urban study area, the amount of information about alien bird occurrence in published data (scientific articles and books) is clearly outmatched by the amount provided by the opportunistic citizen science data we compiled, both in spatial and temporal coverage (Costa et al. 1997; Matias 2002; Equipa Atlas 2008; Matias 2008; Catry et al. 2010; Saavedra et al. 2015; Luna et al. 2016; Equipa Atlas 2018). Accordingly, we assume that opportunistic citizen science data is currently the most reliable source of information that can be used to understand the process of establishment of alien bird species and to estimate distribution trends in studied urban area, but likely also at the country level. This may also be the case of other urban regions in countries that have a regular use of eBird or similar platforms by birdwatchers (Sullivan et al. 2014; Hochachka et al. 2021).

Our alien bird dataset comprised records from 30 species (Psittaciformes and Sturnidae), which is far more than the seven species from these two groups that have been reported in the three most recent Portuguese bird atlases coinciding temporally (breeding bird atlases: Equipa Atlas 2008, 2022; non-breeding bird atlas: Equipa Atlas 2018). The six most frequently recorded alien birds in our study area include three of the most successful worldwide bird invaders in urban environments: rose-ringed parakeet, monk parakeet and common myna (Menchetti and Mori 2014; Cohen et al. 2019; White et al. 2019). These three species are at different levels of colonization in Europe, since the crested myna is only established in our study area, whereas the blue-crowned parakeet also occurs in some Spanish cities and the rose-ringed parakeet is widespread over central and southern European cities (Saavedra et al. 2015; Keller et al. 2020; Carrete et al. 2021).

The rose-ringed parakeet had the most records, and its area of occurrence (and presumably also its population) seems to be consistently increasing, especially from 2006 onwards, as also suggested by Luna et al. (2016) using roost counts in Lisbon. On the contrary, the common myna and the monk parakeet, despite being regularly present in the study area for two decades, showed a restricted distribution, suggesting their populations are not expanding, although we cannot determine their establishment status with certainty. The reasons for the failure to expand may be related to small founder populations or competition with other already established alien bird species. We can speculate that the competition with the larger crested myna may be a limiting factor to the common myna, since both species explore similar foraging habitats and food resources (Craig and Feare 2010), which combined with a small founder population may have determined the non-expansion of this species. Still, the common myna and the monk parakeet have self-sustaining populations across the Mediterranean countries (Holzapfel et al. 2006; Cohen et al. 2019; Postigo et al. 2019; Keller et al. 2020), and therefore, a future range expansion should not be discarded, since these species have high invading potential, resulting from a generalist diet and/or behavioural dominance over native species (Lowe et al. 2000; Craig and Feare 2010; MacGregor-Fors et al. 2011; Martin-Albarracin et al. 2015; Saavedra et al. 2015; Di Santo et al. 2017; Carboneras et al. 2018).

The second species with more records in our study area was the crested myna, which apparently showed a marked increasing trend in its distribution range in the urban region of Lisbon. This considerable increase was also noted by Saavedra et al. (2015), who suggested this species is well adapted to the environmental conditions of the region. The crested myna has also been introduced in a few locations in Spain and Austria, but the region of Lisbon seems to be the only established population currently in Europe (Saavedra et al. 2015; Dyer et al. 2017; Craig and Feare 2018; Keller et al. 2020). The species has a very limited alien range across the world when compared to the common myna (Dyer et al. 2017). However, considering the ecological similarities between the two species, the potential impacts of the crested myna should not be neglected, since it has a larger body-size than the common myna, known to compete with native species (Lowe et al. 2011; Carboneras et al. 2018). Mynas are capable of colonizing non-urban areas ecosystems, which may cause additional impacts, such as crop damage (Downs and Hart 2020).

The blue-crowned parakeet and the Senegal parrot are the two following species with most records, having been detected regularly since 2008. While our data suggests that the blue-crowned parakeet seems to be established and its distribution range is increasing, the status of the Senegal parrot is not so clear. The lower numbers of the Senegal parrot compared to the blue-crowned parakeet is a common fact to other European countries, which has often been attributed to interspecific differences in survival rate (Arnold et al. 2018; White et al. 2019). However, this difference should not be related with the number of imported birds to Portugal, as between 1980 and 2020 it was much higher for the Senegal parrot than for the blue-crowned parakeet (more than 80,000 individuals against less than 4,500 individuals; Table S5 in ESM1).

The opportunistic citizen science data included a relatively regular number of records of the budgerigar (*Melopsittacus undulatus*) and cockatiel (*Nymphicus hollandicus*) along the study period, although with very few records every year (Table S3 in ESM1). Apparently, these two popular cage bird species have not been capable of establishing populations, which suggests that the individuals escaping from captivity have low probability of survival, as observed in other northern hemisphere countries (Carrete and Tella 2008; Menchetti and Mori 2014; Arnold et al. 2018; Uehling et al. 2019). The climate in our study area may not be a limitation to these species, whereas the trend may be due to food and nest-site limitation, namely through competition with other species, as observed in the established population of the budgerigar in Florida (Wenner and Hirth 1984; Butler 2005). Still, the use of opportunistic citizen science data seems capable of monitoring the status of less frequently observed alien species in urban areas. Furthermore, a growing number of citizen science initiatives is demonstrating the utility of this source of information to detect invasive alien species across different taxonomic groups (Johnson et al. 2020; Price-Jones et al. 2022).

In conclusion, opportunistic citizen science data can be a powerful and growing tool, which can be used to detect the establishment of alien bird species, particularly in urban areas, where the amount of information is generally larger. However, the estimation of population and distribution trends using this source of data should always be preceded by a careful inspection, looking for potential spatial and temporal bias in coverage and other limitations. Therefore, the analysis of trends should always account for variations in effort, incorporating this factor in the models, independently of using a simple or more complex approach. Opportunistic citizen science data may be the best source of information available in countries that are facing a disinvestment in the collection of systematic data on bird distribution and population (i.e., bird atlases and structured monitoring schemes). The tradition of birdwatching and its growing trend are positive indications that non-professional birdwatchers can contribute as driving forces of knowledge to address the present and future challenges for biodiversity and sustainability. Urban areas are frequently the place of introduction of alien birds and may provide early warning for more widespread invasions towards non-urban environments. Online platforms, such as eBird, encourage users to collect additional information (e.g., photos, videos, and sound recordings), which can further improve the value of opportunistic data. Ultimately, this can provide important information about alien bird species, such as: 1) feeding habits, which can contribute to evaluate potential economic impacts; 2) breeding evidence, which help determine the establishment; and 3) interspecific interactions, which indicate potential impacts on native communities (e.g., IBISurvey https://ibisurvey.uevora.pt).

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Data availability All the data used in the manuscript is available for download on request from the eBird project www.ebird.org.

Declarations

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Consent to publication All the authors have read the manuscript and agreed to its submission.

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