Kerala Bird Atlas 2015–20: features, outcomes and implications of a citizen-science project

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Citizen-science driven exercises (e.g. bird surveys) and online platforms (e.g. eBird) provide voluminous data on bird occurrence. However, the semi-structured nature of their data collection makes it difficult to compare bird distribution across space and time. Bird atlases are based on standardized surveys and describe the distribution of bird species over a predefined region and have fewer biases, and thus are better suited for use in research. The recently concluded Kerala Bird Atlas (henceforth KBA) is Asia's largest bird atlas in terms of geographical extent, sampling effort and species coverage. The entire state of Kerala was systematically surveyed twice a year during 2015–20 and over 0.3 million records of 380 species from 25,000 checklists were aggregated. The dataset was filtered and various metrics were estimated. A total of 915 cells were laid out for systematic surveys, of which 888 were surveyed in either or both the seasons – dry season (January–March) and wet season (July–September); 27 cells could not be surveyed in either of the seasons due to logistical constraints. However, this variation in sampling effort had a minimal effect on survey completeness. The slope of the species accumulation curve suggested near-complete species sampling in over 70% of the cells. After eliminating nocturnal and pelagic species, data from 361 species were analysed. Species count was higher in the dry season than in the wet season. Species richness (count) and evenness were higher in the northern and central districts than in the southern districts. High elevation regions of the southern Western Ghats were the largest contiguous areas lacking sufficient sampling. We found that most of the endemics were concentrated in the Western Ghats, but threatened species were as likely to occur along the coasts as in the Ghats. The KBA dataset is a valuable resource for testing various ecological hypotheses and suggesting science-backed conservation measures. KBA model could be replicated for similar atlases in other states or biogeographic regions of India.

Keywords: Bird atlas, birdwatching, citizen-science, Indian ornithology, Kerala, Western Ghats.

DATA on the distribution of species and the factors governing the same are prerequisites for effective and efficient conservation efforts[1]. Such information is necessary to inform the selection of protected areas, to assess habitat associations and to predict the likely effects of future environmental changes[2]. Historically, data on bird species distribution were sourced from field guides, ornithological field notes by experts, and museum collections. The increasing popularity of recreational birdwatching has made available fine-scale distribution data in the form of global and regional data repositories such as eBird[3], Bird Count India (www.birdcount.in) and iNaturalist (www.inaturalist.org). eBird (http://ebird.org/) is the most widely used citizen-science platform that allows birdwatchers to share and manage their sightings on a globally accessible database[4]. Scientists have utilized eBird data to study the abundance and distribution of species in real-time, to prioritize conservation efforts and to test ecological hypotheses[5–7]. The data submission protocol in eBird is fairly simple and flexible. This leads to a large variation in efforts across checklists[8], and the spatial precision is low for any fine-scale (<1 sq. km) analysis[9]. There can be many sampling biases in such datasets like spatial, taxonomic, or temporal. Spatial bias refers to uneven sampling efforts across a region. Taxonomic bias can include over- or under-representation of certain species in the dataset. Temporal bias occurs when records are collected in one season only, or more often at certain times of the year, or when species have very specific environmental triggers for activity periods[10]. Such biases in the dataset can have a profound influence on the inferences made[11].

While the eBird platform is fairly new, globally available since 2010, the concept of citizen-science is not. Amateur birdwatchers have contributed to ornithology since the 1950s via bird atlas projects. Bird atlas projects collect occurrence or breeding data and rely largely on groups of volunteers for data collection[11]. A bird atlas describes the distribution of birds within a gridded framework over a predefined region based on systematic surveys[12]. The first ever bird atlas was prepared for the birds of Britain and Ireland in 1952 (ref. 13) and over the years several national bird atlases and annual breeding bird atlases have been prepared across the world[2,11,12]. Bird atlas data has multiple uses in the areas of conservation, ecological research and public outreach[11,14]. National and regional bird atlases can help managers in protection, conservation and management of local breeding and migratory populations by providing an accurate assessment of species' abundance and distribution[14].

Bird atlases can have similar biases as online citizen-science platforms, but these biases are small and can be easily overcome by various means, such as efficient planning and estimation of sampling effort (per record)[11] during data analysis. Taxonomic bias may be corrected for by using a measure of observability based on comparisons between results of quick surveys and more extensive surveys and assigning a score to every species based on detectibility (species easy to detect when present versus species difficult to detect). Another merit of bird atlases over online citizen science platforms is that the former can be explicitly driven by specific hypotheses such as the evaluation of the effects of a given human activity or set of activities on the avian community, or as a means of regular monitoring (e.g. annual breeding bird surveys on a gridded region).

Most bird atlases have been produced in Europe and North America, while the biodiverse tropical regions such as those in Asia are poorly represented in global atlas databases[2]. Despite a long-standing tradition of ornithology in the country, systematic state-wide or biogeographic region-wide bird atlases have not been prepared in India. It must be noted that an atlas of the birds of Delhi and Haryana was prepared in 2005, but it lacked systematic sampling, as the pre-existing data was mapped onto a grid[15]. Availability of volunteers with bird identification skills is a must for taking up atlas projects or bird surveys over a large spatial scale. In the past, involvement of the general public in documenting avian biodiversity had been very limited in India. The state of Kerala is an exception to this, and amateur birdwatching has been popular in the state since the 1960s. This could be attributed to Sh. K. K. Neelakantan's *Keralathile Pakshikal* (Birds of Kerala, published in 1958)[16], a classic piece of ornithological literature in vernacular language which helped popularize birdwatching among the general public. As a result, Kerala has had an active network of birdwatchers, and volunteer-based regular bird-monitoring surveys in the Western Ghats have been conducted regularly since 1990s (ref. 17).

India has a rapidly growing community of birdwatchers and, as of March 2021, the eBird-India dataset has grown to a total of over 14 million observations across 1342 species submitted by over 24,600 birdwatchers from all over the country. This voluminous citizen-science data was recently utilized to assess the distribution, abundance, and trend (increase/decrease) in population for 867 species from India, and to highlight species of conservation concern[18]. The rising popularity of recreational birdwatching and the availability of volunteers have opened possibilities of preparing systematic bird atlases in India. The first systematic bird atlas in the country was prepared for the city of Mysuru, Karnataka[19]. The Kerala Bird Atlas (KBA) is a first-of-its-kind state-level bird atlas in India and was inspired by the Mysuru Bird Atlas, and follows a similar sampling design[20]. The entire state of Kerala was divided into grids and was systematically surveyed twice a year, during the wet (July–September) and dry (January–March) seasons. The surveys for the KBA were conducted during 2015–20 and it is the Asia's largest bird atlas in terms of geographical extent, sampling effort and species coverage[20].

A succinct introduction to KBA, its methodology, survey protocol, and season-wise distribution maps of 377 species have been published as a book[20]. This book primarily caters to the partner agencies, the Forest Department, volunteers, and the general public. In this article, we present various scientific aspects of KBA not covered in the aforementioned book. We perform some exploratory analyses on KBA data and discuss the observed patterns.

Methodology

Team structure

Several prominent birdwatchers from various parts of the state met at Kerala Agricultural University, Thrissur in June 2015 and prepared the blueprint for a state-wide bird atlas. The entire planning and implementation of KBA was driven by volunteers. Birdwatchers and ornithological organizations from across Kerala took up the task of conducting atlas surveys in their respective districts. One or two volunteers from every district acted as the district coordinator and liaised with birdwatchers in their regions. Information about the atlas initiative was shared among the local birders via personal communication channels and press release. Volunteers were assigned to survey teams, informed about the survey dates, protocols and sites to be covered. Locus Free, an android GPS application was used by several birdwatchers to locate sampling plots when internet connectivity was not available in the field. Bird checklists and related information were uploaded by volunteers to eBird and the same was reviewed by district coordinators for protocol, location and duration. An online Google Maps visualization was created to track the progress of the survey and to mark the surveyed sub-cells.

Spatial extent

Kerala lies between 8°18′N and 12°48′N lat. and 74°52′E and 77°22′E long. in southwestern India. Wedged between the Arabian Sea and the windward side of the Western Ghats, it receives abundant rainfall (180–360 cm) and experiences a tropical climate[21]. Elevation in the region varies from –2.2 m (Kuttanad) to 2695 m (Anamudi peak). It is spread across an area of 38,863 sq. km, of which 27% is under forest cover, 66% is under cultivation and 7% constitutes built-up areas/wetlands/uncultivated land. One-fourth of the Western Ghats range falls within Kerala[22]. Surveys for KBA were conducted in all 14 administrative units (districts) of Kerala (Figure 1).

Temporal extent

Field surveys were conducted from 2015 to 2020, twice a year, during dry (mid-January to mid-March) and wet (mid-July to mid-September) seasons, exactly for 60 days in each season per year. The dry season coincides with the peak activity of migratory species while the wet season (monsoon) coincides with the breeding period of many resident species[23]. There was the possibility of passage migrants (e.g. Eurasian Cuckoo, Amur Falcon) crossing through Kerala for a very short duration (a couple of weeks) during the intervening un-surveyed months. The atlas survey did not focus on such passage migrants.

Sampling protocol and data resolution

Kerala was divided into cells of size 3.75 min × 3.75 min (equivalent to 6.6 km × 6.6 km) aligned to Survey of India maps. A total of 915 cells were laid out covering the entire state. Each cell was further divided into four quadrants of size 3.3 km × 3.3 km. Each quadrant was then sub-divided into 9 sub-cells of size 1.1 × 1.1 km. A single, randomly selected sub-cell in every quadrant was chosen for the survey (Figure 2). Grids were laid and the randomly selected sub-cells were marked on the map prior to the survey. A total of 63 sub-cells were found to be located in inaccessible cliffs or valleys, and these were replaced by adjacent accessible sub-cells with the same habitat type from the same quadrants. Before undertaking the surveys, volunteers were informed about the protocol and the sub-cells to be surveyed. The following points were ensured during the surveys:

(1) Survey teams consisted of 2–5 volunteers, with at least one experienced birdwatcher in the team.

(2) Teams were advised to conduct surveys during morning or evening hours. However, individual teams were left to decide the survey time based on the habitat, anthropogenic disturbance and bird abundance.

(3) Volunteers were instructed to cover all major habitat types in the sub-cell. Volunteers chose a location within their allotted sub-cell and walked a trail to enumerate bird species using checklists. Volunteers selected survey sites at their discretion based on local topography and weather conditions.

(4) Each checklist was of a fixed duration of 15 min and volunteers recorded all bird species that were seen (perched or in flight) or heard. Only the presence (detection) was recorded and not the individual counts.

(5) Four checklists were created for each sub-cell per season and all of them were uploaded to eBird.

(6) Whenever possible, the four checklists from a sub-cell were made by different teams and on different dates.

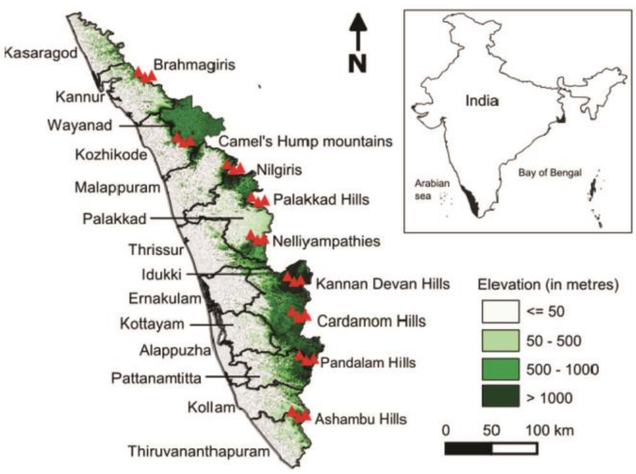

Figure 1. Map of Kerala showing location within India (inset), districts, prominent hill ranges of the Western Ghats (red triangles) and topography.

Data collection

Besides avian species, volunteers were advised to record three additional observations during surveys: presence of any water body of area >10 sq. m (standing/flowing), presence of fruiting fig trees, and presence of any of the four common invasive plants, viz. *Lantana camara*, *Eichhornia crassipes*, *Salvinia molesta* and *Mikania micrantha*. This was done to derive additional ecological information about the surveyed sub-cells. Volunteers provided the additional information as comments in their checklists.

Data filtering

Volunteers uploaded checklists from the surveyed sub-cells to eBird, using the website or the App, and this data was later downloaded for analysis. Taxonomy and English names followed Clements *et al.*[24]. Only English names have been mentioned in the present article and scientific names are mentioned in Supplementary Table 1. From the complete dataset, we eliminated ambiguous species such

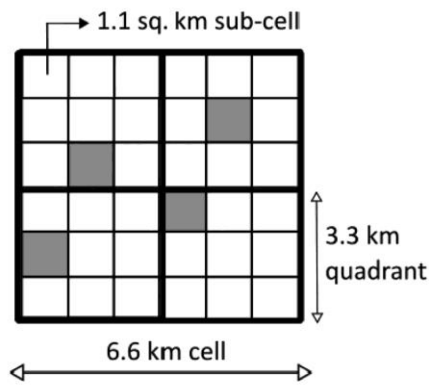

Figure 2. Sampling design of Kerala Bird Atlas. Gray sub-cells represent randomly chosen survey units.

as 'spuhs' (e.g. 'passerine sp.') and 'slashes' (e.g. 'Malabar starling/Chestnut-tailed starling'). There were a few exceptions to this: 'spiderhunter sp.' was recorded as 'Little Spiderhunter' since there is only one spiderhunter species in Kerala. Similarly, 'Little/Saunders's Tern' was recorded as 'Little Tern' and 'Fork-tailed/Square-tailed Drongo-Cuckoo' was recorded as 'Fork-tailed Drongo-Cuckoo'. Since Green/Greenish Warbler and Booted/Sykes's Warbler were likely to be misidentified, we merged records of these sister species pairs into single taxa, Green Warbler and Booted Warbler respectively. Since KBA protocols were designed to survey diurnal and land birds, we eliminated pelagic (storm petrels) and nocturnal (frogmouths, owls and nightjars) species, but retained Jungle Owlet as this species was not strictly nocturnal[25].

Survey completeness

We estimated survey completeness per cell in R platform[26] using the R package 'KnowBR v.2.0' (ref. 27). We formatted the occurrence information into a species-by-cell matrix where each checklist was treated as an independent survey within the cell. KnowBR estimates survey coverage per cell as the final slope of the relationship between number of collected species and number of checklist records, which is used as a surrogate of survey effort. This accumulation curve (i.e. the accumulated increase in the number of species with the addition of checklist records), is estimated according to the Exact estimator, as well as by performing 200 permutations of the observed data (random estimator), to obtain a smoothed accumulation curve. Based on the slope of the species accumulation plot, KnowBR calculates a completeness percentage (percentage representing observed number of species against predicted one).

Estimating species abundance index

In several studies, where abundance was not specifically recorded, an abundance index for species has been inferred using relative reporting rate. The relative reporting rate for a species is calculated as the proportion of the total number of checklists for a grid cell on which that species is recorded[11]. An earlier study[28] found significant relationships between reporting rate and empirical abundance for three out of the four species studied, and a marginally significant relationship for the fourth species. We estimated species abundance index using a similar approach (proportion of checklists in which the species occurred/ total checklists from the sampling unit).

Seasonal changes in species abundance index

The detectibility of a species varies across seasons. Increase in activity and vocalizations, and presence of breeding plumage and courtship displays may make a species easily detectable during the breeding seasons[29]. Migratory species will show higher abundances (detectibility) in wintering grounds during the migration cycle. Thus, higher abundance index in one season than another could indicate breeding season or seasonal local movement or migration. We classified the species detected during KBA as 'summer visitor', 'winter migrant' or 'resident' based on information provided in ornithological literature[25]. For certain rare species, movement trends in Kerala were uncertain and we classified them based on expert opinion. We calculated the species abundance index in every cell for the dry and wet seasons separately. To observe changes in seasonal abundance indices, we subtracted dry season values from wet season values and expressed the difference as percentages (dry season value – wet season value/dry season value + wet season value). We obtained the mean of percentages from all the cells for each species. The resulting value varied from –100 to +100. We used a cutoff of 20% to assign significant changes in seasonal abundance index. Differences could be significantly positive (i.e. ≥20%, higher abundance in dry season than wet), or negative (i.e. ≤–20%, higher abundance in wet season than dry), or close to zero (value between –20% and 20%, no seasonal differences in abundance).

Species-rank abundance plot

Species-rank abundance plots aid in visualizing species richness (total species count) and species evenness (relative abundances of species). Species are ranked according to their abundances and are plotted against a measure of species abundance. Species richness can be viewed as the number of different species on the chart, while species evenness is reflected in the slope of the line that fits the graph. A steep gradient indicates low evenness as the high-ranking species have much higher abundances than the low-ranking species. A shallow gradient indicates high evenness as the abundances of different species are similar[30]. There are noticeable climatic and anthropogenic differences across Kerala. The total annual rainfall in the state varies from 360 cm over the northern parts to about 180 cm in the southern parts[21]. Also, northern regions receive most of the rainfall during southwest monsoon (June–August), while the northeast monsoon (October–November) contributes up to 27% of annual precipitation in southern regions[21]. Southern Kerala has a higher and denser human population than the northern regions[31]. Since high elevation regions of southern Kerala were poorly sampled, we eliminated all high elevation areas (>600 m) for this particular analysis and split the remaining observation records from northern, central and southern Kerala. We then plotted $\log_{10}$-transformed species abundance rank against a normalized abundance index to see if there were differences in species count and evenness across Kerala. High evenness would hint towards effective niche partitioning and a healthy ecosystem where no single species dominated the community; low evenness would suggest highly uneven community with few abundant species and many rare species.

Species of conservation concern

We calculated the endemic score of every cell based on the number of endemic species reported from it. We gave a score of '1' to the species restricted to Western Ghats–Sri Lanka biodiversity hotspot and '0' to the rest (non-endemic species). We estimated the endemic score as the sum of scores/total species count per unit checklist. Similarly, we calculated the threat and SoIB (State of India's Bird) score for every cell. Threat categories were based on the IUCN Red List[32] and were scored as follows: critically endangered '4', endangered '3', vulnerable '2', near-threatened '1', and least-concern '0'. SoIB utilized the eBird data to estimate indices of population trends (long-term trend over the last 25 years and current annual trend over the last 5 years), and range size for 867 of India's 1333 bird species. Based on the population trend (increase or decline) and distribution range size, SoIB classified species in three concern categories – high, moderate and low[18]. SoIB concern categories were scored as follows: High '2', Moderate '1', Low '0'. The threat score and SoIB score were mapped separately for wet and dry seasons. We overlaid the protected areas map of Kerala (available from wiienvis.nic.in/) over these maps to visualize the overlap of distributions of endemic and threatened species with the protected areas.

Data analysis

All analyses were performed in R v 4.0.3 using the package 'tidyverse v.1.3.0' (ref. 33). Checklists from all the surveyed sub-cells were pooled and summarized at cell or sub-cell level as deemed suitable. Geospatial data was handled in R via the package 'sf v.0.9-7' (ref. 34), and QGIS v 2.18.24. Results from R were exported as shapefiles to QGIS for plotting, and figures were prepared in Inkscape v 0.91. The dataset and R script used in the analyses have been made publicly accessible (https://doi.org/10.5061/dryad.zpc866t8g).

Results

Data collection

After filtering, the KBA dataset consisted of 293,915 bird records in 24,495 unique checklists from 888 cells (3266 sub-cells). Additional details sought (presence of water bodies, fruiting fig trees and invasive species) were not consistently reported; only 28% of checklists had these additional details. These additional details have not been utilized in any analysis reported in this work.

Sampling effort

Sampled cells: Initially, 915 cells were laid out covering the entire state of Kerala, of which 888 cells (3266 sub-cells) were sampled. Due to logistical constraints, few cells could be surveyed in only one season. The 869 cells (3211 sub-cells) were sampled in the dry season and 824 cells (2929 sub-cells) were surveyed in the wet season; while 805 cells (2874 sub-cells) were surveyed in both the seasons (Supplementary Figure 1). Thus, 10% of the total area of Kerala (3266 sub-cells each spanning 1.21 sq. km = 3952 sq. km) was surveyed under KBA.

Checklists per cell: A total of 32 checklists (4 sub-cells × 2 seasons × 4 lists per season) were to be made for every cell. For cells overlapping with the territorial boundaries of Kerala, many sub-cells were in the neighbouring states or in the Arabian Sea, and such sub-cells were excluded. The total number of checklists was less than 32 for all such cells. Excluding 129 'boundary' cells, 80% (611 out of 759) had 32 checklists (Figure 3 *a*). In the wet season, 81% cells (621 out of 759) had complete sampling, i.e. 16 checklists per cell, while in dry season 96% cells (733 out of 759) had complete sampling.

Number of observers: Though the protocol mentioned 2–5 volunteers for atlas surveys, 13% of checklists did not comply with this. About 87% (21,254 out of 24,495) were submitted by teams of 2–5 observers, 11% (2866 out of 24,495) by single observers, and the remaining by teams of 6–13 observers.

Temporal patterns

Wet season surveys began in 2015 and concluded in 2020. About 90% of the wet season surveys were done during 2015–17. Dry season surveys began in 2016 and concluded in 2020. Nearly 70% of the dry season surveys were done in 2016–2018, and 55% of all surveys were done during weekends. All checklists were made between 0600 and 1800 h; ~70% during 0600 to 1000 h and 21% during 1500 to 1800 h. Average number of species encountered during survey was highest during the morning hours (0600–0800) and lowest during the noon hours (1100–1400). This pattern was consistent across the seasons (Figure 4).

Taxonomic coverage and species count

In total, 361 species from 76 families were analysed: 353 species from 75 families in the dry season, 298 species

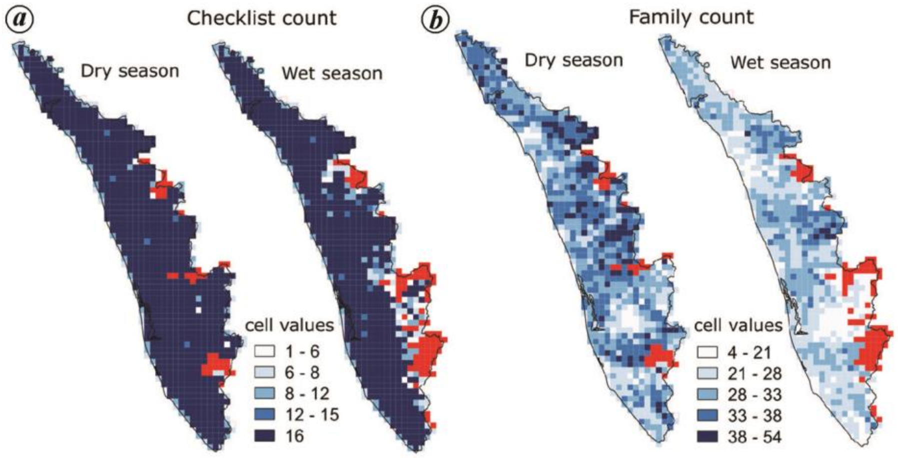

Figure 3. Figure showing (***a***) total checklists (survey effort); (***b***) number of avian families reported per cell for wet and dry seasons. Unsurveyed cells are marked in red.

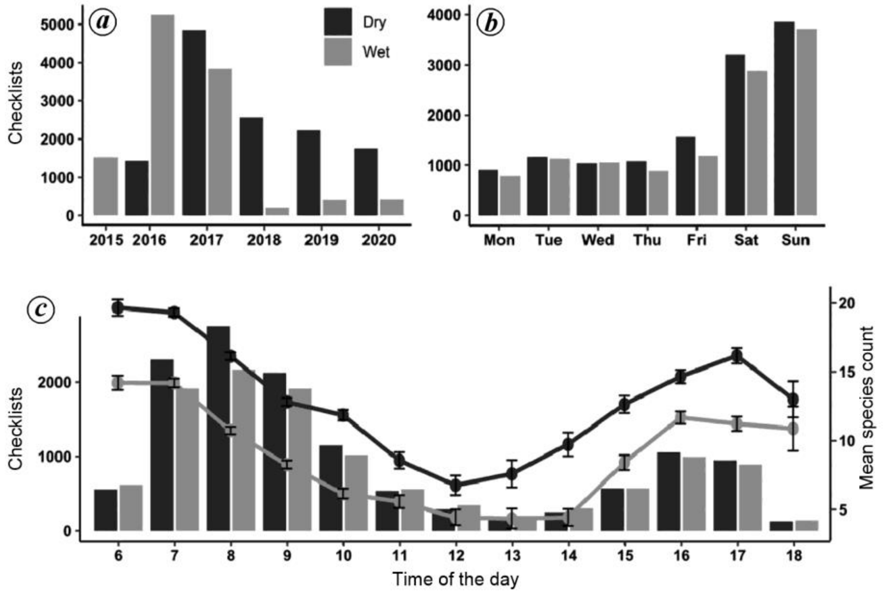

Figure 4. The temporal pattern in survey efforts in wet and dry seasons: (***a***) Across years; (***b***) Across weekdays; (***c***) Across day-hours (bar plot, left *y*-axis). The line graph (right *y*-axis) in panel (***a***) shows mean species-per-checklist and confidence intervals at specific hours of the day.

Table 1. Distribution of species in various categories based on the occurrence records (dry and wet season combined)

Category	Criteria	Species count	Total records	Contribution to the KBA dataset (%)
Very rare	0.1% of max records (<14 records)	94	484	0.1
Rare	0.1–1% of max records (14–138 records)	103	5,683	2.00
Common	1–10% of max records (139–1385 records)	110	56,987	19.40
Very common	10–50% of max records (1386–6925 records)	44	137,625	46.83
Most abundant	>50% of max records (>6652 records)	10	93,100	31.68
	Total	361	293,879	100

from 72 families in the wet season. The number of records per species varied greatly (Table 1); White-cheeked Barbet (13,855 records) and House Crow (12,380 records) each had over 10,000 records, while 20 species had single occurrence records. The number of species reported per cell varied from 4 to 122. The number of families per cell

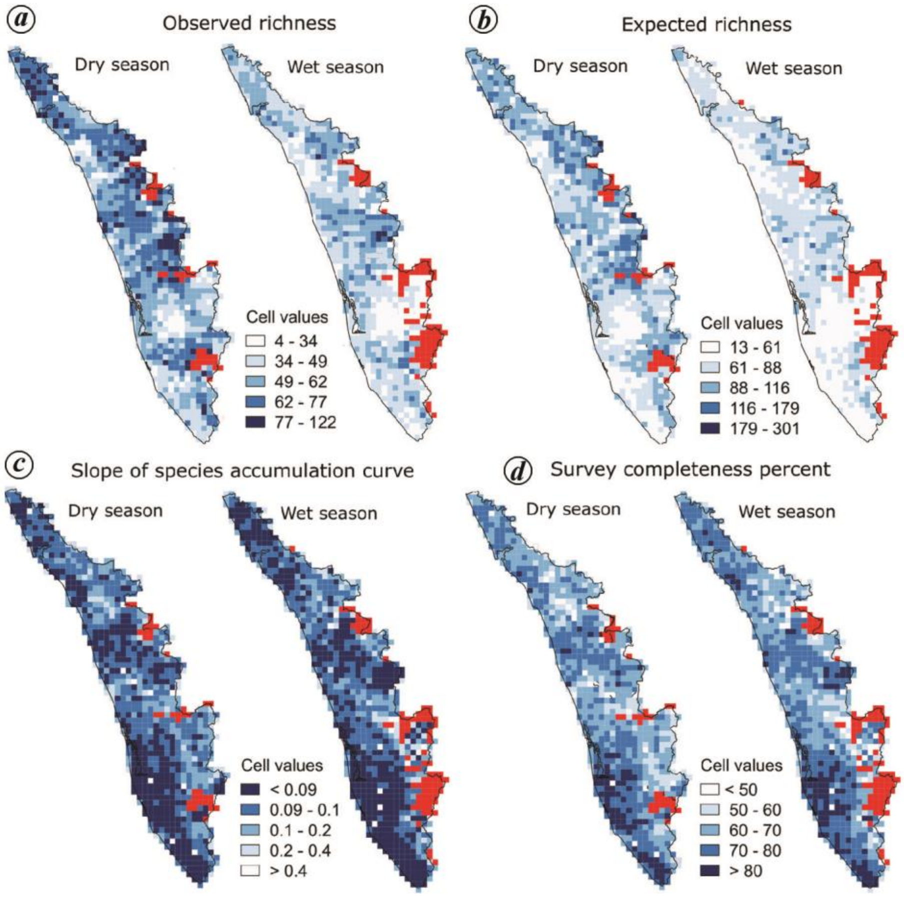

Figure 5. Outputs from survey completeness analysis for the wet and dry seasons. (***a***) Observed richness shows the number of species encountered during surveys; (***b***) Expected richness shows the extrapolated number of species based on slope of species accumulation curve (in ***c***); (***d***) Survey completeness is the percentage representing the observed number of species against predicted one. Unsurveyed cells are marked in red.

Table 2. Seasonal change in abundance of birds based on Kerala Bird Atlas data. Values show the number of species in the corresponding category. Classification of species as resident/migrant is based on literature[23]

	Increased abundance during dry season	Increased abundance during wet season	No change
Winter migrant	57	2	0
Resident	75	25	110

varied from 4 to 54 (Figure 3 *b*). Northern and central districts showed higher species count than southern districts across seasons (Figure 5 *a*).

Survey completeness

Overall survey completeness was high across Kerala, except for the high elevation regions of southern Western Ghats (Kannan–Devan hills, Cardamom hills, Pandalam hills), Nilambur hills and Wayanad–Kozhikode hills (Camel's Hump mountains) (Figure 5 *b*). About 70% of the cells (638) had more than 70% completeness. This corresponds to a slope value of less than 0.1 in the species accumulation curve (Figure 5 *c*).

Seasonal changes

Among the 361 species analysed, 249 were residents, one was a summer visitor and 111 were winter migrants (Supplementary Table 1). About 47% of winter migrants and 16% of resident species were 'Very rare'. We eliminated all the 94 'very rare' species due to low occurrence records and assessed the remaining 267 species (Table 2). Lesser whistling-Duck, Baya Weaver, Tricoloured Munia, Scaly-breasted Munia, and Lesser Coucal showed over 50% higher abundance in the wet season, while 95% of the winter migrants analysed, showed over 50% higher abundance in the dry season. Yellow-throated Sparrow, a resident species, showed 100% increase in abundance in the dry season, while it was not recorded in the wet season. Resident and widespread species such as Common

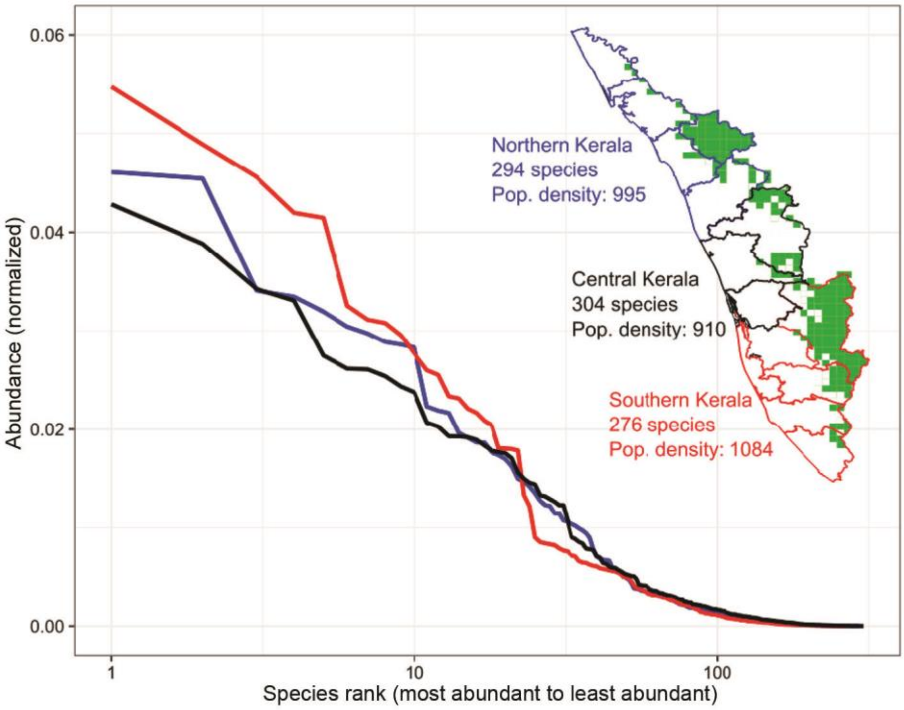

Figure 6. Species-rank abundance curves (species-rank ($\log_{10}$) versus normalized abundance) contrasting the different regions of Kerala. The top-right plot shows different regions of Kerala (northern, central, southern) and the cells excluded from this analysis (green, >600 m amsl). The total species count in the KBA dataset and average population density (person per sq. km) as obtained from the Department of Economics and Statistics, Government of Kerala (ecostat.kerala.gov.in) have been shown.

Myna, Loten's Sunbird, Greater Racket-tailed Drongo and Spotted Dove showed no change in abundance.

Species-rank abundance plot

Different regions of Kerala differed in terms of species richness and evenness. The steeper curve for southern Kerala in the plot indicates an uneven distribution of relative abundances of the species recorded. Central Kerala shows high species count and species evenness despite occupying a lower geographical area than the other two regions. Northern Kerala is of intermediate species richness and evenness (Figure 6).

Endemic and threatened species

In total, 33 species from 21 families endemic to the Western Ghats were detected. Six endemic species had over 1000 occurrence records in the KBA dataset which were: Yellow-browed Bulbul, Nilgiri Flowerpecker, Orange Minivet, Crimson-backed Sunbird, Malabar Parakeet, and Malabar Grey Hornbill. A total of 34 species from 17 families were of conservation concern which included 2 'Critically Endangered', 3 'Endangered', 11 'Vulnerable' and 18 'Near Threatened' species. Six species of conservation concern had over 100 records each, namely: black-headed Ibis, Oriental Darter, Woolly-necked Stork, Palani Laughingthrush, Grey-headed Bulbul and Great Hornbill. With respect to SoIB categories, 25 species were 'high', 135 'moderate' and 201 species were 'low' conservation concern. A list of the 361 species with endemic status, threat category, SoIB category, and total records in the KBA dataset is provided in Supplementary Table 1. Cells overlying the Western Ghats had high SoIB and endemic scores and overlapped with protected areas while the cells with high threat score were more dispersed and fell outside the protected area network (Figure 7).

Discussion

How consistent was the sampling effort across Kerala?

Sampling effort is usually quantified by examining the number of records submitted per sampling unit[35]. In the present study, sampling effort in terms of checklists submitted per cell was largely uniform, except for cells overlapping the Kerala boundary and a few topographically rugged regions (Figure 3). During peak monsoon showers some cells could not be surveyed. The largest single patches of unsampled cells were in Pathanamthitta district (Pandalam hills) and Idukki district (Kannan-Devan

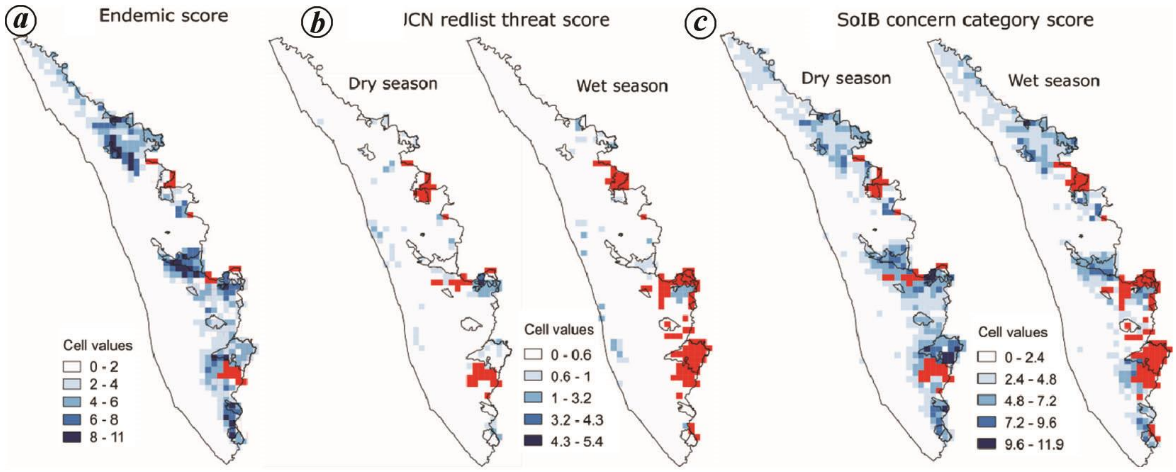

Figure 7. Figure shows average score of the cells for (***a***) endemic species; (***b***) IUCN threat categories; (***c***) SoIB categories. Unsurveyed cells are marked in red, outline of various protected areas of Kerala is provided.

hills). The former region has largely remained uncovered in previous surveys as well[17], due to inaccessibility.

Number of observers and the time of the survey are expected to affect species detection and species counts. These variables were not consistent as the number of observers and survey timings differed across checklists. Surveys done during noon hours counted fewer species (Figure 4 *a*) and teams consisting of 2–3 observers counted highest species-per-checklist (Supplementary Figure 2). Teams of observers ≥ 6 recorded least species-per-checklist; they also had marginally more checklists from noon hours than other teams (Supplementary Figure 2). We reaffirm that our survey protocols were effective, and teams of 2–3 observers and surveys during mornings and evenings were most productive.

Rare species are more likely to be missed during the bird atlas surveys[14]; while targeted surveys in the area of occurrences are preferred for such species. Bird atlases are best suited to study patterns of abundance/distribution of common species. The survey completeness analysis suggested that most of the cells covered during KBA were near-complete in terms of species detected in both the seasons (Figure 5). The slope of the species accumulation curve for over 70% of the cells was less than 0.1, suggesting that additional sampling efforts would have recorded few additional species, albeit with low occurrence records (rare species).

How does the species occurrence vary along the spatial and temporal scales?

Chandran *et al.*[36] enlisted 527 species in 90 families from Kerala. Of these, apart from pelagic species (Procellariidae, Stercorariidae, Fregatidae, Phaethontidae, Sulidae), buntings (Emberizidae), bustards (Otididae), crab-plovers (Dromadidae) and sandgrouses (Pteroclididae), families all were reported in KBA dataset[20]. Excluding nocturnal species, we analysed 361 species (68.5% of the species reported from Kerala).

Species count, richness and evenness were higher in northern and central Kerala than southern Kerala, despite sampling effort being consistent across all regions (except Idukki and Pathanamthitta districts) (Figure 3). There are minor differences in terms of rainfall, mean elevation, and human density across these three regions of Kerala which could explain the observed pattern. The Palakkad gap brings in a component of habitat heterogeneity in central Kerala, and besides tropical evergreen and moist deciduous forests, it supports dry deciduous and open forests not found elsewhere in Kerala[37]. This possibly explains high species count and richness in central Kerala. Low species richness and evenness in southern Kerala could also be attributed to high human density[31] and resulting land-use patterns. Species rank-abundance plot suggests high evenness in north and central Kerala. It suggests a 'healthy' ecosystem and species assemblage where species occupy multiple niches and no one species dominates the assemblage. Species-habitat associations analysis based on a fine-scale land-use-land-cover (LULC) map might be able to provide conclusive evidence in this regard.

Most of the endemic species and SoIB concern category species are distributed in the Western Ghats. The two northernmost districts (Kasargod and Kannur) lie entirely in the midlands and lowlands (below 300 m elevation) and have higher species count, endemicity scores and SoIB scores than their southern counterparts. About 10% of the total land area of Kerala along the Ghats is protected (~1% in the two northern districts) and provides refuge to the endemic species. However, threatened species are not restricted to Western Ghats alone, but are also distributed across the western regions (Figure 7).

Among the winter migrants analysed, 95% showed higher abundance during dry season than in the wet season.

This pattern is expected since winter migrants start arriving in Kerala post-monsoon, i.e. September–October. Among the resident species, 52% showed no change in abundances, 35% showed higher abundance in dry season, and 12% showed higher abundance in the wet season. Species-specific analysis of natural history coupled with season specific environmental niche modelling can reveal whether this pattern is due to life-history phenology (breeding) or due to differences in wet and dry season habitats (suggesting local movement).

What are the potential uses of the Kerala Bird Atlas dataset?

The KBA book[21] provides distribution maps of 377 species based on KBA surveys and these maps are a great aid for visualizing the distribution and abundance of various species in Kerala. Application of bird atlas data is not restricted to species-specific distribution maps; researchers have utilized atlas data for the study of macroecology[38], climate change[39] and species-habitat associations[40], to name a few. For avian atlases conducted more than a decade ago, efforts to repeat the atlases are underway to quantify changes in species distributions and to draw inferences[41]. A recent review[42] found that over 3000 scientific studies had utilized data from the first European Breeding Birds Atlas[43] to derive new information on species distribution, ecological traits, environmental pressures, and population sizes. Thus, the usefulness of bird atlas data such as the KBA, from both an academic and a conservation perspective span decades as well as multiple domains of ecology. The next step for us is to utilize the KBA data to guide on-ground conservation efforts, to model the occupancy and distribution of selected species and to assess the impact of future climate change and land-use scenarios on the species. Decadal change in LULC for Kerala shows 50% decrease in swamps and mangroves, 80% decrease in fallow land, 190% decrease in wastelands (grassland, scrub land, sandy area, barren rocky), and 250% increase in rural built-up area during 2005–06 and 2015–16 (ref. 44). Thus, our first priority is to use KBA data to understand the responses of species to these LULC changes and to predict how future LULC changes would affect them. Secondly, we aim to model the distributions of selected species to identify areas of conservation significance outside the protected regions and to propose site-specific conservation recommendations. Besides conservation, KBA data will also be useful in academic research, such as understanding co-occurrence patterns among species (e.g. co-occurrence of primary and secondary cavity nesters) and factors driving bird assemblages (e.g. relationship between primary productivity and species diversity). When KBA is repeated in a few years from now, the new data can then be compared with the present data to model population changes and the factors driving it.

Limitations of the Kerala Bird Atlas

Atlas projects often face a tradeoff between quality and quantity[11]. In order to increase volunteer participation, survey protocols were kept simple. During the KBA, only species' presence and absence were recorded. Species' count data was not collected, nor was the sighting assigned to any distance bin. Hence, methods such as distance-sampling cannot be applied to the KBA dataset for estimating species abundances. The high elevation regions of the Western Ghats were under represented in the KBA dataset. Few such cells either could not be covered or had incomplete sampling. The KBA dataset should not be used for conservation reserve networks in those regions. Taxonomic bias in any atlas data is unavoidable as detection probability varies across species. With the similar sampling effort, common species and those with distinct plumage/vocalization are much easy to detect than rare species or those with cryptic plumage/vocalization. Kerala has four species of barbets and sunbirds each. In the unfiltered KBA dataset, only 9 checklists had ambiguous barbet species (recorded as 'Asian barbet sp.') as compared to 966 checklists with uncertain sunbirds (recorded as 'sunbird sp.'). Hence, any cross-species comparisons based on atlas dataset must be interpreted with caution.

Recommendations for future bird atlases

The successful completion of KBA, a citizen-science project driven entirely by volunteers over a five year time span has proven the mettle of Kerala's birdwatching community. The community of birdwatchers is expanding in other parts of the country too. Since 2015, India has been among the leading nations in terms of participation in global birdwatching events such as the Great Backyard Bird Count, facilitated by Bird Count India (www.birdcount.in). Regional annual birdwatching events such as Pongal Bird Count (Tamil Nadu), Onam Bird Count (Kerala), Bihu Bird Count (Assam) have been seeing an increase in public participation over the years. Thus, it is now feasible for India's birdwatching community to plan and implement a national bird atlas or bird atlases focussing on particular biogeographic zones such as Sahyadri, Vindhya, Satpura or the Eastern Ghats. We foresee some major challenges in implementing such a large scale atlas project which could be: (i) Reduced randomness in topographically challenging terrain: if several randomly selected sub-cells fall in inaccessible areas, they have to be replaced by the nearest accessible area, thus compromising the randomness of the sampling process; (ii) Temporal incongruence: most of India receives heavy rain during 3–4 months of monsoon and forest areas will be inaccessible during this period. Rainfall patterns and day length vary across regions. Sampling season and survey timings will have to be adjusted to suit local weather, hence a common sampling window might not work for the entire country; (iii) Choice between quality and quantity of data: citizen-science projects at large spatial scales are only possible with the help of volunteers, a majority of whom would not have an academic background in ecology or allied subjects. Survey protocols with elaborate technical details might weary out volunteers and reduce participation. Thus, it is important to make a choice whether only bird presence (detection) data will be collected as part of surveys, or additional data on breeding status, plumage, feeding details, weather and habitat are also to be collected; (iv) Experienced versus amateur birdwatchers: we found a team of 2–5 observers as optimum for bird surveys; each team headed by an experienced birdwatcher and assisted by amateur birdwatchers. Barring metropolitan cities, birdwatching is still in nascent stage across most regions of India. Lack of experienced birdwatchers to lead the survey teams can be a limiting factor. Hence, efforts can be made to train more people into birdwatching and introduce the concept of citizen-science via state-wide annual bird count events on significant dates, e.g. Baisakhi bird count (Punjab), Chhath bird count (Bihar and Uttar Pradesh). States with active birdwatching communities can plan city level atlases before undertaking state-wide bird atlas; (v) Controlling biases in data: one method to eliminate temporal, spatial or taxonomic bias in the dataset is to identify such biases in real-time during data collection and to modify sampling to counter such biases[11]. While the field surveys are undertaken by amateur birdwatchers who volunteer their resources and time for atlas data collection, it is important to appoint a dedicated atlas coordinator who can track the survey progress, identify biases in the dataset and communicate these to the data collectors.

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