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RESEARCH

Unveiling the migratory patterns of scarlet flycatchers using citizen science databases

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Abstract

The migratory patterns of many Neotropical bird species remain largely unknown. Numerous logistic challenges prevent such studies, from research costs, often prohibitively expensive to Neotropical research institutions, to equipment weight limitations. Therefore, it is paramount to explore new possibilities in the field of migratory bird research such as the abundant records from citizen science platforms. In this study, we investigated the spatial and temporal migratory patterns of the scarlet flycatcher *Pyrocephalus rubinus* using two citizen science platforms: eBird and WikiAves, which provided 40,837 records of the species. Our findings indicated that scarlet flycatchers arrive at the wintering grounds in central-western Brazil, central-eastern Bolivia, and eastern Peru around May and June. We also found that scarlet flycatchers arrive at breeding grounds in central and eastern Argentina, southern Brazil, and Uruguay between August and October, where it stays in the months thereafter (November, December, January). The year-round records of the species in northern Argentina and southern Paraguay deserve further studies. Understanding migratory patterns is imperative for predicting population dynamics and climate influence on the breeding biology of these species in the face of a rapidly changing world.

Keywords Citizen science · Migration · Neotropical birds · *Pyrocephalus rubinus* · Scarlet flycatcher

Introduction

Bird migration has been of constant human interest due to its widespread occurrence among members of this taxonomic group and its influence on ecosystem dynamics (Whelan et al. 2008; López-Hoffman et al. 2017). Research on the migratory patterns of birds is often carried out using several methods, such as bird rings, GPSs, geolocators, and stable isotopes (Robinson et al. 2010; Hobson and Wassenaar 2018). Although these methods are well explored and yield robust results, they have important constraints regarding their costs and technical limitations (e.g., battery life, weight). In recent years, citizen science projects have been explored as important sources of data for studying bird migration (Cooper et al. 2014; Schubert et al. 2019; Jahn et al. 2019; Weisshaupt et al. 2021). Both citizen science projects as well as studies performed using their large amounts of data are a worldwide occurrence (e.g. Newson et al. 2016; La Sorte and Somveille 2020; Wang et al. 2024), being particularly useful to study birds that migrate through underfunded regions like the Neotropics (Faaborg et al. 2010). In this research, we used data from citizen science databases to investigate the migratory patterns of the scarlet flycatcher *Pyrocephalus rubinus* in South America.

The genus *Pyrocephalus* is traditionally considered monospecific and widely distributed in the Americas, but morphological and phylogenetic data suggest that it can be divided into four species (see Carmi et al. 2016). Scarlet flycatchers occur east of the Andes in southern South America, and vermillion flycatchers (*P. obscurus*) are widespread from the USA to Chile (Carmi et al. 2016; Gill et al. 2021). The ranges of the two other species, Darwin's flycatcher (*P. nanus*) and the extinct San Christobal flycatcher (*P. dubius*), are/were restricted to the Galapagos Islands (Carmi et al. 2016; Gill et al. 2021). The geographical limits of the breeding and wintering grounds of scarlet flycatchers are still not

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well understood. The species is known to breed in central and eastern Argentina, southern Brazil, and Uruguay from October to January (Azpiroz 2003; Somenzari et al. 2018; de la Peña 2019). The breeding status of the birds in Paraguay is still uncertain, but the species also seems to breed in the southern portion of the Chaco (Short 1975; Hayes et al. 1994). With the end of the breeding season, adult scarlet flycatchers migrate northwards to the wintering grounds in central-western Brazil, central-eastern Bolivia, and eastern Peru (Schulenberg et al. 2007; Herzog et al. 2016; Carmi et al. 2016; Somenzari et al. 2018). Juveniles are understood to stay on the breeding grounds for two or three more months before migrating northwards (Hudson 1920; Somenzari et al. 2018). It has been suggested that there are resident populations of scarlet flycatchers in central Brazil (Sick 1997), southern Paraguay (Hayes et al. 1994), and northern Argentina (López Lanús 1997; Di Giacomo 2005), however, there is a lack of robust data to support this hypothesis (Somenzari et al. 2018). Given these uncertainties, and considering that previous studies about the migration of this species considered the genus *Pyrocephalus* as monospecific, we investigated the migratory patterns of scarlet flycatchers using data from two main citizen science platforms (eBird and WikiAves). We also propose a breeding range delimitation for *P. rubinus* using citizen science data and records gathered from the literature and oological collections.

Methods

Data collection

The records from eBird were obtained after a data request to the website (https://ebird.org) in October 2021. Wiki Aves records were downloaded using the guidelines from Schubert et al. (2019), also in October 2021. Other citizen science platforms, like iNaturalist and EcoRegistros, are known to the authors, but were not used considering that the aim of our study has been reached with the large amount of data retrieved from eBird and WikiAves, and the increased risk of adding replicates to our dataset. We used R version 3.6.3 (2020) and RStudio version 1.4.1106 (2021) to download the WikiAves data, which were geocoded using the R package "tidygeocoder" (Cambon 2021). From eBird, we used all available photographic, audio, and observational records until 01-Jan-2021. Given that WikiAves uses the time stamp in the photograph to automatically determine the date of the observation, records before 01-Jan-2000 are likely misdated, thus we only used photographic and audio records documented between 01-Jan-2000 and 01-Jan-2020. To exclude observations of vermillion flycatcher, which is still considered conspecific to scarlet flycatcher by eBird, we did not consider all records westwards of the Andes, assuming that the mountain range is a geographical boundary for the species (Fjeldså and Krabbe 1990; Carmi et al. 2016). Records of scarlet flycatchers northwards of the Amazon River (Fig. 1) are rare (Zimmer 1941; Ridgely and Greenfield 2001; Restall et al. 2006); therefore, we assume that this species is an occasional visitor of the region. For this reason, all records northwards of the Amazon River were also excluded.

Males of scarlet flycatcher are brightly coloured, and both females and males are relatively easy to distinguish from other sympatric bird species. Furthermore, both eBird and WikiAves use validation systems in which experts verify records to exclude misidentified birds. Apart from this, we checked three hundred records from WikiAves and found no misidentified specimen. Therefore, we assumed that if there are misidentified records in our final dataset, the number is negligible. Both citizen science platforms occasionally contain double records of the same bird by different observers. However, given the large number of records, we ignored the influence of double records on our results.

Data analysis

To test whether the records of scarlet flycatchers exhibited temporal and spatial relationships, we built a linear model using R version 3.6.3 (R Core Team 2020) and RStudio version 1.4.1106 (RStudio Team 2021). We sorted all records among grid cells, with square sizes of 1° latitude by 1° longitude, using the function "rasterize" from the R package "raster" (Hijmans 2020). Consecutive numbers were subsequently assigned to these grid cells as grid IDs. These grid IDs were assigned at the upper left (grid ID = 1) and ended at the lower right corner of the map. Subsequently, per month, a list was made of the grid IDs that contained at least one record of a scarlet flycatcher. A linear model was then performed using these grid IDs as numeric variables. Given that the known breeding areas are in central and eastern Argentina, southern Brazil, and Uruguay, with breeding records extending from October to January (Azpiroz 2003; Somenzari et al. 2018; de la Peña 2019), we assigned December as the reference month because most individuals should be present at the breeding grounds and engaged in breeding activities. In addition to the grid ID analysis, we built a map to display the distribution of records through the 12 months (Jan-Dec). The base map was retrieved from Natural Earth (https://www.naturalearthdata.com) via the "rnaturalearth" package (South 2017). The extent of the map was cut off at 5° to -55° latitude and −90° to -30° longitude to coincide with the main range of the species. We constructed a raster with grid squares with a size of 1° latitude by 1° longitude using the function "rasterize" from the R package

Fig. 1 A map of South America showing key localities cited along the text. (source: Natural Earth)

"raster" (Hijmans 2020). Additionally, the packages "rgeos" (Bivand et al. 2020) and "rgdal" (Bivand et al. 2020) were used to work with geospatial information for the map. Grid squares were coloured according to the proportion of scarlet flycatcher observations, which we calculated by dividing all scarlet flycatcher observations by all species observations in the two citizen science databases. Grid squares with a high proportion of scarlet flycatcher observations (> 5%) were assigned an orange colour, and grid squares with a low proportion of observations (< 1%) were dark blue. Grid squares with zero observations were not filled in.

We constructed plots of 50% and 95% kernel density isopleths of both observations during two wintering months (June and July), and two breeding months (December and January). These plots were made using the R package "ks" (Duong 2024). For both plots a manual bandwidth of 0.88 was applied, since the default plug-in bandwidth selector (HPI) of the "ks" package resulted in underfitting. Since scarlet flycatchers are not known to occur offshore, isopleth lines running over the ocean were manually cropped out using the photo editing software Inkscape (Inkscape Project 2020).

Finally, to investigate the migratory patterns of scarlet flycatchers at a local scale, we constructed a bar plot of the monthly proportions of observations from four well-sample regions: the province of Buenos Aires (Argentina), the province of Formosa (Argentina), the state of Rio de Janeiro (Brazil), and the Distrito Federal (Brazil). The proportion of observations was calculated by dividing the number of observations of scarlet flycatchers per month in the region, by the total number of observations of all species per month in that region to account for temporal differences in sampling intensity.

Results

We obtained a total of 68,072 records, of which 489 records were left out because they were located north of the Amazon River, and 26,746 records were left out because they were either records of Darwin's flycatcher from the Galapagos islands or vermillion flycatchers from west of the Andes. This resulted in a total of 40,837 records of scarlet flycatchers from the two citizen science databases, 32,501 records from eBird and 8,336 from WikiAves. Our findings indicated that there was a statistically significant difference between the grid IDs in December and those in March, April, May, June, July, August, September, October, and November (Table 1). We found no statistically significant differences between the grid IDs in December and those in January and February (Table 1). Our results show that, during December, January, and February, scarlet flycatchers are observed at different locations than during the months from March to November. The results thus imply that the species occupies distinct breeding and wintering grounds during these months.

Table 1 Linear model analysis of the spatial distribution of scarlet flycatchers per month. December was used as the reference month. These findings indicate the significance of differences in location between a given month and a reference month

	Estimate	Std. Error	t value	Pr(>|t|)
January	0.536	35.136	0.015	0.9878
February	1.206	35.978	0.034	0.9733
March	-84.082	34.374	-2.446	0.0145
April	-306.403	31.440	-9.746	<0.01
May	-481.291	30.950	-15.551	<0.01
June	-565.328	31.324	-18.048	<0.01
July	-569.954	30.558	-18.652	<0.01
August	-509.847	30.443	-16.748	<0.01
September	-389.550	29.742	-13.098	<0.01
October	-224.563	30.415	-7.383	<0.01
November	-79.950	32.819	-2.436	0.0149
December	(Reference month)			

General occurrence data from citizen science databases (Fig. 2) and breeding records from the literature and citizen science (Fig. 3) showed that from November to February, records of scarlet flycatchers were mostly concentrated at the breeding grounds in Uruguay, southern Brazil, and central and eastern Argentina. From May to August, most observations of scarlet flycatchers took place on wintering grounds, in a wide portion of central South America, roughly with the Amazon River serving as a northern border, the Atlantic Ocean serving as an eastern border, and the Andes serving as the western border. During other months, September, October, March, and April, the records were spread between breeding and wintering grounds (i.e., transient birds).

The kernel density analysis showed that there was a distinct difference in 95% kernel density isopleths between wintering and breeding seasons (Fig. 4). The 95% kernel density isopleth for the breeding season coincides largely with the breeding records available for the species (Figs. 3 and 4). The 50% kernel density isopleths are largely distinct between seasons, however, there are multiple locations where the 50% isopleths overlap. These locations are mostly in northern Argentina and southern Paraguay, as well as along the foothills of the eastern slopes of the Andes.

Data from four well-sampled regions (Fig. 5) provided additional evidence for the migratory pattern described above. There was a noteworthy variation in the seasonal abundance of scarlet flycatchers in the province of Buenos Aires (a well-established breeding ground), with most records spanning from September to April. In the state of Rio de Janeiro, where scarlet flycatchers are not known to breed (Fig. 3), most records of the species span from April to November, without a marked peak in abundance in any particular period. In the Distrito Federal in Brazil (a well-known wintering ground), records of scarlet flycatchers were concentrated from May to July. In Formosa, a northern province of Argentina, scarlet flycatchers were recorded year-round, but the proportion of observations during the breeding season was much lower than during the wintering season.

Discussion

In this study, we used citizen science data to investigate the migratory patterns of scarlet flycatchers in South America. Our results showed that the species breeds exclusively in its southern range, with the first individuals arriving at the breeding grounds in the last days of August and early September, corroborating observations of previous authors

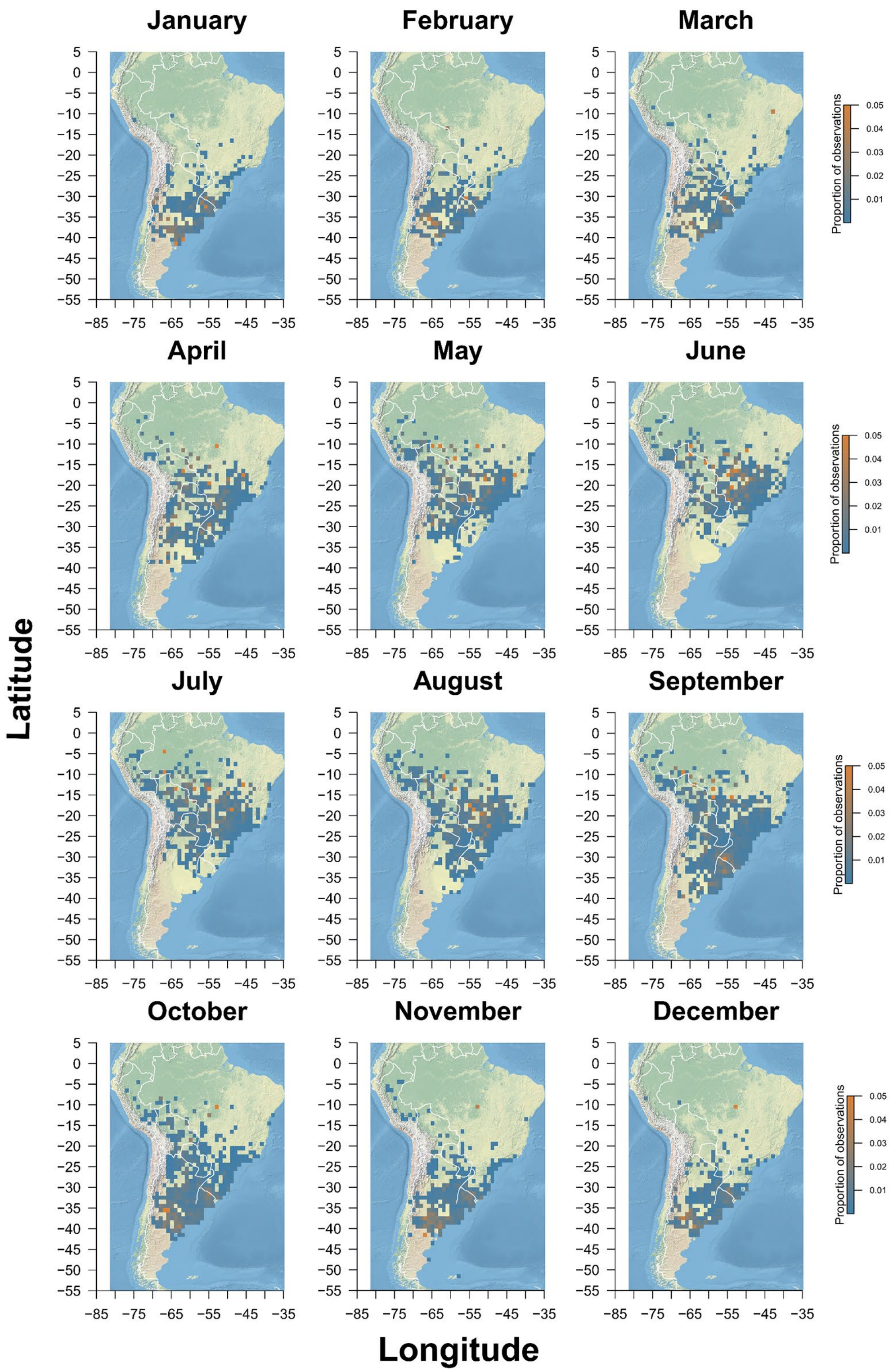

Fig. 2 Spatial distribution of scarlet flycatchers per month based on citizen science data from WikiAves and eBird. The colouration corresponds to the proportion of scarlet flycatcher observations compared to all observations in the database

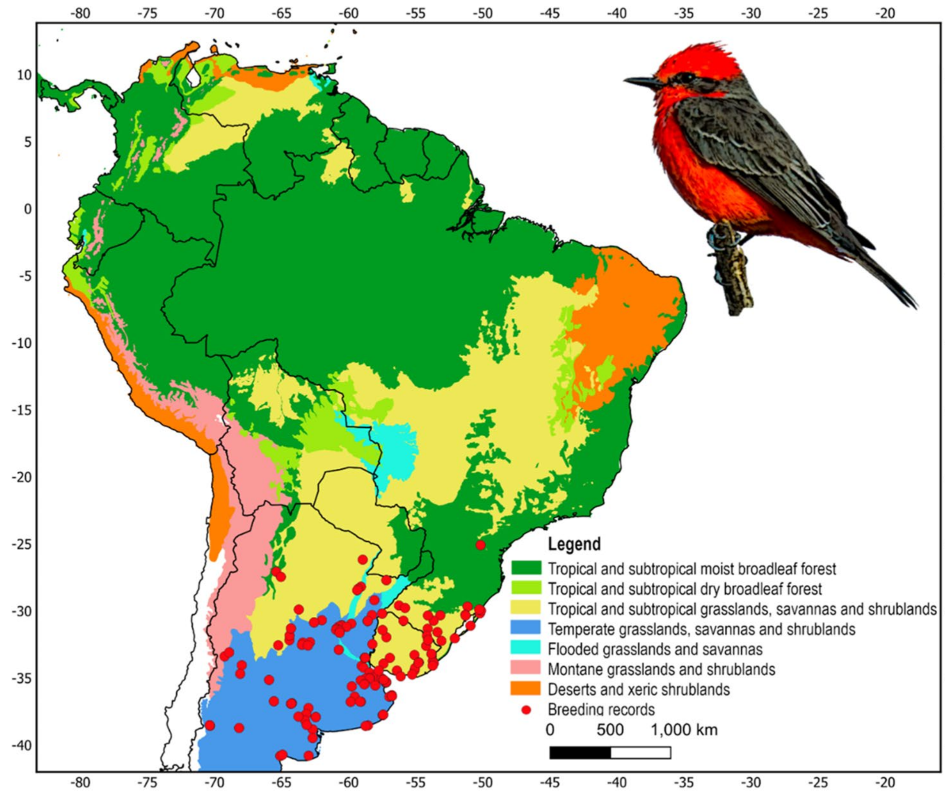

Fig. 3 Breeding records of scarlet flycatchers based on citizen science and literature data. The main biomes follow Olson et al. (2001)

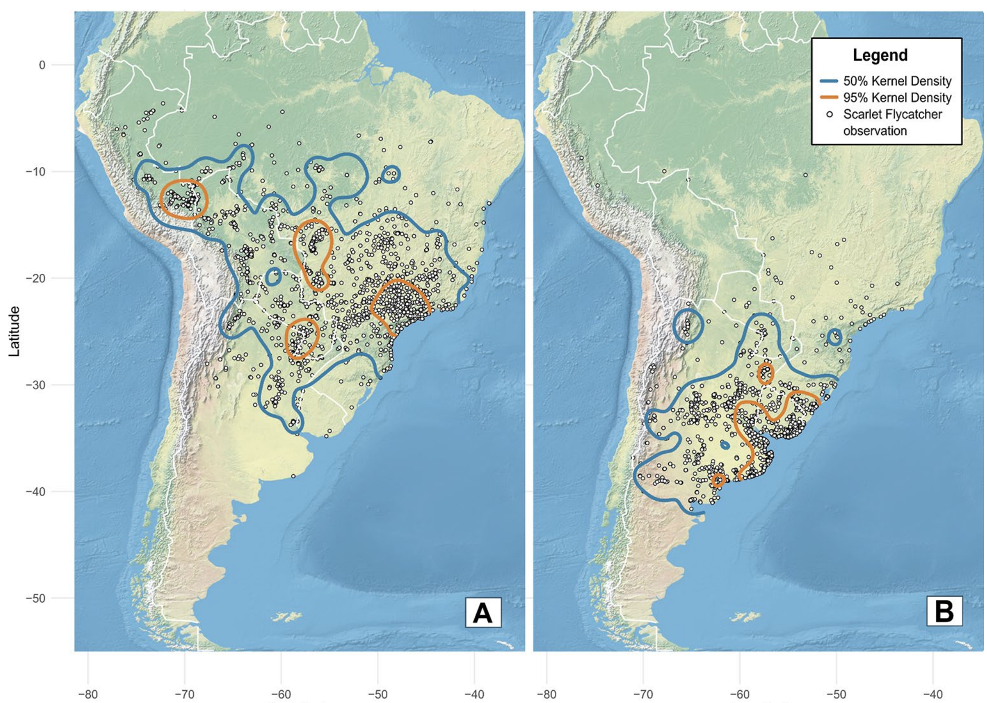

Fig. 4 50% and 95% isopleth lines of the kernel density analysis of scarlet flycatcher observations during the wintering season (**A**) and breeding season (**B**). These plots were constructed using data from citizen science platforms eBird and WikiAves

(Fraga 1977; Belton 1994). Birds collected in late September in the northern Paraguayan Chaco, close to the Bolivian border, were found to have a considerable volume of subcutaneous fat (Zyskowski et al. 2003), indicating that they were still on their journey southwards to the breeding grounds. In October, most birds have arrived in central and eastern Argentina, southern Brazil, and Uruguay, where the species breeds. The first records of nests took place in early October, and breeding extends to late January (Fraga 1977; Mason 1985; Mezquida 2002; Fiorini and Rabuffetti 2003;

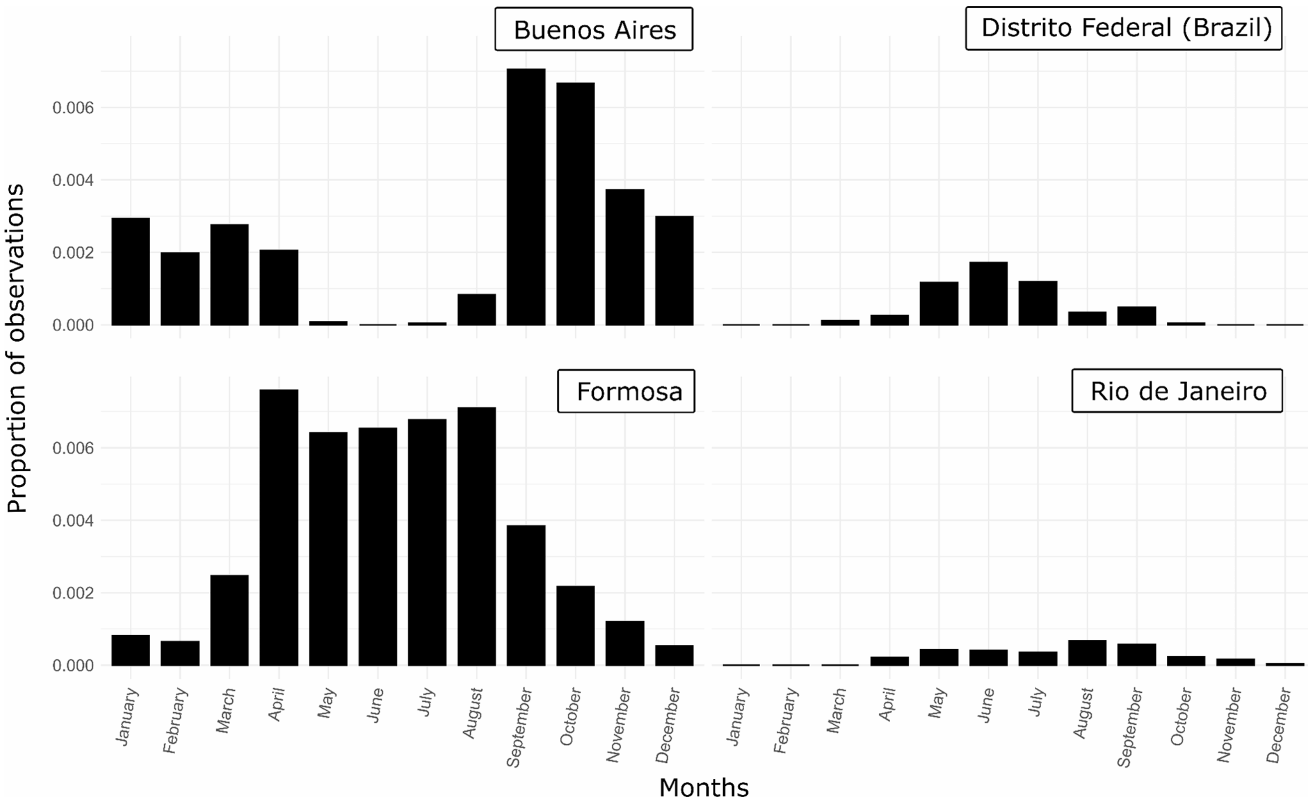

Fig. 5 Observations of scarlet flycatchers in the province of Buenos Aires, Distrito Federal (Brazil), Formosa, and the state of Rio de Janeiro in proportion to the total monthly observations of all bird species in the corresponding province/state. This figure was made with data from citizen science platforms WikiAves and eBird

Di Giacomo 2005; Munhoz 2015; de la Peña 2019; Rebollo et al. 2021). This is an extension to the previously known breeding area as specified by the latest IUCN review, which specifies only Uruguay as breeding area (BirdLife international 2021). Most breeding records are located in tropical, subtropical, and temperate grasslands, savannas, and shrublands (Fig. 2), which coincides with the general habitat of the bird, which is described as open woodland and shrublands (Del Hoyo et al. 2004). It is noteworthy that we have not found any reliable breeding records of the species for southern Paraguay, which demands additional field investigation. However, based on its seasonal pattern of occurrence in Paraguay it is expected that scarlet flycatchers do breed there (Short 1975; Hayes et al. 1994), probably in small numbers. Our findings on the migratory patterns of scarlet flycatchers are supported by the 'Status and Trends' model of eBird, which is a graphic depiction of movement and seasonal range of birds. The interactive model provided for scarlet flycatchers [https://science.ebird.org/es/status-and-trends/species/verfly/abundance-map] shows similar ranges, as the data used to create this model is largely coincident with the data we collected.

Previous studies described that adult scarlet flycatchers begin to leave the breeding grounds in mid-January, and by mid-March almost all adults have departed and would then be heading toward their wintering grounds; juveniles are said to stay at the breeding grounds until late March and early April (Hudson 1920; Cuello and Gerzenstein 1962; Fraga 1977; Belton 1994; Fig. 2). However, it cannot be stated with certainty that the alleged "juveniles" observed in the field have indeed been born during the preceding breeding season, or if they are adult birds exhibiting a purported alternate (i.e. "winter"), female-like, plumage. This is because, even though scarlet flycatchers are speculated to exhibit an alternate plumage, vermillion flycatchers appear to exhibit a Complex Basic Strategy, including a complete pre-basic moult and an incomplete performative moult (Allen 1892; Grant 1911; Zimmer 1941; Pyle 1997; Sick 1997; Ellison et al. 2021). Thus, the recognition of an alternate plumage in vermillion flycatchers by previous authors is likely a misinterpretation of a protracted performative moult (Pyle 1997; Ellison 2021). Therefore, considering the uncertainties about moult strategies in genus *Pyrocephalus*, readers must be careful about the idea of differences in migration timing between adult and juvenile birds. Additional field and museum studies are needed to solve this puzzle.

Regarding the southern part of its breeding range, roughly from −35° latitude southward, a few isolated individuals have been recorded on breeding grounds throughout the wintering season (Capllonch et al. 2009; Fig. 2), but as observed for other Neotropical migrants, they likely represent individuals who failed to migrate (e.g., in poor body condition), vagrants, misdated records, or even identification mistakes (Lopes and Schunck 2022; Lopes et al. 2022). Therefore, we found no evidence of resident populations of the species in the southern part of its breeding range. Contrastingly, in the northern part of its breeding range, in northern Argentina and possibly southern Paraguay, observations of scarlet flycatchers have been obtained year-round, despite marked seasonal variation in its abundance (Figs. 2 and 5). In this region, previous authors have described alleged resident populations (Hayes et al. 1994; López Lanús 1997; Di Giacomo 2005), a claim that needs to be confirmed. This is because there are three possible explanations for year-round records of scarlet flycatchers in northern Argentina and southern Paraguay: (1) artifacts caused by the almost continuous records of transient birds that breed at southern localities and winter northwards, since this region is close to the border between the breeding and wintering grounds of the species; (2) occurrence of 'chain migration', with breeding populations being seasonally replaced by wintering populations of the same species (Newton 2008); and (3) occurrence of partial migration, where a part of the population resides in the area throughout the year, and another part of the population migrates (Şekercioğlu 2010; Jahn et al. 2012; Hegemann et al. 2015). Field studies with marked individuals are necessary to investigate these concurrent hypotheses.

From March to September, records of scarlet flycatchers were concentrated along flying routes (mostly March, April, September, and October) and on wintering grounds (mostly from May to August). This pattern is corroborated by long-term monitoring data from well-studied sites along the entire wintering grounds, including Minas Gerais (Faria et al. 2009), Distrito Federal (Negret 1988), Mato Grosso (Allen 1892; Lopes et al. 2016), São Paulo (Barbosa et al. 2021), and eastern Bolivia (Hanagarth and Specht 2000). The species probably exhibit winter site fidelity, as documented for a colour-ringed population studied in eastern Bolivia, where a male was recorded at the same site during four consecutive winters (Jahn et al. 2009).

During September and October, there is a marked peak in the number of scarlet flycatcher records in Buenos Aires, where they breed (Fig. 4). This peak in records can be explained by an amalgamation of scarlet flycatcher birds that are settling to breed in the area and birds that are heading toward more southern breeding grounds, such as La Pampa (Fig. 3). As discussed above, previous studies have suggested that while adult birds migrate northwards soon after breeding, young scarlet flycatchers would stay at the breeding ground awaiting their first moult (Hudson 1920; Fraga 1977; Belton 1994) (also see the image records: e.g., https://www.wikiaves.com/2483271, https://www.wikiaves.com/5374720). Thus, the relatively high proportion of records that took place in Buenos Aires until April can be explained by those lingering juveniles.

Our findings also showed that scarlet flycatchers occur seasonally further east and northeast in Brazil than previously known (Ridgely and Tudor 1994; Carmi et al. 2016). Anecdotal observations suggest that the range of this species has expanded to eastern Brazil in the state of Rio de Janeiro, where it has been known to occur in coastal *restinga* vegetation since at least the 1940s (Novaes 1950), and in the state of Espírito Santo (Bauer et al. 1997; Venturini and Paz 2003; Silva 2008). The scarlet flycatcher possibly invaded areas formerly covered by the Atlantic Forest, a pattern already reported for several open-area species originally restricted to central Brazil (Lopes 2008). With the data available, however, it is not yet clear whether scarlet flycatchers overwinter in these areas or if these records represent transient or vagrant birds.

Data from citizen science platforms can be used to predict and investigate spatial and temporal movements of populations of migratory birds (Lees 2016; Schubert et al. 2019; Barbosa et al. 2021). Citizen science databases, however, are not reliable for tracking individual movements of birds, such as in studies using geolocators or stable isotopes. Therefore, when citizen science is used to study bird migration, challenges can arise in regions that provide year-round observations, such as scarlet flycatchers in northern Argentina and southern Paraguay. Another example of information that can be difficult to retrieve during citizen science data analyses, is a difference in arrival times between males and females. This has been described in a field study with scarlet flycatchers, which revealed that males arrive first (Rozas Sia et al. 2020). An important caveat that comes with citizen science is the local increase in records due to reasons other than bird migration. This could, for example, be a simple indication of economic disparity and thus of the time and money needed to spend on hobbies such as birdwatching. Additionally, birdwatching parties (i.e., many birders record the same bird) and holiday effects may distort the representation of actual differences in observations per location and/or per month (Lopes and Schunck 2022; Tubelis 2023). To reduce socioeconomic effects on our findings we used the proportion of records of the species compared to all bird records. Compared to other migratory research techniques, our approach requires relatively little effort and has a low cost. The results of this and other similar studies are promising for the future of studying migratory birds in understudied areas of the world, all due to the use of citizen science, a comparatively new and unexplored method for assessing the ecology of birds. Finally, this method can also be used to reveal changes in bird migration in response to changing climates, e.g., different times, different distances, and different directions of migration or, in some extreme cases complete withdrawal of migration (Zaifman et al. 2017; Jahn et al. 2020; Da Silveira et al. 2021).

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Author contributions JT obtained the data, performed the data analysis, and wrote the manuscript. FC and LL conceptualized the idea and wrote the manuscript.

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Data availability All data is publically available at wikiaves.com and ebird.org.

Declarations

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Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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