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Central Chile comprises a previously unknown nonbreeding area for the migratory population of Turkey Vulture (*Cathartes aura ruficollis*) breeding in the northwestern Argentine Patagonia

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ABSTRACT

Bird migration in the Neotropics is complex and highly diverse. Indeed, for many taxa, basic questions such as where they go are still relevant. Satellite-tracking studies of Turkey Vulture (*Cathartes aura*) migration have revealed extensive variability in their movement strategies, contributing to their widespread distribution. However, South American migratory populations are still among the least explored. By integrating five years of satellite-tracking data, citizen science databases and classical raptor monitoring techniques, we present a case study reporting a hitherto unknown nonbreeding area for the Turkey Vulture subspecies *ruficollis*. Specifically, we document that a minor proportion of the population that breeds in northwestern Argentine Patagonia migrates northwards to central Chile at the beginning of the austral autumn. Our findings improve our basic knowledge of the Turkey Vulture migration within the Neotropics and establish a baseline to study the movement strategies of the migratory *ruficollis* populations breeding in high latitudes of South America.

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Argentina; Chile; eBird; home range; migration; nomadism

Introduction

Bird migration in the Neotropics is highly diverse, and historically patterns have been difficult to detect because most movements occur over relatively short distances (Jahn *et al.* 2020). Perhaps more complex, partial migration is common, and resident individuals may mask the movements of migratory ones (Chesser 1994; Jahn *et al.* 2006). Thus, which taxa migrate and where they go remain basic questions limited by a lack of information. Nevertheless, advances in tracking technologies, large citizen science databases, and modern analytical approaches provide an unprecedented ability to detect fine-scale migratory patterns, greatly facilitating the study of bird migration within the Neotropics (Jahn *et al.* 2020).

The partial migrant Turkey Vulture (*Cathartes aura*) is the most extreme of all migratory vultures. Annually, at least 3 million individuals migrate in flocks and show diverse patterns from short-distance, long-distance and trans-equatorial migrations (Alarcón and Lambertucci 2018; Bildstein 2022). Of the six subspecies currently recognised, it is well known that North American breeding populations of the *meridionalis* and *septentrionalis* subspecies migrate into Central and South America during the boreal winter (Mandel *et al.* 2008, 2011; Dodge *et al.* 2014). In contrast, the migratory behaviour of the less-studied *ruficollis* subspecies, which breeds in the Neotropics, specifically in the Argentine Patagonia, remains relatively underexplored (but see Dodge *et al.* 2014; Graña Grilli *et al.* 2017, 2019). That subspecies typically migrates northward to Bolivia and Brazil and occasionally trans-equatorially as far north as Colombia during the austral winter (Bildstein 2004, 2022). Here, using satellite tracking, citizen science and spatiotemporal occurrence data, we document that a portion of the population that breeds in northwestern Argentine Patagonia migrates to central Chile, a novel nonbreeding area for the subspecies *ruficollis*.

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Materials and methods

Tracking data were provided by the Vultures Acopian Center USA GPS study *via* Movebank Data Repository (https://www.movebank.org). From six *ruficollis* Turkey Vultures tagged in November 2017 in northwestern Argentine Patagonia (study name: Turkey Vultures in South America), we focused our work on the tracking data of the only individual (#163486) that seasonally crossed the Andes range towards Chile, a previously undescribed movement pattern. Device (Microwave PTT-100; 30 g) duty cycles were programmed to record one GPS position every 1 h from 05:00 to 22:00 h local time. We truncated the track from 2018 to 2022 (i.e. five annual cycles). Since the device does not provide calibrated error information, we assumed a horizontal error rate of ±18 m for our analyses according to Microwave Telemetry documentation.

To explore and quantify seasonal movements, we followed an approach in which a latent-state model uses the net squared displacement (NSD) as an observed time series to elucidate movement strategies, such as migration, dispersal, nomadism and range-residency (i.e. restricted use of space) (Börger and Fryxell 2012; Bastille-Rousseau *et al.* 2016). We consider northward migration as the autumn movement from Argentina to Chile and *vice versa* for southward migration in spring. The analyses were carried out with the *lsmnsd* R package (for more details see Bastille-Rousseau *et al.* 2016).

According to periods of restrictive space use, we followed a continuous-time stochastic process modelling (CTSP) approach to quantify home range and core area in the tagged individual (Calabrese *et al.* 2016). Briefly, a family of CTSP models that assume restricted space use and different autocorrelation time scales were fitted. The best model was chosen *via* the corrected Akaike Information Criterion. Once an appropriate model was selected and fitted, we used area-corrected autocorrelated kernel density estimation ($AKDE_C$) to quantify the utilization distribution (UD) with confidence intervals (CI) (for more details see Calabrese *et al.* 2016). The choice of the median area (50% UD) was used to determine the core area or the area with the highest intensity of use (Laver and Kelly 2008). Finally, to quantify the home range overlap between years (i.e. site fidelity), we used the bias-corrected Bhattacharyya coefficient (BC) for the $AKDE_C$ (Winner *et al.* 2018). BC measures the relative similarity between two UD (from 0 for no overlap to 1 for identical UDs) accompanied by an uncertainty measure *via* the estimation of CI (Fieberg and Kochanny 2005). The analyses were carried out with the *ctmm* R package (Calabrese *et al.* 2016).

Complementary to satellite tracking analysis, we collected data on spatiotemporal occurrences of subspecies *ruficollis* in Chile. To ensure a comprehensive dataset, we employed two approaches. First, we conducted occurrence surveys ~8 days a month, with 6 h of observation each day from January 2022 to March 2023, in areas proximate to those used by the tagged individual during the austral autumn and winter in Chile. Second, we examined all photo-supported observations of Turkey Vultures in Chile up until March 2023, archived at The Cornell Lab of Ornithology's Macaulay Library *via* eBird (Sullivan *et al.* 2014). We accurately identified the photographs of adult *ruficollis* individuals based on their diagnostic markings: transverse yellowish or greenish-white lines on the posterior surface of the crown and hindneck (Wetmore 1964). Juvenile individuals forming part of a flock of adults clearly identified as *ruficollis* were assumed to be of the same subspecies.

Results

Over the five-year tracking period, the tagged individual exhibited seasonal migratory movements between its breeding area in the Argentine Patagonia and its nonbreeding area in central Chile (Figure 1). The vulture began its first-tracked northward migration to the nonbreeding area at the end of February, occurring progressively closer to early April in the subsequent years (Table S1). The satellite track reveals that the individual crossed the Northern Patagonian Andes in a northwesterly direction towards the Central Depression of south-central Chile (Figure 1(a)). In the first two years of tracking, the vulture made stopovers near Chillán, central Chile (36°39'S; 72°00'W), whereas in the subsequent years the northward migration was completed without stopovers (Figure 1(b)). The individual arrived at the nonbreeding area in the surroundings of San Javier, central Chile (35°39'S; 71°37'W), after an average migration duration of 12.1 days (range = 6.9–22.8) (Table S1). In late September to early October, the vulture returned to the breeding area in Lácar, Argentine Patagonia (40°23'S; 71°13'W), using the same migratory route as in autumn (Figure 1(a); Table S1). The mean duration of southward migration was 6.3 days (range = 4.9–8.9) (Table S1). The total distance covered during the full annual cycle averaged 1,078 km (range = 988–1,182) (Table S1).

During its breeding season in Argentine Patagonia, the tagged individual exhibited range-residency movements (Figure S1; Table S2). Over the successive breeding seasons, both the home range and core area diminished in size (Figure S1; Table S2). The BC analysis confirmed an overlap of 0.6 (95% CI = 0.5–0.7) within these areas across the five years of tracking, suggesting fidelity to the

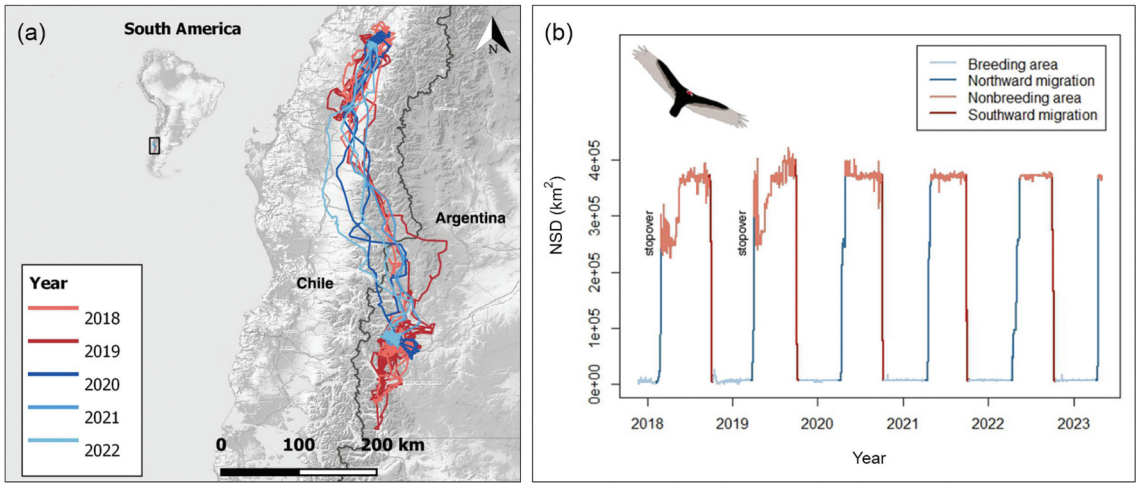

Figure 1. Seasonal migratory movements of a tagged Turkey Vulture (*Cathartes aura ruficollis*) during five consecutive annual cycles. (a) GPS track of the migratory route between the breeding area in northwestern Argentine Patagonia and the nonbreeding area in central Chile. The black line shows the boundary between Argentina and Chile. (b) Net squared displacement (NSD). The panel summarizes the results of the latent-state NSD models for classifying seasonal movements. Note the irregular and ascending NSD (i.e. nomadic movement pattern) during the first two nonbreeding seasons.

breeding area. In contrast, in central Chile, the vulture exhibited nomadic movements for the first two years of tracking before transitioning to range-residency movements (Table S2). Over the last three nonbreeding seasons, both the home range and core area progressively decreased in size (Figure S2). During this period, the BC analysis confirmed an overlap of 0.7 (95% CI = 0.6–0.8), suggesting that once established, the vulture showed site fidelity to the nonbreeding area.

We collected records of 93 occurrences of the subspecies *ruficollis* in Chile, consisting of 45 individual and 48 group occurrences (Figure 2(a)). These group occurrences varied in size from two to ten individuals, encompassing mixed-age class flocks (Figure 2(b)).

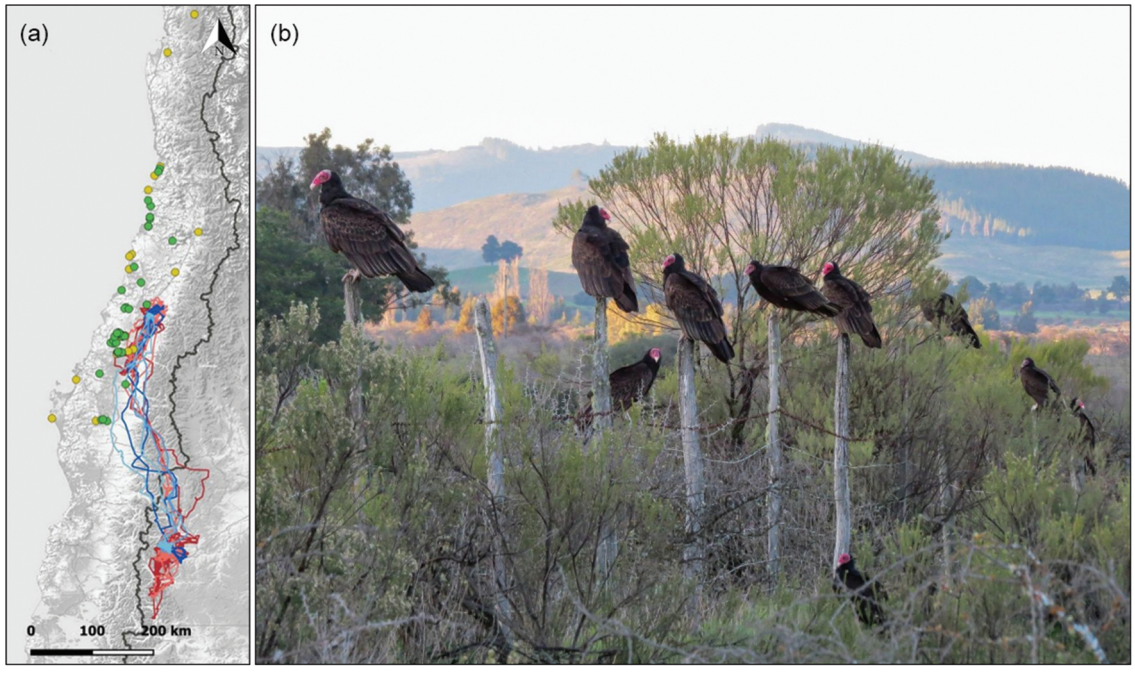

Figure 2. Occurrence surveys of Turkey Vulture (*Cathartes aura ruficollis*) in Chile. (a) Green dots represent observations during the austral spring and summer, and yellow dots represent observations during the austral autumn and winter. The black line shows the boundary between Argentina and Chile. The GPS tracked migratory routes are added for comparative purposes. (b) Mixed-age flock of Turkey Vultures observed in central Chile on August 19, 2022.

Our observations spanned the entire annual cycle: 48 occurrences were recorded during the austral spring and summer, corresponding to the period when the tagged individual was in breeding areas in Argentine Patagonia, while 45 occurrences were documented during the austral autumn and winter. The latitudinal range of occurrences covers from La Higuera in the north (29°27'S; 70° 42'W) to Angol in southern Chile (37°48'S; 72°30'W) (Figure 2(a)).

Discussion

Migratory populations of Turkey Vulture exhibit extensive variability in their movement strategies, a key aspect contributing to their widespread distribution (Dodge *et al.* 2014). By integrating satellite tracking technologies, citizen science data and classical raptor monitoring techniques, our study provides new evidence for the existence of a previously unknown nonbreeding area for the *ruficollis* population breeding in northwestern Argentine Patagonia. Interestingly, our data reveal that the tagged individual completed its entire annual migratory cycle within the temperate zone of South America (i.e. South American cool-temperate migration; Joseph 1997), following one of the shortest routes known for any Turkey Vulture population in America. Of the individuals tagged in northwestern Argentine Patagonia, one migrated short distance towards Uruguay, also using the South American cool-temperate migration system (see Graña Grilli *et al.* 2017, 2019). Conversely, the remaining tagged individuals migrated northward as far as Bolivia, Brazil, and even Colombia (see Graña Grilli *et al.* 2017, 2019), crossing the tropic of Capricorn (i.e. South American temperate-tropical migration; Joseph 1997). Although our data are limited to a single case study, the flocking behaviour of the Turkey Vulture during migration (Bildstein 2022), added to our numerous sightings of *ruficollis* individuals and flocks in Chile, suggests that the migratory route crossing the Andes range towards Chile is used by more individuals than the tagged one.

During the first two tracked nonbreeding seasons, the tagged individual showed both the use of a stopover site and nomadic movements. This suggests an exploratory tendency during the immature stage, essential for gaining information for future prospecting (Mueller and Fagan 2008; Teitelbaum and Mueller 2019). Subsequently, the individual experienced a gradual transition from nomadism to range-residence movements. This shift to restricted spatial use is likely driven by the predictability of the carrion resource (Abrahms *et al.* 2020). Through social facilitation, vultures are well adapted to find the carrion, so learning where the carrion is predictably available influences the selection of communal roosting sites and site fidelity (Thompson *et al.* 1990). Range-residence movements in the breeding area also exhibited an almost constant decrease in home range and core area size, likely driven by the existence of suitable breeding sites and the encounter with abundant food sources, as suggested by Dodge *et al.* (2014).

The regular migration of *ruficollis* to central Chile, an area that provides a suitable nonbreeding and oversummering area, prompts the question: why has this phenomenon not been reported before? Two potential explanations arise. Firstly, the massive presence of the resident subspecies *jota* in central Chile complicates the accurate identification of *ruficollis* individuals by local ornithologists. A similar issue occurs in raptor migration counts in North America, where resident Turkey Vultures mask the counts of migratory individuals (Bildstein 2022). Secondly, it is plausible that northward migration to Chile is relatively recent. The Andes range, perceived as an obstacle for the passage of *ruficollis* from Argentina, has led local ornithologists to consider this subspecies as vagrant. If the first sightings of *ruficollis* in central Chile were pioneering vagrant individuals that found suitable nonbreeding habitats, it presents an intriguing avenue for future research (see Dufour *et al.* 2024).

Acknowledging its limited inference, this study improves our basic knowledge of Turkey Vulture migratory behaviour in the Neotropics and suggests a series of novel avenues for further research. For instance, the migratory corridor used by the tagged individual to cross the Andes Mountain range offers an unexplored opportunity for future monitoring. Indeed, at the time of writing this manuscript, the tagged individual successfully undertook the sixth tracked southward migration. Remarkably, understanding the relevance of this subpopulation in relation to the complete breeding population of northwestern Argentine Patagonia is urgent, especially considering the current growing threat posed by wind energy projects in central Chile (e.g. Garvin *et al.* 2011).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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