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ABSTRACT

The Ruddy-headed Goose (*Chloephaga rubidiceps*) has two separate populations: one sedentary, which resides in the Falkland/Malvinas Islands and one migratory that overwinters mainly in the Pampas region (Argentina) and breeds in Southern Patagonia (Argentina and Chile). The migratory population has decreased considerably to less than 800 individuals and is categorised as Endangered in Argentina and Chile. Knowing the dates at which birds leave the wintering grounds might help to predict the arrival date at stopover sites and breeding areas. We aimed to examine the effect of meteorological conditions on the decision of Ruddy-headed Geese to start spring migration and their migration strategy. We used data from six adults, equipped with satellite transmitters, over 4 years (2015–2018), giving 12 individual departure dates. Weather conditions on departure dates were compared with that during the 15 preceding days. We tested the influence of weather conditions on the response variable measured as a comparison of pre-migration dates versus departure dates. Our results showed that Ruddy-headed Geese departure from their wintering grounds is in association with high wind speed, good visibility and low percentage of cloud cover. The relationship between meteorological conditions and the species decision to start spring migration is essential information for future management plans to prevent potential human-sheldgeese conflicts to escalate along their migration route. Recommendations for the conservation of this species that include implementing mitigation measures to reduce bird collision at human infrastructure, could be applied more specifically during the periods when birds are expected to arrive in each area.

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Migration decision; meteorological conditions; human-geese conflict; satellite transmitters; patagonia

Introduction

One of the most important decisions faced by animals is how and when to move in time and space. These movement decisions will determine how to find food or avoid adverse weather conditions, find a mate and evade predators (Miller *et al.* 2017). Hence, these decisions affect individual survival and fitness (Sharma *et al.* 2009).

Several long-distance migratory birds travel across inhospitable oceans or deserts (Alerstam and Hedenstrom 1998; Alerstam 2009). The severe fitness cost of long under arduous conditions presumably have selected migrants that adaptively manage time, energy, and exposure to adverse meteorological conditions (Alerstam and Hedenstrom 1998; Alerstam 2009). Migrants also show behavioural plasticity in terms of when to depart or selection of stopovers, based on local weather conditions (Alerstam and Hedenstrom 1998). Furthermore, wind conditions (direction and speed) could influence the cost of transport and the risk of being blown off to less advantageous routes (Navedo et al. 2010). In addition, moonlight is associated with behavioural and physiological changes in animals (Portugal *et al.* 2019). Other studies indicated that warmer temperatures increased the probability of departure of migrants birds (Bauer *et al.* 2008), and can also enhance opportunities to refuel at a given site by affecting food availability and, as a consequence, physiology (Ktitorov *et al.* 2021). Moreover, visibility and cloud cover might affect the ability to navigate and spot suitable stopover sites (Newton 2007). Thus, high or rising temperatures, clear sky and no rainfall are associated with more frequent departures

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from wintering or staging areas (Liechti 2006). In particular, rainfall negatively affects migratory progression (Gordo 2007) and impacts the decision to depart for some long-distance migratory birds (Navedo et al. 2010).

Among waterbirds, the Ruddy-headed Goose (*Chloephaga rubidiceps*) is the smallest of the five South American sheldgeese and has two separate populations: one sedentary, which resides in the Falkland/ Malvinas Islands, and one migratory that overwinters mainly in the Pampas region (Argentina) and breeds in Southern Patagonia (Argentina and Chile) (Pedrana *et al*. 2020). Recent findings postulated that these two populations are genetically isolated (Bulgarella *et al*. 2014; Kopuchian *et al*. 2016). Still, the Ruddy-headed Goose is considered as Least Concern (Birdlife International 2016) by the IUCN Red List because it has a large global population (ca. 43,000 to 82,000 individuals; Woods and Woods 2006). While the sedentary population appears to be stable, the migratory population has decreased considerably and current estimates indicate that there are less than 800 individuals (Cossa *et al*. 2017; Pedrana *et al*. 2018a). As a result, this population has been categorised as Critically Endangered in Argentina (AA/AOP, and SAyDS 2008) and endangered in Chile (CONAMA 2009). Pedrana *et al*. (2020) provided the first documentation of consecutive migration cycles of this species using satellite tracking devices and identified stopover sites along their flyways, and breeding and wintering grounds. The authors showed that tracked individuals used the eastern Patagonia migration route along the Atlantic coast and showed philopatry to their breeding and wintering sites (Pedrana *et al*. 2018b, 2020).

The migratory population of Ruddy-headed Geese overwinters in the Southern Pampas, which is one of the most human-modified temperate grasslands ecosystems of the world (Baeza and Paruelo 2020). This species was historically considered harmful to agriculture and local farmers have decimated geese populations (Blanco and de la Balze 2006). Unfortunately, Ruddy-headed Geese encounter another threat during their migration routes along the Atlantic coast (Pedrana et al., in press). Currently, wind farms are being installed all along the Patagonian coast. Knowing the precise moment this species decides to leave its wintering grounds might help to predict the arrival date in stopover sites and breeding areas. Our aim was to examine the effect of meteorological conditions on the decision of Ruddy-headed Geese to start spring migration. We hypothesised that this decision depends on the prevailing weather conditions, and predicted that individuals would start migration on days with high wind speeds and temperature, favourable southerly wind direction, clear sky, good visibility, high percentage of moonlight and low precipitation, humidity and pressure (Table A1).

Methods

Study area and Ruddy-headed Geese tracking data

Six Ruddy-headed Geese were captured in their wintering area in the southern Pampas (38°33′S; 59°42′W, Figure B1) using foot-noose carpets in August 2015 and July 2016 (Pedrana *et al*. 2020). Directly after catching, birds were equipped with solar-powered satellite transmitters (Model 23GS, North Star, USA) which were attached to the back using a Teflon harness (Humphrey and Avery 2014). Platform Transmitter Terminal (PTTs), including harness, weighed 30 g which represented less than 1.8% of the adult body mass (Pedrana *et al*. 2020). Procedures for capture and handling were approved by the Buenos Aires Provincial Agency for Sustainable Development (OPDS), Argentina. PTTs were programmed to transmit with a duty cycle of 6 h on/ 18 h off (local time, GMT-3). Geographical locations were provided by the Argos service, with location accuracy (class designation) calculated using the Kalman filtering method (ARGOS 2016). We used only good quality positions with Argos Location Classes (LC) 3, 2, and 1 (accuracy ≤ 1500 m), which were incorporated into a Geographical Information System.

Weather during pre-migration and departure dates

Ruddy-headed Geese arrive in their main wintering grounds around mid-May and start their spring migration between mid-August when they fly to their breeding grounds (Pedrana *et al*. 2020).

Gorosábel *et al*. (2019) reported that the number of Sheldgeese feeding on wheat crops was lower at the end of the wintering season (mid-August), which agrees with data from other waterfowl species that also spend less time feeding when they are close to start migration (Shariati Najafabadi *et al*. 2010), and that Sheldgeese gather in big assemblages around 2 weeks before they start migrating. Since the wintering area is large, most of these lands are private, and birds make daily movements between feeding and resting sites while in the Pampas region (Pedrana *et al*. 2020), it was impossible to know the exact day that these birds begin the spring migration by direct observation. Therefore, we can determine the exact date these birds start spring migration only by tracking individuals.

Weather conditions during departure dates from the wintering grounds were compared with those during the 15 preceding days. We tested for possible effects on nine meteorological variables: wind velocity, wind direction, cloud cover, visibility, precipitation, humidity, air pressure and moonlight (Figure 1, Table A1). We obtained hourly values for each variable from the weather station (120 ± 35 km) provided by the Weather Information Service (www.ogimet.com) nearest to location of each tracked bird (Based on those in Argos LC 1–3). We developed a script to automatically download the weather conditions for any date and location (https://gitlab.com/lailakaz1986/obtaining-climatic-variables-from-website).

Statistical framework

We built Binomial Generalised Linear Mixed Models (GLMMs) to study the influence of weather conditions (Table A1) on the response variable measured as a comparison of pre-migration dates versus departure date (Appendix A). The departure date was set as 1, while the previous fifteen days considered were set as 0. We set the identity of each individual, (Figure 1, Table A1) the year and their interaction as random effects. We used the Spearman rank correlation coefficient (rs) to detect if two variables were correlated (rs > 0.6). For the model selection, we started with a full model, which included all non-correlated predictors and used the p-value to eliminate non-significant variables. Models were compared using the Akaike Information Criteria (AIC) value, Bayesian Information Criteria (BIC) and Analysis of Variance (ANOVA) test in order to select the best one.

Results

All Ruddy-headed Geese captured in their main wintering grounds were males and weighed ca. 1.83 ± 0.19 kg (Table B1). Over the years, all tracked geese returned to the same capture areas and departed from their wintering sites (Figure B1) between the 12th and 30th of August to start their spring migration (Table B1). We recorded the departure date of six individuals during three consecutive years (i.e. a total of 1325 positions from 2015-Pedrana *et al.* 2020), with a total of twelve departure dates because some individuals stopped transmitting.

The most parsimonious GLMM model for the tracked Ruddy-headed Geese that tested the influence of weather conditions on the decision to start spring migration incorporated three variables: visibility, wind speed and cloud cover (Table 1). As hypothesised, the probability of this species starting south-bound migration increased on days with good visibility, low percentage of clouds and high wind velocity (Table 1). Departure dates of Ruddy-headed Geese from their wintering grounds were characterised by a mean visibility of 20 km (se = 8, Maximum = 30 km), wind velocity of 14 km/h (se = 7, Maximum = 43 km/h), and cloud cover of 24% (se = 21, Maximum = 46%). Meanwhile, weather condition during the 15 preceding days were characterised by a mean visibility of 12 km (se = 5, Maximum = 30 km), wind velocity of 12 km/h (se = 5, Maximum = 25 km/h), and cloud cover of 36% (se = 24, Maximum = 62%).

Table 1. Meteorological variables included in the most parsimonious model testing the response variable measured as a comparison of pre-migration dates versus departure date in Ruddy-headed Goose. Variance estimates for the variable Year as random effect: intercept: 0.52, Residual: 0.73.

Parameters (cj Eq.2)	Estimate	SE	z-value	p-value
Intercept	6.84	1.17	5.84	< 0.0001
Wind velocity	3.73	1.73	2.15	0.0316
Visibility	−9.37	1.50	−6.26	< 0.0001
Cloud cover	−1.98	0.98	−2.16	0.0312

Discussion

This study uses satellite-tracking data to assess for the first time how meteorological conditions affect the decision of Ruddy-headed Geese to depart from their wintering grounds. Our results suggest that Ruddy-headed Geese depart from their wintering grounds in southeast Buenos Aires province (Argentina) under high wind speed, good visibility, and low cloud cover.

Wind conditions are recognised as an important factor affecting timing of migration (Åkesson and Hedenström 2000). Navedo et al. (2010) concluded that wind helps birds to take the direct route with lower associated travel costs and allow them to arrive at the next stopover site at an optimal time to rebuild their energy stores. Following the hypothesis of the 'departure time window', after a period in the area storing enough energy for flight, birds should depart when favourable wind conditions will assist flight (Weber *et al.* 1998). Ruddy-headed Geese are in their wintering grounds since the end of May, feeding on wheat crops while building up their energy reserves. At the end of their wintering period, the number of geese eating on wheat crops is lower and they gather in big assemblages before they start migrating (Gorosábel *et al.* 2019).

On the other hand, good visibility conditions and low cloud percentage could also affect the ability to navigate (Newton 2007). Visual cues for flight departure could be important during night flights for orientation, and clear sky and good visibility could allow birds to have access to celestial orientation cues (Åkesson *et al.* 2021). Reduced cloud cover and higher visibility were found

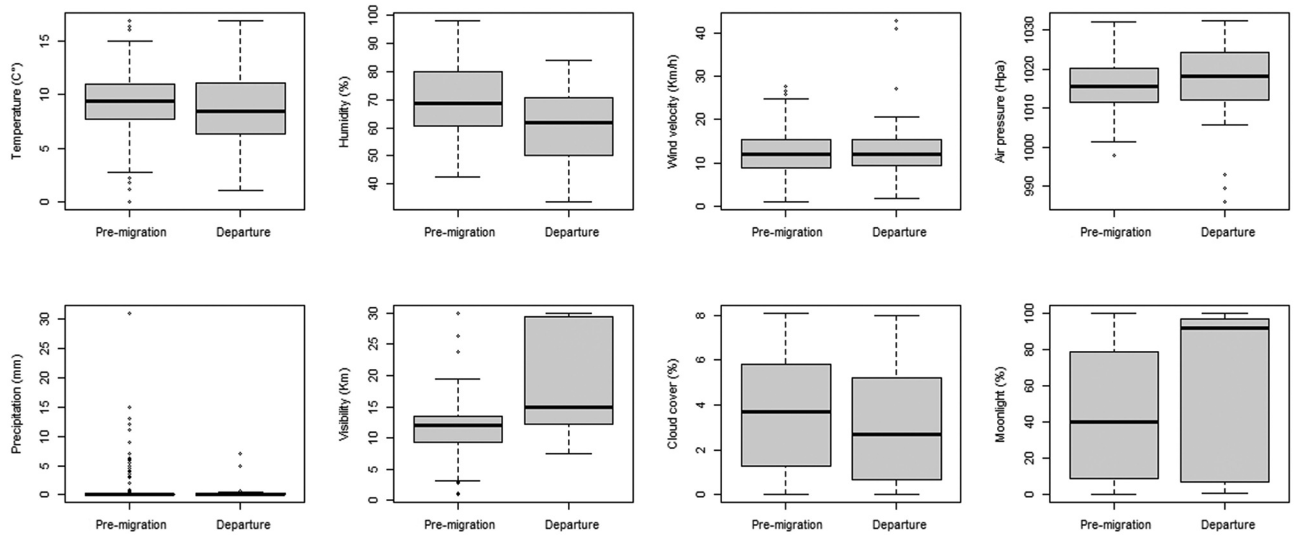

Figure 1. Boxplots of weather variables between pre-migration and departure dates in Ruddy-headed Goose tracked between 2015 and 2018 in the southern Pampas, Argentina.

to be important factors in triggering departure (Åkesson and Hedenström 2000). Even though this suggests a possible explanation, more studies are needed to understand this relationship in waterfowl. Cloud cover was also related to the effect of artificial light at night and moon phase on sleep patterns in geese (Van Hasselt *et al.* 2021). Although we did not find an association with the moon phase in our study, Van Hasselt *et al.* (2021) suggested that cloud cover in new moon nights could amplify the immediate effects of artificial light at night, which could also increase their risk during flight, inducing disorientation and circular flight paths around the light (Van Doren *et al.* 2021).

Although we worked with only six tracked individuals, our results highlighted the importance of understanding the relationship between meteorological conditions and the decision of Ruddy-headed Geese to start spring migration. This information is essential for future management plans to prevent an escalation of potential human-sheldgeese conflicts along their migration route. Future studies should focus on increasing the number of sampled individuals and improving the quality of weather data by installing portable weather stations in the fields used by the species. Pedrana *et al.* (2020) reported that the Ruddy-headed Geese migration is faster in the spring than the autumn, and that the time spent in each stopover site was shorter during spring. We believe that it is possible to predict the arrival date of Ruddy-headed Geese in stopovers and breeding areas based on the dates they decide to leave their wintering grounds. Thus, recommendations for conservation of this species that include intensifying efforts to prevent illegal hunting (Cossa *et al.* 2017) and implementing mitigation measures to reduce bird collision at wind farms, could be applied more specifically during the periods when birds are expected to arrive in each area. In addition, considering the number of wind farms along the migration route, being able to predict when this species is going to fly through these areas can allow authorities to implement mitigation measures to reduce bird mortality (Heuck *et al.* 2019; Marques *et al.* 2020). We encourage managers to consider shutting down turbines during strong winds, good visibility and low cloud cover between mid August and mid September each year.

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Disclosure statement

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

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