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ORIGINAL RESEARCH

Using drones to reduce human disturbance while monitoring breeding status of an endangered raptor

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Abstract

In birds, obtaining information related to nest occupancy, offspring status or breeding success is essential for population monitoring, particularly for species of conservation concern. Traditionally, nest monitoring demands a lot of time and effort in order to gather accurate information and avoiding nest disturbance. Instead, Unmanned Aerial Vehicles (UAVs, hereafter drones) present an alternative to traditional methods, but few studies have been done measuring their influence on birds' behavior and reproductive success. We addressed the utility of drones equipped with an on-board camera in examining nesting status of the endangered Chaco Eagle *Buteogallus coronatus* in semiarid environments of central Argentina, as well as the degree of disturbance of drone flights to individuals. We performed 76 drone flights at 41 Chaco Eagle nests registering flight duration, tree height, nest relative height and pilot proximity to nest. Of those, 38 flights were done over occupied nests where we recorded adult behavior. Before drone took off, most adult eagles remained in the nests or in the surroundings (<100 m away), particularly during the incubation period and in tall trees. During drone flights, only one adult flew as a response to drone flights. The rest of them remained vigilant or emitted alarm calls while incubating or perched on the nest platform. No attack toward drones was registered. The use of drones for monitoring Chaco Eagle's nests significantly reduced levels of disturbance when compared with traditional methods where all adults flew away during climbing. Additionally, this method was almost three times faster in comparison to traditional climbing (performed at the end of the reproductive season) and had no negative effects on reproductive success of Chaco Eagles. Although responses to drones could be species-specific, our results encourage researchers to consider and test the use of drones as a less disturbing and rapid method to monitor breeding raptor populations.

Introduction

Information about nest occupancy, offspring status or breeding success is essential for monitoring bird populations (Caro, 2005; Furness & Greenwood, 1993; Morrison, 1986). For birds of prey, breeding monitoring has been traditionally conducted with ground-based surveys (direct observation and nest climbing) or even using manned aircrafts for large or inaccessible remote areas (Bird et al., 2007; Fleming & Tracey, 2008; Helander et al., 2008; Meyburg et al., 2008; Newton, 1979; White & Sherrod, 1973). All of them take a considerable amount of time, money and field efforts to be performed correctly, so as to gather proper and accurate information and avoiding risks related to both researchers and birds (Andersen, 1990; Sutherland, 2006; Watts et al., 2010; Wiegmann & Taneja, 2003). This fact is exacerbated for species that are easily disturbed or that nest in distant and difficult-to-access areas (Carey, 2009; Gardner et al., 2008; Grenzdörffer, 2013; Koh & Wich, 2012; Sardà-Palomera et al., 2012, 2017).

Besides, Unmanned Aerial Vehicles (UAVs, hereafter drones) offer an alternative to standard nest monitoring methods (Watts et al., 2010; Weissensteiner et al., 2015). Drones are flying objects that can be remotely controlled from the ground. When drones are equipped with a camera, this technology offers new opportunities for biological research (Anderson & Gaston, 2013; Chabot & Bird, 2012, 2015; Gonzalez et al., 2016; Koh & Wich, 2012; Marris, 2013; Schiffman, 2014). One of these is the chance to monitor nests in a more efficient, safer, time-saving, accurate, and cost-effective way than traditional methods (Canal & Negro, 2018; Chabot et al., 2015; Grenzdörffer, 2013; Hodgson et al., 2016; Sardà-Palomera et al., 2012; Weissensteiner et al., 2015). Also, the use of drones can avoid tree damage and physical hazard for researchers associated with tree climbing (Weissensteiner et al., 2015).

The use of drones in avian research is a rather young issue, since there are few studies examining the impact of these aerial vehicles on birds. Some studies have used drones during the breeding period for a variety of purposes (Canal & Negro, 2018), such as to count nests and/or colonies (Chabot et al., 2015; Grenzdörffer, 2013; Hodgson et al., 2016; Sardà-Palomera et al., 2012, 2017), to monitor nest status (Potapov et al., 2013; Weissensteiner et al., 2015) or to make census on bird flocks (Chabot & Bird, 2012) without causing apparent disturbance to individuals. Nevertheless, drones may affect individuals´ behavior and reduce their reproductive output, thereby altering species' fitness and biasing research results (Borrelle & Fletcher, 2017; Grenzdörffer, 2013). Evidence for drone disturbance to birds has been already found (Brisson-Curadeau et al., 2017; Dulava et al., 2015; Egan et al., 2020; Lyons et al., 2017; Rümmler et al., 2016), also in the case of raptors (Junda et al., 2016; Lyons et al., 2017). Raptors are particularly suitable species for breeding monitoring using drones because they build large open-nests on top of tall trees or at the slopes of cliffs (Newton, 1979), which usually are easy to access with these aerial vehicles. However, the use of drones for research purposes should always be carefully evaluated. Studies using these vehicles must avoid any risk of death or physical damage for birds either by accidental collisions or deliberate attacks, and should minimize the disturbance or alteration of birds´ behavior that would result in nest failure (Weston et al., 2020). These conditions must be observed for any research involving drones but especially when species of conservation concern are targeted in the study.

Here, we assess the usefulness and efficiency of drones when monitoring breeding raptors using the endangered Chaco Eagle *Buteogallus coronatus* as a model species. We also examine the degree of nest disturbance reached in comparison with traditional monitoring methods. Chaco Eagle is among the largest Neotropical birds of prey ($\sim$3 kg), being one of the rarest and most severely threatened (Sarasola et al., 2018). The species´ productivity is very low, as it takes several years for eagles to reach sexual maturity and breeding pairs lay only one egg per annual breeding attempt. Besides, very little is known about its responses to human disturbance or on its nest defense behavior. Therefore, establishing efficient protocols for nest monitoring that minimize individuals´ distress is crucial to reduce nest disturbance and hence to diminish risks of nest failure. The specific objectives of this study are (1) to evaluate the accuracy and efficiency of drones to monitor Chaco Eagle nests in comparison with traditional methods, (2) to examine whether drone flights may pose any additional and severe disturbance (i.e.: distressed behaviors) to breeding pairs when compared to traditional monitoring methods and (3) to assess the effects that drones could have on breeding performances of this endangered species.

Materials and Methods

Study species

Chaco Eagle inhabits savannah-like ecosystems, pastures, open woodlands and dry shrub lands from southern Brazil to northern Patagonia in Argentina (Ferguson-Lees & Christie, 2001; Sarasola et al., 2010). The global population estimated for this endangered species is of less than 1000 reproductive individuals with negative population trends (Birdlife International, 2016). Main identified threats for Chaco Eagle include habitat fragmentation, human persecution, electrocution with power lines, and drowning in water reservoirs (Fandiño & Pautasso, 2013; Galmes et al., 2018a; Sarasola et al., 2020; Sarasola & Maceda, 2006; Sarasola et al., 2010). Chaco Eagle builds its nests on top of the tallest trees available on breeding territories, or even on human-made structures such as steel towers (Sarasola, 2018).

Study area

The study was carried out during five consecutive breeding seasons (2016–2020) throughout western La Pampa province, central Argentina (approx. 37°S, 66°W). This area of ca. 60 000 km^2 comprises the temperate-arid ecoregions of Espinal and Monte Desert and the ecotone landscapes between them. Both ecoregions are characterized by high temperatures in summer (up to 44°C), when most of the scarce annual rainfall occurs (Espinal: 300–550 mm; Monte Desert: 80–330 mm). Typically, Espinal is represented by deciduous xerophytic forests of caldén

Prosopis caldenia, grassy savannahs and bushy steppes, whereas Monte Desert includes high shrub-steppes with isolated trees of algarrobo *Ceratonia siliqua* but also other native tree species such as chañar *Geoffroea decorticans* (Busso & Fernández, 2017; Cabrera, 1976). The study area is a flat plain, where mountains, hills and dunes are typically lacking.

Field procedures

Chaco Eagle nests were located during field surveys by car and on foot, and by means of interviews with local landowners and rural workers, from mid-September to mid-February each year. This procedure was conducted both for those previously identified Chaco Eagle breeding territories (Galmes et al., 2018b), which were visited in order to ensure their activity, as well as for new breeding territories and nests located during this study. Once a potential Chaco Eagle active nest was found, it was visited repeatedly until the nestling fledged or, otherwise, until nest failed (Fig. 1). During the reproductive period, nests were visited, on average, three times in order to check their status. Relative heights of nests were assessed stating if they were on top of the tree or at intermediate heights. Nest supporting trees were classified as dead or alive and their heights were measured using the relative flight altitude of the drone.

Nest monitoring

A DJI Phantom 3 Standard drone (DJI Technology Co., Shenzhen, China) was employed to monitor all nests. This drone model is a four rotary-winged or quadcopter with a built-in, 12-megapixel resolution camera that allows both video and photo recording. This type of multirotor drone is known to be less disturbing to birds than other types of drones (Egan et al., 2020). Diagonal length is 350 mm and weight is 1030 g. The model employs a 15.2 V lithium and 4480 mAh battery that allows a flight endurance of ca. 25 min. Noise level is 60 dB at 2 m, which is under the levels admitted for experiments producing noise to wildlife (Wright et al., 2010). The drone was operated with a radio-controller, while the camera and the camera gimbal were controlled via the DJI GO app on a smart-phone. Using this app we continuously recorded and stored flight features such as flight altitude, speed and total distance traveled. Some of these variables were later used in the analyses (e.g., tree height and distance to nest).

In order to develop nest surveys with the drone and to record adults´ behavior during them, two people were necessary: a pilot, in charge of assembling the aircraft, bringing it to the launch site, flying, controlling the camera, disassembling and carrying the aircraft back to the car, and a spotter, responsible for recording eagles´ behavior during the survey (Junda et al., 2015). We divided nest surveys into three stages: approach, flight, and withdraw. In the course of approach stage, the spotter started recording adult eagles´ behavior after going out from the car (~150 m from the nest) while Pilot assembled the drone and both got to a strategic location where to launch the drone. This place, hereafter called "flight starting point", was the same as the one used during traditional monitoring to start the walk toward the tree (see paragraph below). Flight starting point was set up at the minimum distance from which we could see the drone and control its movements, given that semi-open forests of La Pampa can entail difficulties for flying the drone. Then, during flight stage, drone took off, reached a height that surpassed in 5–10 m the height of the tree supporting the nest and started flying over the nest (Fig. 2), attempting to capture an image of the content of it (close-up flight: Chabot & Bird, 2015). In no case the drone flew within less than 3 meters above and 5 meters of the nest (Junda, Greene & Bird, 2015; Vas et al., 2015) and mean speed when approaching was 5 m/sec. When the aircraft landed, we started withdraw stage, which ended when we left from the place with the car and stopped watching the nest. We recorded the time needed for (1) assemblage: vehicle assembling and disassembling and (2) flight: drone flight (from take-off until landing), both making drone monitoring (Junda et al., 2016).

All nests were climbed after the breeding season in order to record the time needed to examine the nest content while avoiding possible disturbance to adults and fledglings. Total time (traditional monitoring) was recorded and divided into two sections: (1) walk: get to the nest tree from the flight starting point (see above) and return (opposite way) and (2) climb: scale the nest up and down. Although nests were also climbed with the purpose of banding fledglings at the end of the breeding seasons, time employed for such procedure was not considered for the comparison with drone flight duration. Climbing nests for banding usually requires more time than doing it only for the inspection of their contents, because of the time needed to catch, manipulate, secure, descent and then take back the young eagle to the nest.

Eagles´ behavior during flights

We recorded Chaco Eagle adults´ behaviors during all three stages of nest surveys, and classified them into six groups of increasing disturbance: indifference, vigilance, observation, alarm, flight, and attack. Indifference behavior comprised all types of comfort or resting movements:

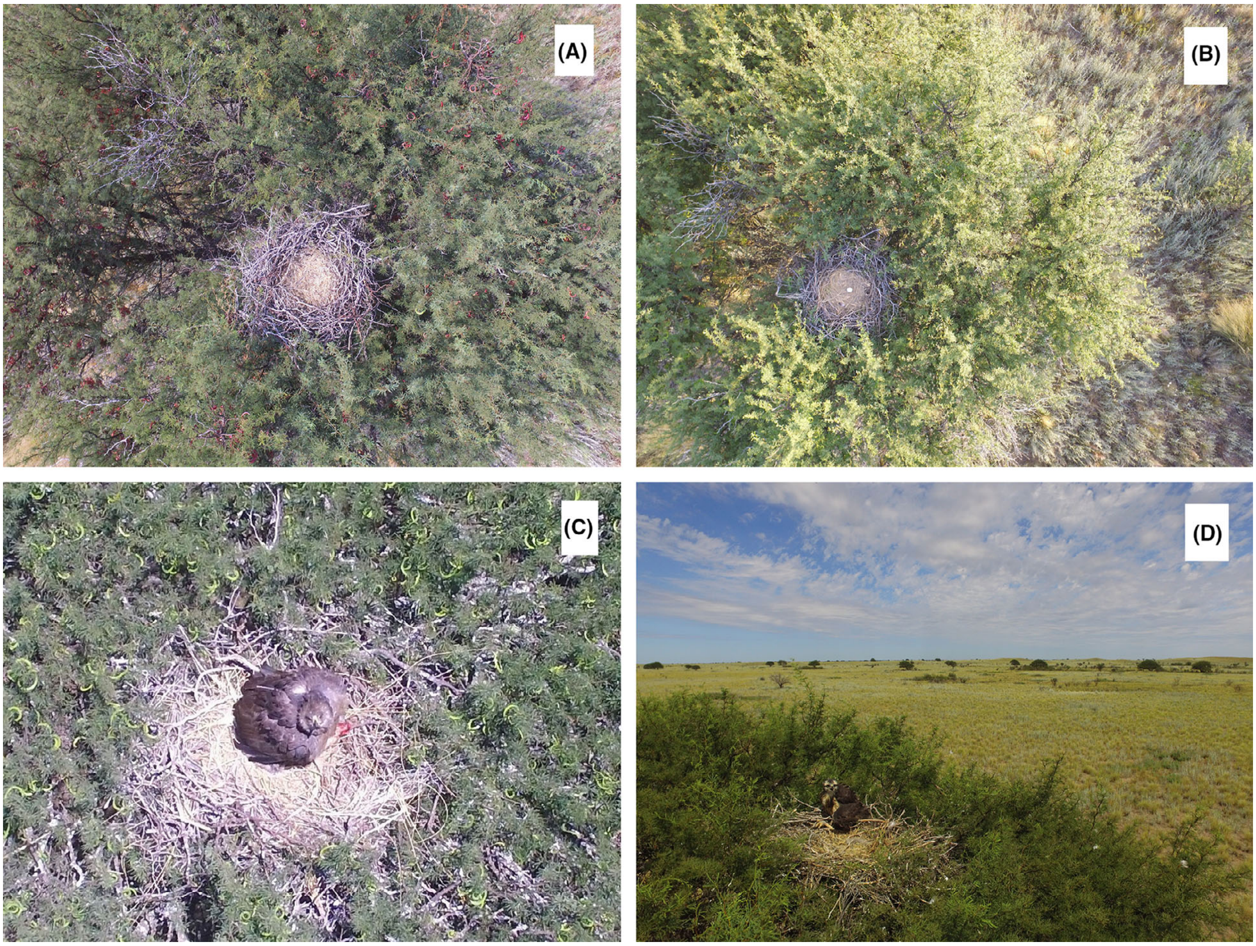

Figure 1. Chaco Eagle nests with (A) fresh material indicating nest/territory occupancy, (B) an egg during incubation period, (C) an adult covering a young nestling and (D) a 30 days-old fledgling. All pictures are shown as taken during drone flights.

sleeping, stretching, preening, or manipulating egg or chick. Vigilant behavior meant that the eagle, while at nest, was looking straight to the drone and the movements of its head indicated attention to the surrounding events. Observation was similar to vigilance, but from a different tree than the one where the nest was. Alarm was recorded when eagles started making vocalizations or calls in the presence of the drone. If adult eagles flew from the nest, leaving it unprotected when drone was approaching, we recorded it as flight behavior. Lastly, attack behavior was considered if the eagle approached and/or dove toward the drone. Finally, and in order to check for the relative disturbance effects of the drone on Chaco Eagle reproductive success (i.e., number of breeding attempts producing offspring over the total number of attempts), we compared the overall reproductive success of eagles (removing those nests which were lost due to climatic or predation events) when monitored with the drone (i.e. seasons 2016–2020) with that of previous seasons in which nests were monitored traditionally (i.e.: climbing) (Galmes et al., 2018b).

Statistical analyses

All statistical analyses were carried out using R (R Core Team, 2016). We performed paired t-tests to compare, for each survey, the times spent for both traditional monitoring and drone monitoring methods. Afterwards, with the aim to check which variables affected drone flight durations, we performed Linear Mixed Models. Because of lack of normality, flight duration (response variable) was transformed to natural logarithms before being included in the models, and the normality of the residuals of the model was checked with Shapiro–Wilk normality test ($W = 0.98$, $P = 0.40$). Nest identity was kept as random factor into the models. Variables examined that could potentially affect flight duration were tree height in meters, tree status (dead or alive, as dead trees allow for

Figure 2. An exemplification of the position of drone and drone's pilot (white arrow) in relationship with Chaco eagle's nest and a 30 days-old fledgling.

better visibility of the nest and shorter flying times to obtain pictures in comparison with foliaged trees), relative height of the nest (on top of the tree or on an intermediate height for the same reason) and the distance from the flight starting point to the base of the tree (hereafter distance). Because during the study period all flights were performed by the same pilot, we included an additional explanatory variable: the chronological order of the flights conducted over a particular nest, which was considered as a proxy of experience gained by the pilot, from 1 (first flight, little experience) and on (last flight, improved experience). The analysis of flight time as a function of experience only included those nests which were monitored with the drone at least twice.

Concerning adult behavior, we built logistic models for stress response by grouping together behaviors related to stress (i.e.: attack, flight and alarm) whereas the remaining behaviors were grouped as less stressed. First, in order to address general recommendations when studying breeding Chaco Eagles, we analyzed adults´ behavior during approach stage (before drone took off) by modeling the probability of adult Chaco Eagles becoming stressed or not depending on the following variables: nest status (egg, chick or none –referring to nests under construction or to recently lost nests-), distance (flight starting point marks the end of this stage), relative nest height and tree height. Secondly, in order to account for drone disturbance effects, we modeled, during flight stage, the probability of adult Chaco Eagles becoming stressed or not depending on nest status, distance and flight time. In all cases, we performed Generalized Linear Mixed Models with nest identity as a random effect and using a binomial distribution and a logistic link function.

For modeling purposes, we started with a model including all explanatory variables and performed a backward-stepwise selection procedure, where we removed non-significant predictors until only significant ones remained in the model (Crawley, 2015). The significance of the variables was tested using likelihood tests, comparing the model with and without the predictor. Significant results were considered when $P < 0.05$, otherwise they were considered non-significant. Before interpreting any model outcome, we performed model diagnostics statistics (e.g.: influential data points, multicollinearity) to avoid misleading results due to statistical artifacts. We explored collinearity between potentially correlated variables by computing Variation Inflation Factors (VIFs), and we found no apparent deviations from the assumptions of linear models (e.g.: VIF <2; Hair et al., 2010).

Results

We performed a total of 76 drone flights over 41 Chaco Eagle nests. Forty nests were made on trees (*P. caldenia* = 33, *G. decorticans* = 3, *Eucalyptus* sp. = 2, *Ulmus* sp. = 1, *C. siliqua* = 1), at a tree height ranging from 3 to 18 m (7.86 ± 3.97 m), and one nest was built on a steel tower of 20 m height (Sarasola, 2018).

Flight starting point was set at a mean distance of 62.30 ± 16.21 m away from the nest. Furthermore, 11 flights (14.47%) were done over dead trees, whereas 65 (85.53%) were done over trees that were alive. Sixty flights (78.95%) were done over nests located on top of the trees (or tower), whereas the rest of them (n = 16; 21.05%) were located at intermediate heights.

Drone monitoring of nests took a mean of 5.96 ± 1.37 min, whereas traditional monitoring took

16.81 ± 17.52 min. Thus, drone monitoring was, on average, 2.82 times faster than traditional monitoring (Welch two sample *t*-test: $P < 0.001$). Moreover, there was significantly less variation in the duration of drone monitoring compared to traditional monitoring (*F* test to compare two variances; F (75, 75) = 162.13, $P < 0.001$; Fig. 3). On the other hand, flight durations were shorter when done over smaller trees (Wald $\chi^2 = 40.03$, d.f. = 1, $P < 0.001$, Fig. 4A), and over nests built on dead trees (Wald $\chi^2 = 8.59$, d.f. = 1, $P < 0.01$). Also, pilot experience reduced flight durations (Wald $\chi^2 = 24.11$, $P < 0.001$, Fig. 4B), but relative nest height (Wald $\chi^2 = 1.52$; d.f. = 1; $P = 0.22$) and distance (Wald $\chi^2 = 0.66$, d.f. = 1, $P = 0.42$) did not affect flight durations.

Eagles´ behavior toward drones

Of 76 drone flights, 43 flights were done over active nests (Table 1) and, of these, five were performed over active nests where adults did not appear, so we discarded them for further analyses of eagle's behavioral response. Thus, during the study period we conducted a total of 38 drone flights over 24 active Chaco Eagle nests belonging to 21 different reproductive pairs (Table 1). During all drone flights, we were able to address nesting status by taking pictures of their contents (Fig. 1). We never recorded both adults at nests at the same time. For behavior recording, and given that Chaco Eagle adults are plumage-monomorphic, we did not distinguish between males and females. Some adult Chaco Eagles flew from the area during approach stage, but all but four remained in the surroundings (Table 1). During this stage (before drone took off), adult Chaco Eagles more likely flew from the nest in smaller trees (tree height; Wald $\chi^2 = 5.87$, d.f. = 1, $P < 0.05$). Also, adult Chaco Eagles more likely remained in the nest while incubating, but were more prone to abandon the nest when it had nothing on it (nest status; Wald $\chi^2 = 5.62$, d.f. = 2, $P < 0.05$).

During flight stage (n = 34, Fig. 5), most adult Chaco Eagles did not show any remarkable reaction to drone flights (n = 21, 61.77%), remaining vigilant from the nest or observing from a nearby perch. Twelve adults (35.29%) were recorded vocalizing toward the drone either from the nest or from a nearby tree, and only one flew as a response to drone flight (Fig. 5). No attack to the drone was registered during flights. Furthermore, Chaco Eagles´ behavior toward drones was not affected by any of the variables considered (nest status: Wald $\chi^2 = 1.02$; d.f. = 2, $P = 0.60$; distance: Wald $\chi^2 = 0.16$; d.f. = 1, $P = 0.69$; flight time: Wald $\chi^2 = 2.61$; d.f. = 1, $P = 0.11$). After flying the drone (n = 34) and before we left the area (withdraw stage), seven adults (20.59%) showed indifferent behaviors, 24 (70.59%) remained vigilant from the nest or in the surroundings (<100 m), and three returned immediately to the nest (8.82%).

Concerning each reproductive period separately (Table 1, Fig. 5), during nest building (n = 4, Fig. 1A), all adults flew away before drone took off and did not return to the nest. In the course of incubation period (n = 8, Fig. 1B), all but one of the adults remained in the nest throughout the whole experiment, and only two of them showed a relative disturbance level by emitting alarm calls while in the nest (Fig. 5). Regarding chick rearing period (n = 23, Fig. 1C and D), five adults flew before drone took off and remained in the surroundings, three of them returning to the nest during withdrawal (Table 1). During drone flights at this stage, 10 adults (43.48%) remained vigilant from the nest or from a nearby perch, 12 (52.17%) emitted alarm calls toward the drone while in the nest and only one (4.35%) flew as a response to drone flight (Fig. 5). In all recently lost nests (n = 3), adults flew away from the nest before drone launching and stayed in the surroundings during withdrawal.

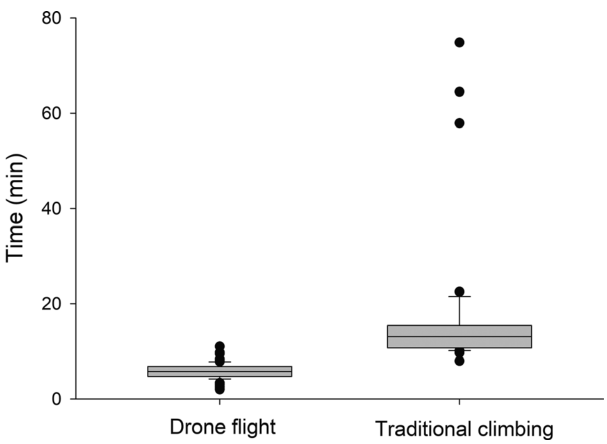

Figure 3. Boxplot for the time (minutes) spent with drone flight (n = 76) and traditional climbing (n = 41) for Chaco Eagle nest monitoring conducted during 2016–2020 breeding seasons (austral spring and summer) in semiarid landscapes of central Argentina.

Effects on reproductive success

Overall mean reproductive success of Chaco Eagles during the period 2011–2015 (nest success: 0.57, n = 44 breeding attempts), when nest monitoring was conducted by traditional methodology, was the same than for the period 2016–2020 period (nest success: 0.45, n = 31), when nests were monitored using drones (*t*-value = 0.99; d.f. = 73, $P = 0.33$). Furthermore, mean breeding success for five particular Chaco Eagle pairs that we monitored using

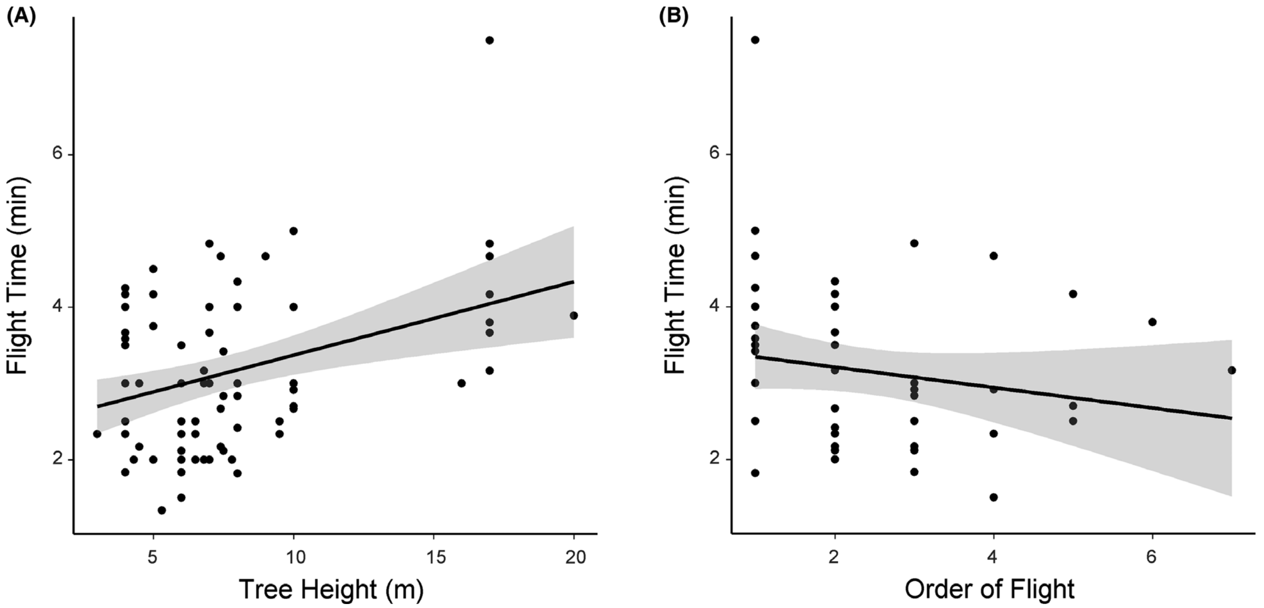

Figure 4. Relationship between the duration of drone flights (in minutes) during surveys on Chaco Eagle nests conducted in 2016–2020 breeding seasons and a) nest tree height, measured in meters (n = 76 flights) and b) the chronological order of flight over the same nest (n = 52 flights). Because flights were always conducted by the same person (who had no previous training as drone pilot), this last was considered as a proxy of pilot experience gained (measured in each tree from 1 and on, being 1 the first flight) throughout the study period.

Table 1. Summary of drone flights on Chaco Eagle active nests during the study period in relationship with the breeding phenology.

		Reproductive period			
	Total Flights	Nest building	Incubation	Chick rearing	Lost nests
Active nests	43	4	9	23	7
Adult presence					
Arrival	38 (32)	4 (3)	8 (8)	23 (19)	3 (2)
Approach	34 (21)	1 (0)	7 (7)	23 (14)	3 (0)
Flight	34 (20)	1 (0)	7 (7)	23 (13)	3 (0)
Withdraw	34 (23)	1 (0)	7 (7)	23 (16)	3 (0)

The number of occasions in which an adult eagle was present at the breeding site when researchers arrived (arrival) and at the end of each stage of monitoring procedure (approach, flight, withdraw) is shown in relationship with each of the reproductive periods. Numbers in brackets indicate the number of occasions in which adult eagles were/remained specifically at nest.

both methodologies (n = 18 and n = 17 breeding attempts for traditional and drone monitoring, respectively) was also the same ($P > 0.27$ for all paired comparisons).

Discussion

Our results suggest that monitoring Chaco Eagle nests with drones is more effective, time-saving, and less disturbing than doing it by means of traditional methods.

First of all, nest monitoring with drones was as accurate and almost three times faster when compared to traditional climbing, a fact which is in accordance with other studies on tree-nesting species (Junda et al., 2015; Weissensteiner et al., 2015). The usage of a drone for continuously monitoring breeding populations (i.e. several nests located far away one from each other in remote areas over the whole breeding period of ~6 months) is key to save time for research. This is of even more importance if the species nests on top of tall trees where traditional climbing is challenging (Grenzdörffer, 2013; Koh & Wich, 2012; Potapov et al., 2013; Sardà-Palomera et al., 2017; Weissensteiner et al., 2015). Furthermore, the drone employed was user-friendly, accessible, and economic, could be operated by a single person and required hardly any previous experience in handling remotely controlled aircrafts. Nevertheless, experience was a rank, since flight durations were significantly reduced as flights went by. Therefore, previous practice with the drone is recommended in order to minimize flight duration and possible disturbance to nesting birds.

Secondly, concerning behaviors, adult Chaco Eagles flew away in all cases when performing traditional monitoring but barely did it when a drone flew over the nest. The use of drones to monitor birds´ nests has resulted in different behaviors across literature (Brisson-Curadeau et al., 2017; Egan et al., 2020; Junda et al., 2016; Lyons et al., 2017; Potapov et al., 2013; Rümmler et al., 2016;

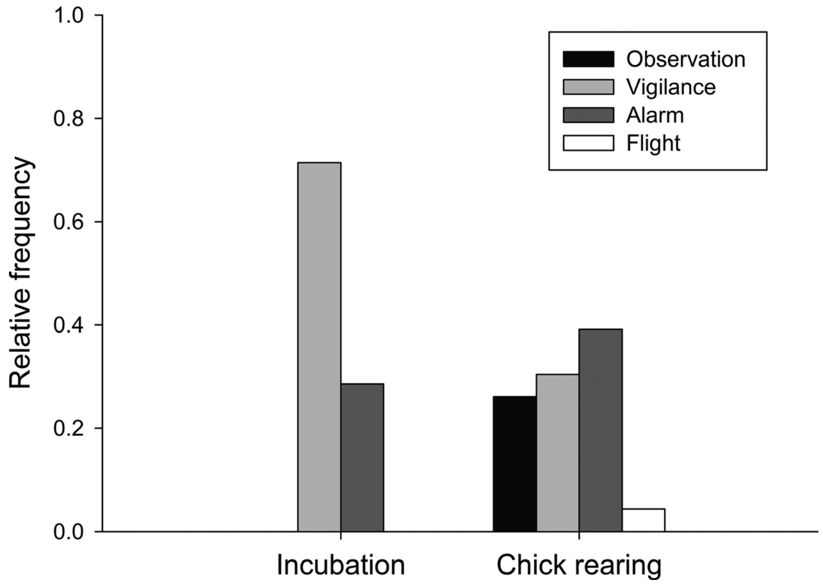

Figure 5. Relative frequency of each behavior (observation, vigilance, alarm or flight) exhibited by adult Chaco Eagles as a response to drone flights during the incubation (n = 7 flights) and chick rearing (n = 23 flights) periods while monitoring status of active nests during the 2016–2020 reproductive seasons in semiarid landscapes of central Argentina.

Vas et al., 2015). No attack to the climber or to drones was registered in any case, contrary with the stronger reactions against disturbance that some raptors tend to exhibit (Junda et al., 2016; Lyons et al., 2017; Morrison et al., 2006). Low levels of parental defense are common for nesting birds which are frequently shot or trapped (Morrison et al., 2006), as is the case of Chaco Eagle (Sarasola et al., 2010). In fact, Bald Eagle *Haliaeetus leucocephalus*, which also suffered from illegal killing (Coon et al., 1970), showed the lowest response to drones when compared to other raptors (Junda et al., 2016). On the other hand, vocalizations may be used both to distract a potential predator and to make the nestlings less conspicuous in the nest (Caro, 2005; Yorzinski & Patricelli, 2010). This behavior involves relatively little cost to the adults when compared to diving or approaching a potential nest predator (Montgomerie & Weatherhead, 1988).

Adult Chaco Eagles showed different behaviors during the experiment across reproductive periods. Before drone took off, all adults flew away when the nest was empty (i.e.: nest building stage or already failed nests), probably to avoid unnecessary risks (Montgomerie & Weatherhead, 1988). Conversely, during incubation period, only one adult left the nest before drone launching and no adult flew due to drone flights. Lastly, chick stage concentrated all types of responses, including the majority of alarm events (calls and vocalizations) and a single event of flight. Such differences could be related to the fact that adults made decisions on whether to remain in the nest or not according to the differential value and vulnerability of the contents of it (Caro, 2005; Montgomerie & Weatherhead, 1988). Most nest predation and failure in raptors occurs during incubation period and early in the nestling period (Newton, 1979), given that grown-up nestlings (or fledglings) could eventually flee from the nest if a potential predator approaches (Andersen, 1990; Montgomerie & Weatherhead, 1988). Thus, during incubation period most Chaco Eagle adults may decide to stay in the nest as a way of protecting the vulnerable egg, but fly from the nest when it contains a nestling. These results were confirmed for the analysis of adults´ behavior before flying the drone. Moreover, no variable considered affected Chaco Eagle adults´ behavior toward drones, a fact that evokes the importance of individual variation in behavior (Caro, 2005). Therefore, more research will be needed to accurately examine the causes and consequences of the different individual responses across nest stages.

Previous literature has highlighted the importance of measuring the impact of nesting raptors to the UAV without the presence of humans at the base of the nest (Junda et al., 2016) to avoid over stressing the adults and confusing the effects of the UAV with those of the "on foot" approach. During our study, we tried to keep flight starting point as far as possible. Nevertheless, since some of the adults flew away from the nest before launching the drone, it seems likely that this distance should be optimized whenever possible, to avoid disturbance and, thus flight initiation (Blumstein, 2003). Previous studies have recommended a minimum distance to fly the drone

(Rümmler et al., 2016; Vas et al., 2015; Weston et al., 2020). However, these studies have generally focused on ground-nesting terrestrial or aquatic birds, but not on raptors, which build their nests at the top of tall trees and thus, would be less disturbed by such distances.

Our results showed that there was a lower probability of adult Chaco Eagles flying from the nest during Approach Stage if trees were higher and depending on the content of the nest. The interaction of tree characteristics, nest status and individuals´ perception of risk by our "on foot" approach made adult Chaco Eagles modify their behavioral decisions accordingly (Caro, 2005). However, most of the adults that left the nest during researchers' approach remained in the surroundings while drone was flying, and a few of them even returned to the nest straight after the drone landed (Brisson-Curadeau et al., 2017; Junda et al., 2015; Junda et al., 2016). Future research will try to remove potential biases in order to accurately define adult responses to drone flights.

Lastly, reproductive success of nests monitored with drones was not different than that of nests which were monitored traditionally. In general, traditional monitoring produces a weak –or absent- disturbance and has no effects on breeding success (Ibáñez-Álamo et al., 2012). In line with those results, Chaco Eagle breeding success was not affected by drone flights. Even with scarce information about potential avian nest predators for Chaco Eagles, it is probable that drone features (i.e.: size, shape, color, and noise) do not resemble any of them, also explaining the fearless behavior of eagles toward drones.

To sum up, this is the first study with raptors where drones were simultaneously used, during consecutive reproductive seasons, for (1) continuous monitoring of breeding populations (effectiveness), (2) estimating the time saved when compared to traditional climbing (efficiency) and (3) accounting for individuals´ response towards drone and reproductive success related to it (disturbance).

Some issues, however, still need more research. For instance, sound level during approaches at nests was not measured. This may be related to the fact that, during vertical movements, drones emit a stronger noise (Rümmler et al., 2016; Vas et al., 2015), and this would evoke a higher disturbance in vertical flights when mimicking a predatory bird attack. On the other hand, it would be interesting to measure habituation to drone flights (Brisson-Curadeau et al., 2017), by systematically flying the drone several times per season, but this situation is delicate in an endangered species like Chaco Eagle. Last but not least, we examined behavioral changes but we did not take into account other stress indicators as increased heart rates or corticosterone levels (Ditmer et al., 2015). The sensitivity of wildlife to disturbances caused by an approaching UAV should be considered when developing guidelines for the use of this technology. We encourage future research to account for this topics while strictly following drone protocols (Barnas et al., 2020).

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Conflict of Interest

This manuscript has not been submitted elsewhere. Both authors (Diego Gallego and José Hernán Sarasola) agree with the contents and the submission for publication, and declare no competing interests.

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