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FIRST SATELLITE TELEMETRY STUDY OF MOVEMENT BEHAVIOR OF JUVENILE GOLDEN EAGLES FROM MEXICO

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Abstract.—The southern limit of the Golden Eagle's (*Aquila chrysaetos*) breeding range in North America is Mexico, where the eagle is the national symbol yet designated as a threatened, high priority species for conservation action. Movement information needed for conserving Mexico's Golden Eagles is sparse; knowledge of dispersal from natal areas is essential to understand the eagle's ecology and help provide for its management. Using satellite telemetry data, we analyzed movements of three males and one female from central Mexico during their first year of life; we documented (1) timing and distance of initial dispersal movements, (2) total distance traveled and maximum distance from natal site by month of age following fledging, and (3) size of areas (based on 95% adaptive local convex hulls) across which eagles ranged following initial dispersal. Individual eagles dispersed from their natal areas between mid-September and mid-November, at 6–8 mo of age. Monthly total distance traveled by males reached approximately 350–1350 km at 8–11 mo; the female's peak monthly travel was 3000 km, at age 7 mo. Monthly proximity to natal sites by individuals at ages 8–12 mo was relatively constant, averaging 17.9 km (SD = 5.7) to 129.1 km (SD = 11.3). After dispersal, the monthly ranging areas overall increased during the first year of life for all eagles, especially the female, due mainly to multiple long-distance excursions. Our data suggest that movement behavior of juvenile Golden Eagles from Mexico is mostly similar to that of conspecifics from nonmigratory populations elsewhere. Our study may help serve as a foundation for future work to better understand movement dynamics and resource selection by Mexico's Golden Eagles.

Key Words: *Golden Eagle*; Aquila chrysaetos; *dispersal*; *habitat use*; *home range*; *Mexico*; *movement behavior.*

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PRIMER ESTUDIO DE TELEMETRÍA SATELITAL SOBRE LAS CONDUCTAS DE DESPLAZAMIENTO DE JUVENILES DE *AQUILA CHRYSAETOS* EN MÉXICO

Resumen.—El límite sur del área reproductiva de *Aquila chrysaetos* en Norteamérica es México, donde es considerada símbolo nacional, y es una especie amenazada y prioritaria para la conservación. La información de sus desplazamientos, necesaria para su conservación en México, es escasa. Además, el conocimiento sobre la dispersión de los juveniles desde sus áreas de nacimiento es esencial para comprender mejor su ecología y proporcionar elementos para su manejo. Usando telemetría satelital, analizamos los desplazamientos de tres machos y una hembra del centro de México durante el primer año de vida, documentando (1) el momento y la distancia de los desplazamiento de dispersión inicial, (2) la distancia recorrida y la máxima distancia desde el área de nacimiento para cada mes de edad después de abandonar el nido, y (3) el tamaño de las áreas de actividad (en base al uso de cascos convexos locales adaptables al 95%) a través de los cuales las águilas se desplazaron mensualmente a partir de su dispersión inicial. Los individuos se dispersaron desde el área de nacimiento entre mediados de septiembre y mediados de noviembre, a los 6-8 meses de edad. La distancia mensual recorrida por los machos alcanzó ~350-1350 km a las edades de 8 -11 meses; la distancia máxima mensual recorrida por la hembra fue 3000 km a los 7 meses de edad. La proximidad mensual a las áreas de nacimiento entre los 8-12 meses de edad fue relativamente constante, promediando entre 17.9 km (DE = 5.7) y 129.1 km (DE = 11.3). Después de la dispersión, las áreas de actividad mensuales en general aumentaron durante el primer año de vida, especialmente para la hembra, debido a múltiples excursiones de larga distancia. Nuestros datos sugieren que la conducta de movimiento en juveniles de *A. chrysaetos* en México es básicamente similar a la de aquellos individuos conspecíficos de poblaciones no migratorias en otras áreas de su distribución. Nuestro estudio podría servir como base para comprender mejor las dinámicas de estos desplazamientos y la selección de recursos por parte de *A. chrysaetos* en México.

[Traducción de los autores editada]

Introduction

The southernmost extent of the Golden Eagle's (*Aquila chrysaetos*) New World breeding range is central to northern Mexico (Katzner et al. 2020), although resident individuals (apparently nonbreeding) and northern migrants have been documented in more southerly states of the country, e.g., Veracruz, Oaxaca, and Puebla (Rodríguez-Estrella 2002, Comisión Nacional de Áreas Naturales Protegidas [CONANP] 2015, Farías et al. 2016). The Golden Eagle is Mexico's national symbol, but its population status in the country currently is categorized as threatened and the eagle is a high priority species for conservation (Secretaría de Medio Ambiente y Recursos Naturales 2014, CONANP 2015). Shooting, poisoning, and degradation and wholesale loss of habitat (e.g., due to urbanization) are thought to be among major limiting factors. When CONANP developed the Action Program for the Conservation of the Golden Eagle, information to support decisions on managing Mexico's Golden Eagles generally was found to be weak (CONANP 2015); basic facets of Golden Eagle ecology, demography, and population size in Mexico are poorly understood. Knowledge of the eagle is based mainly on incidental observations, limited distribution surveys, and general natural history studies in several regions (Rodriguez-Estrella et al. 1991, Rodríguez-Estrella 2002, CONANP 2008, 2015, Guerrero-Cárdenas et al. 2012, Bravo et al. 2015, Farías et al. 2016). Recently, however, an intensive study of Golden Eagle ecology was conducted in Baja California by De León-Girón et al. (2016), and a comprehensive survey of the species' distribution across Sonora was documented by Flesch et al. (2020). Movement behavior data for Mexico's Golden Eagles have not been published, although migration and dispersal of Golden Eagles from more northerly regions of North America into Mexico were documented by McIntyre et al. (2008) and Murphy et al. (2017).

Knowledge of natal dispersal movement is essential for understanding the population ecology and distribution of raptors and as such can have substantial management implications (Penteriani and Delgado 2009, Whitfield et al. 2009, Millsap et al. 2014). Basic understanding of the behavior of Mexico's Golden Eagles during dispersal could help resource managers identify regional populations and comprehend their connectivity, and distinguish factors that may directly and indirectly influence survival. Documenting the process of dispersal from natal areas during the first year of life is an initial step in understanding movements of Mexico's eagles. Surprisingly, detailed descriptions of first-year dispersal among nonmigratory Golden Eagles in North America are limited to a single study, centered in the Southern Rocky Mountains and Colorado Plateau regions of the United States of America (USA; Murphy et al. 2017), although multiple studies of nonmigratory populations of Golden Eagles and other *Aquila* spp. have been completed in Europe (Gonzalez 1989, Soutullo et al. 2006, Balbontin and Ferrer 2009, Weston et al. 2013). To begin to understand movement behavior of juvenile Golden Eagles in Mexico, we analyzed satellite telemetry data obtained from four individuals in central Mexico during fledging through the end of the first year of life (i.e., the 2–3 yr prior to reaching breeding age; Katzner et al. 2020). Our objective was to document the timing and distance of the eagles' dispersal movements, and the sizes of areas across which eagles ranged before and during this dispersal period.

METHODS

We studied four juvenile Golden Eagles from different areas in three neighboring states of central Mexico (location centroid 22.2°N, 102.5°W), one each from northwestern Aguascalientes, central Guanajuato, and southwestern and northern Zacatecas. Our study area encompassed these general areas, all within the Mexican Altiplano physiographic region in the southern portion of the Chihuahua Desert (Fig. 1). The region was dominated by grasslands and *izotales* (i.e., shrubland dominated by *Yucca* spp.). Major mountain ranges bordered these broad land cover types to the east and west (Sierra Madre Oriental and Sierra Madre Occidental, respectively). Intermediate-elevation mountain ranges occurred within, where the vegetation transitioned to temperate woodlands of pine (*Pinus* spp.), oak (*Quercus* spp.), or mixed pine and oak. Dominant land cover encompassing natal sites of the eagles included (1) temperate pine-oak woodland (Aguascalientes); (2) oak woodland (Guanajuato); (3) pine-oak woodland (southwestern Zacatecas); and (4) temperate pine-juniper (*Juniperus* spp.) woodland and native grasslands (northern Zacatecas). Areas used by the eagles after leaving their natal areas also were within the Mexican Altiplano and were dominated mainly by grasslands and *izotales*, plus pine-oak woodlands in higher elevations. Croplands were scattered throughout the region; the growing season coincided with the annual period when rain was most likely, as little irrigation has been developed (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad 2008, 2012). Elevation across the region ranged from 1700 to 3000 masl. Climate was cool semi-arid, with mean annual precipitation ranging from 45.4 cm/yr in northern Zacatecas to 72.8 cm/yr in western Zacatecas (Comisión Nacional del Agua 2019). Natal nests of the eagles we studied were located on cliffs. The nest in Aguascalientes was surrounded by pine-oak vegetation, and in Guanajuato the surrounding vegetation was a regenerating oak forest. In southwestern Zacatecas, the nest was located in a small canyon surrounded by oak-pine with abundant lechuguilla (*Hechtia* spp.). The nest in northern Zacatecas was surrounded by pine woodland.

When the nestling eagles were approximately 8 wk old based on plumage (Driscoll 2010), i.e., 1–2 wk younger than the species' typical fledging age of approximately 65 d (Palmer 1988, US Geological Survey [USGS] unpubl. median value in Katzner et al. 2020), we tagged each with a platform terminal satellite transmitter (PTT; solar GPS model PTT-45; Microwave Telemetry, Inc., Columbia, MD, USA), accurate to within about 18 m. Eagles were tagged during mid-May through mid-June in 2014 (Golden Eagle number GE1, a male from Aguascalientes), 2015 (GE2, a male from Guanajuato; GE3, a male from southern Zacatecas), and 2017 (GE4, a female from northern Zacatecas). PTTs were attached via backpack harnesses (Meyburg and Fuller 2007) constructed of Teflon ribbon (Bally Ribbon Mills, Bally, PA, USA). Total weight of a PTT-harness package was approximately 50 g, $<2\%$ of each eagle's mass (Kenward 2001, Walls and Kenward 2007). Our database was composed of GPS locations recorded by PTTs hourly during 0900–1600 H. However, PTTs did not always record locations for all eight hourly time slots on a given day, and any GPS location that was >4000 m above ground level or >120 km from the preceding and subsequent locations was considered erroneous and was discarded (Poessel et al. 2016).

To determine the date that a juvenile Golden Eagle initiated dispersal from its natal area, we used "method 7" in Weston et al. (2013): the eagle was considered dispersed when it first moved >9 km from its natal site and then remained >6 km away for ≥ 10 d. Only GPS locations recorded at 1100 H daily were used to identify the dispersal date because this was the hourly time slot when a location was nearly always recorded. We used *adehabitatHR* software (Calenge 2011) in RStudio to estimate total monthly

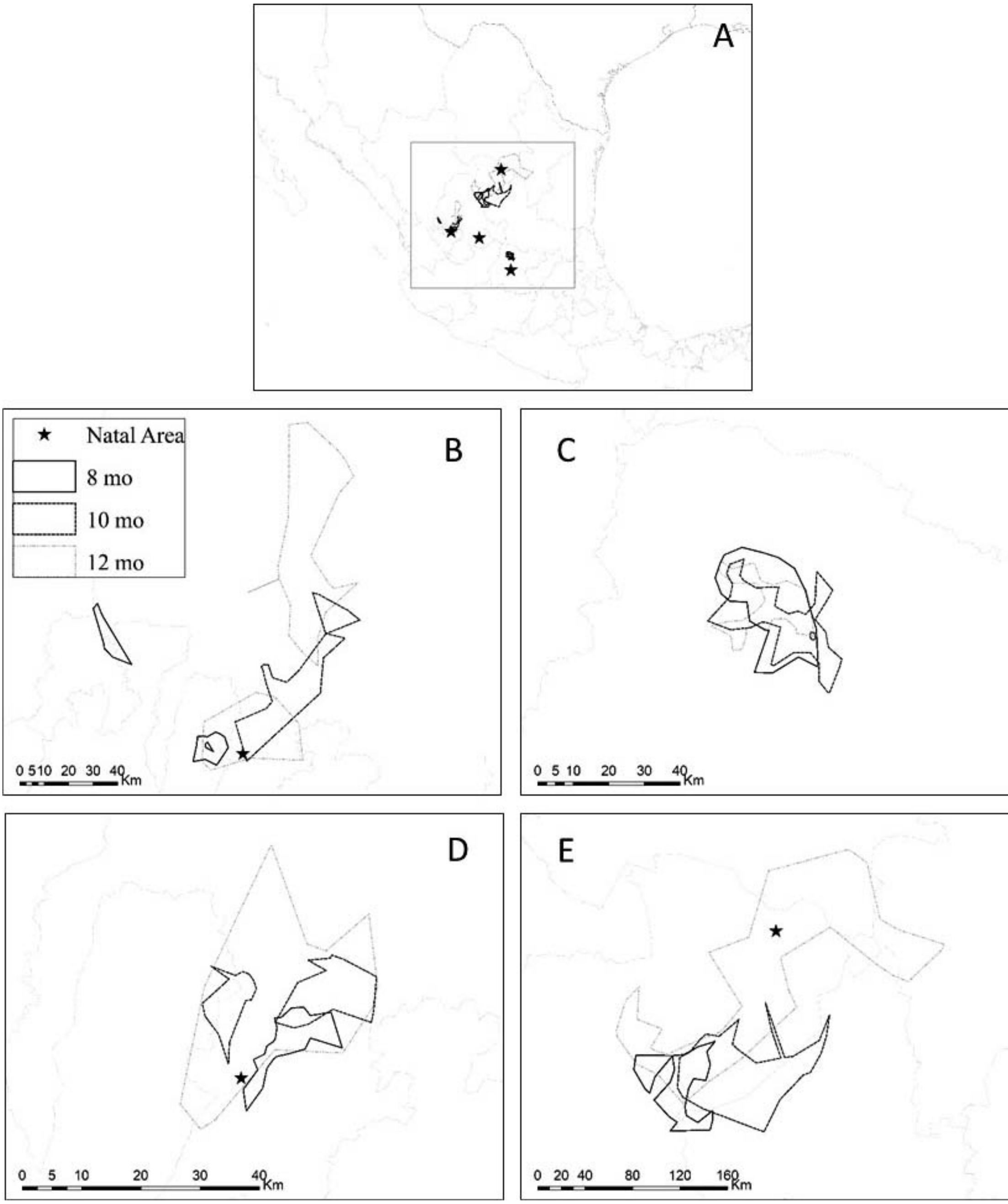

Figure 1. (A) Study area in central Mexico. (B–E) Location of natal areas and boundaries of ranging areas of four Golden Eagles tracked in central Mexico at 8 mo, 10 mo, and 12 mo of age.

Table 1. Approximate hatching and fledging dates, and date, age, and distance of initial dispersal by four juvenile Golden Eagles from their natal areas in central Mexico, 2014–2017.

EAGLE CHARACTERISTIC OR MOVEMENT METRIC	EAGLE IDENTIFICATION NUMBER				MEDIAN	MEAN (SD)
	GE1	GE2	GE3	GE4		
Sex	Male	Male	Male	Female		
Hatching date[a]	19 Apr	13 Mar	15 Mar	5 Apr	26 Mar	29 Mar (17.7 d)
Fledging date[b]	23 Jun	17 May	19 May	9 Jun	30 May	2 Jun (17.7 d)
Dispersal date[c]	29 Oct	11 Sep	16 Nov	15 Oct	22 Oct	18 Oct (27.9 d)
Dispersal age (mo)	6.4	6.1	8.2	6.4	6.4	6.8 (1.0)
Dispersal distance (km)[d]	129.2	49.2	35.1	186.0	89.2	99.9 (70.8)

[a] Approximated by backdating from estimated age (approximately 56 d) at time of tagging at the nest.
[b] Based on usual fledging age of approximately 65 d (Palmer 1988; USGS unpubl. median value in Katzner et al. 2020), projected from approximately 56 d of age estimated at time of tagging at the nest.
[c] Determined by method 7 in Weston et al. (2013): date when the eagle first was >9 km from its natal site and remained >6 km away for at least the following 10 d.
[d] Maximum distance from nest during the initial 10 d of dispersal.

distance traveled by an eagle starting at 3 mo of age, and *Raster* R Package (Hijmans and van Etten 2012, R Core Team 2018) in RStudio (RStudio Team 2015) to calculate the maximum distance traveled by an eagle from its natal site each month. We used 95% adaptive local convex hulls (Getz et al. 2007, Poessel et al. 2016) in *adehabitatHR* to quantify size (km^2) of the area across which a given eagle ranged prior to dispersing from natal areas and during each month of age following initial dispersal. Rather than refer to these areas as home ranges, we use the term "ranging area" (hereafter RA) because juvenile eagles we studied generally did not exhibit consistent, progressive settling from month to month and instead ranged widely (>1000 km^2) for at least 1 mo after initiating dispersal. A local convex hull method was appropriate for this purpose because the method incorporates relatively little unused space when based on large numbers of animal locations (Lichti and Swihart 2011), such as in our study (207–225 GPS locations/mo/eagle). To conduct the RA analysis for a given eagle in a given month, we defined the nearest neighbor distance (*a*) as the maximum distance between any two locations, per Getz et al. (2007). In one instance the analysis failed to proceed but was resolved by multiplying *a* by 1.1 (Poessel et al. 2016). In figures, we extend monthly distance and RA measures through 13 mo of age to better convey trends at the end of the first year of life. Due to small sample sizes in some instances, we reported ranges and medians to convey central tendency rather than means, which tend to be more strongly distorted by outlying values.

RESULTS

We recorded means of 6.9–7.5 GPS locations daily from PTTs carried by the four juvenile Golden Eagles. Before dispersal onset, males exhibited moderate RA sizes (GE1: 178.8 km^2, GE2: 182.34 km^2, GE3: 82.5 km^2), but the female ranged across a large area (GE4: 963.6 km^2). The eagles dispersed from their natal areas during mid-September thru mid-November, at ages 6–8 mo (Table 1, Fig. 2). The eagle that dispersed latest (male GE3) did so when about 1.5 mo older than the others (Table 1). During the first 10 d of dispersal, individual eagles moved 35–186 km (median = 89 km) from their respective natal sites, with the farthest distance by the female (GE4; Table 1). For all eagles, monthly total distance traveled increased steadily through age 7 mo (Fig. 2). However, total distance traveled by the female at age 7 mo was 2- to 3-fold greater than that of the males, coinciding with her relatively long initial dispersal distance (Table 1); this contrast with the males also was evident at age 12 mo (Fig 2). Monthly total distances traveled by individual males following dispersal onset ranged widely (approximately 350–1350 km) during age 8–11 mo, but became more similar (approximately 700–1050 km) by the end of the first year. In contrast to total monthly distance traveled, maximum distances from natal sites exhibited by individual Golden Eagles were relatively constant during months following dispersal onset (8–12 mo of age; Fig. 2). Males GE1, GE2, and GE3 remained within averages of 129.1 ± 11.3 (SD), 58.6 ± 2.0, and 17.9 ± 5.7 km of natal sites, respectively, and the female's (GE4) mean distance (121.4 ± 11.2 km) was similar to the largest

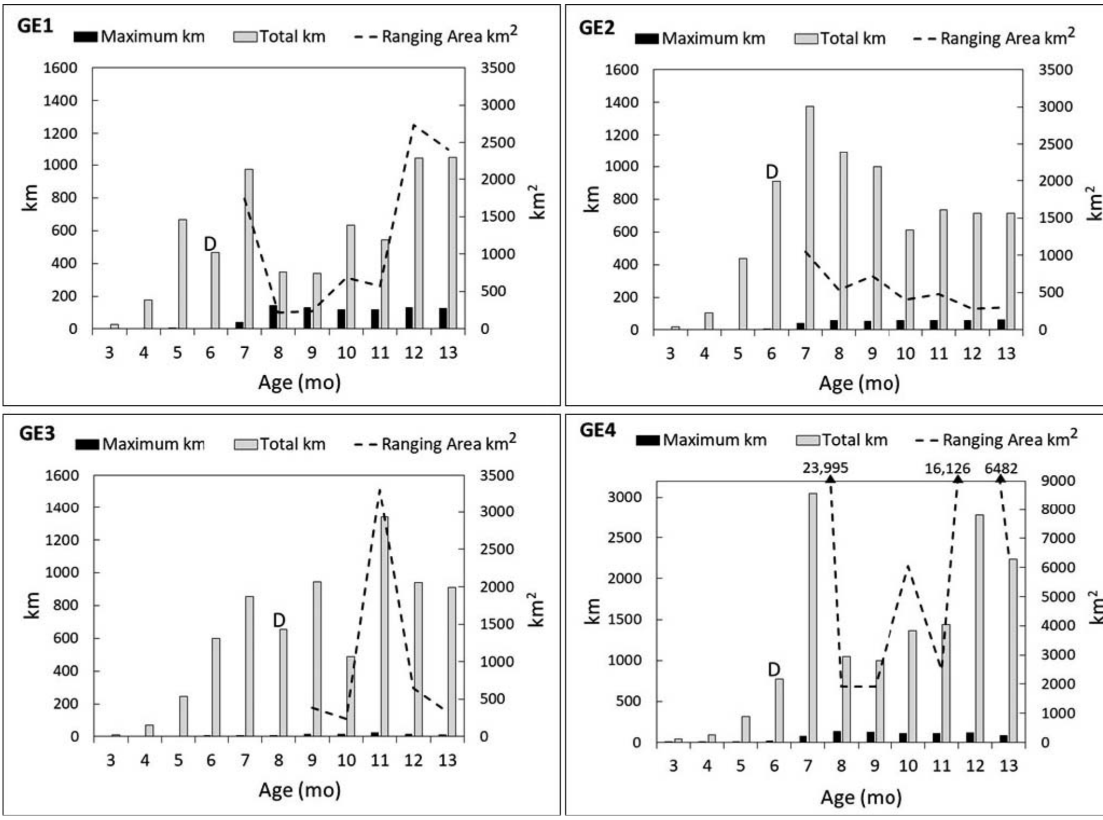

Figure 2 Each panel shows the progression in total distance traveled (total km; gray bars) by month of age for four juvenile Golden Eagles in central Mexico (males GE1, GE2, and GE3; female GE4; bird ID shown in the upper left corner of each panel); maximum distances traveled from natal sites (maximum km; black bars) by month of age; and post-dispersal ranging areas (dashed line), based on location data from satellite transmitters during 2014–2018. Ranging area boundaries were determined by 95% adaptive local convex hull methods. A given eagle initiated dispersal from its natal area during the month preceding that designated by a "D" over its respective data bar symbol. Note that the scales differ for GE4.

of the males' ranges. Following initial (1–2 wk) dispersal movement, the size and shape of areas across which eagles ranged monthly varied among individuals. Although the monthly ranges used by male GE2 overlapped each other remarkably well, the monthly RAs of the other three individuals varied in size, shape, and location (Fig. 1). Sizes of RAs used by GE2 and GE3 decreased at the end of the first year while that of GE1 increased (Fig. 2). Substantially higher RA size for a given eagle-month mostly reflected wandering movement far from natal areas (Fig. 1). For example, GE3's RA size was 3306.9 km^2 at age 11 mo, which was also when the eagle traveled its greatest total monthly distance (Fig. 2).

Discussion

We used satellite telemetry to conduct the first analysis of movement behavior of juvenile Golden Eagles in Mexico. Although our sample is relatively small (four individuals), the data provide evidence that Golden Eagles dispersing from natal areas in Mexico during their first year of life exhibit movement behaviors that are in many ways similar to those of conspecific juveniles from other nonmigratory populations including the southwestern USA (Murphy et al. 2017). Specifically, these include the timing and age of departure from natal areas, and total distance traveled, maximum distance from natal area, and RA size by month of age.

Variation in RA size among juvenile Golden Eagles between fledging and dispersal onset (i.e., during the post-fledging dependence period [PFDP]) is influenced by size of the parental territory and the availability and distribution of critical resources within the territory. During this period, juveniles increasingly track their parents when the latter are searching for food, water, and protection (Weston et al. 2018). Thus, we can expect that the spatial distribution of resources used by parents indirectly influences the extent of ranging by juveniles. This use of the parental territory during the PFDP allows juveniles to improve their flight capabilities and foraging skills while offering protection, and thus is critically important for shaping movement behavior and enhancing survival of young Golden Eagles (McIntyre and Collopy 2006, Weston et al. 2018). Certainly, the PFDP of juvenile Golden Eagles in Mexico should be closely studied to better understand needs of juveniles at a critical time for their survival (Weston et al. 2018).

Individuals in our study initiated dispersal during mid-September to mid-November, as did most juveniles studied by Murphy et al. (2017) even though natal areas of juveniles in their study were approximately 1400–1800 km north of our study area. Similarly, juvenile Golden Eagles in our study initiated dispersal at a median age of 6.4 mo, close to the median of 6.8 mo documented by Murphy et al. (2017); in both studies, all juveniles dispersed before the end of their first year of life, consistent with Golden Eagles in other nonmigratory populations, all in Europe (Soutullo et al. 2006, Watson 2010, Weston et al. 2013).

After initiating dispersal, eagles moved monthly distances that were relatively similar among individuals, except that the sole female eagle we studied (GE4) traveled about three times farther than the three males at 7 and 12 mo of age. In general, the female also moved much greater distances and across larger RAs than did the male juvenile eagles we studied. We do not have a large enough sample size to speculate whether this pattern is determined by sex; it may be better explained by environmental conditions and suitable foraging areas within the individual female's range (Ferrer 1993, Soutullo et al. 2006). Her natal area was in coniferous woodland within a range of small mountains in northern Zacatecas, but was surrounded by an arid, open landscape. Juvenile Golden Eagles in arid environments may disperse earlier and move much greater distances from natal areas than their counterparts from less arid environments (Murphy et al. 2017).

We also noted some important differences between our findings and those of others. Juvenile eagles in our study could be characterized as "short-distance dispersers," *sensu* Murphy et al. (2017), in that they generally did not travel much farther than 120 km from their natal sites. One-third of juvenile Golden Eagles studied in the southwestern USA dispersed much farther from natal sites, up to 1379 km. Juvenile Golden Eagles in our study also maintained relatively constant distances from their natal sites following the onset of dispersal. This was true for short-distance dispersers in the southwestern USA (Murphy et al. 2017), except that in the latter study, eagles became increasingly distant from natal sites, on average, toward the end of the first year. Juveniles we monitored began to move relatively short distances from their natal sites at age 3 mo yet maintained an affinity to natal areas. By age 5 mo, however, they exhibited brief exploratory excursions beyond their natal areas and what likely were limits of their respective parents' territories. Such excursions from natal areas during the pre-dispersal period have been postulated as searches for opportunities, e.g., for areas that have prey available or that have little conspecific competition (Soutullo et al. 2006, Weston et al. 2013, Nygård et al. 2016, Murphy et al. 2017). As such, the excursions may help juveniles determine generally when and where to disperse. However, not all juveniles make such excursions; 14 of 66 juvenile Golden Eagles in the southwestern USA did not exhibit excursions before dispersing from their natal areas (Murphy et al. 2017).

Following initiation of dispersal, monthly RAs of juvenile Golden Eagles in our study generally increased through the rest of the first year of life, except RA sizes of one male decreased at the very end of the year. General increases in spatial use by Golden Eagles through the first year of life in our study are consistent with findings for nonmigratory conspecifics in Spain and the USA (Soutullo et al. 2006, Murphy et al. 2017). Differences in shapes of RAs may also be interesting: although one eagle used monthly RAs of similar shapes, the rest of the individuals had heterogeneous RAs. Similar behavior by the Spanish Imperial Eagle (*Aquila adalberti*) has been attributed to the irregular distribution of resources and the different environmental conditions of the territories (Bosch et al. 2010). Variations in the shapes of the monthly RAs by juveniles such as GE4 may be due to the distant or sparse distribution of resources; in contrast, the overlapped monthly RAs used by GE2 may indicate that resources are concentrated in well-defined areas of the landscape.

Despite our novel study of movements of young Golden Eagles from Mexico, more information is needed to effectively plan and implement conservation for this population. Actions to improve knowledge especially include (1) identifying areas of concentrated use by eagles; (2) acquiring data to support habitat models for distinguishing potentially high quality areas for conservation consideration; (3) documenting resource selection in environments of Mexico that are novel for the species; and (4) understanding and reducing effects of habitat fragmentation.

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