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REPRODUCTIVE CHARACTERISTICS OF RED-TAILED HAWKS IN YELLOWSTONE NATIONAL PARK, AN INTACT TEMPERATE LANDSCAPE

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Abstract.—Red-tailed Hawks (*Buteo jamaicensis*) are common across North America and are well-adapted to human-altered landscapes. Yellowstone National Park offers an opportunity to study this nearly ubiquitous species in a relatively unaltered and intact temperate ecosystem. In anticipation of future habitat and environmental change, we monitored Red-tailed Hawk territories and nests across the park's northern range to establish a baseline of hawk density, reproduction, and population status. We used a combination of intensive territory monitoring at two different scales and roadside point count surveys, analyzed using detection-dependent density modeling. From 2011 through 2015, we monitored between 17 and 44 territories each year and, in total, documented at least 60 territories in the northern range. Territory density across the northern range was comparable with other regional estimates, but local density was particularly high on the Blacktail Deer Plateau. On average, 87% of territorial pairs (range: 75–100%) laid eggs and breeding success averaged 63% (range: 48–89%). Hawk reproductive rate averaged 1.07 (range: 0.46–1.74) young per occupied territory and brood size averaged 1.73 (range: 1.30–1.96) young per successful nest. Reproductive rate varied significantly between study years but on average was well below the level thought necessary for a stable population, underscoring the importance of continued monitoring to better understand the drivers of population trends.

Key Words: *Red-tailed Hawk;* Buteo jamaicensis; *breeding*; *nesting*; *population*; *reproduction*; *survey*; *undisturbed habitat*; *Yellowstone National Park*.

CARACTERÍSTICAS REPRODUCTIVAS DE *BUTEO JAMAICENSIS* EN EL PARQUE NACIONAL YELLOWSTONE, UN PAISAJE TEMPLADO INTACTO

Resumen.—*Buteo jamaicensis* es una especie común a lo largo de América del Norte, que está bien adaptada a los paisajes humanos alterados. El Parque Nacional Yellowstone ofrece una oportunidad para estudiar esta especie, casi ubicua, en un ecosistema templado relativamente intacto e inalterado. Anticipándonos a futuros cambios de hábitat y del medio ambiente, monitoreamos los territorios y los nidos de *B. jamaicensis* a lo largo de la parte norte del parque para establecer información de base sobre su densidad, reproducción y estado poblacional. Usamos una combinación de monitoreo intensivo de los territorios a dos escalas diferentes y censos en puntos de conteo a lo largo de las rutas, analizada por medio de modelos de densidad dependientes de la detección. Desde 2011 hasta 2015, monitoreamos entre 17 y 44 territorios cada año y documentamos en total al menos 60 territorios en la parte norte. La densidad de territorios a lo largo de la parte norte fue comparable con otras estimaciones regionales, pero la densidad local fue particularmente alta en la meseta del venado de cola negra (Blacktail Deer Plateau). En promedio, un 87% de las parejas territoriales (rango: 75–100%) pusieron huevos, mientras que el éxito reproductivo promedio fue del 63% (rango: 48–89%). La tasa reproductiva promedio de los *B. jamaicensis* fue de 1.07 (rango: 0.46–1.74) jóvenes por territorio ocupado y el tamaño promedio de la nidada fue de 1.73 (rango: 1.30–1.96) jóvenes por nido exitoso. La tasa reproductiva de *B. jamaicensis* varió significativamente entre las áreas de estudio, pero, en promedio, estuvo bien por debajo del nivel que se piensa que es necesario para una población estable, resaltando la importancia de realizar monitoreos continuos para entender mejor los factores que determinan sus tendencias poblacionales.

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Although ecological research often focuses on the study, conservation, and recovery of wildlife species already imperiled, the study of abundant or widespread species is often overlooked even though common species may be better indicators of broad-scale ecosystem health than rare or highly specialized species (Koch et al. 2011). Red-tailed Hawks (*Buteo jamaicensis*) are common raptors, nearly ubiquitous on power and fence poles lining roads and highways throughout North America (Knight and Kawashima 1993, Farmer et al. 2008, Preston and Beane 2009). These hawks are well-adapted to human-altered landscapes and many studies have investigated their nesting success, productivity, or habitat use in landscapes altered by agriculture or grazing (Johnson 1975, Howell et al. 1978), silviculture (Moorman and Chapman 1996), and urban/suburban development (Minor et al. 1993, Berry et al. 1998, Stout et al. 2006). In contrast, relatively little is known about this species in areas away from human infrastructure and habitat fragmentation. Yellowstone National Park (YNP), Wyoming, USA, presents an opportunity to study this common species in an environment largely isolated from encroaching human development and habitat fragmentation.

The western United States faces both broad-scale and localized landscape changes due to fluctuating climate patterns and direct human disturbance. Although YNP represents a largely intact temperate zone ecosystem, the park is vulnerable to a variety of habitat disturbances, including invasive plants (Olliff et al. 2001), evolving fire regimes (Westerling et al. 2011), increasing human visitation (Liddle 1997, Steidl and Powell 2006), and climate change (Chang and Hansen 2015). The potential effects of these changes on Red-tailed Hawk and other raptor populations is largely unknown, and a better understanding of the current status of Red-tailed Hawks within the park may help future researchers identify drivers of patterns in hawk reproduction and territory density. Furthermore, if land managers can more accurately predict the response of hawk populations to ongoing and future habitat change and visitor-use patterns, they can better manage current hawk populations by defining a reasonable target population size and determining the most appropriate strategies to maintain that population. Thus, we investigated Red-tailed Hawk abundance, density, breeding success, and productivity in YNP's northern range from 2011 to 2015. Our objective was to establish a baseline from which to compare populations under alternate disturbance regimes, both contemporary populations outside of YNP and future populations within the park boundaries.

METHODS

Study Area. YNP comprises nearly 9000 km^2 in Montana, Idaho, and Wyoming. Red-tailed Hawks typically arrive in YNP in March, when much of the park remains covered in snow but the northern range (an area defined by the northern Yellowstone elk's wintering range; Houston 1982, Fig. 1A) is relatively open and free of snow. During initial surveys in YNP prior to intensive monitoring, the northern range appeared to have a high number of Red-tailed Hawks compared with other areas of the park (Baril et al. 2017), recommending this area for further research on hawk reproduction.

Within the park's boundaries, the northern range comprises roughly 994 km^2 of sagebrush (*Artemisia tridentata*) steppe and grassland communities (49%) and patchy forests (50%), dominated by Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*; Despain 1990). The remaining areas are composed of willow (*Salix* spp.)-lined riparian corridors, talus slopes, and mudflows. Elevation of YNP's northern range varies from 2100 to 2600 masl, and averages 2400 masl.

Centrally located within the northern range, the Blacktail Deer Plateau (Fig. 1B) appeared to have a high territory density even compared with other areas of the northern range. Thus, we chose the plateau for a more focused, intensive study of hawk territory density. The plateau comprises approximately 56 km^2 and has an average elevation of nearly 2200 masl (Fig. 1B). Compared with the entire northern range, grasslands and sagebrush steppe are dominant on the plateau (44 km^2; 78%) and there is relatively little patchy Douglas fir forest (12 km^2; 22%).

Territory Monitoring and Reproduction. We located and monitored breeding Red-tailed Hawks through ground-based surveys from April to July of 2011–2015. To locate territories across the northern range in our initial field season, we conducted lengthy observations in areas where we expected to find territorial birds and where hawks had been sighted incidentally or in preliminary surveys prior to the start of this study. In subsequent field seasons, we continued to search for new hawk territories and, as logistics allowed, revisited territories known from previous years. Limited personnel in some years restricted the number of territories we were able to

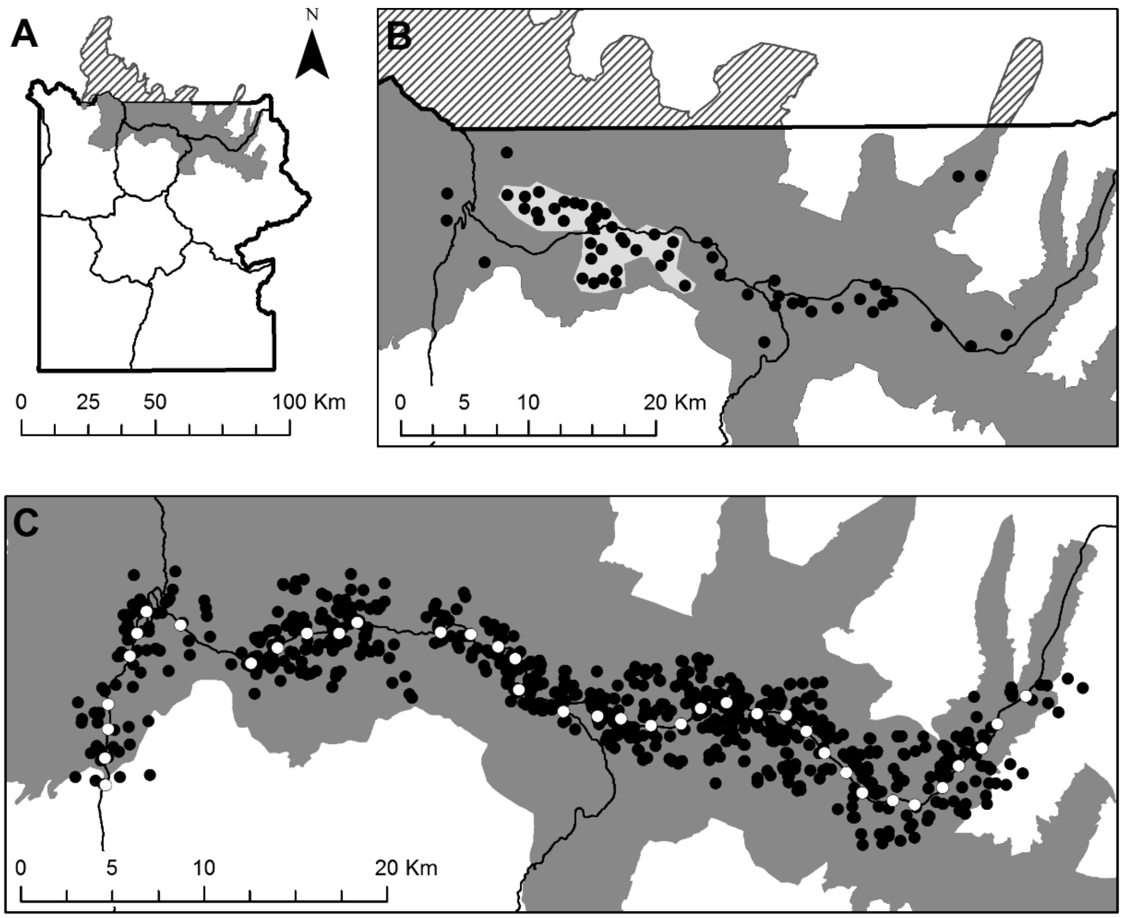

Figure 1. Red-tailed Hawk survey area in Yellowstone National Park's northern range (solid dark grey; A–C). In (A) and (B), the grey hatched area is the portion of the northern range outside the park's boundary, and beyond the extent of this study. In (B), black dots are locations of Red-tailed Hawk territories, monitored from 2011 and 2015. The light grey polygon is the area of dense Red-tailed Hawk territories on the Blacktail Deer Plateau. In (C), white dots are roadside survey points and black dots are Red-tailed Hawk detections from 2012 to 2015. Bold black lines are park boundaries and thin black lines are park roads.

revisit. However, we monitored at least 67% of known Red-tailed Hawk territories each year and, on average, monitored 82% of known territories.

During each breeding season, we assessed territories for occupancy and nests for evidence of egg laying and breeding success. To determine occupancy of territories, we conducted at least two 4-hr surveys, at least 10 d apart, from elevated locations. Following Steenhof and Newton (2007), occupancy was indicated by the presence of a mated pair of adult birds (i.e., pair seen copulating, adding material to a nest, or engaged in courtship displays or territory defense), a single bird exhibiting territorial behavior (e.g., undulating flight), nest structures that contained new material, or by other reproduction-related activities (i.e., an adult in incubation posture or young in the nest). If there was no evidence of occupancy during the surveys, we considered the territory unoccupied. In occupied territories, we conducted further observations as necessary to locate nests and monitor nesting behavior. We sometimes found new nest locations by observing territorial birds carry material to the nest or during an incubation exchange; in some cases, however, we actively searched trees within the territory using scopes and binoculars. In each study year, we assigned new nest locations to either a new territory or a previously identified territory based on proximity to other known nests and observations of behavior and habitat use by the territorial pair. We assigned adjacent nests to unique territories if they were used by different pairs in the same study year or, if they were not used simultaneously, had known territory associations. Adjacent nests that were not used in the same year were $\geq$1.4 km apart.

We determined a territorial pair was breeding if we observed either an adult in incubation posture for at least 30 min, or if young were present in the nest. We monitored each nest until it failed or the nestlings fledged; we considered nests to be successful if at least one nestling reached 34–37 d old (approximately 80% of fledging age; Preston and Beane 2009). Locating young at or after fledging is often difficult (Steenhof and Newton 2007), and nestlings that reach 34–37 d have a high probability of fledging. In cases where we found a nest empty when young should have been near fledging age, or we were unable to revisit the territory before fledging, we attempted to locate the young birds in the territory.

We calculated laying rate, breeding success, productivity, and brood size at fledging across all northern range nests in each study year and used one-way ANOVAs to test for differences in productivity and brood size between years. We defined laying rate as the proportion of monitored territories (with known breeding status) where at least one egg was laid (McIntyre and Adams 1999). We defined breeding success as the proportion of laying pairs that successfully fledged at least one young (Steenhof and Newton 2007). Productivity was the average number of young fledged per occupied territory, and brood size at fledging referred to the average number of young fledged per successful nest (Steenhof and Newton 2007). Using an aging guide (Moritsch 1983) and an estimated 28-d incubation and 45-d nestling stage (Preston and Beane 2009), we calculated nesting chronology (onset of incubation, hatch date, and fledging date) for all successful nests by back-calculating from the estimated age of nestlings prior to fledgling.

Roadside Point Counts. We established 38 point count survey locations for Red-tailed Hawks along the northern road through the park (Fig. 1C). Count locations were constrained by the locations of roadside pullouts. Thus, while most count locations were approximately 1500 m apart, greater distances separated points where pullouts were unavailable or topography made the road a poor survey location. From 2012 through 2015, we conducted 20-min surveys at each count location in both mid-May and mid-June, when most territorial birds were either incubating or had young chicks. We began surveys no earlier than 0900 H and ended by 1600 H. During each survey, the observer scanned the sky and trees for flying and perched birds in all directions using binoculars. When necessary, a spotting scope was used to identify unknown raptors first observed with binoculars. Observers counted all Red-tailed Hawk detections and recorded on a topographic map the approximate location of each bird observed. Using ArcMap (v.10.3.1), we mapped our detections from 304 surveys and calculated the distance between each count location and the associated detections. Finally, we quantified the total number of Red-tailed Hawks observed in each survey year; for each survey location, we included only detections from the survey with the highest number of recorded observations and then totaled observations across locations for each year.

Density Estimation. We used two different methods to estimate Red-tailed Hawk territory density over two spatial scales in YNP. On the Blacktail Deer Plateau (Fig. 1B), we conducted lengthy observations from the ground, aiming to locate all territorial pairs. Our density estimate for this area was then calculated simply by dividing the total number of identified territories by the surveyed area (56 km^2). To estimate the density of Red-tailed Hawks across the entire northern range, we considered the potential effects of detectability and conducted detection-dependent density modeling of our hawk observations collected during the roadside point count surveys (see survey methods above) using the packages "Distance" and "mrds" in the program R v.3.3.3 (Laake et al. 2017, Miller 2017, R Core Team 2017). We compared models with half-normal or hazard-rate key functions and cosine or simple polynomial adjustment functions with an optimized number of adjustment terms. We assessed models within three model sets: no binning or data truncation, truncation at 2.5 km, and truncation at 4 km. Within model sets with the same data truncation, we compared models using AIC. From these three top models, we identified the best overall detection model using Cramer-von Mises goodness of fit and visual assessment of q-q plots. To refine model selection, we applied guidance from Buckland et al. (2001) that recommends a data truncation distance at which the probability of detection is

Table 1. Red-tailed hawk reproduction in Yellowstone National Park's northern range from 2011 to 2015. In each study year, all monitored territories were occupied.

Year	Territories Monitored	Occupied with Known Outcome	Laying Rate (%)[a]	Breeding Success (%)[b]	Total Young Produced	Productivity (SE)[c]	Brood Size (SE)[d]
2011	17	14	100	79	19	1.36 (0.25)	1.73 (0.19)
2012	34	27	100	89	47	1.74 (0.17)	1.96 (0.14)
2013	44	37	81	87	43	1.16 (0.16)	1.65 (0.14)
2014	30	28	75	48	13	0.46 (0.13)	1.3 (0.15)
2015	30	29	76	55	22	0.76 (0.20)	1.83 (0.24)
Average	31	27	87	63	29	1.07 (0.09)	1.73 (0.08)

[a] Proportion of occupied territories with known outcome where eggs were laid.
[b] Proportion of nests with eggs where at least one young fledged.
[c] Young fledged per occupied territory with known outcome.
[d] Young fledged per successful nest.

approximately 0.10. Finally, using the overall best detection model, we estimated the abundance and density of Red-tailed Hawks across the area of the northern range within YNP.

RESULTS

Territory Monitoring and Reproduction. We monitored between 17 and 44 territories in each year from 2011 to 2015. Although staffing and logistics did not allow us to monitor all territories in all study years, we monitored an average of 82% of known Red-tailed Hawk territories each study year; 73% of territories were monitored in every year after they were discovered. We have no reason to expect that incomplete resampling in each survey year has biased our estimates of territory occupancy or productivity. Furthermore, territories that were repeatedly monitored were always found to be occupied. Across all study years and across the northern range (including territories on the Blacktail Deer Plateau), we documented 60 Red-tailed Hawk territories and 99 nest locations (mean = 1.68 nests per territory, SE = 0.12; Table 1, Fig. 1). Most nests were in snags ($n = 47$) or live conifers ($n = 35$). The remaining nests were on cliffs ($n = 12$), or in live cottonwood (*Populus* spp.; $n = 3$) or aspen trees (*P. tremuloides*; $n = 2$).

Reproduction. Between 2011 and 2015, Red-tailed Hawk laying rate was high across the northern range, averaging 87% (Table 1). Overall average breeding success was 63% but fluctuated widely over our study period, ranging from a high of 89% in 2012 to a low of 48% in 2014 (Table 1). Red-tailed Hawk productivity followed a similar pattern, averaging only 1.07 young per occupied territory across all study years but varying between years ($F_{4,130} = 7.91$, $P < 0.001$; Table 1). Average productivity was lowest in 2014 at 0.46 young per occupied territory, but peaked at 1.74 in 2012 (Table 1). Across all study years, average brood size was 1.73 young per successful nest (Table 1). Brood size did not vary between years ($F_{4,78} = 1.79$, $P = 0.14$).

Nesting chronology. We estimated that, in most study years, successful Red-tailed Hawks on the northern range initiated egg-laying during the second week in May (Fig. 2). In 2015, however, hawks laid eggs several weeks earlier, in late April. Eggs typically hatched during the first week in June, except in 2015, when they hatched during the last week of May. Young hawks generally fledged during the second or third week in July.

Density. On the Blacktail Deer Plateau, we identified 33 hawk territories across the study period. Using this count, we estimate a hawk density on the plateau of 0.59 pairs/km^2 (Fig. 1).

Across the northern range, we recorded 785 detections of Red-tailed Hawks during four years of roadside point count surveys (Table 2). Based on maximum counts across the two visits to each point count location each year, we observed an average of 138 Red-tailed Hawks (SE = 13) across the northern range each year. Most observations occurred in the central portion of the northern range, east of the Blacktail Deer Plateau (Fig. 1C). The lowest density of Red-tailed Hawks was along the westernmost edge of the northern range.

Using detection-dependent density modeling, we found the best model used the hazard-rate key function with no adjustments and truncated our observations at 2.5 km (see Appendix for full model comparison). From this model, we estimated a total abundance of 183.2 Red-tailed Hawks (SE = 38.1;

Table 2. Red-tailed Hawk detections at roadside point count locations (n = 38) in Yellowstone National Park's northern range from 2012 to 2015.

YEAR	AVERAGE[a]	SE	TOTAL DETECTIONS	TOTAL MAXIMUM DETECTIONS[b]
2012	2.03	0.25	154	114
2013	2.51	0.24	188	125
2014	2.45	0.24	186	121
2015	3.38	0.34	257	168

[a] Average number of detections per visit to each point count location.
[b] Total of maximum detections across two visits to each point count location.

95% CI = 122.0–275.1) across the area of the northern range within YNP, a density of 0.18 birds/km^2 (SE = 0.04).

DISCUSSION

We assessed Red-tailed Hawk density in YNP in two ways—time-intensive territory monitoring on the Blacktail Deer Plateau and roadside point counts across the northern range—that produced notably different density estimates. We chose to monitor the productivity of the Blacktail Deer Plateau based on prior reports of high hawk density in this region and, as expected, the hawk density we observed there was notably high (0.59 pairs/km^2) compared to both the broader northern range survey (0.18 birds/km^2) and also estimates from nearby regions. In western Wyoming, Red-tailed Hawk density fell from 0.39 pairs/km^2 in 1947 to 0.23 pairs/km^2 in 1975 (Craighead and Mindell 1981). In the Gallatin Valley in southwestern Montana, hawk density was 0.13 pairs/km^2 in 1971 and 0.11 pairs/km^2 in 1972 (Johnson 1975). More recently, Red-tailed Hawk density in western Wyoming was only 0.19 pairs/km^2 in 2002 (Craighead and Smith 2002); by 2015, density in the same area had dropped to 0.16 pairs/km^2 (R. Crandall pers. comm.).

Red-tailed Hawk territory density may be regulated by the availability of nest sites, perch sites, and suitable prey (Janes 1984, Preston and Beane 2009), none of which we assessed directly. The high territory density we observed on the Blacktail Deer Plateau, however, may be enabled by the presence of particularly suitable landscape features, including a high proportion of open sagebrush and grasslands punctuated by relatively few small stands of coniferous trees. The plateau may also be a preferred habitat for small mammals, such as Uinta ground squirrels (*Urocitellus armatus*), and may provide reliable foraging opportunities for nesting hawks. Further investigation into the vegetative characteristics of the plateau, as well as local small mammal populations, is necessary to better understand what makes this area high-quality nesting habitat for Red-tailed hawks.

We conducted the roadside surveys while most nesting hawk pairs would have been incubating or brooding very young nestlings and thus the density estimate may more accurately reflect the number of pairs rather than the number of individual birds. Under that assumption, the roadside survey density estimate for the northern range is comparable to observations from nearby areas of Montana and Wyoming.

We observed significant variability in Red-tailed Hawk productivity between study years. On average, however, Red-tailed Hawk productivity on the northern range was intermediate relative to estimates from nearby areas. In southwestern Montana, Red-tailed Hawk productivity averaged 1.36 young per occupied territory in 1971–1972 (Johnson 1975) and 1.50 young per occupied territory in the Centennial Valley in 1987–1988 (Restani 1991). In Grand Teton National Park, hawk productivity in 2002 averaged only 0.66 young per occupied territory, possibly due to unseasonably cold and wet weather conditions near the time of hatching (Craighead and Smith 2002).

Based on fluctuating productivity over this 5-yr study, it is difficult to determine if the YNP population of Red-tailed Hawks is stable, increasing, or in decline. Henny and Wight (1972) estimated that northern Red-tailed Hawk populations must produce on average between 1.33 and 1.38 young fledged per breeding-age female to maintain a stable population, well above our observed average productivity of 1.07 young per occupied territory. Although the high number of Red-tailed Hawks observed on the northern range throughout this project may indicate a healthy population, the area may serve as a population sink in some years (e.g., 2013–2015) and a source in others (e.g., 2012). Future surveys from which to compare the baseline established in this study will provide additional insight into long-term population trends.

The initiation of hawk incubation varied across breeding seasons. In general, however, Red-tailed Hawks in YNP laid eggs and began incubating later than hawks at lower-elevation areas in the Rocky Mountains (Luttich et al. 1971, Johnson 1975,

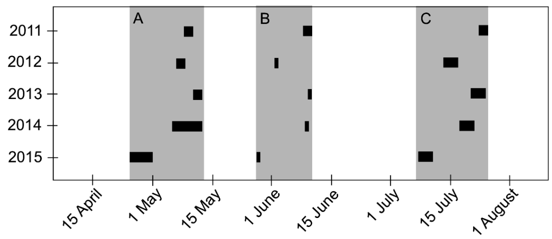

Figure 2. Nesting chronology of Red-tailed Hawks in Yellowstone National Park's northern range from 2011 to 2015. Gray blocks indicate estimated periods of laying (A), hatching (B), and fledging (C) across all study years. Black bars represent the observed variability within each study year.

Preston and Beane 2009). In Montana's Gallatin Valley, Red-tailed Hawks initiated incubation between 15 April and 6 May in 1971 and between 5 April and 6 May in 1972 (Johnson 1975). In Alberta, eggs were laid around 1 May (Luttich et al. 1971) but, in Colorado's Front Range, the average incubation-initiation date was 28 March (Preston and Beane 2009). Notably, our estimates of nesting chronology were based on nests that were all successful and thus may be biased. For example, if nests that were initiated early were more likely to succeed, our back-calculation of egg-laying date from successful nests would result in an average laying date that was biased early.

Spatial and temporal variability in hawk reproduction has elsewhere been attributed to weather or climate patterns (Stinson 1980, Craighead and Smith 2002), prey availability (Stinson 1980, Janes 1984), interspecific competition (particularly with other *Buteos*; Schmutz et al. 1980, Janes 1984), and nest parasites (Smith et al. 1998). We do not have the data needed to understand factors that influence hawk productivity in YNP's northern range, and we recommend further investigation into the determinants of egg-laying rate and date, egg survival, and nestling survival. In particular, the dynamics of Uinta ground squirrel populations should be a target of future research. Ground squirrels are a primary food source for Red-tailed Hawks across western North America in general (Luttich et al. 1970, Janes 1984, Steenhof and Kochert 1988), and may become even more important to hawk breeding success and phenology as YNP's northern range experiences a changing climate; hawks may time breeding activities with ground squirrel emergence, which in turn is correlated with warming spring temperatures (Knopf and Balph 1977).

Conservation, Management, and Future Monitoring. The purpose of this study was to establish a baseline for Red-tailed Hawk abundance, productivity, and breeding success on the northern range. Our observations represent a snapshot in time for breeding Red-tailed Hawks in YNP and may be most useful in comparison with future monitoring. Variability in Red-tailed Hawk productivity and population size also highlights the need for a better understanding of the less common raptors. The Swainson's Hawk (*Buteo swainsoni*) is a species of concern (US Fish and Wildlife Service 2008, Wyoming Game and Fish Department 2017) that breeds within the park at low densities (Baril et al. 2017). In other regions, these two hawk species compete for territories and nesting sites (Rothfels and Lein 1983, Janes 1984, Restani 1991) and, although further investigation into factors that influence local raptor populations is clearly necessary and warranted, it is likely that Red-tailed Hawk demographic trends and distribution patterns in YNP will be important for predicting Swainson's Hawk population stability as habitat and environmental conditions evolve.

Because of the observed variability in hawk productivity, we recommend that future efforts to study Red-tailed Hawks conduct several consecutive years of monitoring. In YNP, hawk-monitoring efforts by the bird program staff and by citizen scientists organized by the park's sister nonprofit organization, Yellowstone Forever, are ongoing. Additional efforts, however, to assess the relationship between climatic variables and spatial and temporal variation in prey availability would aid in interpretation of patterns in hawk reproduction and in the development of clear assessments of hawk population status in America's first National Park.

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Appendix. To assess Red-tailed Hawk density on the northern range of Yellowstone National Park (YNP), we used survey data collected from 2012 through 2015 at 38 roadside point count locations and conducted detection-dependent density modeling using the packages "Distance" and "mrds" in the program R v.3.3.3 (Laake et al. 2017, Miller 2017, R Core Team 2017). We compared models with half-normal or hazard-rate key functions and cosine or simple polynomial adjustment functions with an optimized number of adjustment terms. We assessed models within three model sets: no binning or data truncation, truncation at 2.5 km, and truncation at 4 km. Within model sets with the same data truncation, we compared models using AIC. We then compared the best detection models from each model set using Cramer-von Mises goodness of fit and visual assessment of q-q plots.

Goodness-of-fit tests and visual assessments of q-q plots did not substantially differentiate model sets. Thus, following guidance from Buckland et al. (2001), we chose the best model from the set that truncated our observations at 2.5 km, which most closely approximated a probability of detection of 0.10. The best fit model, utilizing the hazard rate key function and no adjustment terms, provided an estimated total abundance of 183.18 Red-tailed Hawks (SE = 38.14) across the area of the northern range within YNP, at a density of 0.18 birds/km^2 (SE = 0.04). Across all considered models, total abundance estimates ranged from 122 to 213 Red-tailed Hawks.

					Probability of Detection				Cramer-von Mises	
Model	Key Function	Adjustments	AIC	ΔAIC	Average	SE	Density	SE	Value	P-value
No bins, No truncation	Half-normal	Cosine (2,3)	1248.05	0.00	0.10	0.01	0.18	0.03	0.03	0.98
	Hazard-rate	Cosine (2,3)	1248.63	0.59	0.09	0.01	0.18	0.03	0.02	1.00
	Hazard-rate	Polynomial (2)	1259.92	11.87	0.11	0.01	0.15	0.03	0.13	0.47
	Half-normal	—	1261.68	13.64	0.14	0.01	0.12	0.02	0.69	0.01
No bins, Truncation at 2.5 km	Hazard-rate	—	626.73	0.00	0.33	0.05	0.18	0.04	0.04	0.96
	Half-normal	Cosine (2,3)	629.78	3.05	0.28	0.06	0.22	0.05	0.03	0.99
	Half-normal	—	635.14	8.41	0.42	0.03	0.15	0.02	0.32	0.12
No bins, Truncation at 4 km	Hazard-rate	Cosine (2)	1144.94	0.00	0.17	0.01	0.17	0.03	0.02	0.99
	Half-normal	Cosine (2,3)	1145.47	0.53	0.15	0.02	0.19	0.03	0.02	1.00
	Hazard-rate	Polynomial (2)	1147.60	2.65	0.16	0.03	0.18	0.04	0.03	0.98
	Half-normal	—	1159.33	14.39	0.24	0.01	0.13	0.02	0.63	0.02