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Applications of an unmanned aerial vehicle and thermal-imaging camera to study ducks nesting over water

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ABSTRACT. Finding and monitoring nests are key components of avian research, but they are often expensive, time-consuming, and inefficient operations. This is certainly true for diving ducks that nest in wetlands with thick emergent vegetation where nests are typically located by teams of technicians that wade through a marsh and beat vegetation with sticks, hoping to flush incubating females or encounter nests without a female present. Taking advantage of recent advances in both unmanned aerial vehicles (UAVs) and thermal-imaging cameras, our objectives were to (1) compare our ability to locate duck nests using a UAV and using traditional on-foot searching methods, and (2) determine if nests monitored remotely with the UAV had different survival rates than nests monitored with traditional nest-site visits. We searched for nests with a UAV system in southern Manitoba during the springs of 2018 and 2019. Using the UAV, we located 48 nests not found by ground crews, ground crews found 164 nests not found with the UAV, and 71 nests were found using both methods. Overall, nests were less likely to be detected with the UAV (0.34) than by ground crews (0.71), but surveys were completed approximately four times faster with the UAV. Detectability of nests varied among duck species (range = 0.55–0.04). We found no difference in nest survival between nests monitored with the UAV (0.95) and those repeatedly visited by ground crews (0.95). However, in 2018, ground monitoring resulted in 19 nests being abandoned by females, compared to only one monitored with the UAV. Our results demonstrate that UAVs equipped with thermal cameras can be used to find nests of ducks located over water, with greater success for species that nest earlier and those whose nests are not buried under matted vegetation. Furthermore, monitoring nests with the UAV resulted in lower rates of nest abandonment, and survival of nests monitored with the UAV was similar to that of nests monitored using traditional methods. Additional species- and habitat-specific studies are needed to fully understand the utility and challenges associated with using UAVs equipped with thermal imaging to survey species of wetland wildlife.

RESUMEN. **Aplicaciones de vehículos aéreos no tripulado y cámaras térmicas para estudiar patos anidando sobre el agua**

Encontrar y monitorear nidos son componentes clave para el estudio de las aves, pero son normalmente operaciones ineficientes, costosas y que consumen mucho tiempo. Esto es especialmente cierto para los patos zambullidores que anidan en humedales con vegetación emergente densa, donde los nidos son encontrados por grupos de técnicos que caminan a través del humedal, golpeando la vegetación con palos esperando espantar hembras que están incubando o encontrar nidos sin la presencia de las hembras. Utilizando avances recientes en el desarrollo de vehículos aéreos no tripulados (UAV) y cámaras térmicas, nuestros objetivos fueron (1) comparar la capacidad de encontrar nidos utilizando UAV y utilizando métodos de búsqueda tradicionales y (2) determinar si los nidos monitoreados remotamente con UAV tienen tasas de supervivencia diferentes que los nidos monitoreados con visitas tradicionales al sitio de anidación. Buscamos nidos con un sistema UAV en el sur de Manitoba durante las primaveras de 2018 y 2019. Utilizando los UAV, encontramos 48 nidos que el equipo en campo no ubicó, el equipo en tierra localizó 164 nidos que no fueron localizados por el UAV y 71 nidos fueron encontrados utilizando ambas metodologías. En general, el UAV ubicó los nidos con menor probabilidad (0.34) que el equipos en tierra (0.71), pero los monitoreos fueron cuatro veces más rápidos utilizando el UAV. La detección de los nidos fue variable a través de las especies (rango = 0.55–0.04). No encontramos diferencias en la supervivencia de los nidos entre los nidos monitoreados por el UAV (0.95) y los que fueron repetidamente visitados por el equipo de tierra (0.95). Sin embargo, en 2018, 19 de los nidos monitoreados por el equipo de tierra fueron

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abandonados, mientras que solo uno fue abandonado utilizando el método de monitoreo con UAV. Nuestros resultados sugieren que UAV equipados con cámaras térmicas pueden ser utilizados para encontrar nidos de patos ubicados sobre el agua, con un éxito mayor en las especies que anidan temprano en la temporada y para aquellos nidos que no están enterrados en vegetación densa. Adicionalmente, el monitoreo de nidos con UAV resultó en una tasa menor de abandono y la supervivencia de los nidos monitoreados utilizando UAV fue similar a la supervivencia de los nidos monitoreados con métodos tradicionales. Necesitamos un mayor número de especies y estudios específicos a un hábitat para comprender enteramente la utilidad y los retos asociados por la utilización de UAV equipados con cámaras térmicas para monitorear especies silvestres en humedales.

Key words: Canvasback, drone, Manitoba, prairie, Redhead, UAS, UAV, waterfowl, wetland

Annual recruitment is an important driver of population dynamics for most birds, and so understanding nesting ecology has long been a research priority (Cowardin et al. 1985, Martin and Geupel 1993). Nest survival is a critical determinant of recruitment (Ricklefs 1969), especially for species like ground-nesting ducks where often fewer than 20% of nests survive until hatch (Greenwood et al. 1995, Baldassarre et al. 2006). Indeed, a full life-cycle analysis of mid-continent Mallards (*Anas platyrhynchos*) revealed that nest survival was the single most important factor in determining population trajectories (Hoekman et al. 2002).

To derive estimates of nest survival, establishing reliable methods to locate and monitor nests has been a mainstay of waterfowl research for the last half century (Gates 1965). Most species of North American ducks either nest in upland habitats or on emergent vegetation platforms built in shallow water. Nests in upland habitats can be found across an expansive geography (thousands of nests across thousands of ha annually; Skaggs et al. 2020) using the chain-drag method where a rope or chain connected between two vehicles is pulled through nesting cover and incubating females flush from nests when the rope or chain passes overhead (Higgins et al. 1969, Klett et al. 1986). Nests over water are more difficult to locate, and the traditional method of nest searching involves wading paths at 1–2-m intervals in hopes of finding nests or flushing females from near nest locations (Sorenson 1997). In general, both upland and overwater searching rely on finding the nest, marking the nest location, and monitoring it regularly until hatching or failure, all of which may increase the risk of nest predation (Hein and Hein 1996) and nest abandonment (Ringelman et al. 2017). Unmanned aerial vehicles (hereafter, UAVs) may provide biologists with a more efficient way to search for duck nests, especially those constructed over water, and may reduce nest-abandonment and predation rates either by reducing or eliminating the need to monitor nests on foot.

Unmanned aerial vehicles have been used to survey a variety of wildlife species, ranging from elephants to canopy-nesting birds (Vermeulen et al. 2013, Weissensteiner et al. 2015). UAVs have been used to estimate the size of congregations of birds (> 1000 individuals) such as wintering populations of Snow Geese (*Anser caerulescens*) and Canada Geese (*Branta canadensis*), as well as numbers of colonial-nesting birds with more precision and accuracy than corresponding ground surveys (Chabot and Bird 2012, Sardá-Palomera et al. 2012). Recently, Pöysä et al. (2018) used a UAV to search for duck broods in Finland and showed that UAV surveys detected the same number of broods as ground teams, and more accurately enumerated ducklings. However, most of the aforementioned studies involved surveys of highly visible species and relied on optical cameras attached to a UAV. Equipping UAVs with thermal-imaging cameras may allow detection of cryptic birds and nests hidden in vegetation.

Recent weight reductions of thermal-imaging cameras have allowed their attachment to UAVs, and these systems have been used to monitor wildfires (Ambrosia et al. 2003), conduct search-and-rescue missions (Rudol and Doherty 2008), and survey wildlife (Haschberger 1996, Elsey and Trosclair 2016, Scholten et al. 2019). UAVs and thermal-imaging cameras have been used to detect large mammals, such as Roe deer (*Capreolus capreolus*) (Israel 2011) and chimpanzees (*Pan troglodytes*) (Van Andel et al. 2015), and have also been found to reliably detect mesocarnivores in prairie landscapes (Bushaw et al. 2019). Recently, UAVs and thermal-imaging cameras have also been used to detect bird nests. Scholten et al. (2019) used a UAV equipped with a thermal camera to assist ground crews in searching for Field Sparrow (*Spizella pusilla*) nests in tall grass and found that UAV-assisted searches detected the same number of nests as traditional methods and completed surveys 28% faster.

We tested the feasibility of using a UAV dual-equipped with a thermal-imaging camera and visible-wavelength optical camera to search for ducks nesting over water in southern Manitoba, Canada. Our objectives were to determine the ability of a UAV equipped with cameras to detect duck nests compared with traditional methods, and monitor some nests remotely with the UAV to determine if rates of either nest abandonment or survival would be affected by repeated visits to nests by ground technicians that create trails through the vegetation.

METHODS

Our study area consisted of four sites (23.30–64.75 km^2) in the Prairie Pothole Region of southern Manitoba, Canada, where high densities of ducks are known to nest and UAV operation could occur without disruption. Two sites were located near the town of Minnedosa, MB (50.20° N 99.77° E), and two near the town of Shoal Lake, MB (50.43° N 100.59° E). The average June temperature in this region is 15.1°C with an average daily minimum of 8.4°C and average daily maximum of 21.7°C. We randomly selected 0.65-km^2 plots (quarter-sections; 160 acres) on each site where permission was granted to search for duck nests. In 2018, all effort was conducted on the two sites near Minnedosa ($N = 48$ plots; 24 per site). In 2019, we expanded our effort to all four sites, but reduced the number of plots per site ($N = 72$ plots; 18 per site). This region of prairie Canada is characterized by high wetland densities and stable water levels that generally inundate the 10–30 m edge of peripheral cattails (*Typha* spp.) and hardstem bulrush (*Schoenoplectus acutus*) (Arnold et al. 1993) that provide suitable nesting cover for ducks that nest over water. Surrounding upland areas consisted primarily of private agricultural land and pasture.

Equipment. We used a battery-powered DJI Matrice 210 quadcopter UAV (6.4 kg, 716 × 200 × 235 mm) powered by twin 22.8-V lithium-ion batteries that permitted a flight time of ~ 20 min. We used a generator (stored in the truck bed near the point of launch) to charge up to 12 batteries in the field, allowing us to operate continuously until surveys were complete or environmental conditions limited usability. The UAV was equipped with two cameras, and we were able to switch between views using the flight-controller tablet. The first camera was a DJI Zenmuse XT thermal-imaging camera (640 × 512 resolution, 19-mm lens, 30 Hz) used to detect thermal radiation (white-hot palette) given off by eggs or incubating females. The amount of radiation emitted depends on both the temperature of the object and its emissivity, which is a measure of infrared reflectivity. The image generated by the thermal camera is not a depiction of the absolute temperature of an object, but a combination of temperature, emissivity, environmental factors such as humidity, and especially the contrast between an object and its background. The second camera, a Zenmuse X4S visual-wavelength optical camera (5472 × 3648 resolution, 8.8 mm lens), was used to identify the species of the incubating female at each nest detected.

Survey protocol. We used roadside pair surveys (Pagano and Arnold 2009) to time our seasonal nest searching efforts to align with the nesting chronology of Canvasbacks (*Aythya valisineria*), one of the first diving ducks to nest in our study area (Anderson et al. 1997). When the ratio of Canvasback pairs to lone males declined to 1:1, we initiated nest searching because the presence of lone males indicates that females are incubating eggs. Nest searching began on 21 May in 2018 and 15 May in 2019; nest searching ended on 30 June in both years to ensure we found both early- and late-nesting species. Following guidelines from Vas et al. (2015), we launched the UAV > 100 m from any wetlands to minimize disturbance. We flew surveys at 31 m above ground level, which was high enough to detect duck nests while eliminating some false-positive heat signatures. At each wetland, we searched all emergent vegetation once for nests. On smaller ponds, we manually flew the UAV along the edge of the wetland, but, for larger wetlands with more vegetation, we flew along transects to ensure complete coverage. Transects were also flown manually; after one transect, we repositioned the drone until objects at the edge of one side of the camera screen shifted to the other side, and flew parallel to the previous flight path as indicated on the flight-controller tablet. Once a potential nest was detected with the thermal camera (Fig. 1), we switched to the optical camera and dropped to lower altitudes (~ 5 m) to identify the species (Fig. 2) and used the flight-controller tablet to mark the location on the integrated global positioning system (GPS). The low altitude required to identify a species, and the high percent of overlap required, precluded us from automating transect searches and stitching images/video for later review (e.g., in Pix4D or other software); we also could not record thermal and color images/video simultaneously. Nest searching began at sunrise to maximize the contrast of warm nests against a backdrop of cool water and vegetation, and continued until temperatures reached a point where so many false positives were visible on the thermal camera that nests were indistinguishable from background noise (before 13:00). No flights were conducting in inclement weather or when winds exceeded 32 km/h. Further details about UAV equipment and methods (Barnas et al. 2020) can be found in Appendix S1.

Objective 1: Comparing detection rates. For this component of our study, we searched all wetlands on 12 plots at two sites in 2018 ($N = 24$), and nine plots at each of the four sites in 2019 ($N = 36$); seven plots were the same in both years. Plots were first searched for nests with the UAV to mitigate bias associated with visible trails through vegetation created by ground crews. The morning after plots were searched with the UAV, ground technicians searched for nests by wading through emergent vegetation, zig-zagging from the dry edge to open water, attempting to either flush females or randomly detect nests. Once a nest was detected, the species, number of eggs, and incubation stage estimated by candling were recorded (Weller 1956), along with a qualitative estimate of the overhead cover at the nest that ranged from 1 (no overhead cover, nest completely visible from above) to 7 (nest completely obscured by overhead vegetation). When a nest located with the UAV was not detected by the ground crew, the ground crew was given the GPS location of the missed nest and the nest was visited to collect nest data. Nests were visited on foot every 6–10 days until hatching or failure.

Fig. 1. Thermal image (white-hot palette) of a Canvasback (*Aythya valisineria*) nest taken from a UAV at a height of ~ 31 m in southern Manitoba, Canada.

Fig. 2. Image of an incubating Canvasback (*Aythya valisineria*) nest taken from a UAV at a height of ~ 5 m in southern Manitoba, Canada.

We calculated the probability of nest detection using Huggins closed capture models (Huggins 1989, 1991) in program MARK (White and Burnham 1999). Each nest was treated as an individual unit, and we assumed equal detection probability across plots. We increased our sample size by combining data from both years for a more robust analysis. We created a two-occasion encounter history for each located nest, where the first value represented detection (1) or non-detection (0) with the UAV and the second value represented detection or non-detection by the ground crew. Because the Huggins closed capture model is conditional on detection, the only three potential encounter histories were 11, 10, or 01. In addition to evaluating detection probability by survey method, we also examined factors that influenced whether a nest was detected with the UAV. We included species and canopy cover because these factors relate to the visibility of nests from the air. We also tested the possible effects of clutch size (more eggs produce a larger heat signature) and incubation stage because ducks spend more time incubating older nests (Croston et al. 2020), and female presence could influence detectability. We evaluated candidate models using Akaike's information criteria corrected for small sample size (AICc).

Objective 2: Effects of ground technician visits on nest abandonment and survival. When searching for nests on foot, flushing females from nests during laying or early incubation can cause them to abandon the nesting attempt (Ringelman and Skaggs 2019). In addition, trails created by repeated visits by ground observers may act as cues or corridors for predators (Picozzi 1975, Hein and Hein 1996), and lead to biased estimates of predation rates relative to nests not visited on foot. In 2018, we randomly selected 12 plots at the two Minnedosa sites ($N = 24$ different plots than used for objective 1) to search for nests using only the UAV. Once we located a potential nest, we used the optical camera to identify the species and collected a GPS coordinate using the flight software. We monitored active nests every 6–8 days with the UAV until we determined they were terminated. We considered a nest terminated if no heat signature was detected on two consecutive days, and then visited the nest on foot to determine fate (hatched, predated, or abandoned).

In 2019, we increased our sample size to nine plots on each of the four sites ($N = 36$ different plots from objective 1), and protocols differed slightly: in 2019, we visited each nest once on foot upon initial discovery to confirm species and gather data on incubation stage and number of eggs. Determining nest fates with confidence was challenging for the drone-only visited nests in 2018. Without knowing the incubation stage at the time a nest was initially found, predicting a hatch date was impossible and this influenced our ability to determine nest fate. Our judgment was that the additional information gained from visiting a nest once outweighed the chance of creating a trail to the nest. Trails only become prominent in the emergent vegetation after repeated visits by ground crews over multiple weeks.

We conducted our nest survival analysis in program MARK (White and Burnham 1999) accessed through the RMark package (Laake 2013) in program R (R Development Core Team 2008). We compared daily survival rates of nests (Dinsmore et al. 2002) monitored using only the UAV to nests visited repeatedly by ground crews (data from objective 1). We combined data from both years and modeled the daily survival rate as a function of monitoring method. For 2019, we also evaluated additional factors suspected to influence nest fates, such as species, incubation stage, and clutch initiation date (Ringelman et al. 2018). Values are presented as means ± SE unless otherwise noted.

RESULTS

Detection rates with the UAV and by ground technicians. During two years of searching plots using both aerial- and ground-survey methods, we found 283 nests of six species, including Canvasback, Redhead (*Aythya americana*), Ring-necked Duck (*Aythya collaris*), Lesser Scaup (*Aythya affinis*), Ruddy Duck (*Oxyuri jamaicensis*), and Mallard (Table 1). We detected 48 nests with the UAV that were not detected by crews on foot, ground crews located 164 nests that were not detected with the UAV, and 71 nests were independently located with both methods. Nest-detection probabilities differed between search methods and were lower with the UAV (0.34 ± 0.03) than for ground crews (0.71 ± 0.04). Using only data from nests found with the UAV, we found that detectability was strongly influenced by species (Table 2), with detection rates highest for Canvasbacks and lowest for Ring-necked Ducks and Lesser Scaup (Table 3). Plots were surveyed in an average of 46 ± 3 min using the UAV compared to 182 ± 8 min for ground crews. When searching for nests with the UAV, we encountered numerous false-positive signatures each day, including nests of other species, natural hotspots (e.g., rocks in the sun), and anthropogenic debris; false positives increased as the landscape warmed throughout the morning. Although we learned to readily distinguish many of these false positives from duck nests, some time was spent during each search to investigate these false signatures.

Effects of technician visits on nest abandonment and survival. Using only 2018 data where UAV-located nests were never visited on foot, we recorded only one instance of nest abandonment (2.5% of nests) compared to 19 abandonments (15.2% of nests) apparently induced by crews monitoring nests on foot. Incubating females rarely flushed when approached with the UAV, whereas ground crews flushed most females from nests. Including sites searched only with the UAV, only by technicians, or where they overlapped, 401 nests were potentially available for the survival analysis. After censoring nests with incomplete or unknown fate data and those of species typically not considered overwater-nesting ducks (i.e., Northern Shoveler, *Spatula clypeata*), we included 357 nests ($N = 151$ in 2018 and $N = 206$ in 2019) in our analysis, with nests of Canvasbacks ($N = 136$), Redheads ($N = 77$), and Mallards ($N = 55$) accounting for 75% of our sample size. Using data from both 2018 and 2019, we first constructed a simple survival model only parameterized with survey method. We found no difference in daily survival rates of nests monitored with the UAV (0.95 ± 0.01) and those repeatedly visited on foot (0.95 ± 0.004); these results qualitatively held when analyzing years separately. Using data from only 2019 when UAV-monitored nests were visited once

Table 1. Sample sizes of duck nests found with the unmanned aerial vehicle system and by ground observers in the Prairie Pothole Region of southern Manitoba, Canada, in 2018 and 2019. Some nests were found using both methods and are counted in both columns

Species	Found with UAV	Found by ground crew
Canvasback	67	79
Redhead	9	41
Ring-necked Duck	4	24
Lesser Scaup	10	46
Ruddy Duck	23	58
Mallard	4	16
TOTAL	118	264

Table 2. Model selection for factors influencing detection of nests of ducks with a UAV in the Prairie Pothole Region of southern Manitoba, Canada. Method appears in all models because it was embedded in the structure of the data

Model	AICc	ΔAIC	Weight	Parameters	-2LogLikelihood
Method + Species	456.14	0.00	0.9968	11	433.60
Method + Cover	467.96	11.82	0.0027	3	461.91
Method + Clutch Size	471.70	15.58	0.0004	3	465.65
Method + Incubation Stage	475.87	19.74	0.0000	3	469.83
Method	477.28	21.15	0.0000	2	473.26

Table 3. Detection probability of each species of duck with a UAV in the Prairie Pothole Region of southern Manitoba, Canada, taken from the best-fitting model

Species	Estimate	Standard Error	Lower 95% CI	Upper 95% CI
Canvasback	0.549	0.059	0.433	0.666
Redhead	0.239	0.063	0.138	0.382
Ring-necked Duck	0.043	0.043	0.006	0.252
Lesser Scaup	0.133	0.088	0.034	0.405
Ruddy Duck	0.387	0.087	0.235	0.565
Mallard	0.270	0.073	0.152	0.433

Table 4. Model selection results for daily nest survival of ducks in the Prairie Pothole Region of southern Manitoba, Canada, in 2019

Parameters	AICc	ΔAICc	Weight	Parameters	−2LogLikelihood
Age found	495.8	0.00	0.499	2	−245.92
Age found + Initiation date	496.7	0.84	0.327	3	−245.33
Initiation date	498.6	2.71	0.129	2	−247.27
Survey block	502.5	6.71	0.017	4	−247.26
Nest cover	504.0	8.16	0.008	3	−248.99
Treatment	504.1	8.24	0.008	2	−250.04
Survey method	504.3	8.51	0.007	2	−250.17
Survey method + cover	505.9	10.08	0.003	4	−248.95
Species	509.9	14.05	0.000	8	−246.91
Nest cover + species	510.8	14.99	0.000	10	−245.36

on foot, our best-fitting survival model including the age of nests when found, and a model that also included nest initiation date was competitive (Table 4). Daily survival rates were higher for nests that were older when found (Fig. 3) and for those initiated earlier in the breeding season (Fig. 4).

DISCUSSION

We found that duck nests located over water could be located using a UAV equipped with a thermal-imaging camera. More nests were located by ground crews than with the UAV, but that was not unexpected because passive nest searching will likely never be able to locate as many nests as ground crews that flush birds from nests. We did not alter the factory settings for gain or temperature of the thermal camera, and leveraged this consistency so the UAV operator could develop a search image for nests. However, a full evaluation of all settings under various environmental conditions merits further investigation.

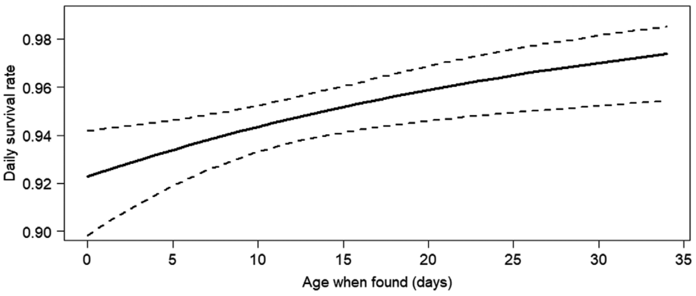

Fig. 3. Nest daily survival rate as a function of the age of the nest when it was found, where age is the summation of clutch size and incubation stage. Data are from nesting ducks monitored in Manitoba, Canada, 2019.

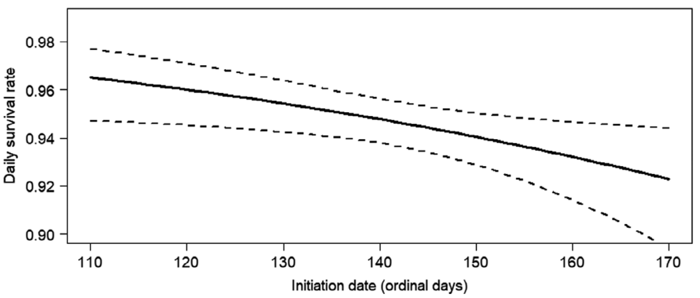

Fig. 4. Nest daily survival rate as a function of the estimated clutch initiation date of the nest. Data are from nesting ducks monitored in Manitoba, Canada, 2019.

The most important factor influencing detectability of nests with the UAV in our study was duck species. Canvasback nests were more detectable than those of other species, and detectability of Lesser Scaup and Ring-necked Duck nests was especially poor. Canvasbacks are the first species to nest at our study site before the emergent vegetation grows taller, and lower ambient temperature and humidity early in the season likely improved detection rates. In contrast, both Lesser Scaup and Ring-necked Ducks nest later in the year and build smaller nests that are typically concealed under heavy mats of dense vegetation (Krasowski and Nudds 1986) that the thermal camera was unable to penetrate. Our low detection probability with the UAV may also be an artifact of timing, i.e., locating nests with the UAV during the laying stage was more difficult because eggs and nests were at ambient air temperature. When ground crews located those nests, they became ineligible to "count" as drone-located, even though the UAV may have well been able to find them later in the incubation stage. We were unable to test this because nests found by ground observers during the laying stage were typically abandoned. Although we cannot definitively determine causes of nest abandonment, disturbance by ground observers is the most likely cause. We had hypothesized that nests might be easier to detect later in the incubation period because females spend more time on nests (Ringelman and Stupaczuk 2013, Croston et al. 2020), but this was not supported by our data. Anecdotally, we found that the presence of a female could, in some cases, obscure the heat signature of warm eggs in a nest (see also Israel and Reinhard 2017) because the dorsal surface of a well-insulated duck early in the morning is at ambient temperature, and does not produce a strong thermal signature.

Although detection probability with the UAV was poor compared to traditional methods, searching for nests with a UAV may still be useful in some circumstances. For example, a UAV could be used in tandem with ground crews to increase search efficiency (Scholten et al. 2019), especially early in the season when nests are easier to locate with a UAV, inexperienced ground technicians are less efficient, and chances of nest abandonment are higher. Indeed, Scholten et al. (2019) were constrained by camera resolution to searches from heights of 2–4 m with transects spaced only 2-m apart, but efficiency gains achieved by our system are potentially much larger because we were able to detect nests from 31 m above ground level. UAV searches may also be useful in landscape-scale occupancy modeling, where the objective is to rapidly determine the presence or absence of nesting ducks across an expansive geography. Finally, despite having approximately half of the detection probability of ground crews, nest searches were complete four times faster with the UAV. In addition, use of ground technicians was more expensive than the UAV system during our 2-year study, so UAVs can be a relatively cost-effective way to locate duck nests located over water.

Nests detected and monitored with the UAV had lower abandonment rates and had survival rates similar to those of nests located and visited repeatedly on foot by ground crews. Trails created by ground crews were obvious from the air using the UAV so we hypothesized that those trails could be used as corridors (Pasitschniak-Arts et al. 1998) by predators like raccoons (*Procyon lotor*), or serve as cues for avian predators (Hein and Hein 1996) like Common Ravens (*Corvus corax*), both of which were common at our study sites. Although we found no evidence of this, terrestrial predators have been reported to follow human trails through grasslands to passerine nests (Skagen et al. 1999) and to artificial duck nests in upland cover (Keith 1961, Olson and Rohwer 1998). One possibility is that, during our study, mammalian predators may in fact have followed ground-crew trails to predate nests, but nests found with the UAV may have been more visible to avian predators, resulting in similar survival rates for nests located using the different methods. However, we found no effect of overhead cover on daily survival rates, which we would have expected if avian predators were targeting more visible nests. Maxson and Riggs (1996) also found no effect of overhead concealment on predation rates of nests of diving ducks, but their study was conducted in an area dominated by mesocarnivores, with few avian predators.

The primary factors that affected daily survival rates in our study were nest age and initiation date. The age of nests when found has often been treated as a nuisance variable (Garrettson and Rohwer 2001, Raquel et al. 2015) because nests that are more easily located are more likely to be quickly found by predators so researchers are more likely to find older nests in higher-quality locations. Additionally, females are less likely to flush from nests later in incubation, concealing the location from predators and increasing the probability of survival (Mallory and Weatherhead 1993, Forbes et al. 1994, Ringelman and Stupaczuk 2013). Nests initiated earlier in the season were also more likely to survive, consistent with the results of other studies of nesting waterfowl (Clark and Shutler 1999, Raquel et al. 2015, Ringelman et al. 2018). Ringelman et al. (2018) suggested that duck nests are less abundant early in the season, but nest predation rates increase as predators develop search images (Nams 1997) and cue on increasing densities of nests later in the breeding season (Larivière and Messier 1998).

Our experience with searching for duck nests located over water suggests that UAVs and thermal cameras may be useful for detecting a variety of wetland wildlife. We routinely detected loafing pads constructed by muskrats (*Ondatra zibethicus*), as well as individuals and nests of American Coots (*Fulica americana*), Pied-billed Grebes (*Podilymbus podiceps*), Red-winged Blackbirds (*Agelaius phoeneceus*), Yellow-headed Blackbirds (*Xanthocephalus xanthocephalus*), rails (*Rallidae* spp.), and smaller passerines we did not identify. Our general impression is that UAVs equipped with thermal cameras are useful for locating animals/nests that either have minimal to moderate overhead cover or are moving, which makes detection easier and ameliorates the effects of overhead cover. We believe that detectability will also vary among habitat types and geographies (e.g., lower at sites with high humidity, green grasses, and surrounded by warm water). An important next step in UAV research will be controlled experiments to evaluate how microhabitatspecific temperature and humidity affect detectability with a thermal camera at the time of observation. Nevertheless, we anticipate that UAVs may eventually revolutionize many aspects of wildlife research (Linchant et al. 2015), and our study demonstrates that their potential use in avian nesting ecology can vary dramatically by species and their associated microhabitat preferences (Pöysä et al. 2018). Additional studies of other species and in different habitat types will be essential for determining where UAVs can reliably detect nests and animals, and thereby what questions can be answered using this rapidly growing technology.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website.

Appendix S1. UAV equipment and methods.