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Original Article

Application of Unmanned Aerial Vehicles and Thermal Imaging Cameras to Conduct Duck Brood Surveys

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ABSTRACT Brood surveys are used to estimate productivity in ducks, but road-side transects, aerial surveys, and double-observer ground surveys have likely underestimated productivity. Duck broods are elusive and prefer wetlands with emergent vegetation where they hide at signs of disturbance, making it difficult to get accurate brood counts. Estimates of brood detection probabilities are typically below 50% and variable, which makes biological inferences about abundance tenuous. We conducted a study to evaluate the efficacy of using an unmanned aerial vehicle (UAV) equipped with a thermal imaging camera to survey duck broods in 2 study areas. In Manitoba we located 669 broods with the UAV, compared to 344 detected by double-observer ground surveys. In Minnesota we detected 225 ducks broods with the UAV, whereas only 105 duck broods were detected by ground observers. Using a Huggins closed-capture model in program MARK we estimated an average detection probability across both sites of 0.55 (SE = 0.02) with the UAV compared to 0.24 (SE = 0.02) for the ground crews. Although the UAV detected twice as many broods as the ground surveys, detection probability with the UAV was impacted by temperature, humidity, vegetation density, and the criteria we used to determine whether a brood could be classified as resighted. Nevertheless, using a UAV equipped with a thermal imaging camera effectively doubled the number of broods detected compared to traditional methods, and surveys were completed 3 times faster. With advancing drone and camera technology we believe UAV brood counts will become increasingly accurate and provide reliable measures of local duck productivity. © 2021 The Wildlife Society.

KEY WORDS duckling, drone, Manitoba, Minnesota, quadcopter, UAS, waterfowl.

The most important geographic area for breeding ducks (Anatidae) in North America is the Prairie Pothole Region (PPR; U.S. Fish and Wildlife Service 2012), where waterfowl managers are tasked with securing and managing habitat to maximize the annual production of ducks (Prairie Habitat Joint Venture 2014). Accordingly, research has focused on understanding wildlife-habitat relationships (Morrison et al. 2012) to identify landscapes that provide the greatest benefit to ducks. Annual efforts to broadly characterize the distribution of breeding pairs across the PPR (Reynolds et al. 2006, U.S. Fish and Wildlife Service 2018) and intermittent attempts to characterize nest survival (Greenwood et al. 1995, Stephens et al. 2005, Skone et al. 2016, Ringelman et al. 2018, Skaggs et al. 2020), largely drive conservation strategies in the region. Although metrics like nest survival rates provide useful indices for evaluating management actions (Pieron and Rohwer 2010), potentially low rates of post-hatch duckling survival (Stafford and Pearse 2007) limit the utility of nesting studies for estimating waterfowl production (Amundson et al. 2013). The best proxy biologists have for estimating landscape-scale duck production is comparing the number of duck pairs to the number of broods that were produced (Cowardin and Blohm 1992, Pagano et al. 2014).

Estimating duck production via brood surveys is challenging because ducklings are small, cryptic, and preferentially use emergent vegetation where they are difficult to detect (Ringelman and Flake 1980). Pagano and Arnold

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(2009) conducted repeated brood surveys along roadsides in the PPR to create a 3-occasion encounter history for each brood, and used closed-capture modeling (Huggins 1989, 1991) to correct for detection probability to estimate duck productivity (Pagano et al. 2014). Walker et al. (2013) used binomial mixture models (MacKenzie et al. 2017) to estimate brood occupancy of individual wetlands, methods that can be scaled up to estimate brood abundance (Carrlson et al. 2018) and duck production at spatial scales relevant to management actions (Kemink et al. 2019). Although statistical advances have improved estimates of duck production, brood surveys—conducted from a roadside or by walking up to a wetland—are still subject to practical constraints, such as locating broods partially obscured by emergent vegetation (Pagano and Arnold 2009). Use of an unmanned aerial vehicle (hereafter UAV) could provide biologists with a more effective method to conduct brood surveys.

Unmanned aerial vehicles have been used to count colonial nesting birds (Sardá-Palomera et al. 2012), with detectability as high as 96% (Chabot et al. 2015). Unmanned aerial vehicle technology has also been used to estimate non-breeding population sizes of birds congregated in large flocks, such as snow geese (*Anser caerulescens*) and Canada geese (*Branta canadensis*), where UAV flights detected on average 60% more individuals than ground surveys (Chabot and Bird 2012). Clearly, UAVs have utility in surveying large-bodied birds that are in the open and are relatively immobile, but duck broods may be harder to detect. In the boreal forest of Finland, Pöysä et al. (2018) showed that UAV surveys with a regular camera detected the same number of duck broods as ground technicians, but they were able to more accurately count the number of ducklings in each brood. Of the broods detected, 86% were dabbling ducks, which tend to hide in emergent vegetation and remain difficult to detect even from the air (Pöysä et al. 2018).

Miniaturization of thermal imaging cameras has made them light enough to be attached to UAVs, and these systems are potentially useful for surveying endothermic wildlife (Christiansen et al. 2014). For example, Bushaw et al. (2019) used a quadcopter UAV equipped with a thermal camera to locate and identify nocturnal mesocarnivores in southern Canada and reported being able to detect animals as small as rodents in grassy fields. Scholten et al. (2019) used a UAV and thermal camera to locate small, well-hidden field sparrow (*Spizella pusilla*) nests in grasslands in the northern United States, and Bushaw et al. (2020) used a similar system to locate diving duck nests in prairie Canada. Here, we evaluated whether UAVs equipped with thermal imaging cameras could be used to locate duck broods. Our goal was to compare the efficacy of the UAV system to traditional walk-up, repeat-visit brood surveys. We hypothesized that the UAV and thermal camera would be able to locate broods not visible to shoreline observers, and that detection probability estimated from repeat visits would be higher for the UAV system than for ground crews.

STUDY AREA

We tested the UAV system in 2 distinct geographies that corresponded to separate research projects, allowing us to diagnose the utility of the UAV system across a range of environmental conditions, habitat types, and duck species. Our first study area was near Minnedosa, Manitoba, Canada (50.20°N, 99.77°E), where the average daily minimum temperature in June was 8.4° C and the average daily maximum was 21.7° C with 10.2 cm precipitation. The region was characterized by permanent or semi-permanent wetlands (0.2–250 ha) ringed by a 10–30 m edge of cattails (*Typha* spp.) and hardstem bullrush (*Schoenoplectus acutus*; Arnold et al. 1993). Historical wetland density ranged from 15–34 wetlands/km^2 (Stoudt 1982), but many wetlands have since been drained (Watmough et al. 2017). Upland areas consisted of private land farmed for canola (*Brassica napus*) and spring wheat (*Triticum aestivum*), with some remnant grasslands. The breeding duck community included diving ducks such as canvasbacks (*Aythya valisineria*), redheads (*Aythya americana*), ring-necked ducks (*Aythya collaris*), lesser scaup (*Aythya affinis*), ruddy ducks (*Oxyura jamaicensis*), and dabbling ducks including blue-winged teal (*Spatula discors*), mallard (*Anas platyrhynchos*) and gadwall (*Mareca strepera*; Anderson et al. 2001). We selected 2, 64.75 km^2 study blocks (A and B) with a high density of wetlands, and surveyed wetlands for broods on 39, 0.64 km^2 replicates (quarter-sections), 24 on block A and only 15 on block B due to logistical constraints and difficulty obtaining landowner permission.

The second study area was near Madelia, Minnesota, USA (44.03°N, 94.25°E), where the average daily minimum temperature in June was 15.6° C and the average maximum was 26.7° C with 18.5 cm precipitation. The region was characterized by row-crop agriculture, primarily corn (*Zea mays*) and soybeans (*Glycine max*), with temporary and seasonal wetlands embedded in crop fields. We constrained our site selection by requiring 60% row crops and a minimum of 5 wetlands (<10.12 ha in size) within 20.72 km^2, in order to fulfill the requirements of a larger research project on brood use of wetlands embedded in row-crop agriculture. We randomly selected 14 sites and conducted brood surveys on all wetlands for which we could secure access. Minnesota sites varied in wetland density, with an average of 4.36 wetlands/km^2. The breeding duck community was dominated by dabbling ducks including blue-winged teal, mallard, northern shoveler (*Spatula clypeata*), gadwall, and wood ducks (*Aix sponsa*).

METHODS

Equipment

We flew a battery-operated DJI Matrice 210 quadcopter UAV (6.4-kg weight, 716 × 220 × 236 mm dimensions; Da-Jiang Innovations, Shenzen, Guangdong, China), powered by two 22.8 V lithium pro ion batteries that permitted surveys of ~20 minutes before changing batteries. A generator and portable battery charger were used to charge extra batteries in the field allowing us to operate continuously each day. The UAVs were equipped with two cameras and we could switch between each on the flight controller tablet. The first camera was a DJI Zenmuse XT thermal imaging camera (640 × 512 resolution; 19 mm lens; 30 Hz; white-hot filter) which we used to detect the thermal signature of waterfowl broods. The strength of the thermal signal is dependent on both the temperature of the object, its infrared reflectivity, and the characteristics of the backdrop against which the object is observed (Ribeiro-Gomes et al. 2017). The second camera, a DJI Zenmuse X4S optical camera (5472 × 3648 resolution, 8.8 mm lens), was used to take pictures to identify the species of each brood we located.

Survey Methods

At both sites, UAV crews followed guidelines laid out by Vas et al. (2015) and launched the UAV >100 meters from survey wetlands to avoid disturbing duck broods. We flew the UAV at a height of 31 m to search for broods, which allowed us to locate them in cover and eliminate some false heat signatures like rocks and red-winged blackbirds (*Agelaius phoeniceus*) perched in vegetation. At some wetlands it was possible to survey the entire wetland by rotating the UAV at a single observational point, and for others it was necessary to fly transects to ensure that the entire wetland and all the emergent vegetation were surveyed. Due to software restrictions of the UAV, all flight routes were flown manually, including transects; after flying a linear transect at the edge of the wetland, we moved the drone until objects seen at the edge of the screen moved to the other side to ensure image overlap, and flew parallel to the previous route using the map on the flight controller tablet. Because all operation was manual, flight speed of transects varied as potential broods were located. Once a potential brood was located with the thermal camera (Fig. 1), we switched to the optical camera and dropped to lower altitudes to identify the ducklings (Fig. 2). At an altitude of ~10 m, it was possible to determine the species of the brood if the hen was present, and to count and age the ducklings (Gollop and Marshall 1954). We took photos of all broods and made a final determination after leaving the field and viewing the images. We did not conduct surveys during inclement weather (i.e., rain or dense fog), or when winds were greater than 32 km/h.

In Manitoba, we surveyed for broods July 9–12 and July 31–August 2 to identify both early- and late-nesting species. Manitoba UAV surveys started at sunrise and were followed by an additional survey at least 2 hours later (range of afternoon survey: 1300–1900 hrs). Each day the UAV crew surveyed 12–13 quarter-sections and the ground crew surveyed 12–13 different quarter-sections. The following day crews swapped areas, allowing us to compare survey techniques while maintaining assumptions of closure (Walker et al. 2013, MacKenzie et al. 2017).

In Minnesota we surveyed July 2–July 19 and July 31–August 15. Minnesota surveys began at sunrise and the second survey took place between 1600 and sunset. Here, wetlands were surveyed one time each day by the UAV pilot

Figure 1. A dabbling duck brood located with a UAV and thermal camera in Manitoba, Canada, in 2018.

(e.g., in the morning) and the ground crew (e.g., later that afternoon), and surveyed again by both teams the next day. We alternated which team surveyed first and started half of UAV surveys in the afternoon. In both study geographies, we used only one UAV crew to conduct surveys, thereby creating the potential for observer bias (i.e., a tendency to look harder for broods previously sighted); however, previous research has demonstrated that prior detection of a brood does not affect the probability of resighting (Pagano and Arnold 2009).

The ground crews followed brood survey guidelines from Carrlson et al. (2018) and Pagano and Arnold (2009). A single observer surveyed all wetlands on a quarter-section, and a second survey was conducted at least 2 hours later. In Minnesota, different observers were used in the morning and afternoon, but in Manitoba the same observer conducted both surveys for logistical reasons. The ground crews walked to every wetland on the quarter-section and surveyed it for broods, staying as long as necessary to record data.

Figure 2. The same dabbling duck brood from Figure 1 from Manitoba, Canada in 2018, identified as a gadwall (*Mareca strepera*) brood using the visible-wavelength camera. Note: the image has been post-processed by cropping and enlarging to facilitate species identification.

At both sites and for both survey methods, if a brood was located during the second survey and it was within one age sub-class (Gollop and Marshall 1954), varied by ≤3 ducklings, and was on the same pond, it was considered a re-sighted brood rather than a new detection (Pagano and Arnold 2009). In addition to counting broods, observers also estimated the percentage of each wetland visible (shoreline vegetation can obscure views into the wetland) and the time it took to conduct each survey; visibility was assumed to be 100% with the UAV. If the hen was absent from the brood, we recorded the age class and number of ducklings present but recorded the species as unknown. Data were collected under Transcanada SFOC permit 58-12-17-132, FAA license 4140054, LSU IACUC permit A-2018-02, and Iowa State University IACUC permit 18-152.

Data Analysis

Each brood was potentially observable 4 times: twice by the ground crew, and twice with the UAV. Therefore, we created a 4-occasion encounter history for each brood that encoded both the survey type and time of day. For example, a brood located only by the UAV in both the morning and afternoon and never located by the ground technicians would have an encounter history of 1100, where ones indicate detection. We analyzed our data using Huggins closed capture models (Huggins 1989, 1991) implemented in Program MARK (White and Burnham 1999), which uses a maximum-likelihood estimator from a logistic model to derive detection probabilities. For both sites, we evaluated detection probability based on survey method and time of day (2-level factor), and also evaluated the influence of species, number of ducklings, age of the ducklings, and ground observer visibility of each wetland on detection probability. We ranked candidate models using Akaike's Information Criteria corrected for small sample size (Burnham and Anderson 2002) and conducted analyses for each location separately. Data are presented as means ± standard error unless otherwise noted.

Some broods may only be detected by one method, and not the other, thus by jointly analyzing both ground data and UAV data together, our goal was to come closer to the true detection probability. As a post-hoc exercise, we analyzed the 2 methods separately by removing lines of data where the brood was never detected by that particular method. For example, if a brood was only located by the drone, we removed it from the ground crew analysis and recalculated detection probability. Thus, we were able to determine what the ground crew would estimate their detection probability to be, without any knowledge of what the UAV had located.

RESULTS

Manitoba

We surveyed 573 wetlands over 2 rounds of surveys in Manitoba in 2018. We found a total of 669 unique duck broods with the UAV system, whereas the ground crew located 346 broods (Table 1). Blue-winged teal ($n = 192$), mallards ($n = 90$), and canvasbacks ($n = 38$) accounted for most of the broods found with both methods. After grouping into species guilds, we located more dabbling duck broods with the UAV system ($n = 399$) than ground crews ($n = 208$), but both methods found similar numbers of diving duck broods (UAV = 156, ground crew = 133). We suspect the discrepancy for dabblers was actually much higher, because the UAV found 114 broods of unknown guild, often obscured in emergent vegetation (typical of dabbling ducks) and only visible with the thermal camera (Fig. 3); the ground crew found 5 broods of unknown guild (Table 1). The UAV and thermal camera system was also more efficient at locating broods; UAV surveys found approximately twice as many broods as ground surveys and took an average of 15 minutes to survey, while the ground crew averaged 45 minutes per survey.

Using the UAV our detection rate was 0.55 during both afternoon and morning surveys, whereas ground crews had a detection rate of 0.27 in the morning and 0.22 in the afternoon (Table 2); models including time of day were not competitive. When we evaluated more complex detection models with covariates, we found that the top-ranked model by AIC score included survey method, survey block, and the number of ducklings (Table 3); however, the number of ducklings was an uninformative parameter ($\beta = 0.52 \pm 0.50$; Arnold 2010). The other competitive model included visibility of the wetland, which was also an uninformative parameter ($\beta = 0.50 \pm 0.50$). We also estimated the detection rate of each species using the UAV and found that northern shovelers and mallards had the highest detection rates for dabbling ducks, whereas redheads and canvasbacks had the highest detection rates for diving ducks (Table 4).

We also constructed a brood detection model using only data collected by the ground crew in order to evaluate detection probability in a typical ground-only scenario (i.e., an analysis where the UAV data did not exist). Because the ground crew was relatively successful at resighting broods, detection probabilities were estimated at 0.61, 3 times higher than the estimate incorporating data from the UAV. In contrast, a UAV crew operating without ground observers would have estimated their detection probability to be 0.65, more similar to the 0.55 derived from the combined analysis.

Minnesota

In Minnesota, we surveyed 115 wetlands in highly altered agricultural landscapes. We found fewer broods than at our

Table 1. Sample sizes of duck broods located with a UAV and thermal camera in Manitoba, Canada, and Minnesota, USA in 2018, compared to the number of broods located by ground crews.

	Manitoba		Minnesota	
	UAV	Ground crew	UAV	Ground crew
Dabbling Duck	399	208	166	98
Diving Duck	156	133	6	0
Unknown Guild	114	5	53	7
Total	669	346	225	105

Figure 3. An image taken from a 2018 brood survey in Minnesota, USA, demonstrating how using the thermal camera enabled detection of broods that would have otherwise gone undetected.

Manitoba site, but the relative efficacy of the UAV and thermal camera in locating duck broods was similar. With the UAV and thermal camera, we located 225 broods, compared to only 105 broods located by ground crews (Table 1). The majority of broods located were mallards ($n = 63$), wood ducks ($n = 60$), unknown dabblers ($n = 53$), and blue-winged teal ($n = 41$). In Minnesota, our brood surveys were conducted on smaller wetlands, and so surveys with the UAV system took an average of 4 minutes, whereas ground crews spent an average of 12 minutes surveying a wetland.

In Minnesota surveys, our detection probability with the UAV system was 0.54 in the morning and 0.48 in the afternoon, whereas the ground crew had a detection probability of 0.30 in the morning and 0.20 in the afternoon (Table 2). Detection probability for blue-winged teal was relatively high (0.62) and similar to Manitoba, but Minnesota mallards were much harder to detect (0.38) than those in Manitoba (Table 5). When we expanded our modeling to include covariates that could influence brood detectability, our top-ranked model by AIC score included covariates for method, time of day, and visibility (Table 6), but visibility was uninformative ($\beta = 0.50 \pm 0.50$). Detection was higher in the morning than in the afternoon ($\beta = 0.547 \pm 0.160$). Without data from the UAV, the ground crew would have estimated their detection probability as 0.47 in the morning and 0.31 in the afternoon. Without data from the ground crew, the UAV operators would have estimated their detection probability as 0.48 in the morning and 0.54 in the afternoon.

DISCUSSION

Extensive sampling across several habitat types gave us confidence that we were able to detect waterfowl broods with the UAV and thermal imaging camera. Surveys with the UAV were more effective at locating broods when compared with traditional ground surveys, as we counted twice as many broods in one-third of the time with the UAV as it took ground crews to complete the same surveys. In Minnesota where we located dabbling ducks, detection rates were higher in the morning than during the afternoon surveys, but not in Manitoba where we located mostly diving ducks. Our site in Minnesota was warmer and had shallower wetlands than that in Manitoba, and we also began afternoon surveys after 1600 hrs (compared to after 1300 hrs in Manitoba), so we had to contend with warmer wetlands, which may have reduced afternoon detectability. Species composition may also have played a role, as dabbling duck broods we commonly observed in Minnesota tend to be more active in the morning (Diem and Lu 1960,

Table 2. Huggins closed-capture model estimates for detection rates of duck broods observed with the UAV and thermal camera compared to ground crews in Manitoba, Canada and Minnesota, USA, in 2018.

Location	Parameter	Detection probability	Lower 95% CI	Upper 95% CI
Manitoba	UAV Morning	0.55	0.52	0.58
	Ground Crew Morning	0.27	0.25	0.30
	UAV Afternoon	0.55	0.52	0.58
	Ground Crew Afternoon	0.22	0.20	0.25
Minnesota	UAV Morning	0.55	0.47	0.62
	Ground Crew Morning	0.30	0.24	0.37
	UAV Afternoon	0.48	0.41	0.56
	Ground Crew Afternoon	0.19	0.14	0.25

Table 3. Model selection results for Huggins closed-capture models of duck brood detection in Manitoba, Canada in 2018. Block is a factor with 2 levels (A and B).

Model	AIC*c*	ΔAIC	Weight	Parameters
Method + Block + Brood Size	3814.66	0.00	0.54	5
Method + Brood Size	3816.07	1.41	0.27	3
Method + Block + Visibility	3817.56	2.89	0.13	5
Method + Visibility	3818.99	4.32	0.06	3

Table 4. Detection probability for species observed with the UAV and thermal camera in Manitoba, Canada in 2018.

Species	Detection probability	Lower 95% CI	Upper 95% CI
Bufflehead	0.71	0.42	0.89
Blue-winged teal	0.65	0.59	0.71
Canvasback	0.65	0.49	0.77
Gadwall	0.57	0.27	0.83
Lesser scaup	0.57	0.27	0.83
Mallard	0.70	0.61	0.78
Northern shoveler	0.78	0.68	0.86
Redhead	0.69	0.47	0.85
Ring-necked duck	0.44	0.13	0.80
Ruddy duck	0.68	0.53	0.80

Table 5. Detection probability for species observed with the UAV and thermal camera in Minnesota, USA in 2018.

Species	Detection probability	Lower 95% CI	Upper 95% CI
Blue-winged teal	0.63	0.41	0.79
Mallard	0.38	0.21	0.59
Wood duck	0.57	0.37	0.75

Ringelman and Flake 1980), and the thermal camera is more effective in the morning when the background temperature of wetlands is cooler. The UAV system was particularly effective at locating dabbling duck species in emergent vegetation, except for mallards in Minnesota which had an anomalously low detection probability. In Minnesota we had a large number of broods we could not classify to species, and so these unknown broods may have actually been resighted mallards.

Conducting brood surveys with the UAV and thermal camera resulted in higher detection rates compared to traditional methods but was still only 55% in Manitoba and as low as 48% in Minnesota. There is some irreducible uncertainty inherent in our estimates which may have resulted in misclassification of broods or ducklings leading to lower detection rates. For example, deciding whether nearly-flighted ducklings are a brood or a group of molting adults, and how to classify mixed canvasback and redhead broods with multiple adults present. Nevertheless, we also think that our estimates for detection rate were affected by several factors, including broods moving within and between wetlands, the criteria we set for classifying a brood as a resight, and environmental conditions that reduced the efficacy of the thermal camera. For example, when we surveyed larger wetlands (more common in Manitoba), we had to fly transects in order to ensure we covered the entire wetland. When dropping to lower altitudes to identify a brood to species, it is possible that other broods not yet located moved into areas that had previously been surveyed, and so they never entered into our sample. Additionally, waterfowl broods move from wetland to wetland 2–5 times a year (Rotella and Ratti 1992, Leonard et al. 1996), and we are fairly certain that some broods switched wetlands between our surveys. That is, on our second visit, 3 out of 4 resight criteria were met (same species, duckling count within 3, within one age class), but the brood was located on a nearby wetland and therefore not counted as a resighted brood.

The thermal camera dramatically improved our ability to detect broods in emergent vegetation that would not have been seen from the ground or the air. The most common type of false-positive detection was a brood of another species (e.g., American coot [*Fulica americana*] or pied-billed grebe [*Podilymbus podiceps*]) which were easily distinguishable by movement behavior. Environmental conditions such as high ambient temperature and humidity reduced the efficacy of the thermal camera, and our ability to distinguish broods diminished as the background vegetation and water warmed during the course of the day. We feel that one of the most important next steps in UAV-thermal camera research is to directly measure temperature and humidity at the surface of wetlands during the time of observation to diagnose effects on detection probability. Some previous studies have encountered similar issues of detectability. For example, Kays et al. (2019) used a thermal camera and UAV to survey primates and noted

Table 6. Model selection results for Huggins closed-capture models of duck brood detection in Minnesota, USA in 2018. Time is a factor variable with 2 levels (AM and PM).

Model	AIC*c*	ΔAIC	Weight	Parameters
Method + Time + Visibility	880.71	0.00	0.39	5
Method + Time	881.30	0.59	0.29	4
Method + Time + Age	882.99	2.28	0.12	5
Method + Time + Brood Size	883.14	2.42	0.12	5
Method + Visibility	886.05	5.34	0.03	3

that detection rates of primates were much higher in the morning when the primates were 3° C warmer than the surrounding vegetation, and detection probability declined with increasing ambient temperature. Similarly, Israel (2011) used a UAV and thermal camera to search for roe deer (*Capreolus capreolus*) fawns before grassland mowing operations, and found that higher temperature and humidity increased the rate of false positives. Even under optimal environmental conditions, we undoubtedly missed some broods that were obscured by very dense vegetation that blocked their thermal signatures. Thick cover has also limited detection rates of wild primates including chimpanzees (*Pan troglodytes*), mantled howler monkeys (*Alouatta palliata*), black-handed spider monkeys (*Ateles geoffroyi*), and kinkajous (*Potos flavus*; Van Andel et al. 2015, Kays et al. 2019).

Although our detection probabilities with the UAV were lower than expected, they were still twice that of the ground crews. One of the fundamental assumptions for dual-observer ground surveys is that all broods are available for detection during each survey (Pagano and Arnold 2009). However, our flights with the UAV and thermal camera show that ground surveys can miss >80% of all broods on a particular quarter-section. As a result, traditional surveys have almost certainly underestimated the number of broods present, even after statistically correcting for detection probability, which would result in an underestimate of duck productivity.

Cowardin and Blohm (1992) noted that broods are so difficult to detect from the ground that attempts to use pair:brood ratios to infer duck productivity should be interpreted with caution. Our results underscore that point, and suggest that UAVs and thermal cameras could be a path forward for biologists and managers interested in estimating duck production at landscape scales. In fact, the thermal camera seemed so effective at locating ducklings we suggest that additional research is needed to determine why detection probabilities remained ~50%. Additional visits to a wetland (Pagano and Arnold 2009, Walker et al. 2013) and longer-term observation (Ringelman and Flake 1980) with the UAV system and marked broods (Stafford and Pearse 2007) would help diagnose how effective broods are at hiding from the thermal camera, and how frequently they move between wetlands.

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