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Applications of Unmanned Aerial Vehicles for Conducting Mesocarnivore and Breeding Waterfowl Surveys in Southern Manitoba

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APPLICATIONS OF UNMANNED AERIAL VEHICLES AND THERMAL IMAGING CAMERAS FOR CONDUCTING MESOCARNIVORE AND BREEDING WATERFOWL SURVEYS IN SOUTHERN MANITOBA

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Abstract

Unmanned aerial vehicles (UAVs) are becoming an increasingly important tool for wildlife surveys and equipping UAVs with thermal imaging cameras could make these surveys even more effective. In my thesis I examined the feasibility of using a UAV equipped with a thermal imaging camera to conduct mesocarnivore surveys, search for duck nests built over water, and conduct duck brood surveys in southern Manitoba.

For my first objective, I conducted nighttime mesocarnivore surveys with the UAV and thermal camera. I used a modified point-count survey from six waypoints and surveyed 29.5 ha in each replicate. I conducted a total of 200 flights over 53 survey nights during which I detected 32 mesocarnivores of eight different species. The UAV and thermal camera were effective at locating mesocarnivores, however given the large home ranges of mesocarnivores, my surveys should be considered estimates of minimum abundance and not a population census.

For my second objective I conducted a two-part survey: 1) I evaluated the effectiveness of a UAV and thermal camera to locate duck nests relative to traditional surveys, and 2) tested the hypothesis that technician visits to nests may influence predation rates. Over the course of my 1st study the UAV located a total of 47 nests that were not located by technicians, however, the technicians located 164 nests missed by the UAV, and both survey methods located 71 of the same nests. There was also no difference in survival rates for nests monitored with the UAV versus those monitored by technicians. Though the UAV completed surveys faster than technicians, the usefulness of this technology was limited, because the UAV has a relatively low detection rates.

My third objective was to evaluate the efficacy of using a UAV and thermal camera to conduct brood surveys. In 2018 and 2019, the UAV and thermal camera located a total of 1569 broods, compared to 666 located by ground technicians, and had higher detection rates (0.48 vs. 0.20). The UAV reliably located twice as many broods as ground technicians and completed surveys four times faster, indicating this technology has great utility for waterfowl biologists.

Chapter 1. General Introduction

Unmanned aerial vehicles (hereafter, UAVs) are rapidly transforming spatial ecological research (Anderson and Gaston 2013) by reducing costs and increasing the effectiveness of wildlife surveys (Koh and Wich 2012). UAVs are currently being used by biologists to survey large flocks of birds (Chabot and Bird 2012), search for African elephant (*Loxodonta africana*) poachers (Bergenas et al. 2013), and monitor large marine mammals (Hodgson et al. 2013). They have been used to search for nests of several species including American alligators (*Alligator mississippiensis*), Black-headed Gulls (*Chroicocephalus ridibundus*), and Chimpanzee (*Pan troglodytes*) nests in treetop canopy cover. UAVs have also been used extensively in the study of marine mammals including the families of Pinnipeds, Trichechidaes, and Delphinidaes (Flamm et al. 2000, Nilssen et al. 2014, Koski et al. 2015) and have higher detection rates and increased efficiency. In addition, UAVs have also shown promise in their ability to obtain morphological measurements of mammals in the field (Seymour et al. 2017). Equipping UAVs with cameras that sense beyond the range of the visual light spectrum may further increase the utility of UAVs for conducting wildlife surveys.

Recent miniaturization of thermal cameras has allowed these cameras to be attached to UAVs for a variety of purposes. UAVs and thermal cameras are currently being used to monitor wildfires (Ambrosia et al. 2003), conduct search and rescue operations (Rudol and Doherty 2008a) and conduct wildlife surveys (Haschberger 1996, Christiansen et al. 2014, Ward et al. 2016). Gonzalez et al. (2016) located koalas (*Phascolarctos cinereus*) loafing in trees, and they were able to locate every known koala with the UAV. Witczuk et al. (2018) showed that UAVs and thermal imaging cameras can be effectively be used to survey for large ungulates including red deer (*Cervus elaphus*) and wild boar (*Sus scrofa*) in a variety of habitats. UAVs equipped with thermal cameras are also becoming an increasingly useful tool for locating black rhinoceros (*Diceros bicornis*) poachers in Africa (Mulero-Pázmány et al. 2014). UAVs equipped with thermal imaging cameras can be used to detect bird nests, as Scholten et al. (2019) used a UAV equipped with a thermal camera to search for Field Sparrow (*Spizella pusilla*) nests and showed that the UAV located the same number of nests as traditional search methods but was able to do it 28% faster.

My thesis focuses on the application of a UAV equipped with a thermal imaging camera to conduct mesocarnivore and breeding duck surveys in southern Manitoba. In the first chapter, I used the UAV to locate small- to medium-sized nocturnal mesocarnivores. In Chapters 2 and 3 I used UAVs and thermal cameras to conduct two breeding duck surveys: nest searching and brood surveys.

Chapter 2. Applications of Unmanned Aerial Vehicles to Survey Mesocarnivores

2.1. Introduction

With the widespread extirpation of apex predators from most modern landscapes, mesocarnivores (carnivores with a body weight <15 kg) such as coyotes (*Canis latrans*) play an increasingly important role in mediating predator-prey interactions and structuring terrestrial food web (Crooks and Soulé 1999, Terborgh et al. 1999, Laliberte and Ripple 2004). Mesocarnivores have been shown to play a larger role in influencing biological communities than their population size would indicate (Gompper et al. 2006, Ray et al. 2013), most clearly observed when mesocarnivores are introduced onto islands, which can have severe detrimental impacts on native species (Nordström and Korpimäki 2004). On the other hand, mesocarnivores can provide beneficial ecosystem services in some contexts, such as carcass removal and crop pest control (Ćirović et al. 2016). Given their relatively high trophic position in many ecosystems, it is important to be able to accurately estimate the population size and densities of these mesocarnivores, which has historically proven to be frustratingly difficult.

Mesocarnivores are typically territorial, have large area requirements that vary by geography, habitat, and season, and so tend to occur at low population densities (Long et al. 2007). Moreover, mesocarnivores are mostly nocturnal and in natural environments are wary of humans, though they do make use of human structures (e.g., roads for travel, barns for denning) (Long et al. 2007). Traditional survey methods for mesocarnivores include camera traps, track

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plates, snow tracking, and hair snares (Barrett 1983, Gompper et al. 2006, Long et al. 2007, Hamel et al. 2013). Baited camera traps have proven successful for certain species such as raccoons (*Procyon lotor*), however, other species such as the coyote have been shown to avoid the cameras (Gompper et al. 2006, O'Connell Jr et al. 2006). Camera traps also tend to miss smaller species such as American mink (*Neovison vison*) and weasels (*Mustela* spp.) (Long et al. 2007). Track stations have proven to be useful in certain situations (O'Neil and Swanson 2010), but their effectiveness can depend on the weather: in one study 65% of exposed track plates were rendered useless by heavy rains (Foresman and Pearson 1998). Snow tracking can be effective in locating wary species (e.g., coyote), but snow tracking requires good snow conditions, which may only be present in certain areas and for short periods of time (Foresman and Pearson 1998). In addition, snow tracking obviously only works in some geographies and with species which are active during the winter; species such as raccoons and striped skunks (*Mephitis mephitis*) will not be detected because they are hibernating (Long et al. 2007). Hair snares are often used as a noninvasive way to survey for mesocarnivores, but results have been mixed. Depue and Ben-David (2007), used hair snares to survey river otter (*Lontra canadensis*) population densities with great success, with over 90% of their snares detecting river otters. On the other hand, hair snares set to survey bobcat (*Lynx rufus*) and fisher (*Pekania pennanti*) populations in Vermont failed to detect a single animal, even though they were known to be in the area (Long et al. 2007). Acknowledging the importance of mesocarnivores as ecological drivers, there is a clear research need to develop more effective population survey methods for these animals.

Recent advances in Unmanned Aerial Vehicles (UAVs) may provide biologists with more accurate survey methods for a variety of vertebrate species. Already UAVs have been used for a variety of tasks, ranging from locating American alligator (*Alligator mississippiensis*) nests in Louisiana (Elsey and Trosclair 2016), preventing African elephant (*Loxodonta africana*) poaching in Kenya (Bergenas et al. 2013), to surveying large flocks of geese (Chabot and Bird 2012). One of the main uses of UAVs has been to obtain population estimates from a variety of colonial nesting birds. Chabot and Bird (2015) compared traditional ground surveys for nesting colonial birds with a UAV survey and found that the UAV was able to detect 91%–98% of the nests located by ground crews with minimal disturbance. Sarda-Palomera et al. (2012) evaluated the feasibility of using a UAV to conduct nesting surveys of black-headed gulls (*Chroicocephalus ridibundus*), and showed that nest counts differed from traditional ground surveys by as little as 0.8%–6.1%, while causing significantly less disturbance. Weissensteiner et al. (2015) used a UAV to study canopy-nesting birds, which are traditionally time-consuming and dangerous to study, and found that not only could they accurately determine number of fledglings and their age but could also do it in 15% of the time and with less disturbance.

UAVs have been used extensively in the study of marine mammals including the families of Pinnipeds, Trichechidaes, and Delphinidaes (Flamm et al. 2000, Nilssen et al. 2014, Koski et al. 2015). Hodgson et al. (2017), found that population surveys for large marine mammals, such as humpback whales (*Megaptera novaeangliae*) conducted with a UAV are more accurate than traditional survey techniques. In additional to counting it is also possible to accurately obtain morphological measurements, such as length and girth of leopard seals (*Hydrurga leptonyx*) (Krause et al. 2017). There is clearly utility in obtaining high-resolution aerial imagery of wildlife for a variety of purposes. Equipping cameras that sense beyond the range of the visual light spectrum may further increase the utility of UAVs for conducting wildlife surveys.

Thermal imaging technology has been used by biologists for years to study everything from honey bee (*Apis* spp.) behavior (Kastberger and Stachl 2003), to surveying population sizes of large mammals such as white-tailed deer (*Odocoileus virginianus*) (Collier et al. 2007). Miniaturization of thermal imaging cameras has allowed them to be attached to an UAV and used for everything from monitoring wildfires (Ambrosia et al. 2003), flying search and rescue missions (Rudol and Doherty 2008a), searching farm land for animals before mowing operations (Israel et al. 2010), and conducting wildlife surveys (Haschberger 1996, Christiansen et al. 2014, Ward et al. 2016). Witczuk et al. (2018) used UAVs and thermal cameras to survey for ungulates in forested habitats and were able to accurately and reliably detect large ungulate heat signatures, although they had difficulty identifying them to species. UAVs and thermal cameras have also been used to survey for large marine mammals such as grey seals (*Halichoerus grypus*) with nearly identical detection rates as field teams (Seymour et al. 2017).

To my knowledge, no study has attempted to use UAVs and thermal imaging cameras to survey for smaller mammalian predators. Here, I evaluated the ability of a UAV equipped with a thermal imaging camera to locate small- to medium-sized nocturnal mesocarnivores in southern Manitoba, Canada. The methods described here are part of a much larger ecological study evaluating how lethal removal of mesocarnivores affects duck nest success. Lethal removal of nest predators has been shown to increase nest survival of upland-nesting ducks (Garrettson and Rohwer 2001) but it is unclear whether managing mesocarnivores also benefits overwater-nesting diving ducks. Despite the fact that mesocarnivore removal is a common management practice for improving duck nest survival (Amundson et al. 2013), evaluating predator populations before and after removal has heretofore been logistically impractical, creating the impetus for our work with the UAV and thermal camera. My objective in this chapter is to describe equipment and methods that were successful in detecting mesocarnivores in prairie landscapes.

2.2. Study Area

My study area consisted of four 12.9 km^2 study blocks located near the town of Minnedosa, Manitoba in the prairie pothole region of Canada (50.20°N 99.77°W); each block was separated by at least 1.6 km. My study was conducted primarily on private land consisting of cereal grains, mainly canola (*Brassica napus*) and spring wheat (*Triticum aestivum*). The remaining areas were either actively grazed pasture land or native grasslands, described in detail by (Kiel et al. 1972). Vegetation height and density varied greatly among survey sites and between survey rounds. On two of my study blocks (Elphinstone and Minnedosa), professional trappers were hired to lethally remove mesocarnivores, in conjunction with an ongoing (2015–present) experimental study examining how the removal of mesocarnivores affects the nesting success of diving ducks. The remaining two study blocks (Odanah and Raven Lake) were (untrapped) control blocks and each block was further broken into 25 study plots. Flight restrictions put in place by Transport Canada limited my horizontal flight distance to 500 m and so combined with logistical constraints on land access and launch protocols, I limited my surveys to 30 ha per study plot.

2.3. Equipment

I used a battery-powered DJI Inspire 1 quadcopter UAV (3.1-kg weight, 570 mm wingspan), powered by a 22.2 V lithium ion battery, allowing me a flight time of ~15 minutes. I used a portable battery charger and generator to charge up to 12 batteries in the field, thereby allowing me to operate continuously until I had completed my surveys. The UAV was equipped with a DJI Zenmuse XT2 R thermal imaging camera (640 × 512 resolution; 19 mm lens; 30 Hz) to detect thermal radiation given off by mesocarnivores. The amount of radiation emitted is dependent on both the temperature of the object and emissivity, which is a measure of the reflectivity of an object. The image generated by the thermal camera is therefore not a depiction of the absolute temperature or infrared radiation of an organism, but a combination of the targets' radiation, emissivity and environmental factors such as humidity and cloud cover, and (critically) the temperature of the background against which the animal is observed.

2.4. Methods

Using ArcGIS 10.3 and the DJI Ground Station Pro v 2.1 iPad application I designed a point count survey which allowed me to cover the entire study area systematically, and to take advantage of easily-programmable flight routes and autopilot flight options. Although it should be possible to use trigonometry to titrate the camera field-of-view at different tilt angles and optimize sample point spacing, I encountered issues with both the rectangular image on the screen (x and y dimensions not equal) and some fisheye distortion near the edge. I concluded that empirical tests would be more reliable than math in this case, and so I conducted simple field trials using a warm (23 °C) plastic water bottle. I began with the UAV at a height of 75 m above ground level with the camera pointed straight down. I placed the bottle at the edge of the camera's field of view, and then tilted the camera toward the horizon until the bottle was on the opposite edge of the camera view. I repeated this procedure until the water bottle was no longer detectable with the thermal camera: a ground-line distance of 300 m. On a separate occasion, I evaluated detection probability using a medium-sized (15 kg) domestic dog (*Canis lupus familiaris*) as a convenient proxy for a wild mesocarnivore. The dog was placed at varying distances from the UAV pilot (me; up to 300 m). Without foreknowledge of the dog's location, I was able to locate it with 100% reliability from 75 m above the ground, allowing me to be reasonably confident that I could locate mesocarnivores from this height and ground-line distance. Preliminary testing was conducted in early evening under conditions of low humidity, ~12 °C air temperature, low grass cover, but after the ground had experienced a full period of daytime heating.

Given my maximum detection range of 300 m, I chose 125 m as a highly conservative value at which detectability of mesocarnivores would approach 100% under the full range of field conditions where drone flight would be possible. Using 125 m as the radius, I designed a point count survey with points approximately 250 m apart. Using ArcGIS and DJI's Ground Station Pro app I determined that 6 points spaced 250 m apart would allow me to cover 29.5 ha of each survey plot (Figure 2.1). I programmed the UAV to fly to each point, whereupon I stopped and rotated the drone 360 degrees three times, adjusting the camera angle on each rotation (as per our testing) to sweep out ever-larger observational arcs (Figure 2.2). While flying at these heights I could readily detect the heat sources given off by mesocarnivores and much smaller animals. For example, during my first survey I was easily able to detect mice (*Mus* spp.) running through the vegetation from a height of 75 m, and so I was highly confident that my detection probability for mesocarnivores approached 100%, given they were present and aboveground during the survey. However, I could not always determine the species identity of every heat source at these heights and dropped to elevations of 15 m–40 m to confirm species identity. I captured both videos and still photos of every mesocarnivore and these were reviewed later to facilitate identification to species.

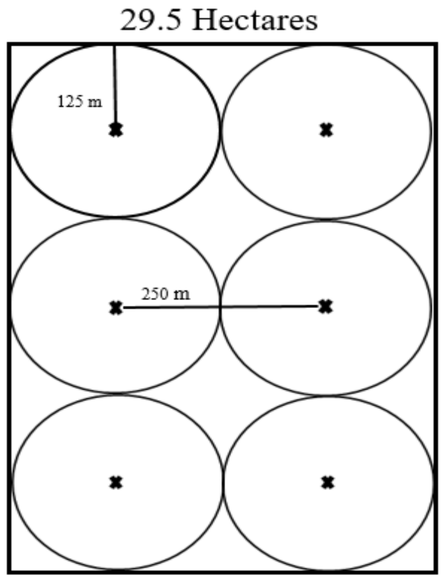

Figure 2.1. Point count survey designed for an unmanned aerial vehicle (UAV) to fly at a height of 75 m. From each of the 6 point-count locations the UAV was able to survey 4.9 ha for a total of at least 29.5 ha.

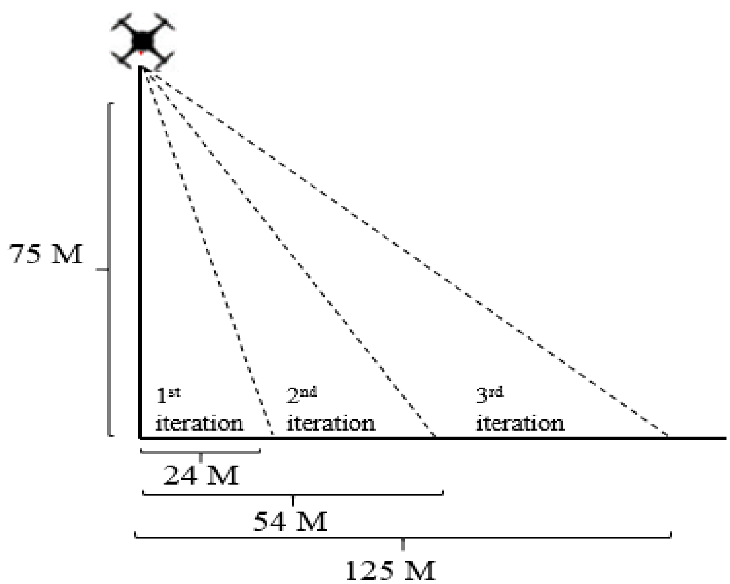

Figure 2.2. At each point count location, we conducted surveys with the unmanned aerial vehicle (UAV) in broadening observational arcs. We began by pointing the camera 90° straight down, and then tilting the camera towards the horizon twice, each time rotating the UAV 360°. We restricted our sampling to 125 m, but 300 m was our maximum detection distance of a heat source approximating a mesocarnivore.

I conducted two rounds of mesocarnivore surveys that corresponded with the predator removal experiment at my site: the first round spanned 25 April–3 June 2017 (before trapping), and the second spanned 16 July–28 July 2017 (after trapping). All surveys were conducted at least 30 min after sunset to maximize mesocarnivore detection (Urban 1970). Surveys were not conducted during inclement weather (precipitation, winds in excess of 32 km/h), and per our Transport Canada Special Flight Operations Certificate (SFOC) permits I was also not permitted to operate the UAV if the cloud cover was below 305 m. All work was conducted by a licensed UAV pilot operating under the SFOC permit 5812-17-132. Data are presented as means ± standard error unless otherwise noted.

2.5. Results

I conducted a total of 200 surveys using my point count survey method. Each mesocarnivore survey lasted 19.8 ± 6.0 min, and I was able to conduct 10.0 ± 4.5 surveys each night. The first round of sampling (25 April–3 June) took longer than expected—40 survey nights—due to inclement weather (winds in excess of 32 km/h and rain) that made flying the UAV impossible. I detected a total of 17 individual mesocarnivores during the first round of sampling including red foxes (*Vulpes vulpes*), coyotes, and striped skunks: four of these I located on trapped sites, and 13 on control sites (Table 1.1). I experienced fewer weather delays during the second round of sampling and completed surveying over the course of 13 nights (15 July–28 July). During the second round I located a total of 15 mesocarnivores: six on trapped blocks, and nine on control blocks (Table 2.1). I needed to briefly drop to heights of 15 m to definitively identify mesocarnivores to species (Figure 1.2a–d). In addition to mesocarnivores, I also located several other species including white-tailed deer, moose (*Alces alces*), American porcupines (*Erethizon dorsatum*), and several species of the Leporidae family and the Rodentia order.

Table 2.1. Mesocarnivores detected at each study site across two sampling periods. Round one was conducted from 23 April–3 June and total of 90 surveys were conducted. Round two was conducted from 15–23 July and a total of 100 surveys were conducted.

Round 1					
	Trapped		Control		Total
	Elphinstone	Minnedosa	Odanah	Raven Lake	
American badger	0	1	2	0	3
Coyote	0	0	3	1	4
Red fox	2	0	1	3	6
Striped skunk	0	1	1	2	4
Total	2	2	7	6	17
Round 2					
	Trapped		Control		Total
	Elphinstone	Minnedosa	Odanah	Raven Lake	
coyote	0	1	0	1	2
red fox	1	0	3	3	7
striped skunk	0	1	0	1	2
American mink	1	0	0	0	1
raccoon	0	0	1	0	1
weasel	0	1	0	0	1
feral cat	1	0	0	0	1
Total	3	3	4	5	15

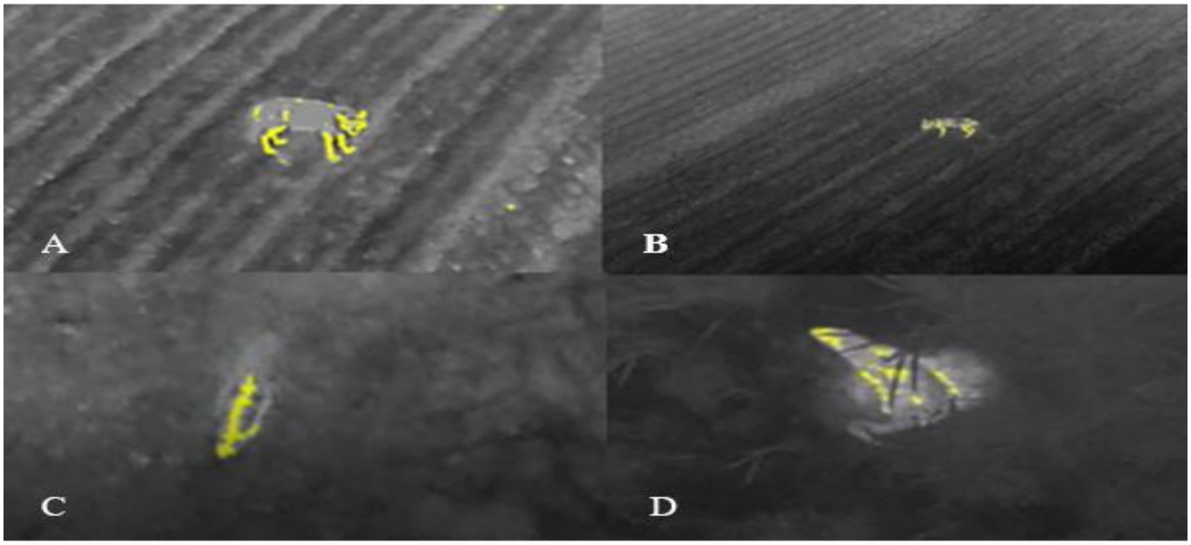

Figure 2.2. At each point count location, we conducted surveys with the unmanned aerial vehicle (UAV) in broadening observational arcs. We began by pointing the camera 90° straight down, and then tilting the camera towards the horizon twice, each time rotating the UAV 360°. We restricted our sampling to 125 m, but 300 m was our maximum detection distance of a heat source approximating a mesocarnivore.

While surveying for mesocarnivores I also qualitatively noted any disturbance caused by the UAV. While flying at the point count survey height of 75 m, mesocarnivores did not measurably respond to the UAV. The only exception were several red foxes that were already in full flight when I was flying to my first survey point. I suspect that these animals were actually fleeing from my noisy and well-lit arrival in a truck. Cattle adjacent to our study plots reacted negatively to the UAV, and often fled to the other side of the field as soon as the UAV was airborne, henceforth, I avoided flying over cattle. When I dropped to lower elevations to identify mesocarnivores, reactions ranged from no visible reaction to running away.

2.6. Discussion

Extensive surveying and testing under various conditions gave me confidence that I was able to reliably detect mesocarnivore-sized animals if they were present on our study sites, as I was often able to locate mice and small birds. It is generally assumed that there are several problems with aerial surveys including double-counting, perception error, and misidentification (Brack et al. 2018). As mesocarnivores are territorial and home ranges are large on the prairies, I only counted >1 mesocarnivore per survey on four occasions: twice I observed different species and twice I captured both animals in view simultaneously, and so I am confident that I did not double-count animals within a survey. However, I acknowledge the possibility of double-counting animals across the two survey periods; without individually marking animals this issue is difficult to overcome. Dropping the UAV to elevations lower than 75 m with the express purpose of identifying mesocarnivores to species, gave me confidence that species identity was resolvable for all animals. The only perception error that seems plausible is unusually low detectability of raccoons. I only located one raccoon over the course of 200 surveys, even though I know (from trapping data and camera traps placed at duck nests) that raccoons were common throughout the landscape. This could be attributed to several factors, including the fact that raccoons tend to prefer wetland habitats, and so may be less visible due to wet fur and heavy vegetative cover. Additionally, water has a very high emissivity, which has the potential to interfere with detection of animals with the thermal imaging camera.

UAV surveys were relatively efficient at detecting mesocarnivores: during ~66 hours of flight time, I detected 32 mesocarnivores (latency of ~2 hours between detections). For perspective, mesocarnivore camera trapping studies conducted over many trap-nights often have latencies ~30 hours (Jordan et al. 2011). My data represent a sample of the mesocarnivore community at each site. Given the large home ranges of many of these mesocarnivores and variable nocturnal activity schedules, my counts of mesocarnivores represent a minimum abundance. More to the point, while I am confident I detected mesocarnivores (except possibly raccoons) if they were present and aboveground during our survey, given the brevity of our survey (20 min) and the large home ranges of mesocarnivores, it is likely that I did not detect all animals that do in fact use the sites we sampled. To estimate populations, I suggest future researcher consider frequent repeat surveys. Even though animals are not individually marked, with new statistical models it may be possible to use this sampling strategy to estimate mesocarnivore occupancy and abundance (Carrlson et al. 2018).

My results suggest that UAVs equipped with thermal imaging cameras are a viable tool for monitoring mesocarnivores at scales up to 30 ha. As I often needed to hover above animals and drop elevation to identify them to species, I recommend rotor-based UAV platforms (as opposed to fixed-wing) for these type of mammal surveys. The primary constraint that limits expansion to larger survey areas is permitting restrictions, which vary across federal and local governments. Flight time is limited by batteries, but in the one year since this study was conducted, operational flight time for similar quadcopter UAVs has increased to ~25 minutes per battery. The area sampled by the methods described here is small compared to the home ranges of most mesocarnivores, but detection probability would increase with repeated surveys flown at different times of night. Unmanned Aerial Vehicles are an increasingly common tool for remotely monitoring wildlife populations, and our results demonstrate the utility of combining aerial surveys with thermal imaging cameras to survey animal species that are otherwise difficult to observe.

Chapter 3. Applications of Unmanned Aerial Vehicles and Thermal Imaging Cameras to Locate and Monitor Overwater Duck Nests

3.1. Introduction

Annual recruitment is the driving force behind avian population dynamics (Martin and Geupel 1993). This is especially true in ducks where annual recruitment—especially nest success—has been shown to be a primary determinant of Mallard (*Anas platyrhynchos*) populations (Cowardin et al. 1985). Accurate estimates of recruitment and population trajectories are especially important for ducks, which are some of the most sought after game animals in North America (Grado et al. 2011). There are several methods for estimating recruitment such as using breeding pair counts and brood surveys to estimate per capita production (Cowardin and Johnson 1979) however, searching for duck nests and monitoring hatch rates is more prevalent (Cowardin et al. 1985) because nest success is the main factor limiting annual recruitment for ducks (Klett et al. 1988, Arnold et al. 1993). Hence, nest monitoring studies have been a mainstay of waterfowl research for the last half century (Cowardin et al. 1985).

Waterfowl use nest sites ranging from upland habitats (dabbling ducks) to nests built up over the water with vegetation (diving ducks). Upland waterfowl nests can be systematically found using chains or ropes pulled between tractors, trucks, ATVs, or held by people (Higgins et al. 1969, Klett et al. 1986, Garrettson and Rohwer 2001, Nosal 2011), walking through potential nesting cover and beating it with sticks (Labisky 1957), using radio-telemetry to follow females to their nests (Thorn et al. 2005), observing the hens returning to the nests (Earl 1950), and using trained dogs to located nests (Keith 1961). There are comparatively fewer options for locating overwater nests; typically, field technicians wade through the emergent vegetation on the periphery of wetland and zigzag back and forth to either flush the hen or find the unattended nest by chance (Arnold et al. 1993, Anderson et al. 1997, Sorenson 1997). Both upland and in particular overwater nest searching methods are time consuming, expensive, and can be logistically challenging to complete (Klett and Johnson 1982). Moreover, searching techniques typically rely on disturbing the female from her nest, which can induce abandonment (Balat 1969, Reed 1975) and nest visitation may also increase the risk of nest predation (Hein and Hein 1996). Using Unmanned Aerial Vehicles (hereafter UAVs) equipped with thermal imaging cameras may provide biologists with a more efficient way to search for overwater nests, while also reducing predation rates by eliminating the need to locate nests on foot.

UAVs have been used to survey a wide variety of wildlife species ranging from canopy-nesting birds to elephants (Vermeulen et al. 2013, Weissensteiner et al. 2015). UAVs have been used to estimate population sizes of non-breeding waterfowl such as Snow Geese (*Anser caerulescens caerulescens*) and Canada Geese (*Branta canadensis*) where the UAV detected >60% more individuals then traditional ground surveys (Chabot and Bird 2012). Several studies have shown that UAVs are useful for counting colonial nesting birds; they cause less disturbance (Chabot et al. 2015, Sardà-Palomera et al. 2017) and have detection rates as high as 93-96%. In Europe, UAVs were used to survey waterfowl broods on boreal lakes, and they detected the same number of broods as technicians on foot and were able to more accurately count the number of ducklings in each brood (Poysa et al. 2018). Equipping UAVs with thermal imaging cameras could help increase detection rates of these wildlife surveys.

Handheld thermal imaging cameras have been used to study animals ranging from honey bees (*Apis* spp.) (Kastberger and Stachl 2003) to white-tailed deer (*Odocoileus virginianus*) (Collier et al. 2007). Recent miniaturization of thermal imaging cameras has allowed them to be attached 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 in the field (Haschberger 1996, Elsey and Trosclair 2016). For example, UAVs with thermal cameras have been used to locate Roe deer (*Capreolus capreolus*) fawns prior to mowing operations (Israel 2010). In Gabon, biologists used UAVs to locate Chimpanzee (*Pan troglodytes*) nests in rainforest treetops (Van Andel et al. 2015). In chapter 1, I used a UAV equipped with a thermal camera to survey mesocarnivores in southern Manitoba and successfully detected mesocarnivores under various environmental conditions in upland habitats.

UAVs equipped with thermal imaging cameras can also be used to detect bird nests. Scholten et al. (2019) used a UAV equipped with a thermal camera to search for Field Sparrow (*Spizella pusilla*) nests. They showed that the UAV located the same number of nests as traditional search methods but was able to do it 28% faster. UAVs and thermal imaging cameras have also been used to search for American Black Duck (*Anas rubripes*) nests in North Carolina (Roald Stander-personal communication), but had limited success due to high ambient humidity and thick vegetation. Regardless, clearly there is potential to locate avian nests, including ducks, with a UAV. Here I tested the feasibility of using a UAV equipped with a thermal imaging camera to locate and monitor overwater nesting ducks in southern Manitoba.

My objectives for this study were twofold: to test the ability of the UAV to locate duck nests compared to traditional ground searching techniques, and to test whether trails left by ground technicians visiting nests influenced nest survival. To accomplish my first objective, I searched for nests using the UAV and the following day ground technicians searched the same area, allowing us to compare searching techniques. My second objective was accomplished by locating and monitoring nests strictly using the UAV, and comparing those survival rates to nests monitored by the ground technicians.

3.2. Study Area

My study area consisted of four survey blocks within the Prairie Pothole Region of southern Manitoba. The four study blocks were selected based on aerial flights to determine areas with the highest wetland densities allowing us to maximize sample sizes of nests. Two of my study blocks were located near the town of Minnedosa, Manitoba (50.20° N 99.77° E) and two were farther west near the town of Shoal Lake, Manitoba (50.43° N 100.59° E). During my first study season in 2018, I surveyed the two blocks (Odanah and Minnedosa) near Minnedosa and they were 64.75 km^2 in size. In 2019, I included two more study blocks (Elphinstone and Raven Lake) near the town of Shoal Lake and all block sizes were cut in half to 23.30 km^2. In 2018 I randomly selected 24 survey sites (12 per study block) each 2.59 km^2 in size to conduct our nesting surveys, and in 2019 I randomly selected 72 survey sites (18 per study block) 2.59 km^2 in size.

The area around Minnedosa is characterized by a diversity of wetlands including large permanent wetlands, and smaller semi-permanent and seasonal wetlands (Trauger and Serie 1974, Stoudt 1982). These wetlands generally contain a 10–30 m edge of peripheral cattails (*Typha* spp.) and Hardstem Bullrush (*Schoenoplectus acutus*) (Arnold et al. 1993). Surrounding upland areas consisted primarily of private land farmed for cereal grains, predominately canola (*Brassica napus*) and spring wheat (*Triticum aestivum*). The remaining areas were either actively-grazed pasture land or native grasslands, described in detail by (Kiel et al.1972). The breeding duck community includes diving ducks such as Canvasbacks (*Aythya valisineria*), Redheads (*Aythya americana*), Ruddy Ducks (*Oxyura jamaicensis*) Ring-necked Ducks (*Aythya collaris*) and Lesser Scaup (*Aythya affinis*) (Klett et al. 1988, Anderson et al. 2001).

3.3. Equipment

I used a battery-powered DJI Matrice 210 quadcopter UAV (6.4-kg weight, 716 x 220 x 236 mm dimensions), powered by dual 22.8 V lithium pro ion batteries which allowed a flight time of ~20 minutes. A portable battery charger and generator were used to charge up to 12 batteries in the field, thereby allowing me to operate continuously until I had completed my surveys. Each UAV was equipped with two cameras and I was able dynamically switch between views. The first was a DJI Zenmuse XT thermal imaging camera (640 x 512 resolution; 19 mm lens; 30 Hz) used to detect thermal radiation given off by nests and/or incubating hens. The amount of radiation emitted is dependent on both the temperature of the object and emissivity, which is a measure of the reflectivity of an object. The image generated by the thermal camera is therefore not a depiction of the absolute temperature or infrared radiation of an organism, but a combination of the targets' radiation, emissivity, environmental factors such as humidity and cloud cover, and the temperature of the background against which the animal is observed. The second camera, a Zenmuse X4S optical camera (5472 x 3648 resolution, 8.8 mm lens), was used to identify the species of each nest located.

3.4. Methods

I timed our seasonal nest searching based on the nesting chronology of Canvasbacks, which are one of the earliest nesting ducks in our study area (Anderson et al. 1997). Following guidelines laid out by Vas et al. (2015), I launched the UAV >100 meters from any wetland to avoid disturbance to the nesting birds. From there, I flew the UAV at a height of 31 m to search for nests, which was high enough to locate duck nests while eliminating some false heat signatures like Muskrat (*Ondatra zibethicus*) loafing pads. At each wetland I searched all emergent vegetation for nests: on smaller ponds I simply flew a circle around the edge of the wetland, but for larger wetlands, it was necessary to fly transects to ensure that the entire wetland was searched. Once a potential nest was located with the thermal camera (Image 3.1), I switched to the optical camera (Image 3.2) and dropped to lower elevations (~5 m). At these altitudes it was possible to distinguish duck nests from other heat signatures like American Coot (*Fulica americana*) or Pied-billed Grebe (*Podilymbus podiceps*) nests. Nest searching with the drone began at sunrise and continued until humidity and temperature reached a point where they interfered with the thermal camera.

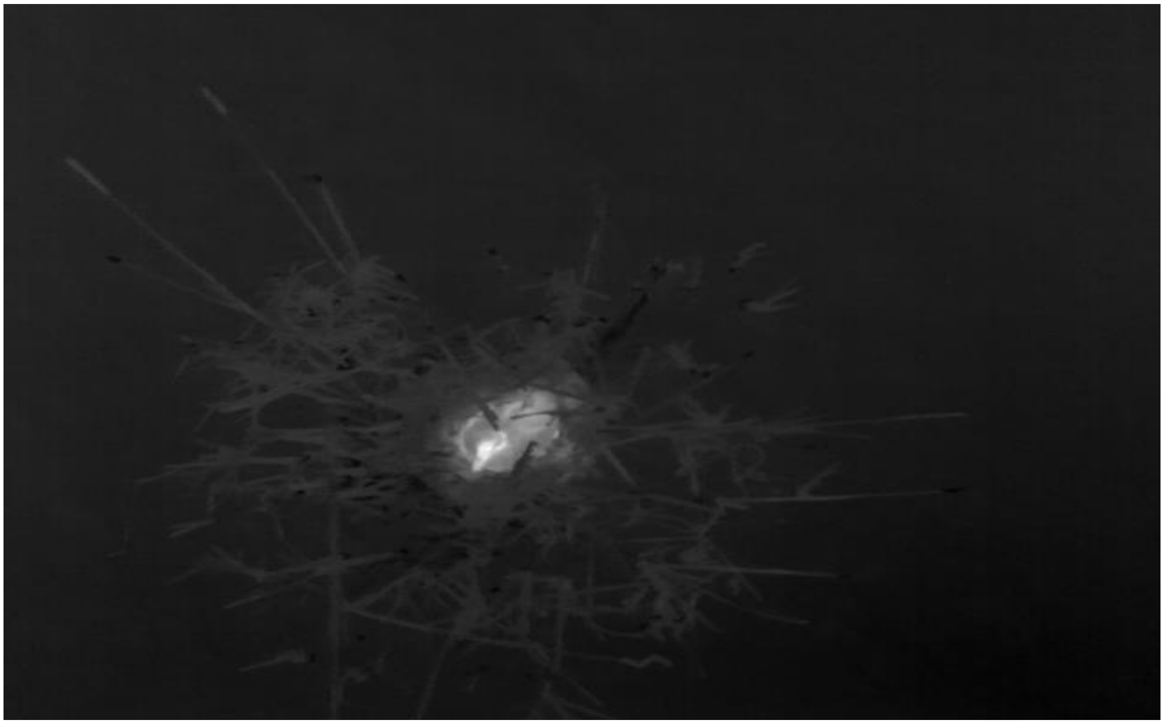

Image 3.1. Thermal image of a Canvasback nest taken with the UAV at a height of ~8m.

Image 3.2. Visual camera image of the same Canvasback from Image 1 taken at a height of ~5m.

Objective 1. Detection rates of the UAV and ground technicians

My first objective was to compare nest detectability using a UAV versus traditional ground surveys. In 2018, I searched 12 randomly selected sites on each block beginning on the 21st of May and ending on the 30th of June. During the 2019 season I searched 9 sites per study block, starting on the 15th of May and concluding on the 30th of June. I always searched a site with the UAV before searching with ground crews occurred, because it was possible to detect and follow trails with the UAV that were left by the technicians during their nest searches. The day after UAV searched a site, ground observers searched for nests by wading through emergent vegetation, zigzagging from the dry edge to open water, attempting to flush hens and locate nests (Strang 1980). Once a nest was located they recorded the species, number of eggs at the time it was located, incubation stages, and canopy cover estimate. If the UAV had located nests the day before that were missed by the ground observers, ground teams would be informed after their search was complete, and would visit those nests to gather data. Ground observers started searching at sunrise and searched for six hours each day, and then conducted nest checks after concluding nest searching.

I calculated the probability of detecting nests using Huggins closed capture models (Huggins 1989;1991) in program MARK (White and Burnham 1999). Each nest was treated as an individual unit within the analysis and I assumed that detection probability was equal between sites. Each nest was potentially observable twice: once by the UAV, and once by the ground technicians. Therefore, we created a 2-encounter history for each nest where survey method was embedded in the coding of the data. For example, a nest that was located by both survey methods would have an encounter history of 11, compared to a nest that was located only by the ground technicians which would have an encounter history of 01 (because the UAV always surveyed first). To test my primary objective, I evaluated detection probability based on survey method. However, I also examined how nest detectability of nests found with the drone varied by species, cover, incubation stage, and clutch size at the time the nest was located. To increase sample size, we combined years. I ranked models using Akaike's Information Criteria corrected for small sample size.

Objective 2. Effects of ground technician trails on nest survival

It is possible that trails and cues left by ground technicians as they locate and monitor nests may act as cues or corridors for predators (Picozzi 1975, Hein and Hein 1996), which would lead to biased estimates of predation rates, relative to nests not monitored by researchers. To test this, in 2018 I randomly selected 24 sites on our Minnedosa and Odanah blocks to survey with the UAV. Once I located a potential nest with the thermal camera, I switched to the regular camera to identify the nest to species. I monitored active nests every 6-7 days with the UAV until the nest was terminated (hatched, abandoned, or depredated). I considered a nest to be terminated if no heat signature was detected, and was also undetected again on the next day to rule out the possibility the hen was on an incubation break. After nest termination I visited the nest on foot to determine its fate. In 2019, I increased my sample size (36 total sites on 4 blocks) and protocols differed slightly: in 2019 I visited each nest once on foot upon initial discovery, to gather data on incubation stage, number of eggs, and nest parasitism. My judgment was that the additional information gained outweighed the chance of creating a trail to the nest; trails only become prominent after repeated visits by technicians.

I conducted our nest survival analysis in Program MARK (White and Burnham 1999) accessed through the RMark package (Laake 2013) and evaluated daily survival rate (DSR) as a function of each covariate (see below) (Dinsmore et al. 2002). I combined data from nests monitored by the UAV with data collected by ground technicians (see Objective 1) to directly compare survival rates of nests monitored with the two techniques. I combined years and modeled DSR as a function of monitoring method, and other factors known to influence nest survival, such as species, the incubation stage when found, and nest initiation date (Ringelman et al. 2018). When a nest is fated (hatched, depredated, or abandoned), MARK estimates the termination date as the midpoint between the last time a hen was present and the last time the nest was checked. While this works for depredated nests where the true fate date is unknown, it is not so with waterfowl since the hatch date is estimable based on candling eggs in the field. I estimated the hatch data for successful nests based on the last incubation stage (Klett et al. 1986) and set this as our date for both last present and last checked to avoid miscalculating exposure days. However, I was only able to do this with nest data collected in 2019 because I lacked the necessary data (i.e., age when found and initiation date) from 2018 because nests were not visited until after nest fate. Thus, models that use nest age and initiation date were constructed using data from 2019 only. I used both years to evaluate the effects of monitoring method on nest survival. Candidate models were ranked our models using AICc scores to evaluate model fit.

3.5. Results

Detection rates of the UAV and ground technicians

During two years of searching my team found a total of 283 nests of five different species: Canvasbacks, Redheads, Ruddy Ducks, Ring-necked Ducks, Lesser Scaup, and Mallards (*Anas platyrhynchos*). I located 48 nests with the UAV that were not located by crews on foot. In contrast, the ground crews located a total of 164 nests on foot that were never located by a UAV, and 71 nests were located by both methods.

The simplest model I constructed evaluated the nest detection probability of the UAV versus the ground technicians. The UAV had a nest detection rate of 33% compared to a 71% detection rate achieved by ground technicians (Table 3.1). When I evaluated which factors might influence nest detectability with the UAV, I found that the top fitting model included the species of the nest which was located (Table 3.2). The UAV had the highest rate of detection for Canvasbacks and the lowest for Ring-necked ducks and Lesser Scaup (Table 3.3). Surprisingly, overhead cover was not a competitive model in our analysis, as we hypothesized that less overhead cover would lead to higher detection rates, although it was not a competitive model in our analysis. Although the UAV had a much lower detection rate for nests than technicians searching on foot surveys were much faster, taking an average of 45 minutes to survey a quarter section compared to 3 hours by a ground technician.

Table 3.1. Detection estimates for nests by both the ground technicians and the UAV, using 2018 and 2019 data.

Method	Detection Estimate	Standard Error	Lower 95% CI	Upper 95% CI
UAV	0.3363	0.0316	0.2773	0.4009
Technicians	0.7075	0.0442	0.6142	0.7862

Table 3.2. Best fitting models for nest detectability using 2018 and 2019 nesting data.

Model	AICc	ΔAIC	Weight	Parameters
Method+Species	456.14	0.00	0.98	11
Method+Cover	467.96	11.82	0.02	3
Method+Clutch size	471.70	15.56	0.00	3
Method+Incubation stage	475.88	19.74	0.00	3
Method	477.28	21.15	0.00	2

Table 3.3. Detection probability for nests of each species located by the UAV.

Parameter	Detection Estimate	Standard Error	Lower 95% CI	Upper 95% CI
Canvasback	0.5493	0.0590	0.4330	0.66604
Lesser Scaup	0.1333	0.0877	0.0335	0.4053
Mallard	0.2702	0.0730	0.1520	0.4334
Redhead	0.2391	0.0628	0.1377	0.3823
Ring-necked duck	0.0434	0.0425	0.0060	0.2522
Ruddy duck	0.3870	0.0874	0.2346	0.5654

Effects of ground technician trails on nest survival

I included 401 nests found during the 2018–2019 nesting seasons in the nest survival analysis, 117 of which were monitored only with the UAV. A total of 283 nests were monitored by ground technicians, but 43 nests were censored due to incomplete data. I included 357 nests in my survival analysis: Canvasbacks (n=136), Redheads (n=77) and Mallards (n=54) accounted for 75% of our sample size. Other species included Ruddy Ducks (n=44), Ring-necked Ducks (n=27), and Lesser Scaup (n=19). I also located one Northern Shoveler (*Spatula clypeata*) that was not included in the analysis.

The simplest model for nest survival showed that there was no significant difference between nests monitored by the UAV and nests monitored on foot (Table 3.4). The best-fitting model of nest survival included only the age of the nest when found, but a model that also included nest initiation date was competitive (Table 3.5). Parameter estimates indicated that nests that are older when they are found, and those that are initiated earlier in the year are more likely to hatch (Figures 3.1 and 3.2). Models that included species were not competitive; however, both Mallard and Ring-necked duck nests had lower and more variable daily survival rates (Table 3.6).

Table 3.4. Comparison of survival rates between nests monitored with the UAV and on foot.

Parameter	Daily Survival Rates	Standard Error	Upper 95% CI	Lower 95% CI
UAV	0.9534	0.0054	0.9414	0.9630
Technician	0.9542	0.0038	0.9461	0.9612

Table 3.5. Best fitting models for nest survival.

Parameters	AICc	ΔAIC	Weight
Age found	495.8	0.00	0.499
Age found Initiation date	496.7	0.84	0.327
Initiation date	498.6	2.71	0.129
Survey block	502.5	6.71	0.017
Cover	504.0	8.16	0.008
Treatment	504.1	8.24	0.008
Survey method	504.3	8.51	0.007
Survey method Cover	505.9	10.08	0.003
Species	509.9	14.05	0.000
Cover Species	510.8	14.99	0.00

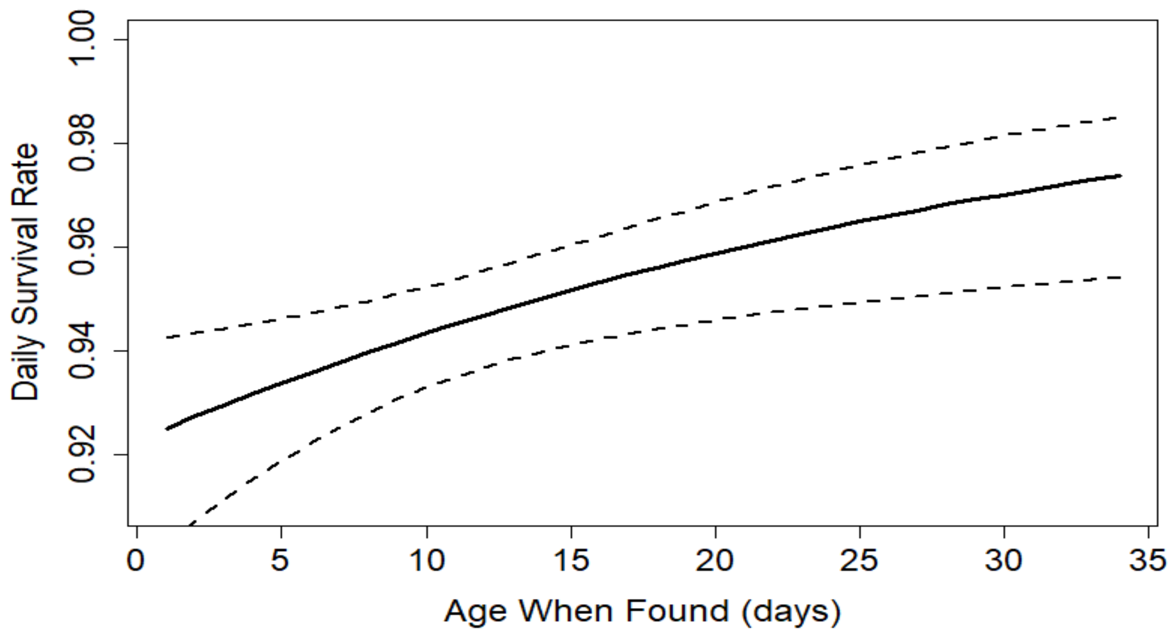

Figure 3.1. Daily survival rates as a function of the age of the nest when it was found.

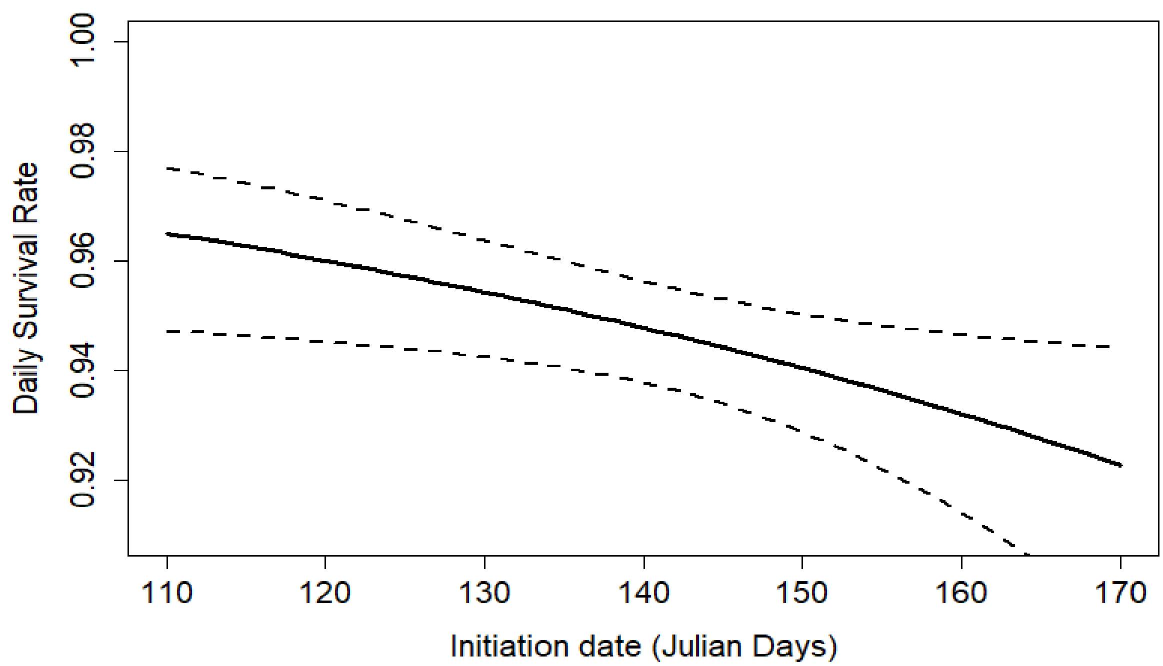

Figure 3.2. Daily survival estimates for nests relative to nest initiation date.

Table 3.6. Daily survival estimates for each species, derived from a species-only model.

Parameter	Daily Survival Estimates	SE	Lower 95% CI	Upper 95% CI
Canvasback	0.9601	0.0046	0.9500	0.9682
Lesser Scaup	0.9677	0.0106	0.9391	0.9832
Mallard	0.9338	0.0111	0.9381	0.9525
Redhead	0.9533	0.0068	0.9382	0.9648
Ring-necked duck	0.9355	0.0148	0.8996	0.9592
Ruddy duck	0.9563	0.0084	0.9369	0.9703

3.6. Discussion

The UAV equipped with a thermal imaging camera was successful at locating duck nests built over water. I found that the UAV had a significantly lower rate of nest detection then ground observers, and that the species of the nest was the most important factor. Surprisingly, the clutch size and the incubation stage of the nest when the nest was found had little impact on the detection probability. Canvasbacks had the highest detection probability when using the UAV with a detection rate of 55%. This may be attributed to the fact that Canvasbacks are one of the earliest nesting ducks in the Minnedosa area, nesting before the vegetation grows taller and they also build more wide open nests then other species (Krasowski and Nudds 1986). Similarly, Lesser Scaup and Ring-necked ducks had the lowest detection rates by the UAV at 13% and 4% respectively. Lesser Scaup and Ring-necked ducks are later nesting species in Minnedosa and tend to build smaller more concealed nests which may be the reason for low detection rates with the UAV (Krasowski and Nudds 1986). I originally hypothesized that nests farther along in incubation would be more detectable due to the high chance of a hen being present on the nest (Caldwell and Cornwell 1975), however this does not appear to be the case.

While detection probability with the UAV was poor there may still be utility in nest searching with the UAV. For example, the UAV may be most useful during the early part of the nesting season when overhead cover is not as thick, allowing for better detection rates. Additionally, the UAV is able to cover ground much faster than ground technicians, so if the goal of a study is to cover as much ground as possible it may be more practical to use a UAV to search for nests. In my study, the detection rate was less than half that of the ground crew, but the UAV was able to complete surveys four times faster. The UAV may also prove useful for surveying large marshes or swamps as they are very difficult to survey on foot due to their large areas and thick cover. During the time it would take to survey one on of these marshes on foot, technicians could have covered several other survey quarters, allowing them to build up a larger sample size of nests.

Nests monitored strictly with the UAV showed no difference in nest survival than those monitored by ground technicians, so it seems that trails and scents left by technicians did not influence nest success. This is similar to other studies such as Skagen et al. (1999), who showed that predators did not follow human scent trails through shortgrass prairies to passerine nests. They hypothesized that it is unlikely that predators learned to associate human scent with food, as human presence is rare in most study sites. Similarly, Keith (1961) concluded that human presence had no effect on artificial waterfowl nests in Alberta, and concluded that repeated visits to a nest did not affect survival rates, and that predation rates on waterfowl nests are high regardless of human intrusion. My study sites are remote and hardly visited by people; in addition, ground technicians were wearing waders which could limit the amount of scent left at each nest.

The top fitting model for nest survival included the age of the nest when found, similar to several other studies on upland-nesting dabbling ducks (Grand 1995, Garrettson and Rohwer 2001, Raquel et al. 2015). In part, this is detection bias, because nests placed in poor locations are found quickly by predators, and so researchers are inherently more likely to find older nests in high-quality locations. However, hens are also less likely to flush from the nest later in incubation which increases the risk of hen mortality, but could increase the survival rate of the nest (Forbes et al. 1994). The date of initiation was also a competitive exploratory variable in my analysis and results showed that the earlier in the season a nest was initiated the more likely it was to survive. There have been several studies that have shown a relationship between earlier initiation dates and higher daily survival rates (Hatchett et al. 2013, Ringelman et al. 2018). Ringelman (2014) hypothesized that predation may be lower earlier in the season due to the fact that duck nests are a rare prey item early in the season and most predation events are incidental. In contrast, several studies have shown that the later a nest is initiated the more likely it is to survive (Grand 1995, Greenwood et al. 1995, Garrettson and Rohwer 2001), and the authors attributed this to an increase in smaller mammals later in the season which shifts predator focus off of duck nests.

Similar to Maxson and Riggs (1996), who conducted overwater nest searching in Minnesota and monitored 155 overwater nests of 5 different species, I found no relation between nesting cover and survival rates. They concluded that overhead over is unimportant in areas with a mammalian predator base (such as their study site), but that in areas with a largely avian predator community, overhead cover may be more important to nest survival. Previous studies in the prairie pothole region area have shown that mammalian predators are a major influence on nest success (Klett et al. 1988, Sargeant et al. 1995, Garrettson and Rohwer 2001), and trapping information and trail camera pictures from my study area show that raccoons (*Procyon lotor*) and American mink (*Neovison vison*) are the major nest predators on my study sites (Mike Johnson, unpublished data).

We have only just begun to scratch the surface of the potential to use UAVs to conduct wildlife surveys. While UAVs are becoming a commonly used tool by biologists to conduct a variety of wildlife surveys (Linchant et al. 2015, Wich et al. 2015, Brisson-Curadeau et al. 2017), my results demonstrate that as of right now, UAVs are not a magic bullet for simplifying searching for overwater-nesting ducks because of low detection rates. However, more intensive studies are needed to study nesting birds in different habitats before we can truly assess the effectiveness of using UAVs to search for nests. UAVs and thermal imaging technology are also improving each year and so they may become a more viable option in future nest searching studies.

Chapter 4. Application of Unmanned Aerial Vehicles and Thermal Imaging Cameras to Conduct Duck Brood Surveys

4.1. Introduction

Ducks are some of the most intensively studied species in the world (Grado et al. 2011, Mattsson et al. 2018) and because more than half of hunter harvest is composed of juvenile birds (Raftovich et al. 2011), waterfowl managers need reliable and accurate methods to measure annual productivity in order to guide management decisions (Cowardin 1992). Traditional methods for evaluating productivity have typically focused on metrics such as clutch size, nest density and nest success. However, this does not reflect actual duck productivity because it does not account for post-hatch mortality of ducklings. Brood surveys, taken in combination with pre-breeding pair surveys are a more direct way to evaluate annual per-capita waterfowl production and estimate the fall flight.

Traditional survey methods for broods include roadside transects, where biologists drive sections of road and survey every wetland within a set distance of the road (Diem and Lu 1960) and fixed observational blinds where all broods are recorded during a fixed amount of time (Ringelman and Flake 1980). Aerial surveys for broods tend to be more accurate the walk-up surveys (Steinhorst and Samuel 1989) however, species such as Common Goldeneyes (*Bucephala clangula*) are less detectable because they dive when the aircraft passes overhead (Ross 1985). Most contemporary brood surveys are walk-up dual-observer ground surveys, where two observers independently observe broods from the shore of a wetland at different times (but close enough to satisfy closure assumptions), which permits statistical estimation of detection probability and brood abundance (Nichols et al. 2000). Nevertheless, due to the secretive nature of duck broods and the tendency for dabbling duck broods to congregate in emergent vegetation (Cowardin and Blohm 1992) it is difficult to get accurate survey counts (Diem and Lu 1960, Nichols et al. 2000), and it is estimated that up to 67% of broods go undetected (Pagano and Arnold 2009). Using an Unmanned Aerial Vehicle (hereafter, UAV) could provide biologists with a more effective and efficient way to conduct duck brood surveys.

UAVs have been used by biologists to survey a diversity of wildlife species, ranging from canopy nesting birds to elephants (Vermeulen et al. 2013, Dos Santos et al. 2014, Weissensteiner et al. 2015). Several studies have used UAVs to count colonial nesting birds (Chabot et al. 2015, Sarda-Palomera et al. 2017), and found that nest detectability with UAV was as high as 96%. UAVs have also been used to estimate non-breeding population sizes of birds congregated in large flocks, such as Snow Geese (*Anser caerulescens caerulescens*) and Canada Geese (*Branta canadensis*), where UAV flights detected on average 60% more individuals then traditional ground surveys (Chabot and Bird 2012). UAVs have also proven useful for conducting duck brood surveys in Europe. Pöysä et al. (2018) showed that UAV surveys were able to detect the same number of duck broods as ground technicians and were able to more accurately count the number of ducklings in each brood. Over 86% of all broods detected were dabblers, which tend to hide in emergent vegetation and are more likely to go undetected by ground technicians (Poysa et al. 2018). Equipping the UAVs with thermal imaging cameras could help increase detection rates even further for broods that are hidden in emergent vegetation.

Thermal imaging cameras have been used study a variety of wildlife, ranging from honey bee (*Apis* spp.) behavior (Kastberger and Stachl 2003), to estimating the population of white-tailed deer (*Odocoileus virginianus*) (Collier et al. 2007). Miniaturization of thermal imaging cameras has allowed them to be attached to UAVs and monitor wildfires (Ambrosia et al. 2003), fly search and rescue missions (Rudol and Doherty 2008), and conduct wildlife surveys (Haschberger 1996, Christiansen et al. 2014, Bushaw et al. 2019, Scholten et al. 2019). Scholten et al. (2019) used a UAV equipped with a thermal camera to locate Field Sparrow (*Spizella pusilla*) nests. Both the UAV and the ground crews found the same number of nests, but UAV searches were 28% faster. In chapter 2, I used a UAV equipped with a thermal camera to search for overwater duck nests in southern Manitoba, and I was able to successfully locate duck nests under various environmental conditions in emergent vegetation. Clearly there is potential to locate small warm objects hidden in vegetation, so I tested whether UAVs and thermal imaging cameras could be used to locate ducklings in southern Manitoba. My objective was to compare UAV brood surveys with traditional double-observer walk-up surveys. I evaluated the ability of the UAV to locate broods, identify them, count the ducklings, and the amount of time it took to complete UAV surveys relative to technicians on the ground.

4.2. Study Area

My study area consisted of four survey blocks within the Prairie Pothole Region of southern Manitoba. The four study blocks were selected based on aerial flights to determine areas with the highest wetland densities. Two of my study blocks were located near the town of Minnedosa, Manitoba (50.20° N 99.77° E) and two were farther west near the town of Shoal Lake, Manitoba (50.43° N 100.59° E). During my first study season in 2018, I surveyed the two blocks (Odanah and Minnedosa) near Minnedosa and they were 64.75 km^2 in size. In 2019, I included two more study blocks (Elphinstone and Raven Lake) near the town of Shoal Lake and all block sizes were cut in half to 23.30 km^2. In 2018 I surveyed 39 sites, 24 on the Odanah block and 15 on Minnedosa, each 2.59 km^2 in size to conduct brood surveys. In 2019 I randomly selected 72 survey sites (18 per study block) each 2.59 km^2 in size.

The area around Minnedosa is characterized by a diversity of wetlands including large permanent wetlands, smaller semi-permanent, and seasonal wetlands (Trauger and Serie 1974, Stoudt 1982). Wetlands generally contain a 10-30 m edge of peripheral cattails (*Typha* spp.) and hardstem bullrush (*Schoenoplectus acutus*) (Arnold et al. 1993). Upland areas consisted mainly of private land farmed for cereal grains, primarily canola (*Brassica napus*) and spring wheat (*Triticum aestivum*). The remaining areas were either actively grazed pasture land or native grasslands, described in detail by Kiel et al. (1972). The breeding duck community includes many diving ducks such as Canvasbacks (*Aythya valisineria*), Redheads (*Aythya americana*), Ruddy Ducks (*Oxyura jamaicensis*), Lesser Scaup (*Aythya affinis*), and Ring-necked Ducks (*Aythya collaris*) as well as a large variety of dabbling ducks including Blue-winged Teal (*Spatula discors*), Mallards (*Anas platyrhynchos*), Gadwall (*Mareca strepera*), and Northern Shovelers (*Spatula clypeata*) (Klett et al. 1988, Anderson et al. 2001).

4.3. Equipment

I used a battery-powered DJI Matrice 210 quadcopter UAV (6.4-kg weight, 716 x 220 x 236 mm dimensions), powered by dual 22.8 V lithium pro ion batteries which permitted a flight time of ~20 minutes. A portable battery charger and generator were used to charge up to 12 batteries in the field, thereby allowing me to operate continuously until I had completed my surveys. Each UAV was equipped with two cameras and I was able dynamically switch between views. The first was a DJI Zenmuse XT thermal imaging camera (640 x 512 resolution; 19 mm lens; 30 Hz) used to detect thermal radiation given off by waterfowl broods. The amount of radiation emitted is dependent on both the temperature of the object and the objects emissivity, which is a measure of the reflectivity of an object. The image generated by the thermal camera is therefore not a depiction of the absolute temperature or infrared radiation of an organism, but a combination of the targets' radiation, emissivity, environmental factors such as humidity and cloud cover, and the temperature of the background against which the animal is observed. The second camera, a Zenmuse X4S optical camera (5472 x 3648 resolution, 8.8 mm lens), was used to identify the species of each brood located.

4.4. Methods

I conducted two rounds of surveys during each season. The first survey was timed based on the peak hatch of Canvasback nests which are one of the earliest nesting ducks in southern Manitoba, so I am confident that few broods would have fledged before my surveys (Pagano and Arnold 2009). The second round began 18 days after the conclusion of the first and targeted later nesting species such as Lesser Scaup and Ruddy Ducks. Following guidelines laid out by Vas et al. (2015), I launched the UAV >100 meters from any wetland to avoid disturbing any duck broods. From there, I flew the UAV at a height of 31 m to search for broods, which allowed me to locate broods in cover and eliminate some false heat signatures like rocks and Red-winged Blackbirds (*Agelaius phoeniceus*) sitting in the emergent vegetation. At some wetlands it was possible to survey the entire wetland by flying the UAV to 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 covered. Once a potential brood was located with the thermal camera (Image 4.1), I switched to the regular camera (Image 4.2) and dropped to lower elevations, ~10

m. At elevations of ~10 m, it was possible to determine the species of the brood if the hen was present, and the age and number of the ducklings.

Image 4.1. Gadwall brood located with the UAV and thermal camera.

Image 4.2. Gadwall brood from Image 3.1 as seen with the regular camera, digitally cropped and zoomed in.

The ground technicians followed brood survey guidelines laid out by Pagano and Arnold (2009a). Surveys started at sunrise each morning: a single observer surveyed all wetlands on a quarter section, and a second survey was conducted 2 hours later. The same observer conducted both surveys for logistical reasons. While the same observer conducting both surveys may have led to a biased second survey, Pagano and Arnold (2009b), found that using the same observer had no impact on brood detectability. The ground technicians walked to every wetland on the quarter section and surveyed it for broods, staying as long as necessary to record data. UAV surveys started at sunrise and were followed by an additional survey at least two hours later. In 2018 I flew both daily brood surveys with the UAV, under the similar assumption that my observations in the morning did not bias my afternoon surveys. Each day the UAV crew surveyed 12-13 quarters and the ground crew surveyed a different 12-13 quarters. The following day we swapped areas, allowing me to directly compare survey techniques while maintaining assumptions of closure (Walker et al. 2013).

In 2019 I added two new study blocks (Raven Lake and Elphinstone), and the size of each block shrunk. In addition, we used two pilots to conduct a true dual-observer survey. We would each fly 9 sites in the morning and then swap in the afternoon; neither UAV pilot would know what the other had located during the morning surveys. Ground technicians' methods did not change during the 2019 season.

At each wetland, ground technicians and the UAV crew identified all broods seen to species and age class and counted the number of ducklings following guidelines laid out by Gollop and Marshall (1954). If a brood was spotted during our second round of surveys and it was within 1 age sub-class, varied by ≤ 3 ducklings, and was on the same pond or an adjacent pond, it was considered a brood resighting rather than a new detection (Pagano and Arnold

2009). In addition to counting broods, technicians also estimated the amount of each wetland visible to them (shoreline vegetation can obscure views into the wetland) and the time it took them 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 and number of ducklings and recorded the species as unknown. For the sake of our analysis we pooled species into three guilds: dabblers, divers, and unknowns.

Each brood was treated as an individual unit within our analysis (Pagano and Arnold 2009), and we assumed that broods have an equal detection probability across sites. 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. I analyzed my data using Huggins closed capture models (Huggins 1989,1991) in program MARK (White and Burnham 1999), which uses a maximum-likelihood estimate of a logistic model for detection probabilities. I evaluated detection probability based on survey method and time of day, and also evaluated the influence of species (dabblers or divers), number of ducklings, age of the ducklings, and visibility on detection probability. I ranked candidate models using Akaike's Information Criteria corrected for small sample size. Due to the differences in blocks and survey methodology I ran each year separately in my analysis.

4.5. Results

In 2018, my first round of surveys began on July 9th and concluded on the 12th of July, and the UAV located a total of 254 broods during this first round of surveys. The second round of surveys began August 1st and concluded on August 4th, and the UAV located 415 broods. In comparison, ground technicians located 130 broods during the first round of surveys and 214 during the second round of surveys. Blue-winged teal (*Spatula discors*), Mallard (*Anas platyrhynchos*), and Canvasbacks (*Aythya valisineria*) accounted for most of the broods located. After grouping species into the guilds, the UAV found 399 dabbler broods compared to the 206 located by the ground technicians and 156 diving duck broods compared to 133 found by the ground crews. The UAV had a much higher rate of unknown broods then the ground technicians, at 114 to 5 (Table 4.1).

Table 4.1. Comparison of broods located by the UAV and ground technicians in 2018.

	Odanah		Minnedosa	
Guild	Observer	UAV	Observers	UAV
Dabbler	92	152	114	247
Diver	75	76	58	80
Unknown	5	81	0	33
Total	172	309	172	360

In 2019, the first round of brood surveys began on the July 6th and concluded on July 10th, and the UAV located 242 broods. The second round of surveys began on July 28th and concluded July 31st and the UAV found 558 broods. In comparison, the ground technicians located 124 broods during the first round and 198 during the second round of surveys. After grouping all broods into guilds, the UAV located 561 dabbling broods in 2019, compared to the 213 located by ground technicians. The UAV located 188 diving duck broods compared to the

101 located by the ground technicians. Again, the UAV had a much higher rate of unknown broods with 51 unknowns compared to 8 for ground crews (Table 4.2).

Table 4.2. Comparison of broods located by the UAV and ground technicians in 2019.

	Odanah		Minnedosa		Raven Lake		Elphinstone	
Guild	Observer	UAV	Observer	UAV	Observer	UAV	Observer	UAV
Dabbler	36	129	93	160	45	175	39	97
Diver	40	65	36	58	18	49	7	16
Unknown	2	12	3	11	3	17	0	11
Total	78	206	132	229	66	241	46	124

I first evaluated brood detection probability of the UAV versus the ground technicians. In 2018, the UAV had a detection rate of 55% during both afternoon and morning surveys, compared with the ground technicians who had a detection rate of 27% in the morning and 22% in the afternoon (Table 4.3). In 2019 detection rates dropped slightly with the addition of two new survey blocks and were 43% in the morning surveys and 36% in the afternoon with the UAV. However, detection rates for ground technicians dropped dramatically to 16% and 12%, respectively (Table 4.4). I also ran brood detection models using only data collected by the ground technicians to evaluate what they would estimate their detection probability to be, if they did not have the benefit of additional broods sighted by the UAV. These detection estimates were 61% during the 2018 season and 51% during the 2019 season (Table 4.5), an overestimate by a factor of ~3.

Table 4.3. Detection probability for broods by both the ground technicians and the UAV in 2018.

Parameter	Detection Probability	Lower 95% CI	Upper 95% CI
Drone Morning	0.5535	0.5206	0.5815
Technician Morning	0.2705	0.2543	0.3044
Drone Afternoon	0.5537	0.5202	0.5844
Technician Afternoon	0.2201	0.2012	0.2522

Table 4.4. Detection probability for broods by both the ground technicians and the UAV in 2019.

Parameter	Detection Probability	Lower 95% CI	Upper 95% CI
Drone Morning	0.4342	0.3998	0.4692
Technician Morning	0.1675	0.1467	0.1907
Drone Afternoon	0.3658	0.3344	0.3984
Technician Afternoon	0.1298	0.1116	0.1506

Table 4.5. Detection probability for ground technicians not considering broods located only with the UAV.

Parameter	Detection Probability	Lower 95% CI	Upper 95% CI
2018	0.6112	0.5727	0.6609
2019	0.5111	0.4665	0.5554

When I evaluated more complex models with covariates, I found that the top model for 2018 incorporated a combination of survey method, survey block, and the number of ducklings, where the presence of more ducklings was associated with higher detectability (β=0.5151 ± 0.0161) (Table 4.6). The other competitive model for 2018 included visibility of the wetland (β=0.5017 ± 0.0020), where higher visibility yielded higher detectability. In 2019, the best model incorporated survey method, block, time of day, and the visibility of each wetland, where again higher visibility led to higher detectability (β=0.5026 ± 0.0019) (Table 4.7). In terms of efficiency, the UAV completed surveys much faster, averaging 15 minutes per survey compared to the 45 minutes it took ground technicians.

Table 4.6. Best fitting models for brood detectability using 2018 data.

Model	AICc	ΔAIC	Weight	Parameters
Method+Block+Count	3814.66	0.00	0.5415	5
Method+Count	3816.07	1.41	0.2669	3
Method+Block+Vis	3817.56	2.89	0.1271	5
Method+Vis	3818.99	4.32	0.0623	3
Method	3827.27	12.61	0.0009	2
Method+Block	3828.31	13.65	0.0005	4
Method+Duckling Age	3829.17	14.51	0.0003	3
Method+Time of Day	3830.70	16.04	0.0001	8

Table 4.7. Best fitting models for brood detectability using 2019 data.

Model	AICc	ΔAIC	Weight	Parameters
Method+Block+Time of Day+Vis	4148.90	0.00	0.9544	17
Method+Block+Vis	4154.99	6.01	0.0455	9
Method+Time of Day+Block	4180.91	32.00	0.0000	16
Method+Vis	4186.81	37.90	0.0000	3
Method+Block	4186.97	38.07	0.0000	8
Method+Time of Day	4193.56	44.66	0.0000	4
Method+Age	4207.50	58.59	0.0000	3
Method+Count	4208.38	59.47	0.0000	3
Method	4209.80	60.90	0.0000	2

I was also interested whether the detectability for broods located with the UAV varied between species guilds, because dabbler and divers react differently to disturbance (Ross 1985, Pagano and Arnold 2009). I found only modest differences between guilds, as dabbling duck broods had a detection rate of 56% whereas diving duck broods had a detection rate of 60% (Table 4.8).

Table 4.8. Detection probability for broods located by the UAV broken down by guild.

Parameter	Detection Probability	Lower 95% CI	Upper 95% CI
Dabblers	0.5612	0.5297	0.5921
Divers	0.6045	0.5495	0.6570

4.6. Discussion

Extensive surveys across multiple environments and geographical areas gave me confidence that I was able to detect waterfowl broods with the UAV and thermal imaging camera. The UAV proved to be much more efficient and effective at locating broods than ground technicians, using the UAV I counted twice as many broods in one quarter of the time it took ground technicians to complete a survey. In 2018 brood detectability was positively influenced by larger the brood sizes. This supports previous research by Pagano and Arnold (2009), who also noted that brood detectability increased with the size of the broods, and the number of ducklings on each wetland. Gabor et al. (1995), also found that more ducklings in a brood made them easier to detect from helicopter surveys.

In 2019, higher visibility was associated with higher detection probability of broods. There have been several studies that have shown that detectability is directly related to the amount of wetland visible to the observer (Gabor et al. 1995, Poysa et al. 2018). Simply put, the more visual obstruction there is around the wetland, the less likely it is that the ground technicians will detect broods. We noted a difference in detection between morning and afternoon surveys in 2019, where detection rates were higher in the morning compared to the afternoon. These results align with several other studies that have shown detection probability is higher in the morning when the broods are more active and environmental factors like wind speed and cloud cover have less of an impact (Diem and Lu 1960, Ringelman and Flake 1980).

While the UAV had a significantly higher rate of detection then ground technicians it was still only 55% during the 2018 season and as low as 36% during the 2019 season. These low detection rates could be attributed to several factors including brood movements, the strict criteria I set for classifying a brood as a resight, environmental conditions, and the tendency of broods to hide in emergent vegetation. Brood movements within a wetland and between wetlands could be a major reason for my low detection rate. When I surveyed larger wetlands, I flew transects in order to ensure the entire wetland was surveyed. While I was flying at lower elevations to identifying a brood to species, it is possible that other broods I had not yet located moved into areas I had previously surveyed, and so they never entered into my sample. Additionally, while waterfowl broods are generally only thought to only move from wetland to wetland 2-5 times a year (Rotella and Ratti 1992), it is possible that the broods moved wetlands between my surveys. There were several times that I located a distinct brood (e.g., a Northern Shoveler brood with 11 ducklings at age class 1), and during the next survey I would not resight it on the same wetland, but I located a Northern Shoveler brood with 9 ducklings at age class I on a different wetland. Given the relative scarcity of broods of this species, size, and age class at the time of the survey, this was probably the same brood, but due to the strict criteria we set for a brood to be considered resighted (≤3 duckling difference, the same age class, and on the same or adjacent wetland) I did not consider it a resighted brood.

Environmental conditions such as ambient temperature and humidity can also affect the detection ability of the thermal imaging camera. Kays et al. (2019) noted that detection rates of monkeys were much higher in the morning when the monkeys had a 3° C difference in temperature from the surrounding vegetation, and that detection probability declined with increasing ambient temperature. This has also been shown when searching for fawns before mowing operations, where higher temperatures and humidity led to an increase in false positive heat signatures which may have led to some fawns being missed (Israel et al. 2010). In chapter 2, I noted that on days with high temperatures and humidity I noticed an increase in interference on the thermal camera and an increase in false positive nests, which caused me to start skipping over more hot spots and possibly miss real nests.

Several studies have shown that broods are secretive and spend a majority of the time hidden in emergent vegetation (Diem and Lu 1960, Ringelman and Flake 1980, Cowardin and Blohm 1992). While I was able to locate broods in emergent vegetation, it is possible that some broods were under very dense vegetation that blocked their thermal signatures. In chapter 2, I noted that overhead cover was a limiting factor when it came to detecting duck nests, so it is likely the same would be true for broods. Thick overhead cover has also been a limiting factor in other studies that used UAVs and thermal imaging cameras to survey for wild monkeys 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).

While detection probability for the UAV was lower than expected, it was still high relative to detection probabilities of the ground technicians, which ranged from 12-27%. However, if I used only the ground technician data, ground technician estimates would estimate their own detection probability as being as high as 61%. One of the fundamental assumptions for dual-observer ground surveys is that all broods are potentially detectable during each survey (Pagano and Arnold 2009). However, my surveys with the UAV show that surveys on foot can miss upwards of 80% of the broods on the landscape. As a result, traditional surveys underestimated the number of brood's present, which would result in underestimating the productivity estimates as well. By using a UAV equipped with a thermal imaging camera, future studies should be able to more accurately estimate the number of broods present on the landscape. My results demonstrate that UAVs and thermal imaging cameras are valuable tools for conducting duck brood surveys. Because brood surveys could provide a simple measure of waterfowl productivity that includes nest effort, nest success, and duckling survival, advances in accurately and efficiently counting broods promises to be greatly beneficial to biologists, and this technology has the potential to revolutionize how biologists conduct duck brood surveys.

Chapter 5. General Conclusions

The goal of this study was to evaluate the use of an Unmanned Aerial Vehicle equipped with a thermal imaging camera to conduct a variety wildlife surveys. Mesocarnivore surveys proved to be successful, although the UAV was limited by flight time and regulations, and my temporally-limited spot-sampling approach undoubtedly missed far-ranging mesocarnivores. Searching for overwater nesting ducks was more successful, although I was only able to locate a third of the nests as technicians on foot. Drone effectiveness was limited this time by overhead vegetation at each nest and environmental factors such as heat and humidity. Conducting brood surveys with the UAV on the other hand, proved to be extremely successful as the UAV was able to locate twice as many broods in one fourth the amount of time as technicians on foot.

Additionally, the use of UAVs is a more cost-effective means of conducting waterfowl surveys. When Delta Waterfowl Foundation conducts overwater nest searching and brood surveys they usually hire a team of 12 technicians. These technicians are paid ~$1600/month and are hired for ~4 months of work. This adds up to a cost of ~$77,000 in technician wages before adding logistical costs. While the UAV, cameras, and peripheral equipment have a relatively high startup cost (~$30,000) the UAV can be used for multiple seasons of work, and a substantially smaller team of technicians. In rough terms, ground teams cost twice as much as UAV teams the first year, and are dramatically more expensive in subsequent years after the UAV equipment has been purchased. UAV teams find fewer nests, but they could potentially make up for this by covering more ground, and they locate twice as many broods. Ultimately, biologists should consider using a UAV equipped with a thermal imaging when conducting brood surveys, and as technology continues to improve, they could become even more useful for conducting overwater nest searching and mesocarnivore surveys in the future.

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Vita

Jacob D Bushaw was born in Waterloo, Iowa but moved to Bismarck, North Dakota when he was one, where he attended grade school. He attended Valley City State University from 2011-2015, where he pursued a Bachelor of Science in Wildlife Management. Upon graduation Jacob went to work for Delta Waterfowl where he spent two summers working on a research project looking at Canvasback nest success. In between working for Delta Waterfowl he also ran banding crews for the North Dakota Game and Fish, and work in Kissimmee, Florida on a Mottled duck hybridization project. In the fall of 2018, he began working with Dr. Kevin Ringelman, on a research project using drones and thermal imaging cameras to conduct mesocarnivore and breeding waterfowl surveys. The goal of this project was to compare traditional population survey techniques with surveys conducted using a drone and a thermal imaging camera. Jacob anticipates finishing his MS in 2020 after conducting these population surveys for two years. He will go on to work for the Nebraska Game and Parks as a Waterfowl Biologist in Lincoln, Nebraska.