2017 Project Abstract
For the Period Ending June 30, 2020

PROJECT TITLE: Moose Calf Surveys and Monitoring
PROJECT MANAGER: Dr. James D. Forester
AFFILIATION: University of Minnesota – Twin Cities
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2017, Chp. 96, Sec.2, Subd. 03j

APPROPRIATION AMOUNT: $ 348,000
AMOUNT SPENT: $ 348,000
AMOUNT REMAINING: $ 0

Sound bite of Project Outcomes and Results

New techniques were developed to allow Unmanned Aerial Vehicles (UAVs) to efficiently home in on radio-collared animals and collect images of surrounding landscapes at multiple angles. UAVs, equipped with thermal and multi-spectral cameras, were then used to determine moose calving success and survival, characterize moose habitat, and estimate deer populations.

Overall Project Outcome and Results

Broad-scale monitoring of populations and ecosystems is needed to improve wildlife conservation and management efforts; however, the required data are often expensive and time consuming to collect. The overall goals of the project were to develop Unmanned Aerial Vehicle (UAV) capabilities to collect novel and important data on wildlife and ecosystems using methods that reduce or eliminate negative impacts on wildlife by removing the need to closely approach or handle them.

We developed new methods to home in on radio-collared animals and collect fine-scale imagery from multiple angles to improve our ability to count wildlife and characterize their habitat. We equipped UAVs with thermal and multi-spectral cameras to test whether UAVs can: 1) remotely confirm moose calving success or mortality events, 2) identify fine-scale habitat selection behavior of moose (e.g., locations of calving, foraging, and mortality), and 3) estimate population densities of white-tailed deer in forested natural areas.

We found that UAVs are a promising tool for quantifying moose calving success, twinning rate, and calf survival. We also determined that analysis of UAV-derived imagery can produce reliable estimates of forage availability and horizontal visibility. Our results indicate that female moose choose calving sites with relatively low visibility (subsequent calf mortality events appear to be associated with large, high-visibility forest patches). In our survey of the deer population at the Cedar Creek Ecosystem Science Reserve, we found that automatic detection of deer using software was not feasible, given the flight elevation required for the survey; however, we developed a methodology in which researchers count animals in a subset of images from the survey area to produce a repeatable count estimate. Overall, our methods provide safe, relatively inexpensive alternatives to traditional approaches of collecting critical data on wildlife populations.

Project Results Use and Dissemination

This project resulted in four scientific presentations, two published conference papers, three accepted journal papers and one submitted journal article; the CSE graduate student working on developing an aerial robotic system and strategy to approach a radio signal beacon from a high altitude was awarded the UMII MnDrive fellowship award from the University of Minnesota. Our research into field applications of thermal imagery for assessing moose calving and mortality events was conducted in close collaboration with researchers from the Grand Portage Band of Lake Superior Chippewa and the MNDNR; we are continuing these collaborations and expect to submit another paper (detailing the calving habitat results) later this year. Our work to develop a new approach to sample deer populations using UAVs and thermal sensors grew out of a need at Cedar Creek to better understand their deer population. We tested our approach in the Cedar Creek Ecosystem Science Reserve and compared population estimates generated from UAV data to those from more traditional pellet-count approaches; we are now working with researchers at Cedar Creek to validate their camera-trap estimates of deer population density. Finally, three undergraduate students, three graduate students, and two postdoctoral researchers received training as part of this project; results from this research have been added into teaching materials in two required Fisheries, Wildlife, and Conservation Biology courses at UMN.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2017 LCCMR Work Plan Final Report

Date of Submission: 06/03/2021

Date of Next Status Update Report: Final Report

Date of Work Plan Approval: 06/07/2017

Project Completion Date: 4/30/2020

PROJECT TITLE: Moose Calf Surveys and Monitoring

Project Manager: Dr. James D. Forester

Organization: University of Minnesota – Twin Cities

Mailing Address: 2003 Upper Buford Circle, Suite135

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Email Address: jdforest@umn.edu

Web Address:

Location:Statewide

Total ENRTF Project Budget:

ENRTF Appropriation:	**$348,000**
Amount Spent:	**$348,000**
Balance:	**$0**

Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 03j

Appropriation Language:
$348,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to assess the use of unmanned aerial vehicles in natural resource monitoring of moose populations and changes in ecosystems.

I. PROJECT TITLE: Non-invasive Moose Calf Surveys and Ecosystem Monitoring with Unmanned Aerial Vehicles

II. PROJECT STATEMENT:

Many species and ecosystems in Minnesota are facing a variety of threats ranging from changing patterns of natural disturbance and human land use to alteration in the timing and amount of precipitation. Broad-scale monitoring of populations and ecosystems is needed to improve conservation and management efforts; however, the required data are often expensive and time consuming to collect. Fortunately, technological advances in the fields of robotics and data processing are opening up new capabilities for natural resource biologists to better identify and understand when and where changes in management strategies are needed. Specifically, Unmanned Aerial Vehicles (UAVs) improve on current technologies and methodologies because they can access remote or difficult terrain, collect large amounts of data for lower cost with reduced risk for humans, and facilitate observations of species that are wary of human presence. The use of UAVs has tremendous potential to advance the quality, scale, and frequency of aerial imagery collection and will enable researchers to better monitor landscapes as they change through time and then understand how wildlife species respond to these changes.

The overall ***GOALS*** of the project are to develop UAV capabilities to **1) collect novel and important data on wildlife and ecosystems** using methods that **2) reduce or eliminate negative impacts on wildlife** by removing the need to drug and handle them. Specifically, we will attempt to develop novel UAV capabilities to home in on VHF signals from collared animals to collect fine-scale habitat use and behavior data without the need to approach or re-handle the individual. We will also develop survey methodologies to utilize UAVs equipped with infrared cameras to count and track the survival of the moose calves without ever needing to handle them; fixed-wing UAVs will fly at high altitudes to avoid affecting moose behavior. We will also produce easy to use software that works with a simple UAV system for the monitoring and analysis of imagery over threatened or sensitive ecosystems such as wetlands and areas experiencing encroaching invasive species. This project will directly lead to better management and conservation ***OUTCOMES*** for **i)** the MN moose population without needing to collar calves, and **ii)** better monitoring and management action for natural areas by providing an approach that could be adopted by natural resource managers to collect finer temporal scale and higher quality land-cover data, enable a fast and effective way to assess results of management actions, and provide a user friendly means of processing the imagery data. These outcomes will provide a set of tools that will help advance conservation in Minnesota and will eventually save taxpayer dollars while simultaneously reducing risk to biologists and pilots.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of 01/01/2018: Now combined in 07/01/2018 status update per instructions from LCCMR staff: "In an effort to manage staff and project manager work load and resources, LCCMR staff is requesting you disregard your first scheduled update. Past history shows there is usually very little activity in the first six months of a new work plan. Please combine your first update status with your second project status update submission. If you have an amendment request, then submit your update as planned. Any amendment request must include an update."

Project Status as of 07/01/2018:
We had a busy fall of 2017 where we spent a good deal of time researching unmanned aerial vehicles and sensors for purchase to help us accomplish our goals. We worked with a local Minnesota company, Sentera (https://sentera.com), to purchase our fixed-wing aircraft and to obtain flight lessons for use in our ungulate surveys. We needed a place to easily test all of our cutting-edge equipment and methodologies prior to moose-calf surveys, so the Fisheries, Wildlife and Conservation Biology (FWCB) graduate student added on an additional component to this project, comparing the efficacy of different methods for determining the abundance of white-tailed deer. We believe this addition will be of great use for research and management in MN as well. During this time, the Computer Science and Engineering (CS&E) team has started to help us create computer code to automatically identify and count the number of deer in a thermal image collected by the UAV.

The CS&E team have been testing custom-built UAVs that can home in on a VHF signal emitted from a collar. While they have had some good success in the lab, more field testing will be required this year before it can be implemented to help us find collared moose. These experiments will be performed at the Cedar Creek Wildlife reserve throughout the summer of 2018.

Some preliminary results have been presented at the Multi-Robots Systems Conference in December. Further results on the algorithm to localize the target has been submitted to IROS 2018 (one of the top two robotics conferences).

Throughout the fall we collected aerial imagery from several locations, often multiple times per week, with our UAV quadcopter. We picked these sites in order to work with imagery and do analyses that would be similar to situations where Minnesota land managers might find UAVs very useful. We are currently using the latest software to analyze this imagery to better understand how UAVs can be incorporated into everyday work for Minnesota land managers.

Currently, the FWCB graduate student along with an FWCB undergraduate student, are in Grand Portage working with the tribal biologists for the initial moose survey season. They have had some success collecting thermal imagery of adults and calves, but importantly, we are learning many ways in which we can improve our methods and success for our second season in 2019. All successes and failures that we encounter in developing these new methodologies will be assessed to determine their utility for future research, conservation and management work. The CS&E graduate student is working to make software that can automatically detect and count the moose in thermal videos.

Amendment Request 04/26/2019: Amendment Approved by LCCMR 6/13/2019

Because we were able to save travel funding due to inexpensive rent found in Grand Portage, and because we paid our field techs salary instead of perdiem, we are asking to shift $12,520 from Travel and $2,566 from Capital Expenditures to personnel. This will cover the increased need for graduate students and undergraduate assistants to collect and process the large amount of image data we have stored. To cover repair of our two UAVs that were damaged in crashes, we need to retroactively transfer $2,111 from Capital Expenditures to Other (service contracts for repair costs from Sentera and DJI) and $2,287 to Equipment/Tools/Supplies to cover replacement batteries, props.

A trip outside of Minneosta was made by the Volkan Isler lab (June 28-July 2 DC trip) to present the findings of our radio tracking approach at a national meeting. At this conference, they were able to get valuable insights from colleagues on how to refine their approach so we are requesting a retroactively requesting $770.40 to be allowed for out of state travel.

Because we are still collecting data now, we are requesting an extension of our completion date (recognizing that the budget will be spent out by 1 July 2019) to 1/30/2020. This will give us the opportunity to complete our analysis and provide a more comprehensive final report. We will provide a progress report on 7/1/2019.

Amendment Request 04/26/2019: Amendment Approved by LCCMR 6/13/2019

The remaining $6,348 in Capital Expenditures will be used for a combined Thermal/Color camera that will allow for more accurate temperature measurements, simultaneously collected color imagery, all of which is geotagged. In our initial year of sampling, we found that the largest roadblock we had to identifying moose calves was not having geotagged color and thermal imagery. This camera will be purchased according to UMN purchasing guidelines; although UMN does not require an official bidding process for material < $10k, we have received three bids for the camera. At the completion of the project, the camera will continue to be used to further develop our wildlife detection techniques and habitat surveys. If this use changes, we will pay back the ENTRF equal to the residual value as approved by the director of the LCCMR.

Project Status as of 04/26/2019:

During the fall of 2018 we collected a second year of landscape imagery at Cedar Creek Ecosystem Science Reserve (CCESR). We collected data over the same forested areas as during the fall of 2017 and over the same wetland and lake shore as was collected in the spring of 2018. During these flights we utilized our multi-spectral sensor which collects several types of additional spectral bands that enabled us to calculate and quantify several metrics such as the normalized difference vegetation index (NDVI); a measure of the greenness or productivity. We have processed the imagery from these flights, calculated various metrics and are currently in the process of analyzing the results.

Students from both the FWCB and CS&E teams went to multiple locations with captive ungulates for the purposes of advancing our methodologies when conducting flights over wild moose. These data are especially useful for furthering the development of algorithms to automatically detect and correctly identify the presence and species of large mammals from thermal surveys. The data collected from both bison at CCESR and white-tailed deer from a deer farm near Bethel, MN will be instrumental in honing our methods for the 2019 field season and final products. Michael McMahon is currently in the field collecting sightability data on collared deer (these animals are similar in body size to moose calves) while he is searching for calving moose in Grand Portage.

Project Status as of 07/01/2019:

In the last two months, we completed the collection of field data. Based on our preliminary analysis, we were able to thermally detect cows with 85% success and correctly identified the presence of one or more calves with 79% success. By adjusting our methodology based on our initial detection model findings, we increased our moose detection success from 25% our first season, to 85% during our second season. We are currently analyzing these results and expect to submit a manuscript in early 2020. The CS&E team continues to work on how to optimize radio tracking from the UAS, and how to process efficiently the imagery we collect.

Amendment Request 01/30/2020:

Because the data analysis has taken longer than expected due to the processing time required for large image files, we are requesting an extension of our completion date (recognizing that the budget was spent out on 1 July 2019) to 4/30/2020. This will give us the opportunity to complete our analysis and provide a more comprehensive final report. We are doing all work after 30 June 2019 on our own time and using non-sponsored funding sources.

In the last months of the project, we needed additional personnel and computer network support to finish the data collection. We are retroactively asking to move $2,285 to Personnel from Equipment and Tools, and $1,020 to Other (Networking and Computer Services) from Other (Repair Fees, $227) and Equipment/Tools ($789). In the last month of funding, a subcontract reallocated funds to complete the project but did not know that an amendment was required. This happened because they realized the need to have more personnel and computer support on the project as they finalized their portion of the analysis of radiotelemetry and image data.

Overall Project Outcomes and Results:

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We developed new methods to home in on radio-collared animals and collect fine-scale imagery from multiple angles to improve our ability to count wildlife and characterize their habitat. We equipped UAVs with thermal and multi-spectral cameras to test whether UAVs can: 1) remotely confirm moose calving success or mortality events, 2) identify fine-scale habitat selection behavior of moose (e.g., locations of calving, foraging, and mortality), and 3) estimate population densities of white-tailed deer in forested natural areas.

We found that UAVs are a promising tool for quantifying moose calving success, twinning rate, and calf survival. We also determined that analysis of UAV-derived imagery can produce reliable estimates of forage availability and horizontal visibility. Our results indicate that female moose choose calving sites with relatively low visibility (subsequent calf mortality events appear to be associated with large, high-visibility forest patches). In our survey of the deer population at the Cedar Creek Ecosystem Science Reserve, we found that automatic detection of deer using software was not feasible, given the flight elevation required for the survey; however, we developed a methodology in which researchers count animals in a subset of images from the survey area to produce a repeatable count estimate. Overall, our methods provide safe, relatively inexpensive alternatives to traditional approaches of collecting critical data on wildlife populations.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Non-invasive methods to monitor the MN moose population

Description:

For this activity, we will utilize UAVs with thermal imaging to better monitor the MN moose population without the need to re-handle adults or collar calves. We will utilize the collars already on adult moose in the Grand Portage Reservation. We will fly our UAV above the adults and utilize thermal imagery to determine the number and survivorship of calves. Data collected non-invasively on moose calves is critical because moose cannot be handled or collared in MN and the methods and technologies pioneered here may be later used in other areas of the state. This activity has two discrete components: **i) a lab component** where a graduate research assistant in the Department of Computer Science & Engineering (CS&E) at the University of Minnesota will work with Dr. Volkan Isler and his lab to develop new UAV capabilities to home in on the location of a VHF signal and, **ii) a field component**, where a graduate research assistant in the Department of Fisheries, Wildlife, and Conservation Biology (FWCB) at the University of Minnesota working with Dr. Mark Ditmer and Dr. James Forester collect data on moose calves. The FWCB graduate research assistant will fly the UAV with thermal and regular (RGB) imagery over the locations of adult moose with GPS-collars and count the number of calves born, track their survival over time, and capture additional data about the habitat selected by the adult moose for giving birth and areas used after the calves are mobile. This data will be processed by the CS&E graduate research assistant and analyzed for ecological and biological interpretation by the FWCB graduate research assistant.

i) For this activity, Dr. Isler and the CS&E graduate research assistant will develop robot control software to autonomously home in on a signal source (i.e. the collar) of an adult moose. First, a multi-rotor aerial vehicle will be fitted with a small computer, a UHF radio signal receiver and a sound card. The characteristics of the signal and its relationship to the source-receiver geometry (in particular with respect to distance and bearing) will be investigated. Second, the flight controller will be modified so that it can take commands from an onboard computer. Third, a "home-in" behavior will be developed so that the UAV can approach the signal source. In ideal conditions, this could be achieved by following the gradient of the signal. However, preliminary tests indicated that due to obstacles such as trees as well as noise from the environment (including the rotors), signal strength is not a reliable indicator of distance. We will develop more sophisticated search behaviors which guarantee successful approach to the target. This capability will be demonstrated in field experiments using a collar and a multi-rotor vehicle near campus.

ii) Prior to developing survey methodologies for conducting UAV flights to collect data on moose calves, the FWCB graduate research assistant will obtain training on UAV flying during August or September of 2017. Following training, the FWCB graduate research assistant will first test out the capabilities of the UAV coupled with a thermal camera by doing field testing on the University of Minnesota's property during October of 2017. This testing will allow us to make any changes to the camera or UAV settings and determine the best altitude for collecting thermal data on large-bodied mammals. To collect data on moose calves, the FWCB graduate research assistant will fly the UAV over the locations of adult moose in the Grand Portage Reservation in northeastern MN, that were previously collared, after they have given birth (typically May through early June). The graduate student will work with the resident wildlife biology for the Grand Portage band, Dr. Seth Moore. We will know when an adult collared moose gave birth because moose based on an existing statistical model that identifies characteristic movement behavior that usually occurs just prior to giving birth. This specific movement, evident from GPS locations transmitted from the moose's GPS-collar via satellite to our computer, consists of a long distance movement away from the individual's usual home range, followed by relatively little movement for several days. Once the calving movement is identified, the FWCB graduate research assistant will fly the UAV to the location of the moose at the highest altitude that can be safely flown in the conditions that allows us to successfully capture thermal imagery for the moose and the calves. The Univ. of Minnesota has a Certificate of Authorization (2016-CSA-63-COA-R) provided by the Federal Aviation Administration that outlines all of the safety requirements and rules that all of our flights will adhere to. Along with the thermal imagery of the moose and the calves, the UAV will also collect regular aerial imagery of landscape using an RGB camera. Data from the cameras will be downloaded and stored on a Cloud-based system and later analyzed by the FWCB graduate research assistant to determine the habitat characteristics selected for by the adult moose for calving relative to the habitat in the surrounding area. During October and December of 2018, both the FWCB and CS&E graduate research assistants will test out the newly developed homing capabilities of the UAV using a similar VHF collar. During May through June of 2019, the same flights over moose in Grand Portage will be conducted by the FWCB graduate research assistant. The second season may involve alterations in methodologies to improve on the outcomes from Season 1 (2018).

Summary Budget Information for Activity 1: **ENRTF Budget: $187,810**
Amount Spent: $ 187,810
Balance: $ 0

Outcome	**Completion Date**
1. Testing of UAV and thermal camera at captive animal facility to determine optimal settings for moose surveys.	11/01/2017
2. Conducting moose survey and habitat flights in Grand Portage collecting counts and survival data using thermal imagery. – Season 1.	07/01/2018
3. Alteration of UAS system to include the capability of tracking VHF collar and field tests with unused VHF collars on campus.	01/01/2019
4. Testing of newly engineered homing technology of VHF collars.	05/01/2019
5. Conducting moose survey and habitat flights in Grand Portage collecting counts and survival data using thermal imagery. – Season 2.	07/01/2019

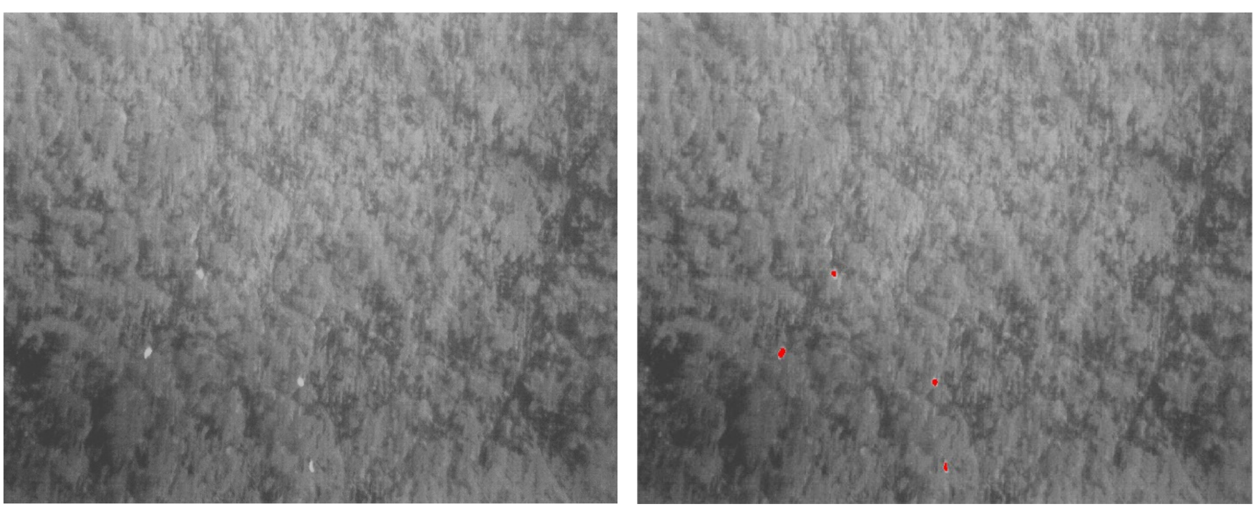
Activity 1 Status as of 01/01/2018: Now combined in 07/01/2018 status update.

Activity 1 Status as of 07/01/2018:

Dr. Volkan Isler and his engineering students have made great strides in developing a UAV that can automatically detect and localize VHF signals for purposes of automated tracking of wildlife. They have overcome many hurdles in terms of developing a search algorithm, processing information while in flight, and the creation of user friendly software. They have built a custom-made quadcopter with an attached traditional Yagi antenna (used for wildlife studies; see image 1A below) and we have tested it out at the University of Minnesota's Cedar Creek Ecosystem Science Reserve (CCESR; see image 1B). The initial tests, while promising, point to a lack of rane that the VHF collar can be detected. Currently, Dr. Isler's team is working on a solution to the limited range and will continue field testing later this year.

Images 1A (left) and 1B (right): 1A-Development of a custom-made UAV for the tracking of VHF signals utilizing a traditional wildlife Yagi. 1B-Testing the VHF-homing UAV at Cedar Creek Ecosystem Science Reserve. We placed VHF transmitters throughout the area and tested the ability of the UAV to detect, collect data, and search out the location of the transmitters.

Because our moose field work in Grand Portage can only occur during the spring, and we are employing new methodologies, we tested our abilities to use UAVs with thermal sensors for ungulate population counts locally. The FWCB graduate student conducted 22 UAV surveys over 5 different areas within CCESR aiming to record and count white-tailed deer. The student is also analyzing data from a camera-trap grid within CCESR and has conducted hundreds of deer pellet count surveys (a traditional approach of estimating deer abundance) in order to compare the estimates of relative abundance and determine the efficacy of these methods for estimating deer populations. The CS&E graduate student is developing computer code to automatically determine and count the deer from these thermal flights. See image 2 for an example.



Images 2A (left) and 2B (right): 2A-Raw thermal imagery from flights over the CCESR. They bright white spots are those of white-tailed deer. 2B-The same image processed with code developed by the CS&E graduate researcher that automatically detects (red) the likely locations of deer from within a series of thermal images.

Currently in Grand Portage, the FWCB graduate student is conducting thermal surveys over moose in the hopes of detecting calves and monitoring their survival throughout the spring season (**Image 3** below). Because of the remote nature of the area, and the thick vegetation, the team has had to work incredibly hard to get the UAV over the current locations of adult female moose who potentially have calves. To date, they have attempted ~40 flights thus far, and based on initial inspection of the thermal data, have only been able to positively identify moose in less than 10 sets of imagery. However, a more formal and thorough search will occur after the field season and will be enhanced with analysis from the CS&E team. We have already learned important lessons from this field season that will increase our success in 2019. For instance, we initially worried that coniferous trees and shrubs would prevent us from sighting the moose, but the conifers do not block our sighting of moose, it has been thick deciduous cover that has created most of the issues. Next year, our student will head into the field a month earlier (mid-April) in order to conduct more surveys prior to deciduous leaf-out in the spring. Additionally, we are conducting surveys of moose calving locations with our multi-spectral sensor to better understand the habitat conditions where moose select to give birth.

Despite some of the initial logistical hurdles, the tribal biologists in Grand Portage are extremely excited by the work and are looking for ways to incorporate UAVs into many more aspects of their wildlife management work. They have asked us to come back in the winter to conduct thermal surveys. This will allow us to further detect survival of moose calves after a summer and fall. They also have interest in using the UAV with thermal capacity for conducting wolf pack counts.

Image 3: Raw thermal imagery from a flight over the location of a collared adult female moose with calf. Thermal video makes this detection even more apparent and we will conduct a more formal analysis of imagery after the field season.

Activity 1 Status as of 04/26/2019:

We used the fall of 2018 to collect imagery, often several times a week at different altitudes, of captive bison at CCESR (**Image 4** below) and also captive deer at a farm near Bethel, MN (**Images 5A & 5B** below). We collected this data for several important reasons: 1) This data was requested by the CS&E team to refine their computer programs that can auto-detect mammals from thermal imagery. By flying the drone at several altitudes, times of day, and with varying levels of ground obstruction (e.g., trees, rocks), the engineers are able to refine their algorithm for detection which accounts for the altitude of the UAV and the size of the species being surveyed. 2) By working with our thermal imagery, the CS&E team have provided updated recommendations for the altitude to that best maximize survey cover and increase the probability that large-bodied mammals can be detected with the thermal camera. 3) Finally, working with captive animals allows us to understand how well the thermal sensor can detect individual animals because we know the exact number of individuals in captivity. We can then compare how detection is influenced on the altitude of the flight, ambient temperature, and types of ground cover.

During our 2018 moose field season (May and June), we flew 26 UAV grid surveys over GPS-collared cow-calf groups and confirmed 7 calf detections (27% success for detecting at least one calf present). We believe that by improving our auto-detection software and flying the surveys earlier in the season, we can improve on our detection rates in 2019.

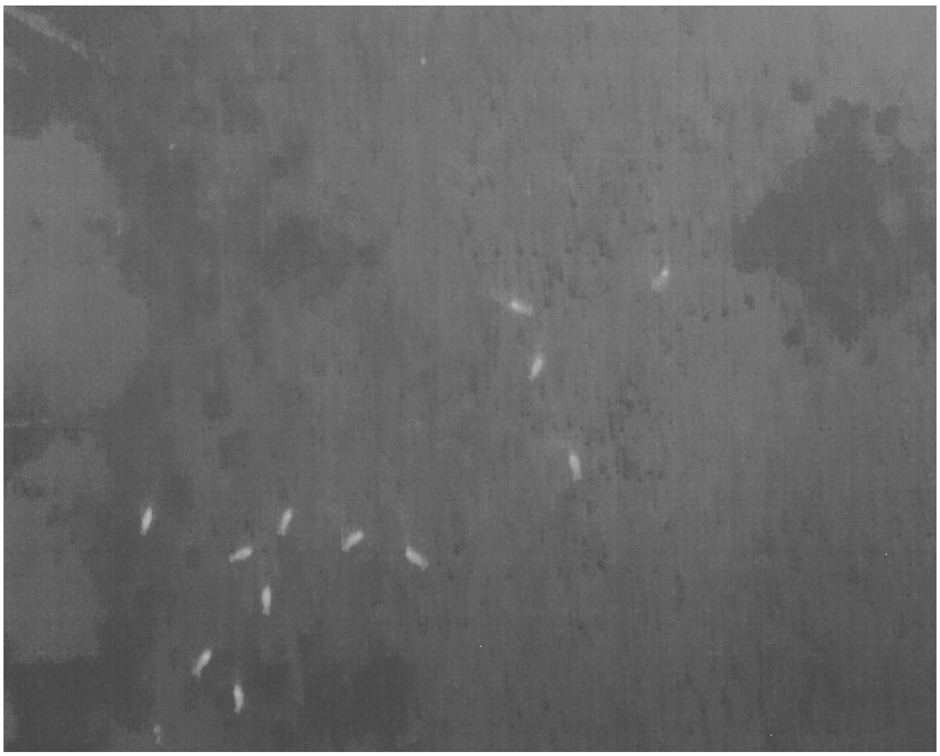


Image 4: Raw thermal imagery from a flight over a captive bison herd at the Cedar Creek Ecosystem Science Reserve. By collecting imagery in areas where we know the number of individuals present, we can improve on our understanding of detection and further refine field and analytical methods.

Image 5A: RGB imagery from flights over a deer farm near Bethel, MN. Collecting RGB imagery in conjunction with thermal helps to understand how vegetation impacts our thermal detection rates.

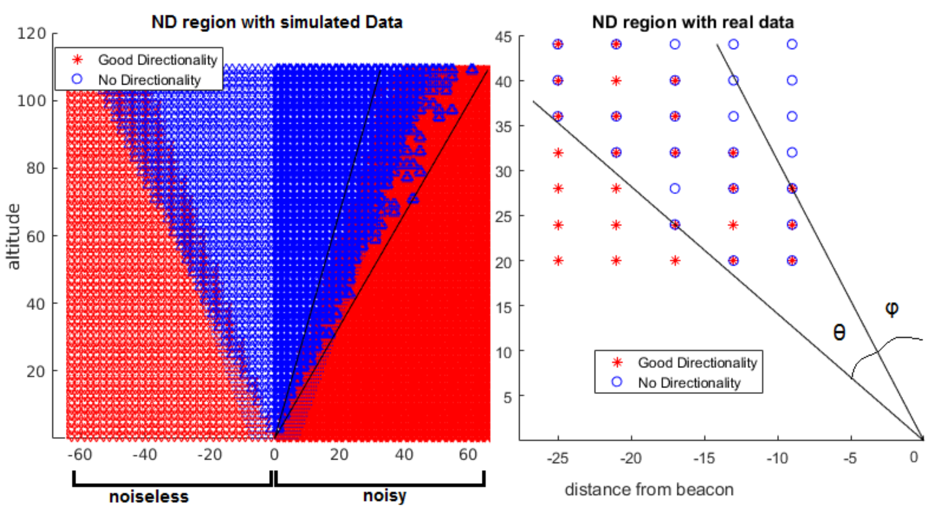
Image 5B: A screenshot from thermal video collected during drone flights over a deer farm near Bethel, MN. Collecting both thermal and RGB imagery at various altitudes, times of day, and various vegetation coverage helps us understand our ability to detect mammals and improve our auto-detection software.

Activity 1 Status as of 07/01/2019:
During 2018 our detection success of adult moose was 25%. After making adjustments to our field methodologies based on preliminary graphical analyses, adult cow moose detection improved substantially to 85% during 2019. We discovered that cloud cover and the amount the vegetation had leafed out were two factors that were extremely important to account for with respect to detections. Overcast skies led to far better detections and late-season flights (when the deciduous vegetation had started to leaf out) were much less successful. We are beginning to work on statistical models that will formally quantify these results.

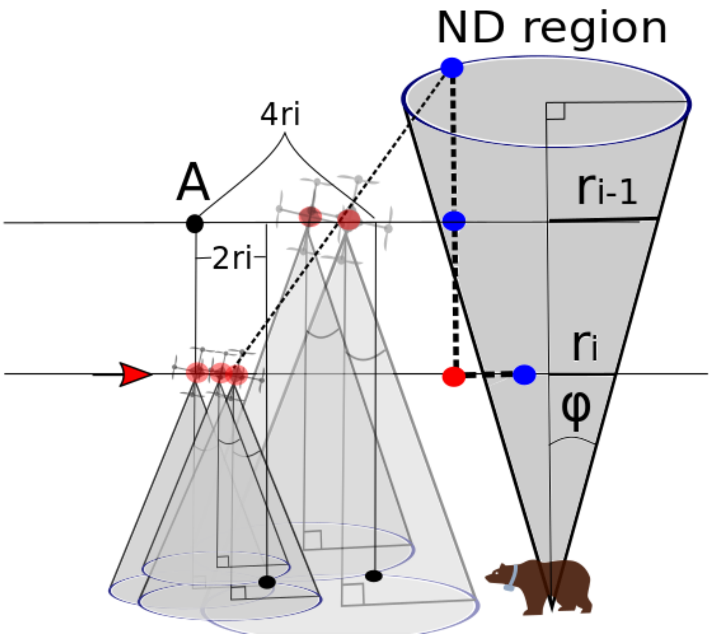
Final Report Summary:

i) For this activity, Dr. Isler and the CS&E graduate research assistant worked on utilizing VHF radio tags with a UAV. First, we fitted a multi-rotor UAV system with a small on-board computer and a directional antenna that can detect the signal source. We developed control software that allows the UAV system to communicate with the autopilot and perform commands from the on-board computer.

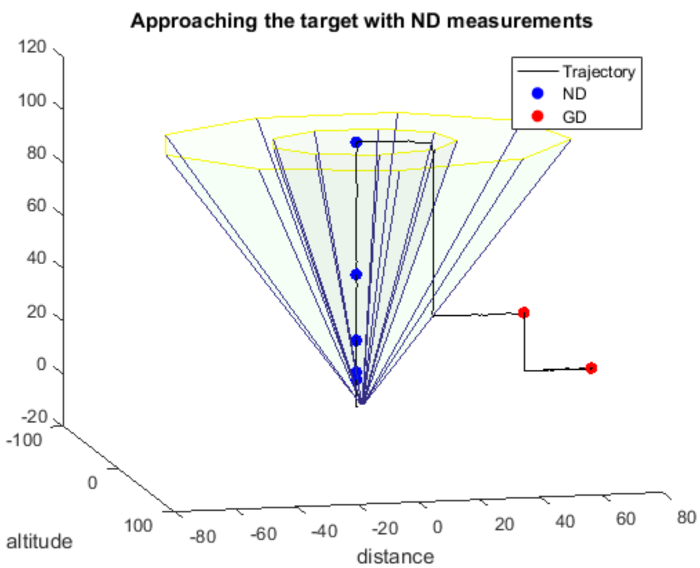
Second, we modeled the area around the signal source based on our antenna radiation field and classify the locations in which we can or cannot obtain reliable directionality measurements (a.k.a. bearing measurements). The results of this modeling resemble a cone-like region above the signal source inside of which bearing measurements lose directionality. In order to verify that our modeling is realistic, we also collected data with a real UAV system.



Finally, we developed a "home-in" strategy that takes advantage of a UAV's ability to change altitude and exploits the special structure of the modeled conic-like region in order to approach the signal source from above.



We analyzed the performance of our strategy and demonstrated through simulations and field experiments that by exploiting this structure we can achieve short flight times. Initial tests and proof of concept experiments were conducted on the UMN campus and at the Cedar Creek Ecosystem Science Reserve.



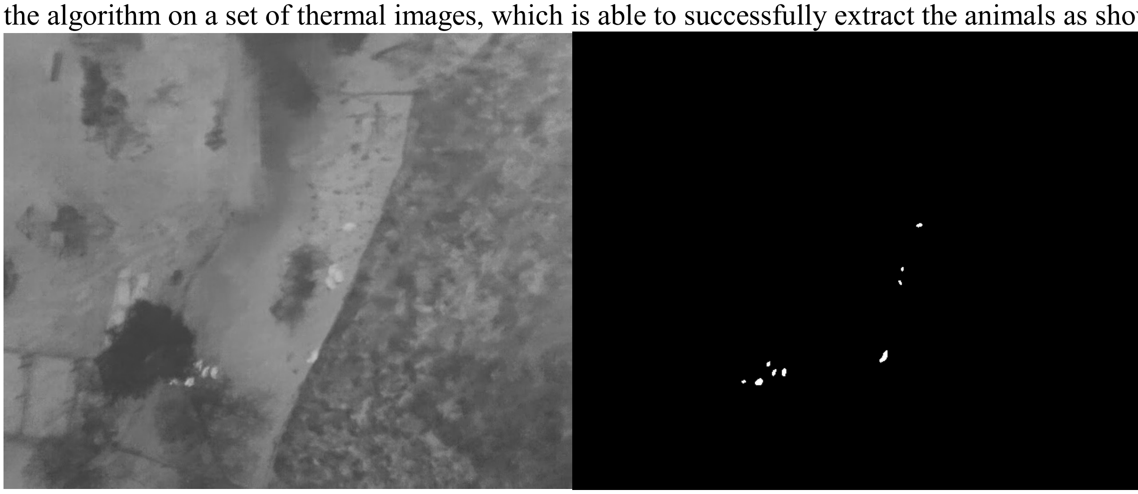
We found that by using the UAV's ability to change altitude, we could process the radio signal in a way that allowed for reduced flight time required to home in on the beacon. The results of this work were published with the IEEE International Conference on Intelligent Robots and Systems (IROS), 2019 under the title "UAV Landing at an Unknown Location Marked by a Radio Beacon" (Stefas et al. 2020).

ii) To study the signals of moose and their calves in the forest using thermal imaging devices, we first tested our equipment and tested the feasibility of using automated detection to identify animals (**Protocol Development and Image Processing**). We then applied the thermal camera approach to identify whether female moose had successfully calved (**Evaluating Unmanned Aerial Systems for the Detection and Monitoring of Moose in Northeastern Minnesota**). Finally, we flew our UAV over areas of moose habitat that were associated with important life history events (calving sites, peak lactation sites, mortality sites, and areas of recent concentrated use) and collected fine-scale multi-spectral data (**Linking multi-spectral vegetation data with moose habitat**).

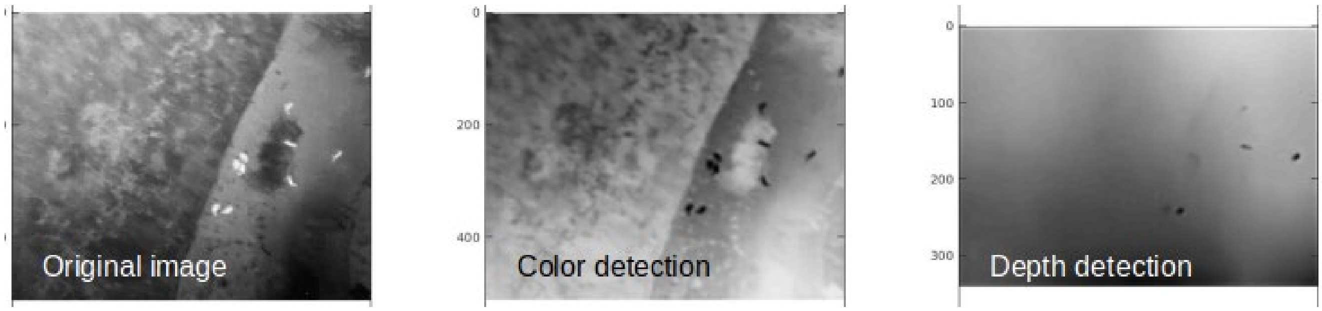
Protocol Development and Image Processing

We first took thermal image data from a local deer farm where the locations and number of animals can be easily acquired. One of the images is shown in here.

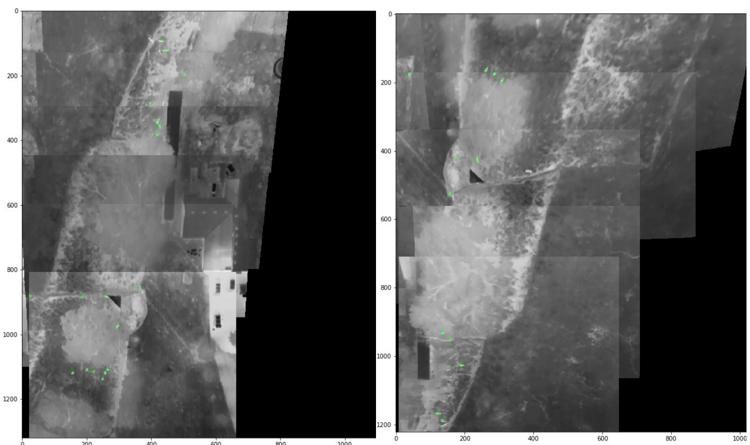
To see the thermal response, images at different altitudes were taken. We then developed a blob detection algorithm to detect the hotspot response from the animals in the thermal images. We analyzed the performance of the algorithm on a set of thermal images, which is able to successfully extract the animals as shown here.



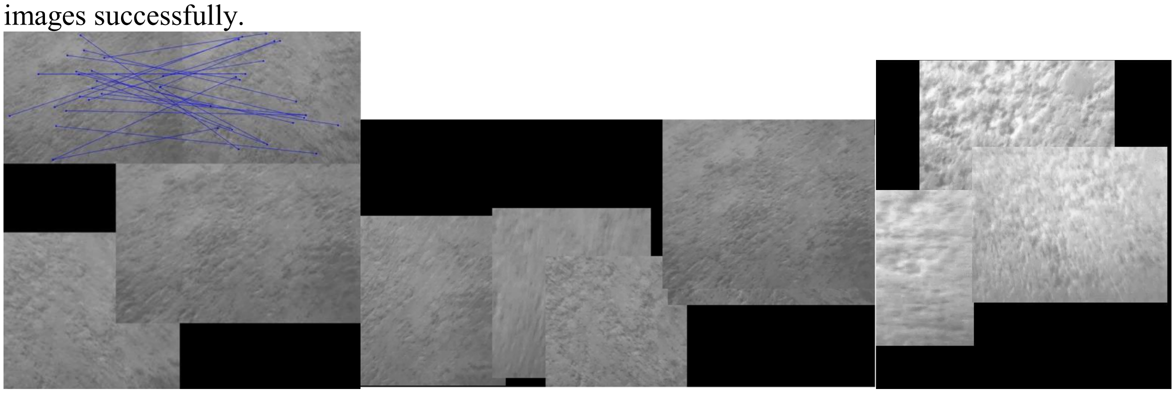
The number of animals extracted from the image and the corresponding black mask is 9.
We also tested depth extraction to validate if the hotspot is above the ground with a certain distance. The purpose is to distinguish the animal from other anomalies such as branches or rocks. The results are shown here.



After detecting and counting the animal for each image, the next step is to detect and count the animals across different images. The stitched mosaic across multiple images from one of the footage is shown here.



However, due to the lack of features in many areas, it is difficult to find the correct correspondences and stitch the images successfully.



When the scene has distinguished features, we developed an algorithm to select less views for ground imagery mosaicking and it is published in Robotics: Sciences and Systems 2017. Despite the difficulties in automatically processing thermal images, we were able to successfully home in on collared moose and determine whether there were calves present.

Evaluating Unmanned Aerial Systems for the Detection and Monitoring of Moose in Northeastern Minnesota

Overview:

Our study population consisted of 22 cow moose fitted with GPS-collars with Iridium-satellite relay capabilities (VECTRONIC Aerospace, Berlin, Germany). Capture and handling of moose was conducted by the Grand Portage Natural Resources Management Department (IACUC Protocol# 1812-36635A). Moose locations were recorded and stored every 30 minutes to GPS collars, with GPS coordinates transmitted to satellites every two hours. We analyzed cow moose movements multiple times a day to identify locations and times for safe and efficient UAV deployment to detect cow moose and calves. Prior to conducting flight missions above cow-calf pairs, we conducted initial test flights over GPS-collared bull moose in May of 2018 to gauge levels of disturbance from UAV flights. We would classify a disturbance if there were any erratic movements (i.e., fleeing from an area) that corresponded in time to UAV launch and flight times. Although none of these initial flights led to a behavioral disturbance, we took precautions in our surveys of cow moose and calves to reduce the risk of disturbance, and continued monitoring movement behavior to identify potential disturbance responses.

We used a DJI Inspire 2 quadcopter equipped with a FLIR Vue Pro 640 for the 2018 surveys and a FLIR Duo Pro R for 2019 surveys. Both thermal sensors were one-band sensors with a spectral interval that measured 7.5 to 13.5 µm. The FLIR Duo Pro R used in 2019 also featured an RGB sensor (4000 x 3000 pixels, 56° x 45° FOV) that allowed us to capture color imagery simultaneously with thermal imagery. Survey flights were planned and conducted using the Pix4Dcapture app (Pix4D, Prilly, Switzerland). Thermal infrared and RGB footage were recorded and stored onboard the UAV for review post flight. Flights occurred from 25 May 2018 to 28 June 2018 (n = 44 flights) and 25 April 2019 to 30 May 2019 (n = 48 flights) at varying times between morning and evening civil twilight (Figure 1.1). Surveys were flown in rectangular grid transects centered over the most recently updated GPS locations of cows. Rectangular grids were used to maximize our coverage in the event that the cow moved off of the last known location prior to launching the UAV, and to minimize the risk of animal disturbance. To minimize animal disturbance from our presence on the ground, we launched the UAV from reservation and county roads or trails that were between 300-m and 600-m Euclidean ground distance from updated moose locations. This distance also allowed us to maintain visual contact of the UAV, and sufficient radio communication between the remote and quadcopter. Additionally, we flew at altitudes that were near the maximum allowable 122 m (~400 ft) above ground level; altitudes ranged from 75 m to 121 m depending on terrain elevations relative to launch points.

Moose Demographic Data and Predation Events:

Thermal infrared video footage was reviewed manually post flight by human observers. Observers were trained to detect living animals in thermal video by viewing sample footage collected over domestic animals (e.g., domestic bison, cows, and captive deer) of known location and abundance, to develop a sight picture for large-bodied mammals in thermal imagery (Fig 1.2). The same observers reviewed thermal video footage for both seasons. Adult moose and calves were visually identified from the video footage by their shape and brightness in the footage, the latter also by their proximity with the cow. Detections of target moose (i.e., bright white silhouettes that often resembled a large animal body with a head) were confirmed by updated cow GPS locations collected during and post UAV survey times. We attempted to utilize object-based image analysis (OBIA) to quantify moose detections from our thermal video footage. However, we would have needed to greatly increase the resolution of our FLIR sensors, or fly the UAV at lower altitudes, increasing the risk of disturbing moose and striking hazards (e.g., tall trees), to effectively apply OBIA methods to discern moose from other objects.

For 2018 flights, moose detections were verified by matching the position of the UAV on the flight transect where a thermal detection was observed (based on flight time) to the location and time stamp from the collared moose that corresponded to that time in the flight. In 2019, detections were verified by matching GPS coordinates of the UAV and of the moose at given flight times. This was possible because the FLIR Duo Pro R used in 2019 featured geotagged video footage that provided GPS coordinates for the UAV every second of survey time, whereas the FLIR Vue Pro used in 2018 did not. Color (RGB) footage was also reviewed for flights with positive thermal detections as an additional verification throughout the 2019 season. Thermal detections of cows and counts of calves were recorded for each flight.

We investigated suspected calf predation events by flying over known collared cow-calf pairs after large movements occurred in a short period of time, with the cow commonly circling back to the suspected predation location. We considered a predation event to be positively confirmed if we could detect the cow without the previously detected calf. Conversely, we concluded that a predation event was unsuccessful or did not occur by thermally detecting the calf with its mother. Our conclusions about predation events through remote sensing were corroborated by subsequent on-foot investigations.

Results and Conclusions:

We successfully applied UAV technology and FLIR sensors to detect collared adult cow moose and calves in a heavily forested region of northeastern Minnesota (Fig 1.4). The increase in detection success from our first to our second field season was a result of developing preliminary relationships between adult moose detection and environmental and temporal covariates. This improvement provides validation that our final detection model (which incorporated both years of flight data) captured useful relationships for researchers planning to conduct ungulate surveys with UAV and FLIR technology. We maximized detection success during our second season by conducting survey flights earlier in the calving season to take advantage of leaf-free conditions. We also concentrated our flight efforts within the early morning hours when temperatures were coolest, and less thermal energy was being emitted from ground objects. Snow cover present in our second season (2019) during the early spring also improved thermal detection by covering ground objects and maximizing the thermal contrast between moose and their environment. Importantly, this research provides a valuable method for determining ungulate reproductive success and calf survival using a less invasive method than handling and collaring calves, which may induce additional stressors.

Our FLIR-equipped UAV demonstrated clear advantages over conventional methodology for monitoring moose calving success by increasing animal detectability while reducing survey cost and effort. The inclusion of FLIR sensing with UAV was crucial for detecting cow-calf pairs in forested environments. Moose were often obscured by canopy cover in RGB footage, whereas FLIR footage allowed for easy detection (Figure 1.3). Challenges of visual detection without FLIR are also reflected in the state-wide aerial counts conducted by the MNDNR. The MNDNR reported an average estimated detection probability of 61% for their 2018 aerial survey using conventional aircraft and visual observation, compared to our detection probability of 85% using UAV and FLIR technology (N.B., the area we surveyed was much smaller than the units surveyed by the MNDNR across moose range). Further, unmanned aerial systems offered a relatively cheap method to collect aerial data and following the initial financial investment for UAV equipment, our operating costs were minimal, with ground transportation being our largest field expenditure.

We intended to integrate object-based image analysis (OBIA) methods for detecting moose in aerial imagery. However, because we employed an economical FLIR sensor with relatively low resolution (640 x 512), we experienced challenges using OBIA. Flying the UAV at lower altitudes may have compensated for low resolution but would have increased the potential to disturb moose and have been problematic for terrain avoidance. Dense forest further convoluted the OBIA process because of the many bright returns caused by heated, non-living ground objects among the trees. These objects sometimes resembled moose in brightness and shape (e.g., vegetation would distort the recognizable silhouette of a moose), greatly decreasing the ability of OBIA software to accurately classify objects. Instead, we opted to manually review the video footage, which served to be a simple and efficient way to identify collared moose, and was especially effective for identifying calves present with cows (distinguishing different sized targets with OBIA adds further complexity). Manual detection required ~ 16 combined hours per observer over our two seasons, averaging ~ 10 min per UAV flight for each observer. Based on our results, we conclude that until sensors with higher resolution become more economical, or OBIA methods overcome lower resolution limitations, the technical hurdles of implementing OBIA may only be worthwhile for researchers with access to high-resolution sensors and those attempting to detect non-collared animals, especially over large spatial extents.

This work served to hone UAV methodology for the application of wildlife research. We found that a readily available off-the-shelf UAV equipped with FLIR technology was an effective platform for detecting collared moose and counting and monitoring calves in a densely forested environment. We identified several ongoing environmental challenges and technical limitations, but we also realized significant improvement in detection success from one season to the next. Our efforts to model factors driving moose detectability allowed us to establish best practices for maximizing UAV efficacy with FLIR sensing for surveys of forest-dwelling animals. It is likely that the continued improvement and reduced costs of UAV and associated sensors, will open new doors to the types of data collection possible and expand on potential target species. We postulate that FLIR sensor-equipped UAV—especially with the capability to collect geo-tagged thermal imagery—could be effective for monitoring reproductive success (e.g., birthing success, twinning rate, and young survival) of other GPS-collared, large-bodied mammals.

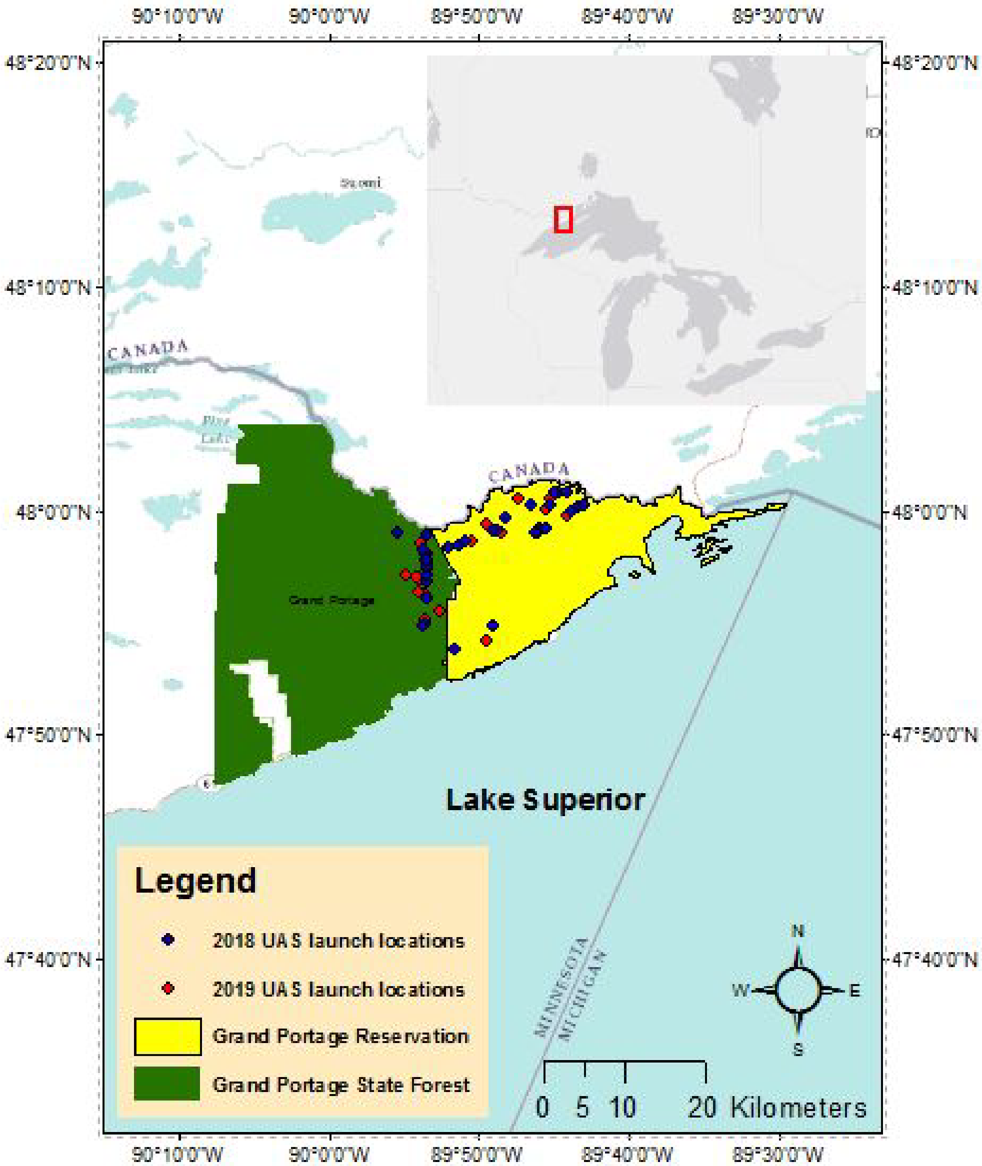


Figure 1.1 Study area of Grand Portage Reservation and eastern Grand Portage State Forest, in northeastern Minnesota, USA. Unmanned aerial system (UAV) launches are shown across the study area for the 2018 and 2019 field seasons.

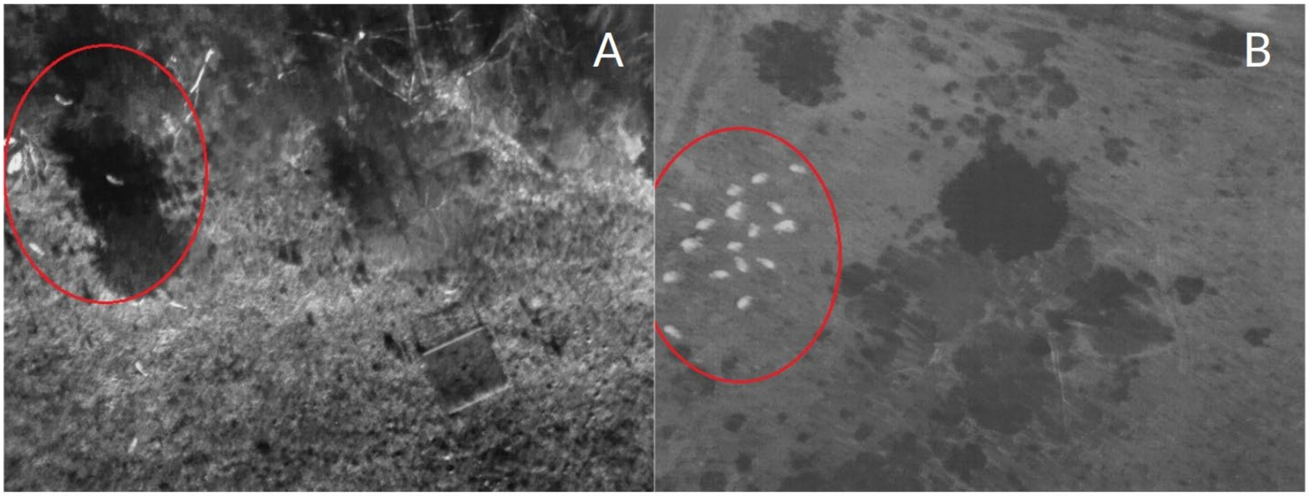


Figure 1.2 Side-by-side comparison of thermal infrared photos of a captive bison herd captured during clear sky conditions (A) and overcast sky conditions (B). Imagery was collected at the University of Minnesota's Cedar Creek Ecosystem Science Reserve during July 2018. This contrast demonstrates the positive effect that overcast sky conditions have on thermal detection.

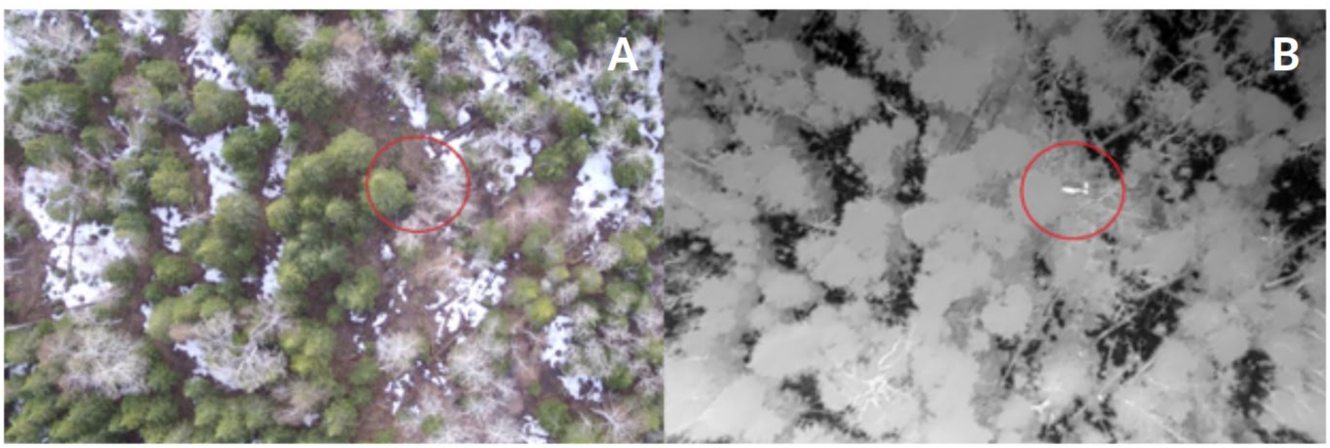


Figure 1.3 Comparison of UAV-gathered RGB imagery (A) and thermal infrared imagery (B) of a cow moose with two calves in northeastern Minnesota during spring of 2018-2019. These photos were captured at the same time and location over this cow and her calves, which demonstrates the advantage of increased detection success from thermal infrared technology over RGB photography.

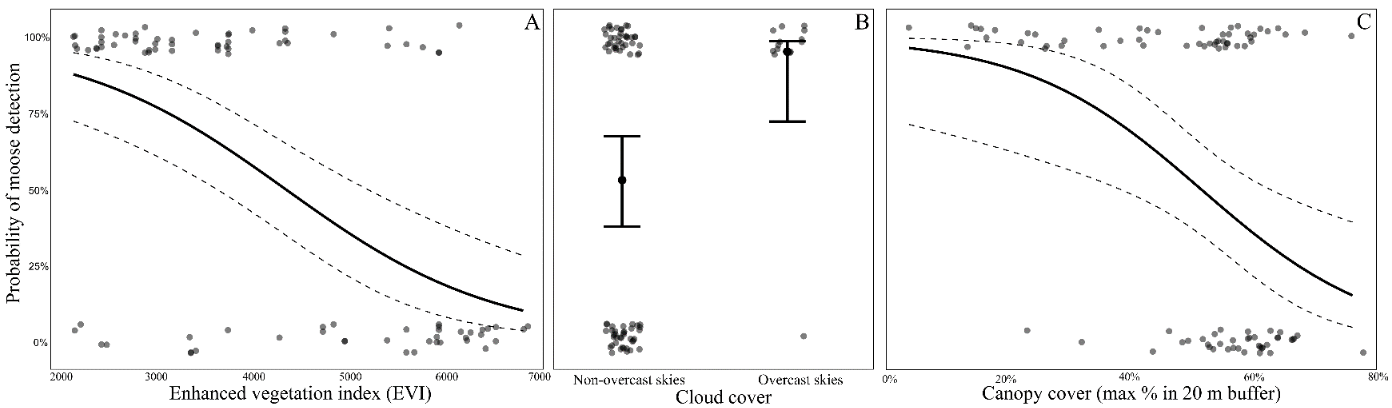


Figure 1.4 Detection success of GPS-collared adult cow moose in northeastern Minnesota during spring of 2018-2019 using thermal technology mounted on a UAV. Moose detections are plotted as raw values on the y-axis as either 100% (present and detected) or 0% (present but not detected). The predicted mean and 95% confidence intervals are based on the best-supported model for detection. We predicted moose detection for all sampled values of A) the remotely-sensed enhanced vegetation indices (EVI) over the moose's location, B) whether or not the sky was overcast during the flight (field-observation) while holding the other values in the best-supported model at their means, and C) maximum canopy cover around the moose's GPS location during the time of the flight.

Linking multi-spectral vegetation data with moose habitat

Overview:

During spring 2019 we flew our quadcopter UAV over areas of moose habitat that were associated with important life history events and collected fine scale multi-spectral data (Figure 1.5). We flew over four types of locations: 1) moose calving sites, 2) moose peak lactation sites (defined as 26 days post-parturition), 3) mortality sites where it was confirmed that moose calves had been killed, and 4) locations where living moose had been recently. Moose calving sites, calf mortality sites, and peak lactation sites were provided to us by Dr. William Severud and Dr. Glenn DelGiudice of the Minnesota Dept. of Natural Resources. Drs. Severud and DelGiudice were interested in collaborating with us for the moose habitat component of our research after we gave a presentation of our capabilities with the UAV and associated thermal and multi-spectral sensors. Most of the sites we flew over were a result of the MN DNR's efforts to understand the causes or moose calf mortality in northeastern MN (Severud et al. 2015). Our aim was to determine if the data from our multi-spectral sensor could collect vegetation data that would allow us to discern patterns in the vegetation density and vegetative productivity that might be related to the type of event that had occurred at the location (e.g., calving site vs. mortality cite). We also assessed whether patterns of vegetation and vegetative productivity differed from the location of the event (e.g., peak lactation site) relative to the surrounding area based on our flight (an area ~ 290,000 – 785,000 m^2 around each location).

To make a more meaningful connection between patterns of vegetative greenness captured by our multi-spectral sensor and moose habitat at these locations, we also flew over sites where Dr. DelGiudice's team collected detailed vegetation data and related the vegetation patterns to neonate moose survival (Severud et al. 2019). Connecting patterns from data collected by our multi-spectral sensor to on-the-ground vegetation surveys would allow us to then relate vegetation patterns at other sites where important moose events occurred but on-the-ground vegetation surveys were not conducted. Data collected at these sites was based on moose ecology in order to assess how well a site provided forage and protective cover from potential predators. Forage was assessed at an 11 m^2 area around the location by counting saplings and shrubs that may provide forage for moose. Calf-visibility (horizontal visibility) was assessed at a 15 m^2 radius around the site by counting the observed visible percentage of a life-size cardboard cut-out of a standing moose calf silhouette from each of the cardinal directions.

UAV Flight Data:

Flights were conducted over 30 moose event sites (calf mortality/predation = 16; calving = 8; living = 5; peak lactation = 4) including five sites that contained on-the-ground vegetation surveys. Flights were conducted in the spring of 2019 as close to the date of historical moose event (all events occurred in the spring of 2015). Our UAV allowed us to collect data over each event site and the surrounding 300-500 m area. The UAV was equipped with our Parrot Sequoia multi-spectral sensor and an RGB camera. Flights were conducted between 300 – 500 feet above ground level depending on tree canopy and other safety precautions.

We processed and ortho-rectified both multi-spectral and RGB data using Pix4D software in Dr. Joseph Knight's remote sensing lab at the University of Minnesota. The multiple bands collected by Parrot Sequoia were used to estimate Normalized Difference Vegetation Index (NDVI), a metric of greenness or plant health at a resolution of ~$1/8^{th}$ – $1/5^{th}$ of a meter depending on the flight altitude (Figure 1.6). For each location we downloaded both current and historical satellite-based estimates of NDVI from NASA's MODIS sensor (Didan 2015) because it provides coarse estimates of NDVI that allow us to compare among sites instead of only within sites (i.e., data from our multi-spectral sensor provides relative estimates of NDVI only).

Analysis:

To assess how moose are using the landscape, we quantified values of NDVI both within a 30 m^2 area of the event location and within areas of increasing distance from the event location (buffered rings at: 30-50 m, 50-100 m, 100-150 m, 150 – 200 m, 200 – 250m, 250 – 300 m, 300 – 350 m, 350 – 400 m; Figure 1.7). We hypothesized that the amount of NDVI alone may not allow us to discern differences among and within our sites. We believed that the configuration of the vegetation may play a strong role in providing both moose forage and cover/protection for moose and calves. To connect our vegetation data with the on-the-ground measurements of moose forage and visibility, we sampled both the center location (where the event occurred) along with randomly located points within each buffer ring (Figure 1.7; Figure 1.8-A). The locations were then buffered by both 11 m and 15 m (Figure 1.8-B), which correspond to the on-the-ground field measurements collected for calf visibility (15 m) and forage (11 m) by Severud et al. (2019). To calculate a variety of landscape metrics associated with the configuration of NDVI in the landscape, we first converted the NDVI into three classes (classified factors are required for analysis) representing the lowest third, middle third, and highest third of NDVI values (Figure 1.8-C). We then calculated over 30 spatial configuration metrics for each 11 m and 15 m location (30 location sites and > 200 random locations within buffered rings). These data were analyzed using the "landscapemetrics" package (Hesselbarth et al. 2019) in program R (R Core Team 2019). Linear models assessing the relationships between our sampled data and both on-the-ground measurements and within site variability were also conducted using program R.

Results:

Overall, we did not find consistent patterns of changes in mean NDVI levels collected from our multi-spectral sensor and the distance to the event site for any category of event (e.g., calf predation [Figure 1.9], calving). However, using NASA's satellite-derived estimates of NDVI we found differences among the site types (Figure 1.10). Locations with living moose had higher overall values of NDVI compared to calving and mortality sites.

We found strong correlations between our estimates of vegetation configuration and on-the-ground moose habitat sampling (Figure 1.11). A landscape metric that estimates the edge and interior shape index of our NDVI classifications had a positive correlation with on-the-ground estimates of moose forage (adjusted $R^2 = 0.92$; Figure 1.11-A). Calf visibility was strongly associated with several landscape metrics and a metric describing NDVI patch heterogeneity had a strong negative correlation with calf visibility (adjusted $R^2 = 0.97$; Figure 1.11-B).

Because of the strong correlations between these aspects of moose habitat and the metrics we calculated, we then used the two most correlated metrics to assess changes in moose forage and visibility at locations where no on-the-ground vegetation sampling was conducted. Among sites, we found estimated moose forage was higher at moose calving, peak lactation, or where moose were currently found (GPS-collared) compared to mortality sites (Figure 1.11-A). Modeled relationships showed that within sites, living moose were found in areas with more available moose forage (relative to calving and mortality sites) and that the living moose were often found in the area of highest estimated forage availability compared to the surrounding area (negative relationship between forage and distance; Figure 1.12-B).

We found significantly lower amounts of estimated horizontal visibility at calving sites relative to calf mortality and living sites using the best landscape configuration metric from our UAV-collected NDVI values. Calving sites had a significant negative relationship between inverse horizontal visibility and distance from the calving site suggesting moose seek out areas with the lowest visibility to give birth at relatively fine spatial scales (300 – 500 m; Figure 1.13).

Conclusions:

- We found strong correlations with on-the-ground measurements of vegetation (based on both NASA satellite-derived overall greenness and relative metrics of NDVI from our UAV-based multi-spectral sensor).
- Sites that had locations associated with living moose demonstrated that moose sought out the greenest patches at a fine spatial scale.
- Moose sought out calving sites in locations with the relatively lowest levels of horizontal visibility; calf mortality sites appear to be associated with areas of higher visibility.
- Our ability to link landscape metrics with important moose resources (forage and horizontal cover) demonstrated that the use of UAV-collected moose habitat data provides efficiency and much larger extents for capturing how moose make fine-scale decisions about foraging and calving.
- Use of UAVs to collect fine scale habitat data, especially when it can be linked with on-the-ground measurements, provides a potentially powerful and time saving tool for managers hoping to understand wildlife-habitat relationships in critical areas.
- Our findings will be further refined and shared with Dr. Glenn DelGiudice of the DNR for further consideration.

Citations:

Didan, K. (2015). MOD13A2 MODIS/Terra Vegetation Indices 16-Day L3 Global 1km SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2019-03-01 from https://doi.org/10.5067/MODIS/MOD13A2.006

Hesselbarth, M.H.K., Sciaini, M., With, K.A., Wiegand, K., Nowosad, J. 2019. landscapemetrics: an open-source R tool to calculate landscape metrics. - Ecography 42:1648-1657(ver. 0).

R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

Severud, W. J., G. D. DelGiudice, and T. R. Obermoller. 2019. Association of moose parturition and post-parturition habitat with calf survival. The Journal of Wildlife Management 83:175–183.

Severud, W. J., G. D. Giudice, T. R. Obermoller, T. A. Enright, R. G. Wright, and J. D. Forester. 2015. Using GPS collars to determine parturition and cause-specific mortality of moose calves. Wildlife Society Bulletin 39:616–625.

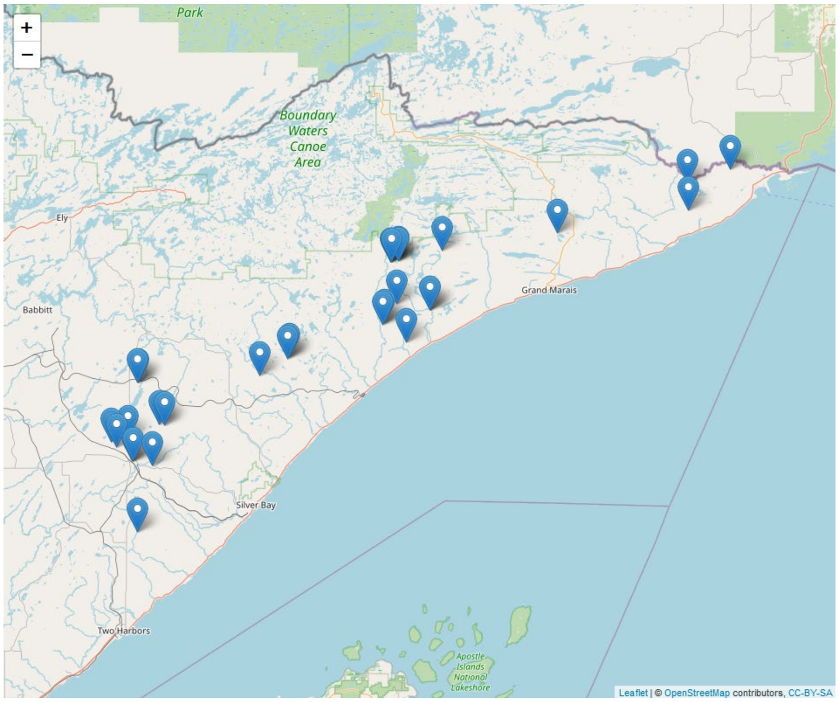


Figure 1.5) Locations of UAV flights in northeastern Minnesota where multi-spectral data was collected at locations associated with critical moose-related events.

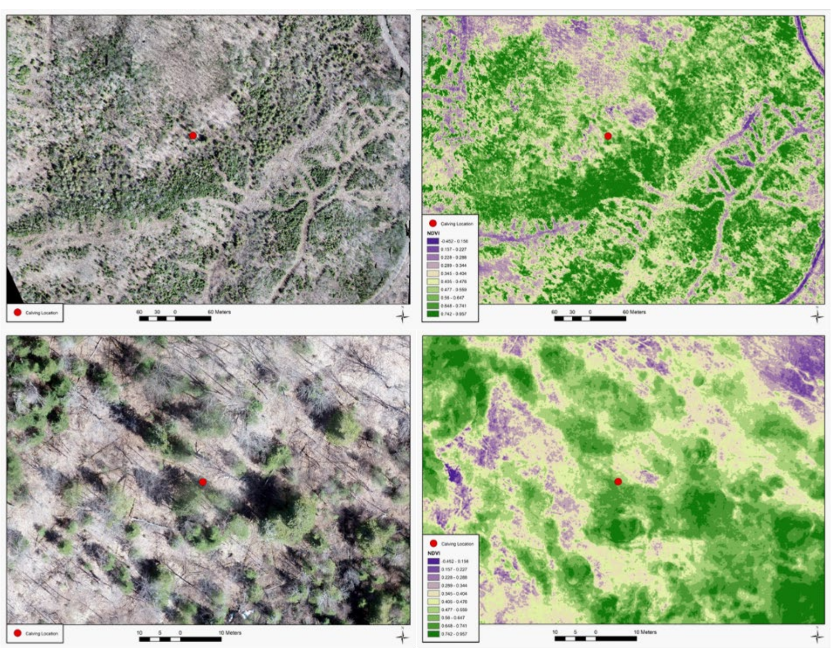


Figure 1.6) RGB (left panels) and estimates of relative NDVI ("greenness"; right panels; purple = lowest, dark green = greatest) at two moose calving sites in 2015.

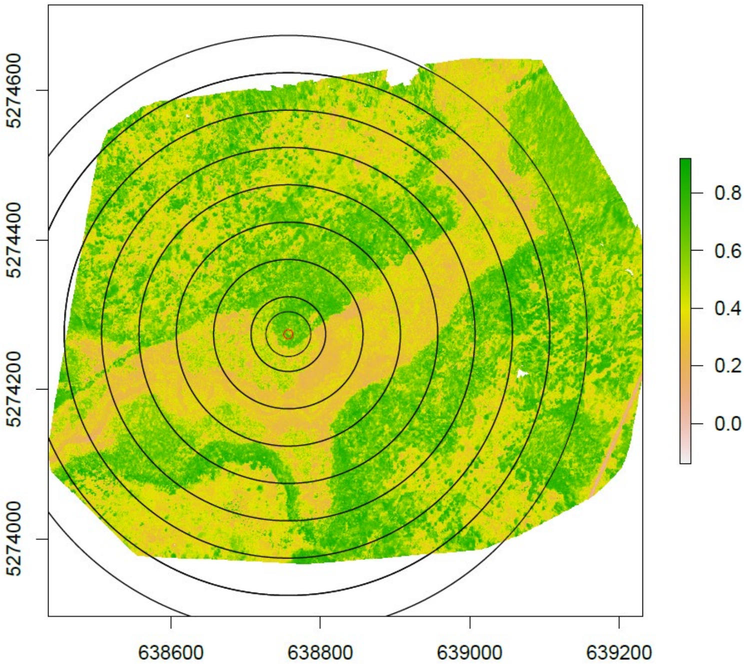


Figure 1.7) Example of the buffered rings used to assess changes in NDVI at each of the 30 moose event sites. The red point in the center is calving location.

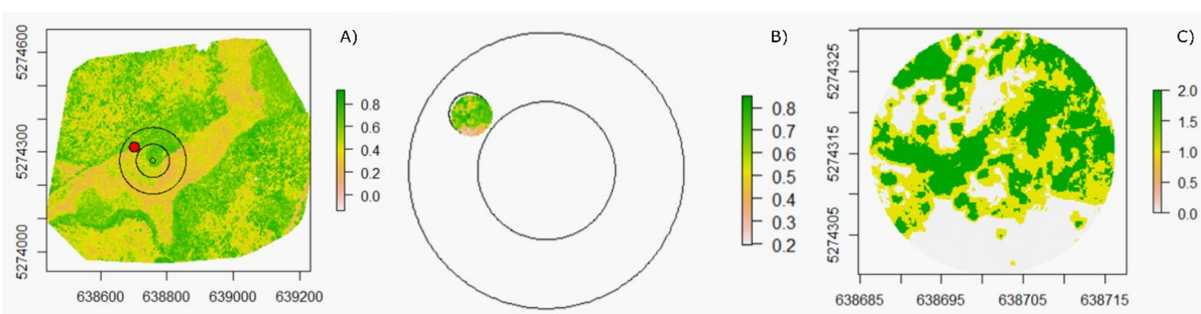


Figure 1.8) 4A: The 50-100 m buffered ring from Figure 3 with an associated random location (red point) inside. Locations were buffered at both 11 and 15 m and we analyzed the UAV-collected NDVI data within those buffered areas (4B). Within those areas we converted the NDVI estimates into low, medium, and high values in order to create landscape configuration metrics associated for each location (4C).

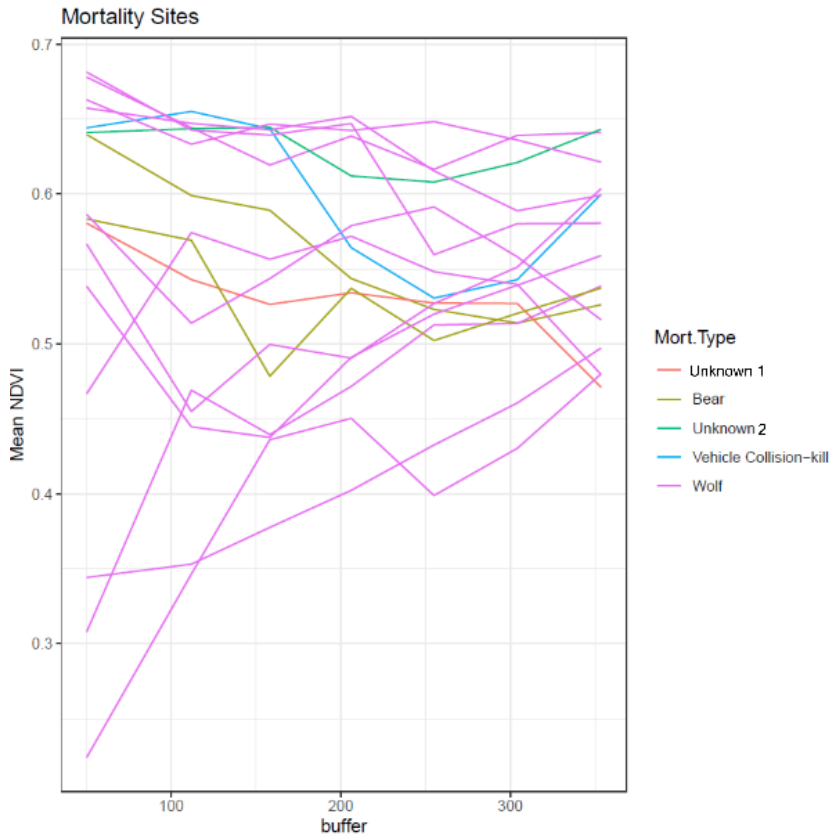


Figure 1.9) Relationship between mean NDVI (Y-axis) at the center of each location and among equal size rings (X-axis; units in meters) for moose calf mortality event sites. Mortality types are designated in the legend. Types were determined by researchers investigating kill sites of GPS-collared calves in 2015.

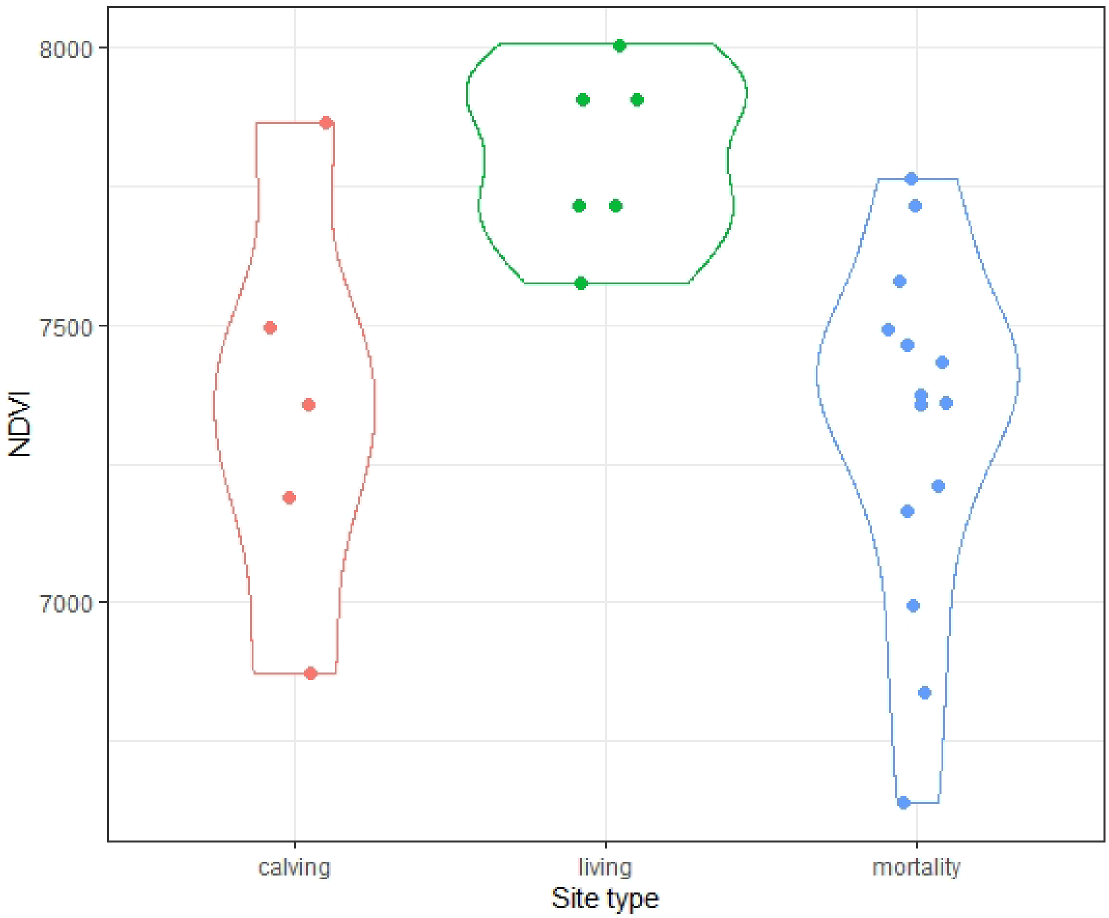


Figure 1.10) Satellite-derived estimates of NDVI (greenness) among different moose event sites.

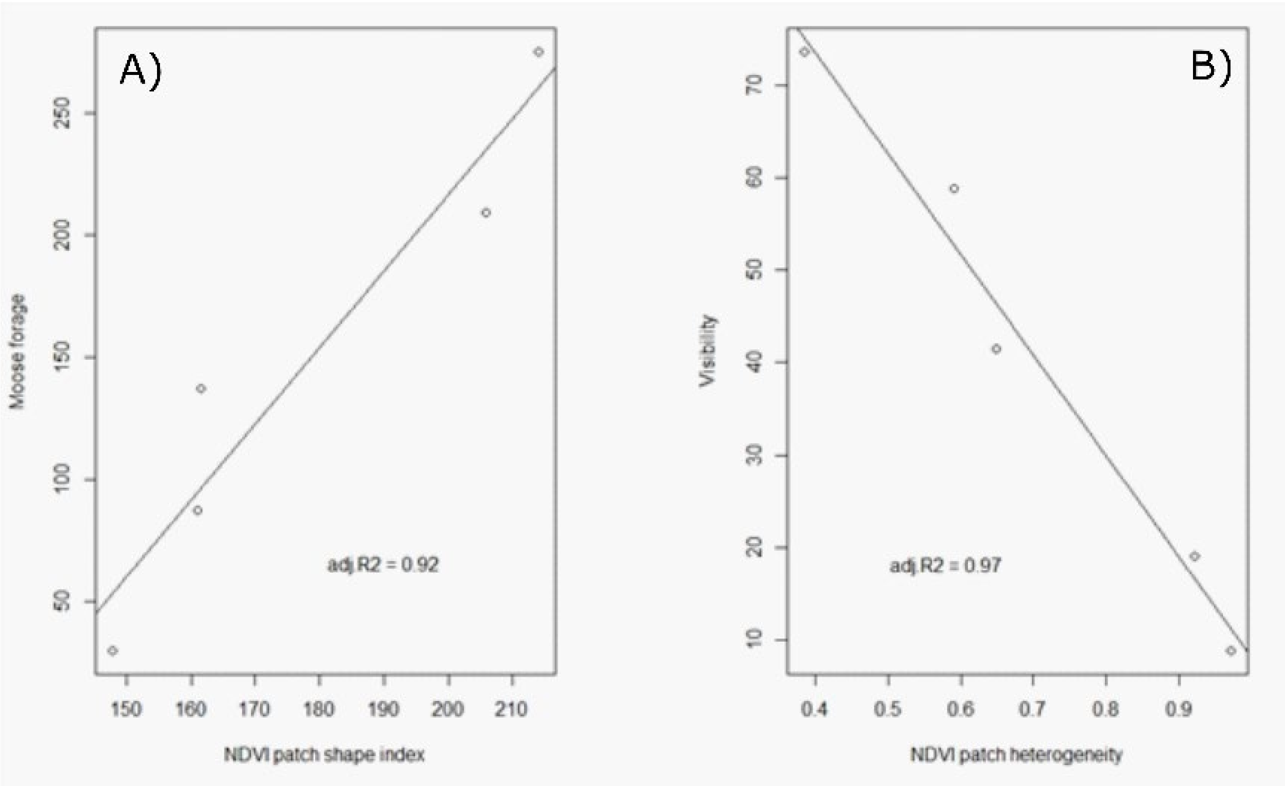


Figure 1.11) Linear relationships between landscape configuration metrics of NDVI from our multi-spectral sensor and on-the ground estimates of moose forage (A) and calf visibility (B).

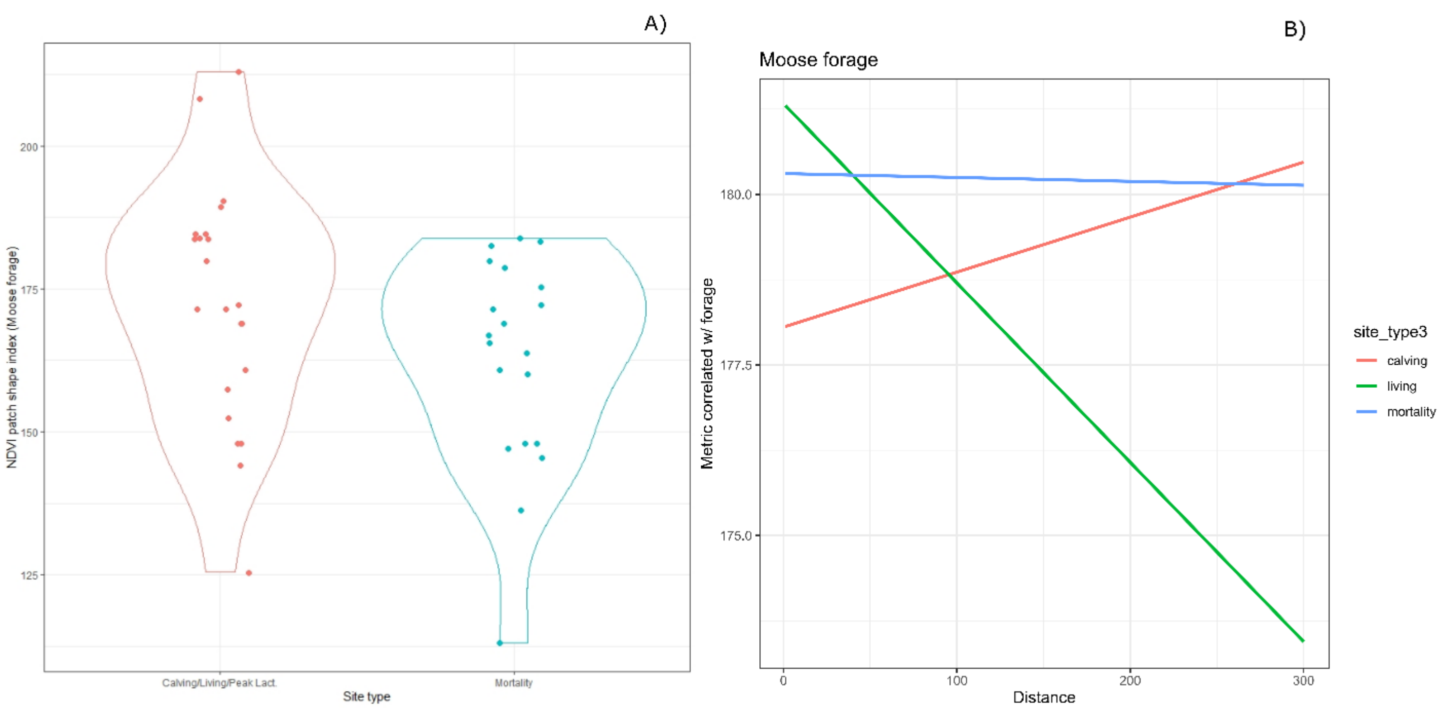


Figure 1.12) Using our landscape configuration metric of NDVI from our UAV-collected data that was most associated with moose forage, we examined the relationship among sites and the amount of estimated

moose forage at the central location for each type of site (calving, etc.; A). We modeled the relationship between distance from the central location and estimates of moose forage within the surrounding landscape (B).

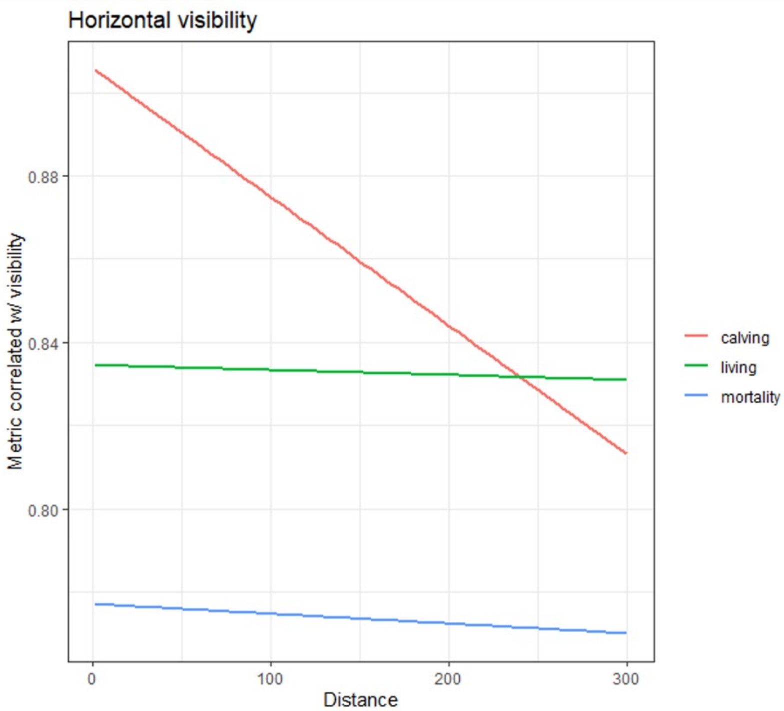


Figure 1.13) Using our landscape configuration metric of NDVI that is negatively associated with calf/horizontal visibility, we examined the relationship among sites and the amount of estimated visibility at the central location for each type of site (calving, etc.). Here we show the modeled the relationship between distance from the central location and estimates of inverse visibility within the surrounding landscape.

Summary (Activity 1)

- Using UAVs to automatically home in on VHF-collared individuals is feasible; however, it still requires custom-built hardware and software. We have made important strides towards making this a viable research technique.
- Small thermal cameras deployed on UAVs can produce images that identify medium to large-bodied mammals. Although the characteristics of these images lack enough unique features to reliably stitch them into large aerial images, we found that individual animals could be manually identified and counted within single images or frames of video.
- Automated processing of thermal images (to identify and count individual animals) is possible; however, it requires a very high-resolution image. We found that that the only way to produce such images was to fly our cameras very low to the ground (thus increasing potential impact on the study animals and also reducing the area that can be surveyed per flight). As thermal camera technology improves, the resolution of collected images will be greater and thus allow for automated ID of animals at higher flight elevations.
- We found that UAVs with FLIR sensing is a promising tool for quantifying moose calving success, twinning rate, and calf survival, and may be effective for monitoring the reproductive success and survival of other wildlife species in densely forested regions.

- We show that UAVs equipped with a muli-spectral camera can produce reliable estimates of forage availability and horizontal visibility. We found that female moose chose calving sites with lower visibility while adult moose usually chose areas with greater visibility yet more forage. Calf mortality sites tended to be in large patches of relatively high visibility habitat.

ACTIVITY 2:
Description: System to monitor and identify changes to sensitive ecosystems

We will utilize an existing UAV system, but develop a user friendly flight planning system that will maximize visual coverage, imagery collection, and post-processing capabilities to summarize collected data across space and through time. We will demonstrate this ability across several ecosystem types. The methods and software we develop for this activity can serve a wide array of ecological research questions, monitoring of the health of ecosystems, the effectiveness of management actions, the spread of disease or invasive species and potentially spills in waterways. This activity also has: **i) a lab component led by the Dr. Isler's graduate research assistant** that focuses on the development of the software and **ii) a field component, conducted by Dr. Forester's graduate research assistant**, to collect aerial imagery across a variety of ecosystems at the Cedar Creek Ecosystem Science Reserve (owned by the University of Minnesota).

i) The CS&E graduate research assistant will consider a number of trade-offs that need to be addressed to effectively use autonomous aerial vehicles in surveying and ecosystem monitoring tasks. The first one is the trade-off between coverage and resolution. Because an aerial vehicle has a downward looking camera, as the altitude of the vehicle increases, so does the camera footprint on the ground (i.e., the vehicle can cover larger areas by flying higher). However, this increased footprint comes at the expense of resolution (the number of pixels occupied by an object of interest in the image). Depending on the task and sensing requirements, the optimal altitude must be determined. Second, the amount of data collected by imaging sensors can easily overwhelm the storage and computation requirements of many systems. Most UAVs have limited storage and computation capabilities. Videos collected over time across multiple surveys can be hard to access and manage for users even after they are copied over to a workstation.

We will develop image processing software to summarize imagery collected in a single flight. This will be in the form of a 2.5 dimensional reconstruction of the environment. We will generate a mosaic corresponding to the (roughly flat) ground plane along with objects such as trees sticking out as convex polyhedral objects. Although existing software can mosaic aerial imagery, the programs usually fail when data are collected at low-altitudes. Therefore a new mosaic software will be developed. The map will be geotagged and aligned so that changes across time can be easily observed by going back and forth in time. We will demonstrate the effectiveness of the software by processing the imagery collected and stored from the UAV surveys conducted by the FWCB graduate research assistant at the Cedar Creek Ecosystem Science Reserve (CCESR). Time and resources permitting, we will investigate automated detection of major changes.

ii) The FWCB graduate research assistant will fly a UAV over areas of CCESR that experience ecosystem change through time. Based on where we have permission to fly transects, we will conduct case studies by collecting data over: 1) oak forests experiencing oak wilt, 2) fields where invasive plant species are spreading (*Elymus repens*), and 3) wetlands where cattails are highly prevalent. We will capture imagery from our UAV system equipped with multiple sensors (RGB and thermal imagery cameras) of these areas during September through October 2017. We chose oak wilt because it is a serious concern in Minnesota. This disease is caused by the non-native fungus *Ceratocystis fagacearum*, and is responsible for killing large numbers of oaks annually in Minnesota. Our second case study, focused on capturing the prevalence and spread of *Elymus repens,* is relevant because it will test our ability to identify the spread of terrestrial invasive plants. Finally, with our third case study, we will test the ability of our platform to map the extent of aquatic invasive species; cattails are of particular interest because the removal of the invasive cattail species often requires large expenditures or intensive management efforts. Collectively, our demonstrations of how UAV's can be utilized to quickly determine the extent and spread of disease and invasive species will be of great use to natural resource managers and researchers. Flights and corresponding safety precautions will follow rules and regulations set forth in the Federal Aviation Administration's Certificate of Authorization granted to the University of Minnesota. The altitude of the flights is will vary for each example, but all will be below 400 feet above ground level and likely about 200-300 feet above ground level. We have been granted access to fly over these areas by the Associate Director (Dr. Forest Isbell) of CCESR.

The aerial imagery provided from these flights will be utilized by the CS&E graduate research assistant to develop the software and provide data to researchers working at CCESR who have an interest in these questions. The FWCB graduate research assistant will conduct more flights at CCESR during 2018 (July- September). We will work with CCESR staff after 2017 to determine if the areas of image collection should change during the following year to answer new questions and also to test our newly developed software with different aerial imagery.

Summary Budget Information for Activity 2: **ENRTF Budget: $ 160,190**
Amount Spent: $ 160,190
Balance: $ 0

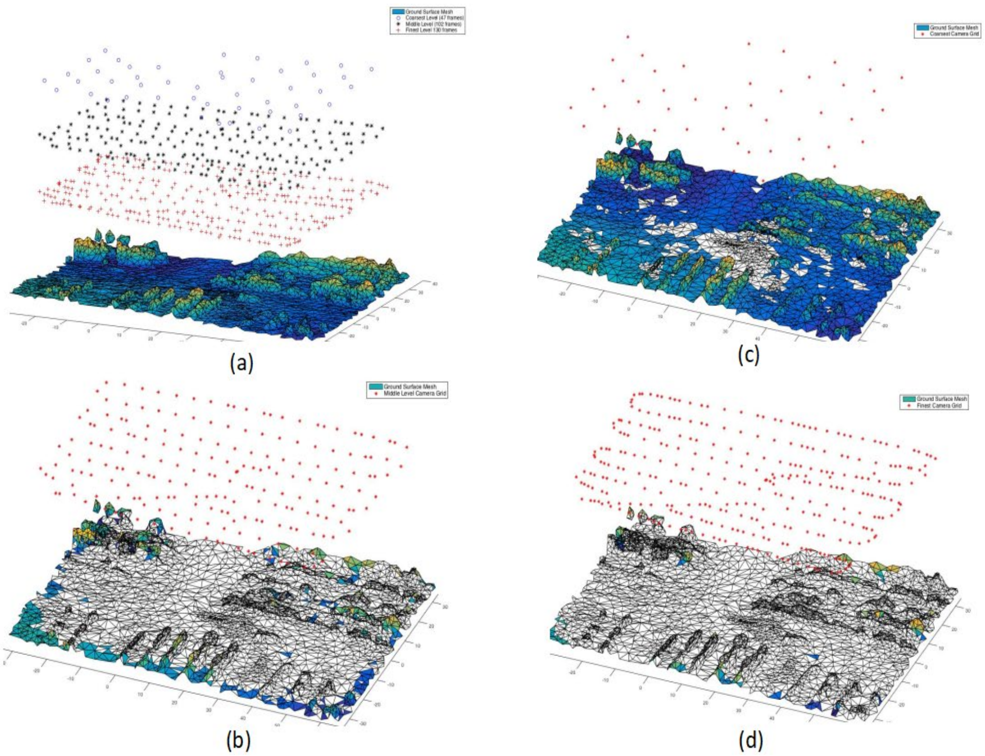
Outcome	**Completion Date**
1. UAV flights to collect data over different ecosystems in the Cedar Creek Ecosystem Science Reserve (CCESR).	12/01/2017
2. Development of capabilities for geo-referencing imagery, comparing changes in the images, and creating a user-friendly interface for the software designed to handle aerial imagery from flights.	07/01/2018
3. Second year of flights at CCESR during a slightly different time of year (and potentially over different area in CRESR) to collect more imagery and further test the software developed in Outcome 2.	09/01/2018

Activity 2 Status as of 01/01/2018: Now combined in 07/01/2018 status update.

Activity 2 Status as of 07/01/2018:
To date, we have collected UAV imagery from three locations that mimic potential management situations for MN land managers. In the first, we partnered with Dr. Rebecca Montgomery in the Forestry Dept. (UMN) to understand how canopy phenology may be linked to oak wilt, a disease killing oak trees in MN (**Image 5**). We conducted flights over an area CCESR where every tree has been catalogued on a twice-weekly basis during four weeks in the fall to identify patterns of leaf senescence. We will repeat these surveys again this fall (2018).

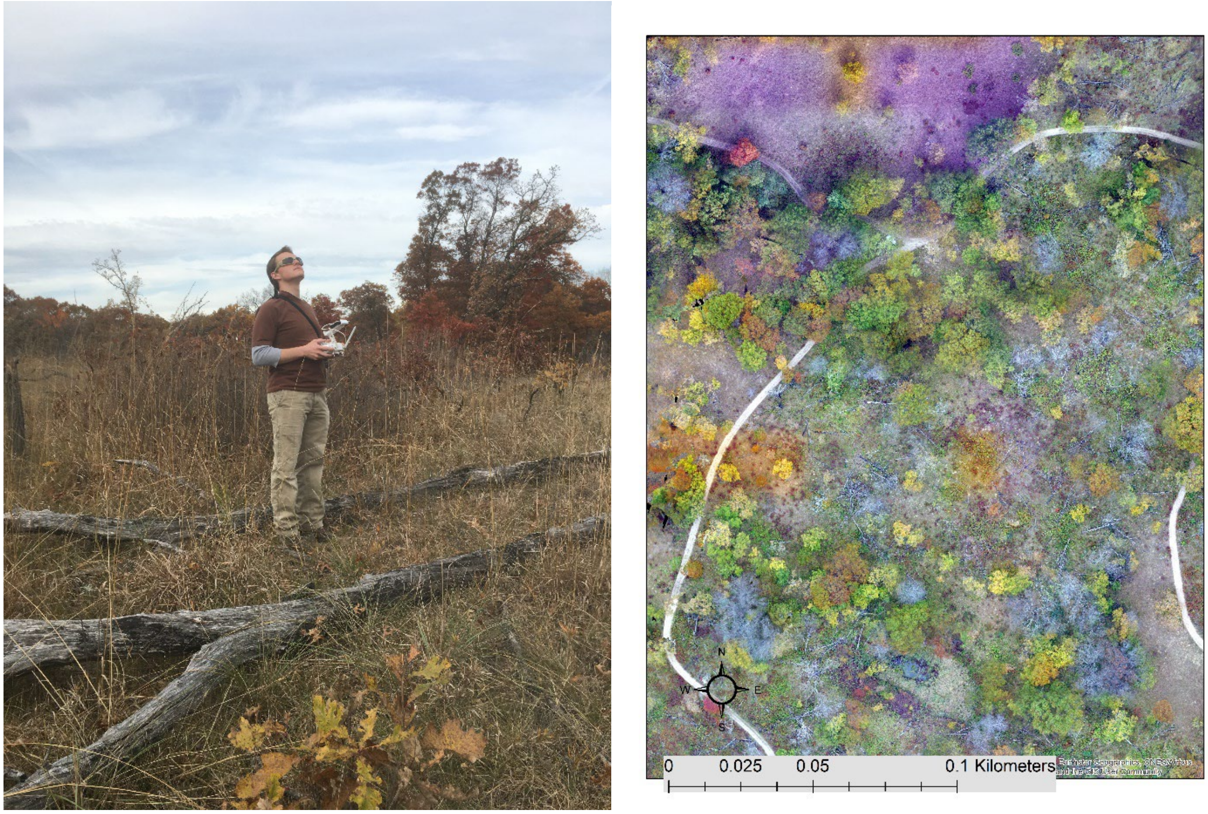
We also conducted flights before and after grass transect harvesting on experimental plots (**Image 6**) at CCESR. The purpose was to understand if we can identify landscape change at a fine scale and determine the size of the change in biomass. Developing protocols like these will help land managers test the efficacy of prescribed burns or invasive species removal.

Finally, we used a multi-spectral sensor to collect imagery along a lakeshore in CCESR. We will repeat this flight again during summer to demonstrate the abilities of the multi-spec to catalog and delineate vegetative changes in aquatic systems.



Dr. Isler and his graduate student Cheng Peng developed a view selection methodology, which can be used to select informative views from an image sequence which can be used as input to off the shelf image reconstruction software such as AgiSoft and Pix4D. With our view selection mechanism, reconstruction and image mosaic creation can be reduced from multiple hours to a few minutes. These results will be presented at a highly selective robotics conference at the of June.

We are currently collaborating with Dr. Joseph Knight (unpaid personnel on this project) who runs a remote sensing lab at the Univ. of Minnesota. We are utilizing the latest software (e.g. Pix 4D, Erdas) to geo-reference and stitch imagery and conduct analyses of landscape change from our thousands of collected images. We will continue to work on ways in which this can be made a more user-friendly experience for MN land managers who wish to incorporate drones to improve management actions and better quantify the efficacy of the results.



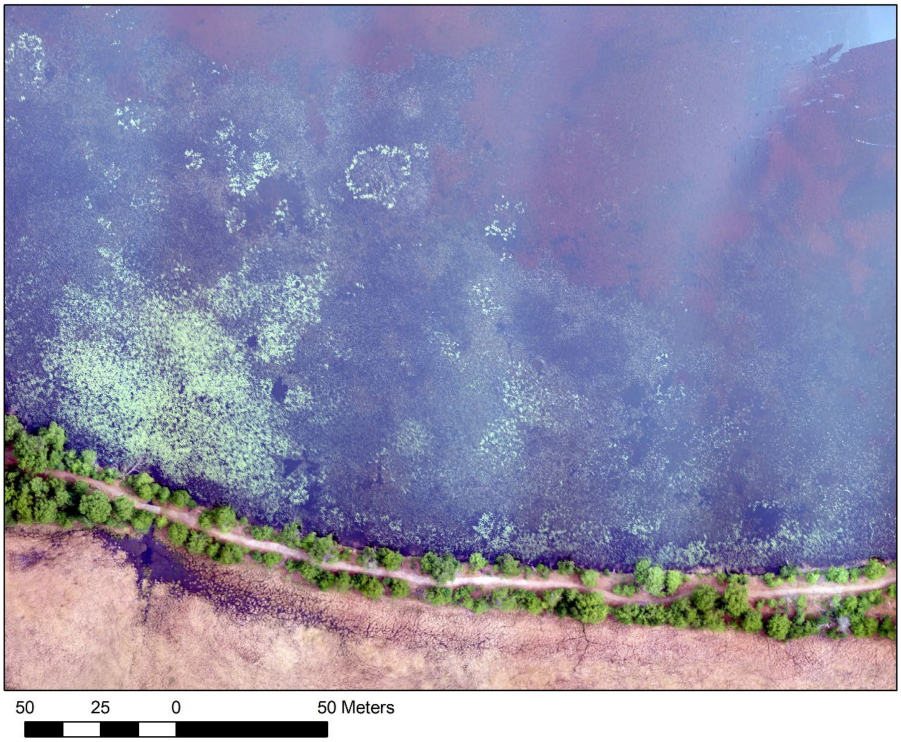
Images 5A and 5B: Fall flights over a forest at the CCESR where every tree is catalogued. We are recording changes in fall foliage and comparing them with patterns of oak wilt within the forest.

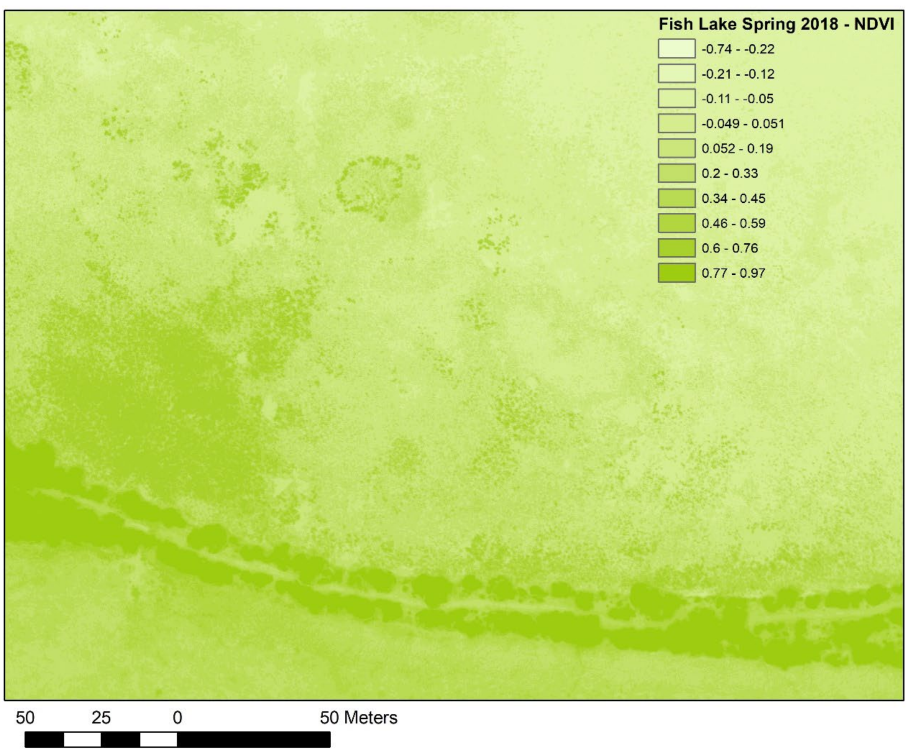
Image 6: Flights over a grassland in the Cedar Creek Ecosystem Reserve where small strips of grass were cut. We are identifying the change in the imagery from before and after the harvest.

Activity 2 Status as of 04/26/2019:
As part of our continuing partnership with Dr. Rebecca Montgomery in the Forestry Dept. (UMN), to understand how canopy phenology may be linked to oak wilt, a disease killing oak trees in MN, we repeated our forest surveys in the fall of 2018. This year our twice-weekly flights not only collected RGB imagery, but we estimated NDVI (normalized difference vegetation index), a measure of the greenness or productivity, using our multi-spectral sensor to track changes in leaf senescence during a 4-week period (see Image 7B below for an example at

another location). The resulting RGB and multi-spectral layers have been stitched together and we are working on the analysis.

We also repeated our flights over a wetland and lakeshore in the CCESR. We chose to fly over this area in the spring and summer to collect imagery that shows a large amount of change in the aquatic vegetation community from one season to the next. We again used our RGB (**Image 7A** below) and multi-spectral sensors and estimated NDVI (**Image 7B** below). Utilizing this imagery in our automatic change detection software (under development) will highlight to managers the incredible usefulness of drones for identifying changes in invasive species, the efficacy of management actions, or simply the vegetative productivity of an area. Typically, vegetation/habitat data are only available at a resolution of either 15 m^2 or 30 m^2, which is often too course and collected too infrequently to inform management of the effectiveness of their actions or changes in the management area. Our imagery allowed us to quantify NDVI at a resolution of one-eighth ($1/8^{th}$) m^2 which can provide very detailed and accurate estimates of change.



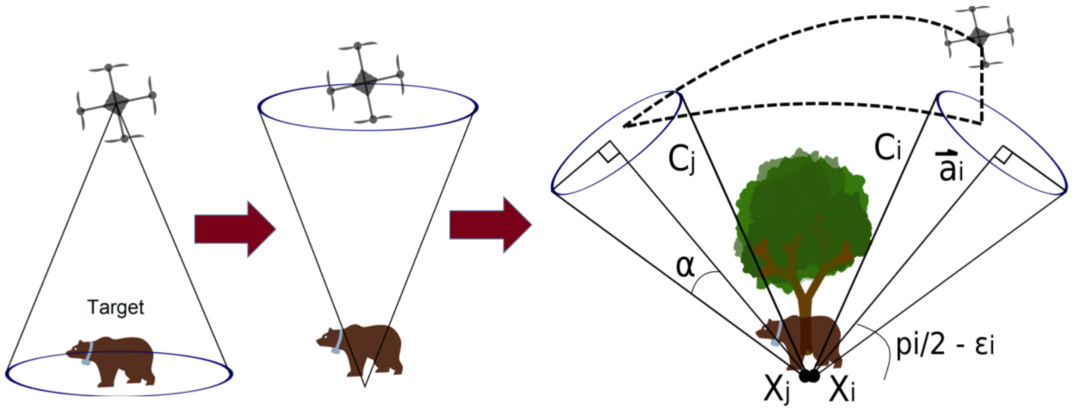


Images 7A and 7B: Flights over a lakeshore within CCESR during the fall using RGB (Image 7A) and multi-spectral imagery that can be converted into NDVI (Image 7B). Our multi-spectral imagery can be used to quantify NDVI at a very fine scale (resolution in image ~ 1.8^{th} m^2).

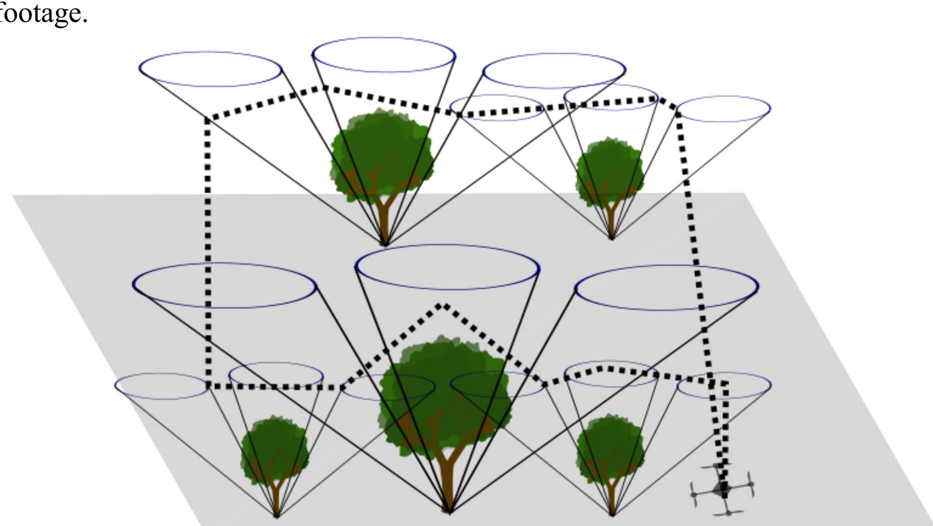
Activity 2 Status as of 07/01/2019:
In the last two months, we have continued to analyze these data and will be continuing to work with them over the rest of the year.

Final Report Summary:

i) For this activity, Dr. Isler and the CS&E graduate research assistant considered a number of trade-offs and proposed solutions for related ecosystem monitoring tasks. First, we considered the relation between the camera resolution and UAV altitude. We associated each camera image with an inverted cone apexed at the location of the interest. The height of the cone is associated with the desired resolution and the apex angle corresponds to camera field of view. In other words, each cone encodes the set of view points from which a target can be imaged at a desired location.

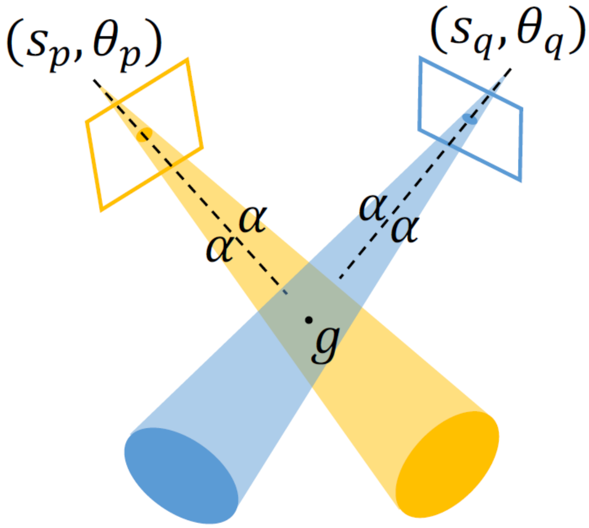


Second, we developed a strategy to efficiently visit a large number of such view cones in order to capture image footage.

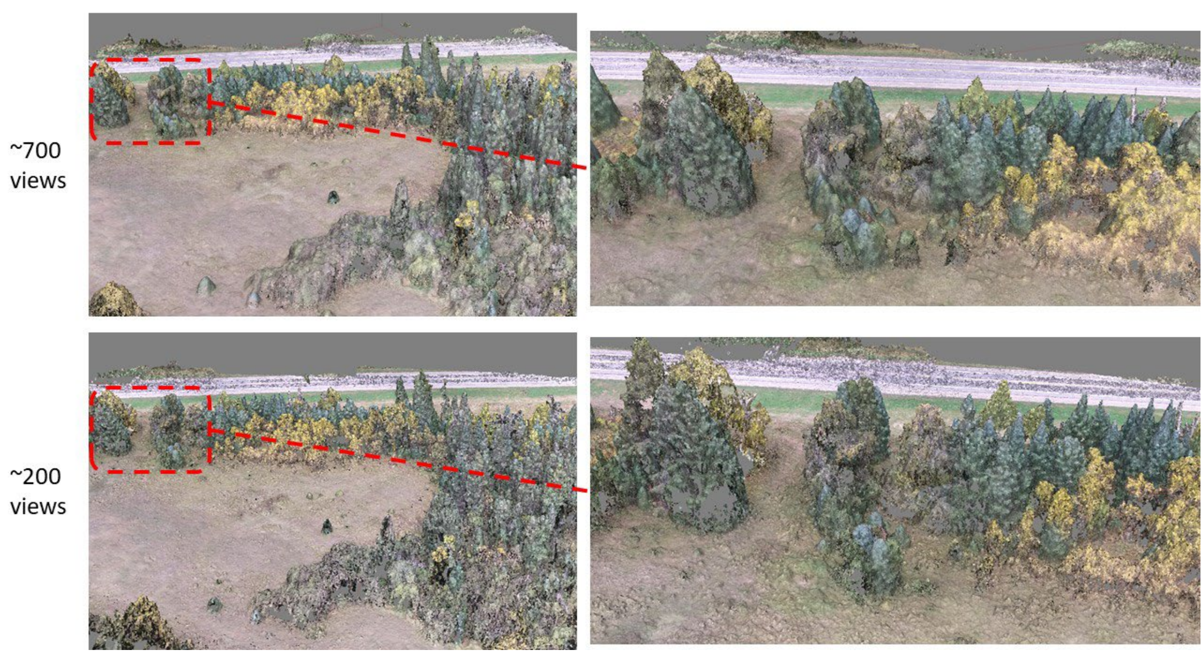


We analyzed the performance of our strategy and demonstrated through simulations and field experiments that by exploiting the special structure of the cones we can achieve shorter flight times than any other available solution. The strategy can be used with any number of cones and split coverage into multiple flights in order to account for limited battery power or image storage. The results of this work was published in IEEE International Conference on Robotics and Automation (ICRA), 2018 under the title “Approximation Algorithms for Tours of Orientation-varying View Cones”.

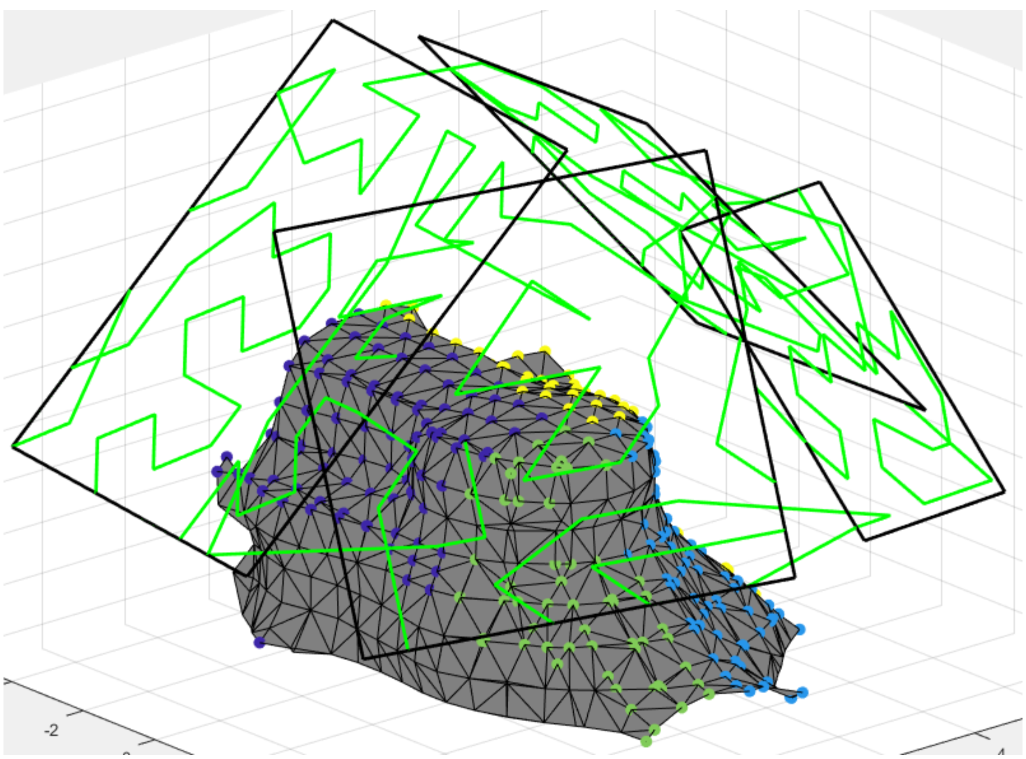
To minimize the number of views selected to build mosaic, we modeled image feature triangulation uncertainties during mosaicking process as intersections of right circular cones. We then analyze the worst case uncertainty behavior with only two views.



The result claims near-optimal performance given orthogonal viewing angles. Therefore, using this insight, we developed a coarse-to-fine strategy to select a subset of views such that the mosaic and reconstruction quality of a field is almost as good as that from using all images. The resulting processing time can be reduced from 12 hours to less than 1 hour. The result is published in Robotics: Science and Systems 2017.



When a scene has significant height variations and the planar assumption no longer holds. We also developed a method to reconstruct 3D geometry by dividing the scene into multiple planes. Our results extend the previous work to cover a broader range of geometry and is published in International Conference on Robotics and Automation 2019.



ii) For the second part of this activity, we first conducted a pilot study at Cedar Creek in which our graduate student learned how to collect multi-spectral data on areas with oak wilt and aquatic vegetation growth. Although the researchers involved with the oak-wilt study determined that hyper-spectral data (i.e., another sensor) was more appropriate for their application, we were able to use the images to refine approaches for mosaic optimization (Stefas et al. 2018, 2020). We decided to use our experience with the multi-spectral camera to better understand fine-scale moose habitat selection (this study is detailed under Activity 1). When we consulted with managers at Cedar Creek about their potential needs for aerial image collection, they indicated that one of their concerns was being able to estimate how their white-tailed deer population changes though time. They are in the process of collecting camera trap data on deer, but had not other way to estimate population densities. We leveraged our experience with thermal imagery from Activity 1 to develop a sampling protocol that we ground-truthed with pellet counts.

Comparing unmanned aerial systems to conventional methodology for surveying a wild white-tailed deer population

Overview:

Here, we compare population density estimates derived from a UAV with a mounted FLIR sensor to estimates based on fecal (pellet-group) surveys, a method frequently used to estimate the density of ungulate populations. Pellet-group counts have been used for decades, and are still in use today, because of their cost effectiveness and ease of implementation. A major drawback of the approach is the requirement to estimate deer defecation and pellet decay rates, which can be difficult to obtain due to seasonal variation in diet and environmental conditions.

Our objectives were to: 1) examine the feasibility of using a fixed-wing UAV for detecting wild white-tailed deer (hereafter referred to as deer) in a forest-prairie interface, 2) determine deer population density from counts of deer in FLIR imagery, and 3) compare deer density estimates from UAV-gathered data to deer density estimates from pellet-group counts. We aim to provide information to wildlife professionals about whether UAV technology provides a significant advantage over cheaper and simpler conventional methodology, and how wildlife managers can most efficiently employ UAV technology to achieve research and management goals.

UAV surveys:

Surveys were conducted at the Cedar Creek Ecosystem Science Reserve (CCESR); located ~50 km north of Saint Paul, Minnesota, USA, near Bethel, Minnesota, in Anoka and Isanti counties (Figure 2.1). This is a 2,200 ha experimental ecological reserve that the University of Minnesota operates in cooperation with the Minnesota Academy of Science. We conducted UAV thermal surveys across the CCESR property from March to April of 2018 and from January to March of 2019. We used a Sentera PHX Pro fixed-wing UAV equipped with a FLIR Vue Pro 640 (640 x 512 pixel resolution, 32° FOV, 19 mm lens, 30 Hz) thermal sensor to detect white-tailed deer. We identified eight survey plots ranged in size from 46.29 ha to 119.82 ha and encompassed 30.69% of the CCESR property in total (Figure 2.1).

We pre-programmed the PHX to fly parallel transects at 121 m above ground level (AGL) over each survey plot using the laptop-based Sentera Ground Control program. We flew each plot at least twice per survey season, for a grand total of 35 survey flights, at various times of day from morning until evening. Parallel transects were used for efficiency and to minimize wildlife disturbance, and we did not observe any behavioral reactions during the course of our study. The onboard thermal sensor was automatically triggered by the PHX's flight computer to achieve the pre-programmed image overlap. Thermal imagery was captured as still photos with 70 to 80% front overlap and 30% side overlap. Each image covered an average ground area of 3,948 m^2 (approximately 60 x 70 m ground distance). Images were geo-referenced from the PHX's GPS system and included data on altitude, speed, and bank angle of the UAV at the time of image capture. Imagery was saved on a mini SD card onboard the UAV, and was transferred post flight to an external hard drive and cloud-based storage system for post-processing.

UAV data analysis
We removed any imagery that was captured with UAV bank angles (amount of side-to-side roll) of >10° because imagery captured at greater angles of bank (e.g., during turn-arounds when the UAV was realigning to start new

transects) would show inconsistent ground areas depending on bank angle, and would likely include space outside of our defined survey plots. We considered any bank angles of <10° to be products of ordinary wind turbulence during flight, based on observing the flight characteristics of the PHX and the distribution of bank angles in our data. We subsampled our thermal imagery for each plot by randomly selecting starting images and successively keeping any image with a centroid that was ≥ 80 m apart from any previously retained image's centroid, using program R. This process yielded a subsample of thermal imagery with a ground distance of 10 m to 24 m between the edges of thermal images to be analysed. This ensured that we did not analyse overlapping imagery, potentially recounting individual deer, and reduced the workload of reviewing the ~ 22,600 total thermal images collected.

We randomly subsampled the images under the constraint that any given sampled image was ≥ 80 m from the centroid of all other sampled images (i.e., no overlap was allowed). We manually reviewed the subsampled imagery from each plot and recorded counts of deer observations that we classified as either 'certain' or 'potential' detections. Certain detections were recorded when we had no doubt that a deer was in the image based on the shape, size, and relative brightness of the thermal heat signature. Potential detections were less certain detections that may have only met some, but not all of our shape, size, and brightness search criteria. Deer were distinguished from other wildlife by relative size and shape, as they were the only animal of their size present (e.g., bears were in dens, and wolves are rarely found in the study area). Coyotes, which were present in the study area, could potentially be misidentified as deer but are generally smaller and less common than deer. Prior to the start of the study, we recorded thermal imagery from a captive deer farm with a known number of deer. We used the imagery from the deer farm for training observers prior to reviewing field data. Imagery of the captive deer was taken with the same FLIR sensor at varying altitudes, angles, and amounts of vegetative cover to provide examples of how deer might appear in thermal imagery.

UAV deer density modeling:

We modeled deer counts (i.e., the number of deer observed in a thermal image) using the glmmTMB package in program R because it allowed for the inclusion of zero-inflated models and random effects. This approach also allows for different model structures in the zero inflation and conditional components. We included in our models the variables of sky cover (0 = clear sky, 1 = overcast sky) and the proportions of habitat cover type as possible fixed effects; a maximum of one cover type proportion was included per model component (i.e., each of the two component models could have at most sky cover and one land-cover proportion as a fixed effect). We used sky cover instead of ambient temperature because sky cover was previously shown to improve models of moose (*Alces alces)* detection over ambient temperature in forested habitats (Activity 1). Ground area (i.e., the spatial area observed within each thermal picture) was added as an offset to the conditional model based on our *a priori* reasoning that a greater area observed would result in a greater probability of deer detection. Survey flight ID and survey year (0 = 2018, 1=2019) were included as crossed random intercepts to account for variation among survey flights and years.

We determined the proportion of cover types within each image by clipping land cover data (MN Land Cover Classification, 2013) with a 35-m buffer around the centroid of each thermal image using ArcMap 10.5.1 (Environmental Systems Research Institute, Inc., Redlands, CA, USA). The radius of 35 m was chosen so that the buffer area around each image centroid equaled the mean ground area captured in the thermal imagery. We calculated the ground area of the thermal imagery for each image from flight altitude data using the Pythagorean Theorem and then averaged across all images. Proportions of each land-cover class (developed, conifer forest, deciduous forest, forested wetland, emergent wetland, grassland, agriculture, and open water [i.e., snow-covered ice]) were considered individually and in meaningful groups: forested upland (conifer + deciduous), open upland (agriculture + grassland), wetland (forested wetland + emergent wetland), non-wetland open area (grassland + agriculture + developed + open water), and no cover (emergent wetlands + grass + water + agricultural + developed). The composite variables were chosen based on the type of resources they might provide in winter (e.g., food, cover) and whether a given vegetation type would likely be tall or dense enough to obscure a deer from aerial thermal detection.

To predict the deer population size across the entirety of the CCESR property using our top-supported models of deer abundance (based on high and low count data), we created a virtual grid in Program R that covered the entire area. Each cell of the grid was 3,948 m^2 (62.83 m x 62.83 m), which equaled the mean ground area captured in the individual thermal images. We calculated the proportion of each land-cover type and composite cover-type variable within every grid cell using the land-cover data set and binning scheme described above. To generate a point estimate of the deer population size, we used the predict function in program R to estimate the number of deer present in each cell; the predictions for all cells were summed to provide an estimate of the deer population within the CCESR property (we use a parametric bootstrap approach to estimate uncertainty in the point estimate).

Pellet-group count surveys:

We arranged pellet-group survey transects within the established UAV survey plots using a stratified random approach. We clipped land-cover data (MN Land Cover Classification, 2013) by the boundaries of the eight UAV survey plots and randomly inserted ~ 20 survey points proportionately with the availability of each cover type within the plot. Our habitat cover types for conducting pellet-group counts included deciduous forest, forested wetland, emergent wetland, grass, and row crops. Transects were planned prior to fieldwork by using our stratified random points as starting locations and laying out a 100-m line in a direction from the starting point that would allow the surveyors to remain in the same habitat cover type for the entirety of the transect.

Pellet-group counts were conducted during the months of April and May (2018 and 2019). We surveyed 133 transects in 2018 and resurveyed 120 of the same transects during 2019. Thirteen of the 2018 transects were not available for resurveying in 2019 due to prescribed burning on the CCESR property. Deer droppings were considered a pellet-group if there were at least 4 pellets of similar size, shape, and color within close proximity (pellets within 30 cm of each other). Pellet-groups were only counted if ≥50% of the pellet-group was within 1 m of the transect centerline, and they were determined to have been deposited after leaf-off the previous fall. Deciduous leaf litter falling between survey periods (2018 and 2019) eliminated the need to age or clear away pellet-groups, as only pellet-groups that had been deposited from fall to spring would be visible above the leaf litter. Where leaf litter was not present (e.g., open habitat types), we examined pellet-groups and determined deposition timing based on the presence of weather exposure, moss, and insect damage. Pellet-groups deposited post fall leaf-off would not likely show any such damage from exposure.

Pellet-group count data analysis and density modeling:

We estimated deer density from pellet count data in two ways. In the first, we used a simple equation (Gable et al. 2017): Deer density (deer/km^2) = pellet groups counted / (pellet group deposition rate * deposition period * sampling unit area [km^2]). We considered the pellet deposition rate to be 25 pellet-groups/deer/day based on pellet count surveys from a study near International Falls, MN (Gable et al. 2017). This value is based on the mean values for deposition rate from two other studies; Rogers (1987) used a deposition rate of 34 and Patterson et al. (2002) used 16. We also calculated a low estimate using the value of 34 pellet-groups/deer/day and a high estimate using 16 pellet-groups/deer/day. Our pellet-group deposition period (time between mean leaf-off date and mean survey date) was 192 days for 2017–2018 and 209 days for 2018–2019. Density estimates were derived for forested (deciduous + forested wetland) and non-forested (emergent wetland + grass + row crops) habitat cover types by pooling count data from specific cover types for calculation, and averaging across survey years. Point estimates of deer density were predicted across CCESR by applying density estimates for forested and non-forested land cover to the proportion of forested and non-forested land cover of each grid cell in the virtual grid system described above in the UAV Deer Density Modeling section.

We also took a second approach, in which we fit a Poisson hurdle model to the number of pellet groups found per transect. We used the same potential covariates, random effects, and parametric bootstrapping approach that we used for the UAV models; we divided the total area of each land-cover type in the landscape into 200-m^2 transect units (i.e., equal in area to our sample transects). The result of predicting this model across each transect unit in the landscape was a “predicted number of pellets,” that we converted to “predicted number of deer” by assuming a 192-day deposition period and the same high, low, and average pellet deposition rates used in the above equation.

Results:

We conducted 2-3 replicate surveys over our eight UAV survey plots at CCESR during winter and spring of both 2018 and 2019, totaling 35 thermal UAV flights with analyzable data. Our thermal surveys required a total of 24.7 hours of flight time with the PHX. We captured a total of 22,626 thermal images and analyzed a subsample of 3,757 non-overlapping images. Of these images, 96.6% did not contain any potential deer detections. We classified 48 thermal images as containing certain deer detections (Figure 2.2-A) and an additional 95 with potential deer detections (Figure 2.2-B). Images with deer detections ranged in count from 1 to 9 individuals and we detected a total of 96 certain deer and an additional 135 potential deer within all survey images (Figure 2.3). Our top detection models predicted mean point estimates for deer density of 12.38 and 6.18 deer/km^2 for the high and low detection estimates, respectively. Point abundance estimates were 273.81 deer and 136.68 deer on the CCESR property (22.12 km^2, Figure 2.4, Table 2). Our bootstrapped estimates of deer density had a mean estimate of 13.77 deer/km^2 for the high detection model, and a mean of 9.40 deer/km^2 for the low detection model. These density estimates equated to a mean of 305 deer on the CCESR property for the high-detection model, and 208 deer for the low-detection model (Figure 2.4).

To ground-truth these estimates, we surveyed 133 pellet-group count transects covering 26,600 m^2 in 2018 and recorded 1,085 pellet-groups. In 2019, we completed 120 transects equating to 24,000 m^2 surveyed, recording 766 pellet-groups. Our predicted point estimates were 5.13, 6.98, and 10.91 deer/km^2 based on high (34 pellet groups/deer/day), mean (25 pellet groups/deer/day), and low (16 pellet groups/deer/day) deposition rates, respectively. Point estimates of abundance were 112.79 deer for high deposition, 153.39 deer for mean deposition, and 239.67 deer for low deposition on the CCESR property (Figure 2.4). The bootstrapped predictions resulted in a mean of 5.15 deer/km^2 for high deposition, a mean of 7.01 deer/km^2 for mean deposition, and a mean of 10.95 deer/km^2 for low deposition. The corresponding bootstrapped abundance estimates for CCESR from our bootstrapped prediction intervals were 113.25 deer, 154.02 deer, and 240.66 deer, respectively (Figure 2.4).

Conclusions:

We successfully applied UAV and FLIR technology to survey a wild population of white-tailed deer and compared the efficacy of this approach to pellet-group count surveys, a widely-used conventional method for surveying ungulate populations. Both of these methodologies yielded similar results for overall abundance estimates (between 200 and 300 animals; Figure 2.4) dependent on assumptions regarding the pellet deposition rates and detection rates, yet varied in levels of sampling effort, cost, and time. Despite increasing use of UAV in wildlife research, many studies rely on expensive UAV and sensors and do not assess how well the approach compares with established methods. However, understanding the logistical, financial and practical hurdles of incorporating UAV is especially important for wildlife managers with limited resources. Our findings provide insights into the process and utility of integrating UAV into monitoring ungulate populations in an efficient and temporally sensitive manner.

The most notable difference between pellet-group counts and UAV surveys was the amount of time and effort required for each approach. Pellet counts took approximately 160 hours (i.e., the time taken to count pellets and hike between survey transects) over both survey seasons, whereas the UAV surveys required only 24.7 hours of flight time in addition to approximately 30 minutes to one hour for set up and take down per launch site, totaling 17.5 to 35 hours of non-flight field effort. Time spent driving between UAV launch sites was negligible. An additional 25 to 35 hours of effort was required for manual review of thermal imagery. The physical effort required for pellet count surveys was greater, requiring large amounts of off-trail hiking to reach survey sites, relative to the majority of UAV launch sites off of drivable roads and trails. Pellet-group counts were also temporally restricted to just prior to spring green up, after all snow cover was melted, for maximum detectability of pellet-groups by human observers. Conversely, UAV FLIR surveys could be carried out with far greater flexibility and would have been feasible anytime from late November through April, which corresponded to leaf-off conditions for deciduous trees. The window of time for deciduous leaf-off conditions is relatively large at northern latitudes and is irrelevant for ungulate surveys in open grassland habitats. This wide temporal range allows researchers and managers greater operational flexibility for surveying ungulates, as compared to being seasonally restricted by pellet-group counts.

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Patterson, B. R., Macdonald, B. A., Lock, B. A., Anderson, D. G., and Benjamin, L. K. (2002). Proximate factors limiting population growth of white-tailed deer in Nova Scotia. Journal of Wildlife Management 66, 511-521.

Rogers, L. L. (1987). Seasonal changes in defecation rates of free-ranging white-tailed deer. The Journal of Wildlife Management 51(2), 330-333.

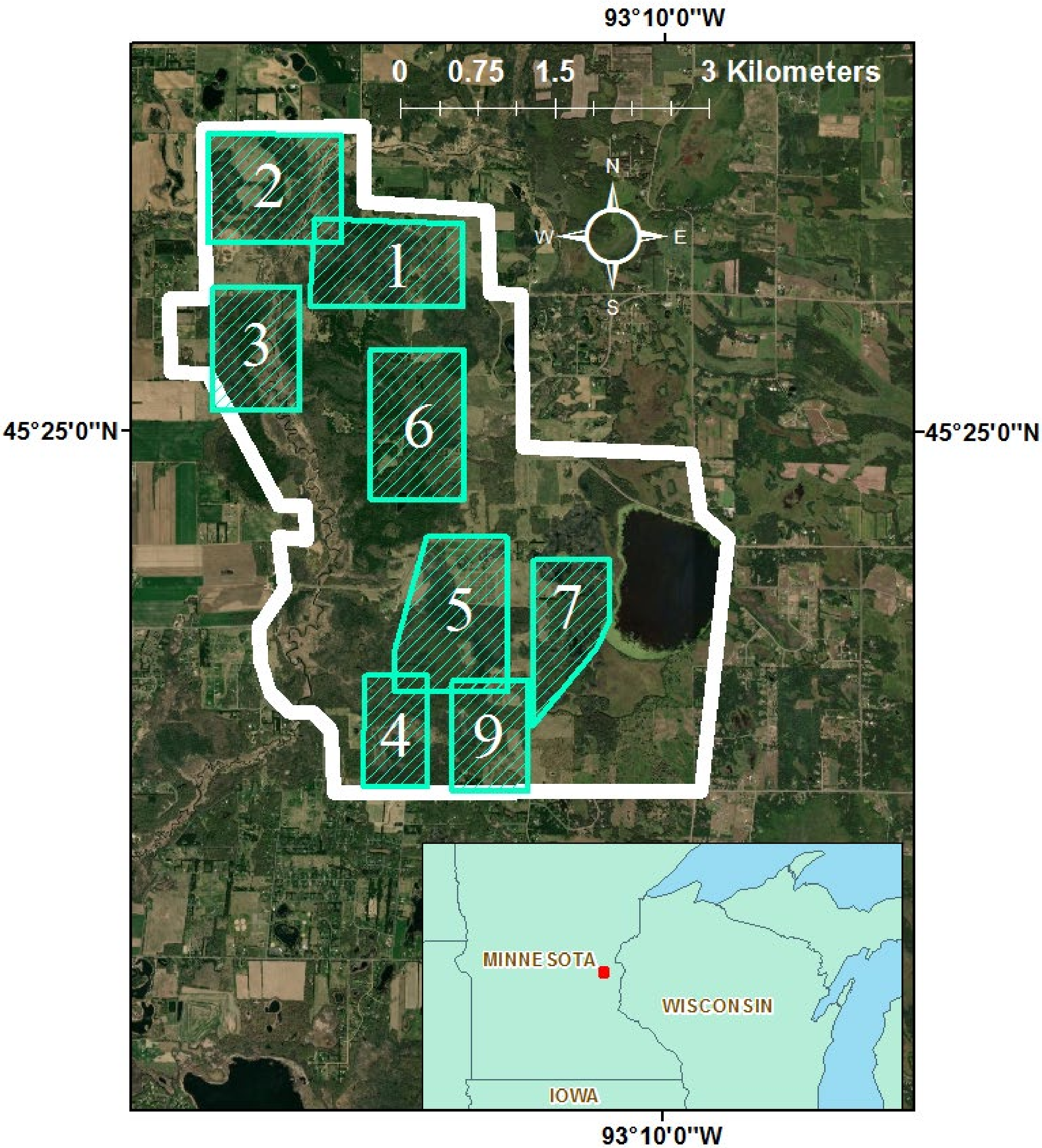


Figure 2.1: Cedar Creek Ecosystem Science Reserve (CCESR) study area, Minnesota, USA. Unmanned aerial system (UAV) survey plots are distinguished by the teal, numbered boundaries. Plot 8 was omitted from our study because of our inability to safely land the UAV at that site.

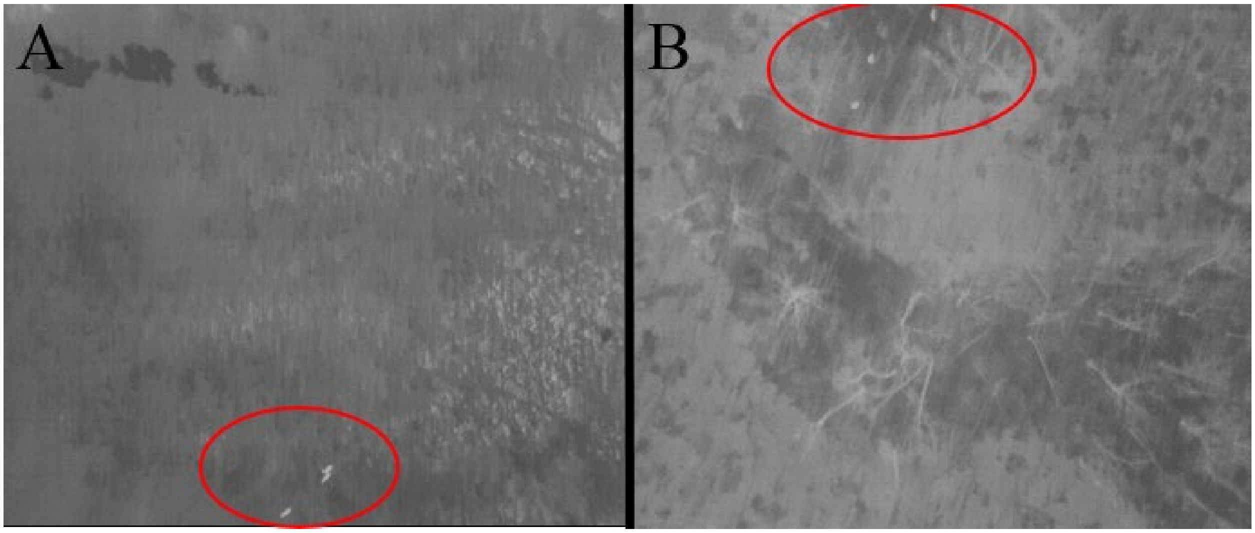


Figure 2.2: Thermal imagery of certain white-tailed deer (*Odocoileus virginianus*) detections (A) and potential deer detections (B) collected at Cedar Creek Ecosystem Science Reserve, Minnesota, USA during UAV surveys from March to April of 2018 and from January to March of 2019. We distinguished between certain and potential deer detections by shape, brightness, and size of thermal signatures. Figure 2A shows clear thermal signatures of deer based on these factors, while figure 2B contains less certainty based on shape. Such signatures were still counted as potential deer because shape can vary greatly in thermal imagery (e.g., when deer are bedded down versus standing/walking).

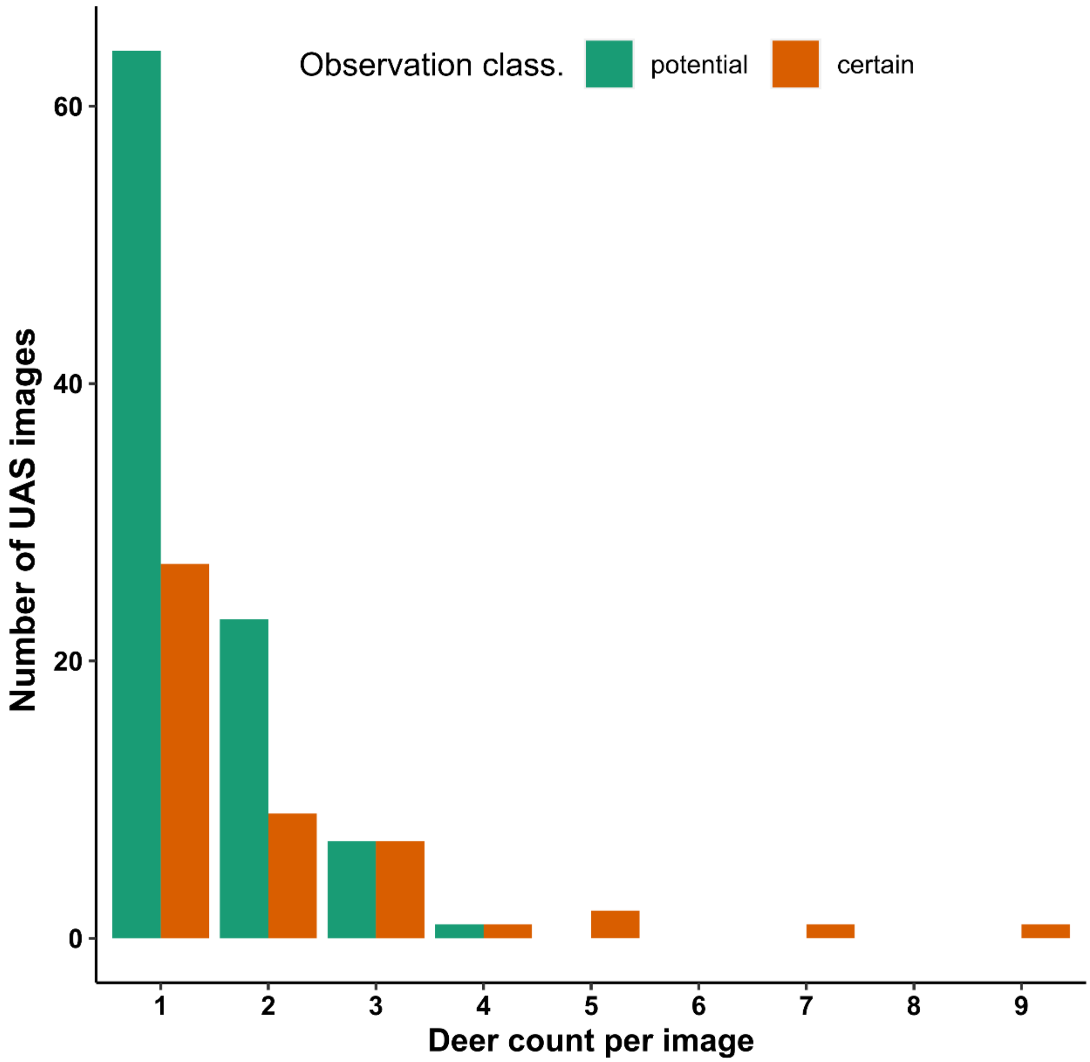


Figure 2.3: Histogram showing the number of UAV images with 1–9 certain or potential white-tailed deer (*Odocoileus virginianus*) detections from thermal imagery during unmanned aerial system surveys at the Cedar Creek Ecosystem Science Reserve, Minnesota, USA from March to April of 2018 and from January to March of 2019. Overall, deer counts per image ranged from 1 to 9 deer, with 3,631 images containing no detection. We distinguished between certain and potential deer detections by shape, brightness, and size of thermal signatures.

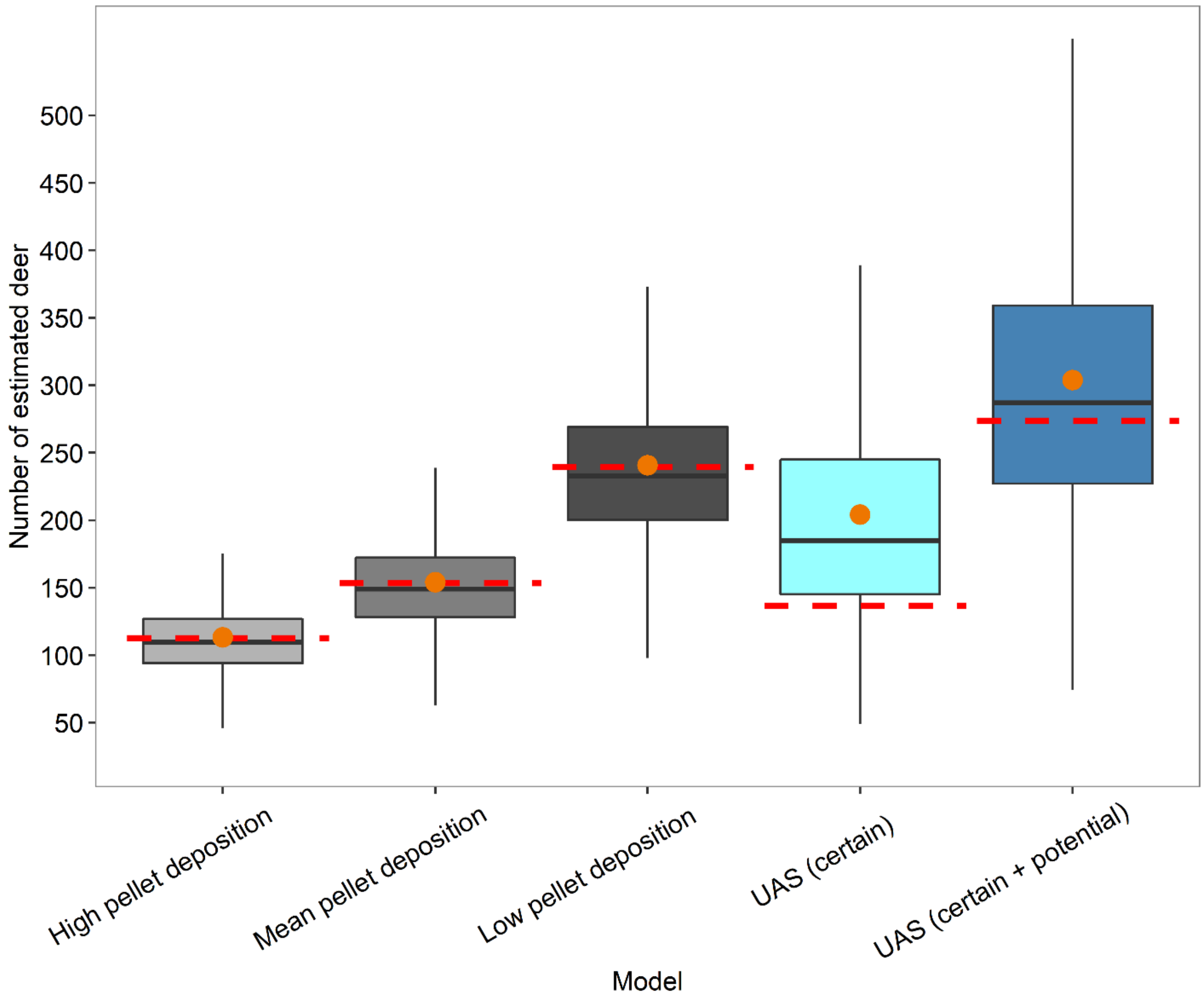


Figure 2.4: Boxplots of the bootstrapped predictions of the number of estimated deer in the Cedar Creek Ecosystem Science Reserve, Minnesota, USA based on pellet-group count models assuming high, mean, and low rates of pellet deposition (34, 25 & 16 pellets per deer per day, respectively) and UAV models using counts of certain and certain plus potential white-tailed deer in thermal images. Surveys were conducted from March to May of 2018 and from January to May of 2019. Orange points represent the means of the bootstrapped predictions. Red-dashed lines on each pellet-based model show the model-free point estimates. The red dashed-lines over the UAV model estimates represent mean point estimates from the top model for certain and certain plus potential deer detections.

Summary (Activity 2)

- We developed a new approach to optimize flight paths of UAVs so that optimal views of the target area could be achieved while avoiding undesirable artifacts such as glare on water or 3-D obstruction from trees.
- We conducted a pilot study in which we developed a workflow for multi-spectral data that allowed us to use a commercial UAV to collect fine-scale forage availability data for moose (for our application of this approach, see Activity 1).
- We used thermal cameras to repeatedly survey the deer population at Cedar Creek. Our approach can be easily applied in other areas and provides a repeatable, spatially explicit approach to estimating the abundance of mid-large sized mammals.

- We found that automatic detection of deer using software was not feasible, given the flight elevation required for the survey; however, we developed a methodology in which researchers manually counted animals in a random subset of images from the survey area. This approach is relatively fast and produces a repeatable count estimate.

V. DISSEMINATION:
Description:
Our development of technology and software, as well as our field methodologies and analyses of biological data, will result in several manuscripts written and submitted for publication in peer-reviewed journals. Findings will be presented at state and national wildlife and ecology conferences (e.g., the annual Minnesota Moose Meeting, state and national meetings of The Wildlife Society). All publications resulting from this project will be made available through the FWCB website or Open Access journal websites.

We expect that as our technologies and methodologies are proven in field tests, there will be a large amount of informal dissemination because we will be working closely with researchers at the University of Minnesota and the Grand Portage Band of the Lake Superior Chippewa. We also have a history of working with researchers and managers from the Department of Natural Resources, The Nature Conservancy, and the US Geological Survey. We have also been approached by Mike Schrage, the wildlife biologist for the Fond du Lac Band, about potential future collaboration and use of our UAV based on this proposal. We expect the MN Department of Natural Resources to have a strong interest in the UAV capabilities and specifically the effectiveness and data resulting from Activity 1 (moose calf surveys and VHF homing technologies). We hope that in the future, we can work closely with them to expand UAV moose surveys in other areas of the state and use UAVs to reduce the impact of studying other species of interest in MN. We will work openly with any of these groups to share our capabilities, software and equipment (as availability dictates), to ensure that our technological advancements and research papers reach a broad audience within their agencies.

Status as of 01/01/2018: Now combined in 07/01/2018 status update.

Status as of 07/01/2018:
We have worked extensively with the tribal biologists for the Grand Portage Band of Lake Superior Chippewa. Our work has sparked interest in additional surveys for other wildlife applications there and with the Fond du Lac Band tribal biologist. They have been impressed by the capabilities of the UAV and sensors and are looking into purchasing their own for management and wildlife monitoring. We plan to do additional surveys for them (wolves, moose in winter when we will likely improve sightability).

The FWCB graduate student is planning to give presentations at the upcoming Midwest Fish and Wildlife Conference and the Minnesota Fish and Wildlife Conference.

Once our methodologies are refined, we will reach out to several DNR collaborators (from previous research efforts) to share the results from this study.

Publications from the CS&E group:

Bayram, H., Stefas, N., Engin, K.S., & Isler, V. (2017). Tracking wildlife with multiple UAVs: System design, safety and field experiments. *2017 International Symposium on Multi-Robot and Multi-Agent Systems (MRS)*, 97-103.
https://ieeexplore.ieee.org/abstract/document/8250937/

Bayram, H., Stefas, N., & Isler, V. Aerial Radio-based Telemetry for Tracking Wildlife, submitted to IROS 2018

Peng, C & V. Isler (2018) View Selection with Geometric Uncertainty Modeling
Robotics: Science and Systems, 2018. Accepted.

Status as of 04/26/2019:

The tribal biologists for the Grand Portage Band of Lake Superior Chippewa have been pleased with the FWCB student's first season and have invited him up during March to collect data about calf survival from spring (2018) through the winter of 2019. The early success of this field work has increased their interest in utilizing drone surveys to track moose and other wildlife in the future.

We are also reaching out to DNR researchers to show the capabilities of our drone flights with thermal and multi-spectral sensors. We are currently discussing working with Dr. Glenn DelGiudice and his former PhD student, Dr. Bill Severud to utilize our mutli-spectral camera to determine fine-scale habitat components for moose calves that survived and those that were predated. This will help to advance part of this project's aim to "capture additional data about the habitat selected by the adult moose for giving birth and areas used after the calves are mobile". The master's student is already collecting this data in Grand Portage, but this collaboration would expand on it to areas further south of our current study area and offer sites to sample.

The master's student, Michael McMahon presented his research as a talk (w/ Dr. Ditmer and Dr. Forester as co-authors) entitled, "Find the Moose: Employing Unmanned Aerial Vehicles for the Detection of Moose in Northeastern Minnesota" at the upcoming Annual Meeting of Minnesota's The Wildlife Society (TWS) and the Society of American Foresters (SAF) in Duluth on February 19-21, 2019.

Status as of 07/01/2019:

No additional outreach activities have occurred in the last two months.

Final Report Summary:

This project resulted in four scientific presentations, two published conference papers, three accepted journal papers and one submitted journal article; the CSE graduate student working on developing an aerial robotic system and strategy to approach a radio signal beacon from a high altitude was awarded the UMII MnDrive fellowship award from the University of Minnesota. Our research into field applications of thermal imagery for assessing moose calving and mortality events was conducted in close collaboration with researchers from the Grand Portage Band of Lake Superior Chippewa and the MNDNR; we are continuing these collaborations and expect to submit another paper (detailing the calving habitat results) later this year. Our work to develop a new approach to sample deer populations using UAVs and thermal sensors grew out of a need at Cedar Creek to better understand their deer population. We tested our approach in the Cedar Creek Ecosystem Science Reserve and compared population estimates generated from UAV data to those from more traditional pellet-count approaches; we are now working with researchers at Cedar Creek to validate their camera-trap estimates of deer population density. Finally, three undergraduate students, three graduate students, and two postdoctoral researchers received training as part of this project; results from this research have been added into teaching materials in two required Fisheries, Wildlife, and Conservation Biology courses at UMN.

- We developed an aerial robotic system and strategy to approach a radio signal beacon from a high altitude with the purpose of obtained image data at a desired resolution. This work resulted in a published conference paper [1] and a submitted journal paper [4].
- We developed a method to generate an optimal trajectory to obtain camera footage of difficult to see areas. This work resulted in a published conference paper [2] and a journal paper [3].
- We used UAV equipped with thermal sensors to estimate calving success for female moose in NE MN; this work resulted in a journal article [5].
- We also developed a new approach to sample deer populations using UAV and thermal sensors. We tested this approach in the Cedar Creek Ecosystem Science Reserve where we compared population estimates generated from UAV data to those from more traditional pellet-count approaches. This work has been accepted for publication in a journal [6].

[1] H. Bayram, N. Stefas, and V. Isler, "UAV Landing at an Unknown Location Marked by a Radio Beacon", IEEE International Conference on Intelligent Robots and Systems (IROS), 2019.

[2] N. Stefas, Patrick A. Plonski, and V. Isler, "Approximation Algorithms for Tours of Orientation-varying View Cones", IEEE International Conference on Robotics and Automation (ICRA), 2018.

[3] N. Stefas, Patrick A. Plonski, and V. Isler, 2020, "Approximation Algorithms for Tours of Orientation-varying View Cones", International Journal of Robotic Research 39(4):389-401.

[4] H. Bayram, N. Stefas, and V. Isler. "UAV Landing at an Unknown Location Marked by a Radio Beacon", IEEE Transactions on Robotics (T-RO) (submitted)

[5] McMahon, M. C., M. A. Ditmer, E. J. Isaac, S. A. Moore, J. D. Forester. 2021. Evaluating unmanned aerial systems for the detection and monitoring of moose in northeastern Minnesota. Wildlife Society Bulletin (in press). DOI: 10.1002/wsb.1167.

[6] McMahon, M. C., M. A. Ditmer, J. D. Forester. 2021. Comparing unmanned aerial systems to conventional methodology for surveying a wild white-tailed deer population. Wildlife Research (in press).

Presentations

McMahon, M.C., M. Ditmer, and J. Forester. Unmanned aerial vehicles for the detection and monitoring of moose calves in northeastern Minnesota. The Wildlife Society Annual Conference. Reno, NV. September 29-October 3, 2019.

Ditmer, M. Quantitative methods in wildlife research. WI DNR, Rhinelander, WI. June 10, 2019.

McMahon, M.C., M. Ditmer, and J. Forester. Find the moose: Employing unmanned aerial vehicles for the detection of moose in northeastern Minnesota. Annual Meeting of the Minnesota Chapter of The Wildlife Society, Duluth, Minnesota, February 19-21, 2019.

Forester, J. D. 2018. White-tailed deer and moose biology and management in mid-west. Norway Student Exchange, University of Minnesota, Saint Paul, MN. 26 September 2018.

Other Outreach:
McMahon, M.C. 2019. It’s a bird, it’s a plane, it’s a...drone! Cedar Creek: Eyes on the Wild project blog. https://eyesonthewild.blogspot.com/2019/02/its-bird-its-plane-its-adrone.html

VI. PROJECT BUDGET SUMMARY:
A. Preliminary ENRTF Budget Overview:
***This section represents an overview of the preliminary budget at the start of the project. It will be reconciled with actual expenditures at the time of the final report.**

Budget Category	$ Amount	Overview Explanation
Personnel:	$298,383	1 project manager at 50%FTE for 2y; 1 engineer at 11%FTE for 2y; 1 wildlife biologist at 8%FTE for 2y; 1 graduate research assistant in CS&E at 50% FTE for 2y; 1 FWCB Master’s student at 50% FTE for 2y.
Equipment/Tools/Supplies:	$8,851	Quadcopter UAV, Parts for both fixed-wing and quadcopter UAVs, and cameras/sensors
Capital Expenditures over $5,000:	$20,798	1 Fixed wing UAV w/ flight training ($14,450), combined color/thermal camera for moose calf

		work ($6,348).
Travel Expenses in MN:	$9,206	Travel to and between data gathering sites and truck rental .Food and housing for field work.
Other:	$10,760	Networking and Computer Services for storage to support UMN projects in the CS&E – such as large files provided by the aerial imagery, repairs
TOTAL ENRTF BUDGET:	**$348,000**	

Explanation of Use of Classified Staff:

Explanation of Capital Expenditures Greater Than $5,000:
The UAV and all of the additional equipment utilized for engineering purposes to enhance the UAV will continue to be used for similar projects and purposes by the Forester and Isler Labs at UMN for the life of the instrument. If other researchers, state or tribal agencies are interested in its use, we will provide it for them whenever possible. If the instrument is sold prior to its useful life, proceeds from the sale will be paid back to the Environment and Natural Resources Trust Fund.

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 4.6

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 0

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
National Science Foundation	$801,000	$0	Not Funded
State			
	$	$	
TOTAL OTHER FUNDS:	**$**	**$**	

VII. PROJECT STRATEGY:
A. Project Partners:
Partners receiving ENRTF funding

- Dr. Mark Ditmer, Research Specialist, Univ. of MN - Dept. of Fisheries, Wildlife and Conservation Biology, $60,549, Project leader – working with graduate students to collect and analyze the data
- Dr. James Forester, Assistant Professor, Univ. of MN - Dept. of Fisheries, Wildlife and Conservation Biology, $19,444 , Wildlife biologist – advising wildlife, ecological, and statistical aspects of the project
- Dr. Volkan Isler – Associate Professor, Univ. of MN - Dept. of Computer Science, $40,232, Engineer – assisting with the development of UAV technologies and imagery software

Partners NOT receiving ENRTF funding

- Dr. Joseph Knight, Associate Professor, Univ. of MN – Dept. of Forest Resources, consultant for remote sensing and aerial imagery classification procedures

B. Project Impact and Long-term Strategy:
Our interdisciplinary research team will develop and implement changes to UAV systems that will have lasting benefits for the ongoing monitoring of any wildlife species large enough to be VHF-tagged (e.g. bat species of concern in MN) and will enable managers to collect much finer resolution data in an autonomous fashion to monitor changes in sensitive ecosystems. Initially, our results will lead directly to better understanding of the

conservation and management needs of moose and highlight the ability of our system to identify changes in sensitive ecosystems. Embracing the new capabilities that UAVs have to offer will provide better data, more cost-effective and safer research, while making research less invasive. Our work will not only research these methods but create easy to use systems that make UAV use and analysis of imagery accessible to researchers and managers. We will train and offer processing support for imagery as a means to get the systems more fully integrated into management and research.

We already have support from the UMN's Institute on the Environment who previously purchased a UAV system for our research on wildlife. The University of Minnesota currently has FAA approval for research in in nearly all areas within the state. Our research team has collaborated extensively with MN DNR researchers and managers in the past. We have access to previously collared animals (bear, bats, and moose), and strong working relationships with researchers throughout the state who have interest in this technology.

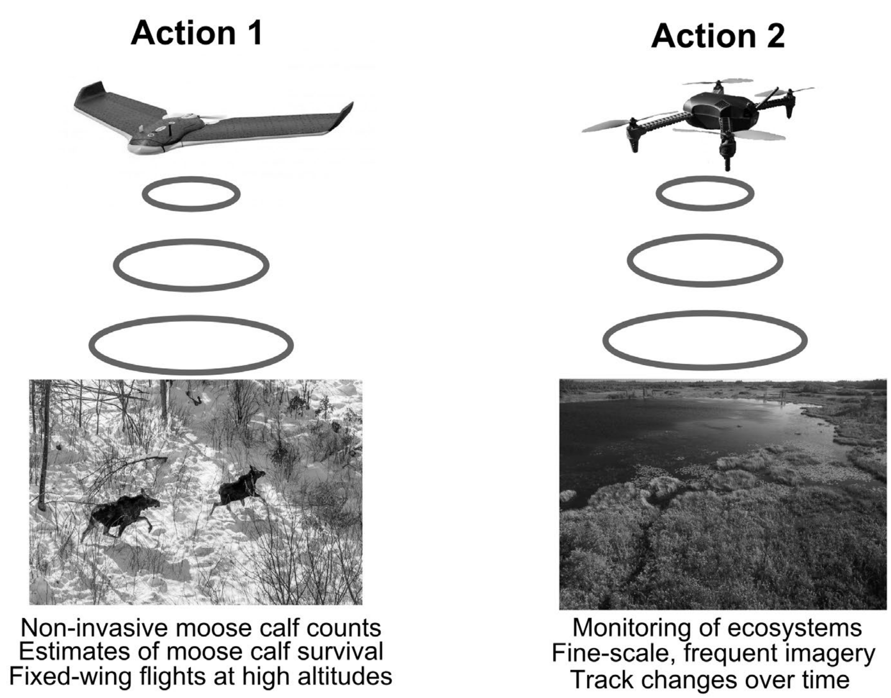
C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
University of Minnesota's Institute on the Environment	12/2013-12/2014	$900
		$
		$

VIII. REPORTING REQUIREMENTS:

- **The project is for 2 years, will begin on 07/01/2017, and end on 06/30/2019.**
- **Periodic project status update reports will be submitted** *01/01* **and** *07/01* **of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2019**.

IX. VISUAL COMPONENT or MAP(S):



Environment and Natural Resources Trust Fund
M.L. 2017 Final Project Budget

Project Title: Moose Calf Surveys and Monitoring
Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 03j
Project Manager: James Forester
Organization: *University of Minnesota*
M.L. 2017 ENRTF Appropriation: $ *348,000*
Project Length and Completion Date*: 2.5 Years, Jan 30, 2020*
Date of Report: 06/03/2021

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 05/10/2020	Amount Spent
BUDGET ITEM		
Personnel (Wages and Benefits)	$149,192	$149,192
Project Manager (Mark Ditmer) - 50 %FTE each year for 1 year (77.6% salary ,22.4% fringe) - Total estimated at: $30,952		
Wildlife Biologist (James Forester) - 8% FTE each year for 2.5 years (66.3% salary, 33.7% Fringe). - Total estimated at: $23,919		
Engineer (Volkan Isler) - 11% FTE each year for 2 years (75% salary, 25% fringe). - Total estimated at: $40,232		
Master's Student - U of M - Dept. of Fisheries Wildlife and Conservation Biology: 50% FTE each year for 2 years: 49.7% salary, 8.7% fringe, 41.6% tuition). - Total estimated at: $66,925		
PhD student – U of M -Dept. of Forest Research: 50% FTE for one semester to aid in UAS deployment and image analysis (49.7% salary, 8.7% fringe, 41.6% tuition). - Total estimated at: $17,979		
Undergraduate research technician (12 weeks at $15/hr) Total estimated: $9,486. Additional tech help was need to finish project.		
Grad Research Student - UMN Computer Science & Engineering - 50% FTE each year for 2 years (58% salary, 10% fringe, 32% tuition). - Total estimated at: $103,652		
Equipment/Tools/Supplies		
Unmanned aerial vehicle: quadcopter - selected through competitive bid		
Replacement and spare parts for either (quadcopter or fixed wing) unmanned aerial vehicle as needed, and computer supplies and materials to support unmanned aerial flights.	$358	$358

Thermal camera for sighting moose calves. A thermal camera will allow us to pick out their heat signature relative to surrounding cool spring ground and vegetation. A rugged camera that is used by several other studies that utilize thermal imagery to get imagery of wildlife from the air.	$3,700	$3,700
High resolution multi-spectral camera for collecting data on vegetation beyond a typical RGB camera - (near-infrared, red-edge, red and green). This data will allow us to discern vegetation types and plant stress far better typical cameras.		
Capital Expenditures Over $5,000		
Fixed wing unmanned aerial vehicle selected through competitive bid (includes basic RGB camera and flight lessons). This unmanned aerial vehicle will be made available to other researchers and state agencies for future work.	$14,450	$14,450
Thermal /color camera with GPS sensors to allow for geotagged simultaneous thermal and RGB surveys with quadcopter. Total estimated at $6,348.	$6,348	$6,348
Travel expenses in Minnesota		
Travel to study areas by research assistants and project management staff and technicians: 1 UMN Fleet Truck Rental at $834 for 2.5 months a year for 2 years (4* $834 monthly rate)= $3,336 + (4 weeks* $274 weekly rate)= $1,096, Total vehicle rental = $4,432; Mileage for fleet vehicle @ $.037 per mile (UMN fleet rate) * 15,000 miles = $5,500; Personal vehicle use to get research assistants and technicians to and from Cedar Creek (no vehicle rental) and project management to field sites (no vehicle rental) = $0.575 per mile (UMN personal vehicle rate) * 3120 miles = 1794. - $11,726	$6,950	$6,950
Room and board for field crew - 1 research assistant + 2 field techs for two month-($1000)	$1,000	$1,000
Travel expenses out of state		
Travel to and registration for a national conference to discuss the robotics portion of this project.		
Other		

Networking and Computer Services (U of M Computer Science and Engineering). Networking and computer charges are expenses charged to sponsored and non sponsored accounts to support the portion of networking and computer infrastructure used by sponsored and non sponsored research projects. In a formula found to be Uniform Guidance compliant by the Office of Treasury Accounting and Internal/External Sales and Sponsored Projects Administration, research specific computing is separated from general-purpose computing. The networking and computer support charge is based on FTEs and special projects that can be attributed to research-only projects. Project Engineer: (100% - 1 sum mo) 173 hrs * $2.26/hr = $392 * 2 years = ($784 total); Graduate research assistant (Computer Science & Engineering): (50% - 12 mos) 1,040 hrs * $3.40/hr = $3,536 * 2 years = ($7072 total). - $7,856. Additional Network/Comp service Needed to finish the project.	$3,928	$3,928
Service contract and repair costs (including postage and repair fees) for fixed wing and quadcopter	$1,884	$1,884
COLUMN TOTAL	**$187,810**	**$187,810**

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND

Activity 1 Balance	Revised Activity 2 Budget 05/10/2020	Amount Spent	Activity 2 Balance	TOTAL BUDGET	TOTAL BALANCE
$0	$149,193	$149,193	$0	$298,385	$0
	$1,653	$1,653	$0	$1,653	$0
$0	$140	$140	$0	$498	$0

$0				$3,700	$0
	$3,000	$3,000	$0	$3,000	$0
$0				$14,450	$0
$0	$0	$0	$0	$6,348	$0
$0	$486	$486	$0	$7,436	$0
$0	$0	$0	$0	$1,000	$0
	$770	$770	$0	$770	$0

$0	$4,948	$4,948	$0	$8,876	$0
$0	$0	$0	$0	$1,884	$0
$0	**$160,190**	**$160,190**	**$0**	**$348,000**	**$0**