Høgskolen
i Innlandet

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Drone-borne monitoring of moose

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Norsk sammendrag

Droner er en lovende ny teknologi for overvåking av viltbestander. I dette prosjektet evaluerte vi bruken av droner som et verktøy for overvåking av elg (Alces alces) populasjoner og beiting i den skandinaviske boreale skogen. Spesifikt forsøkte vi å finne de beste deteksjonsforholdene for elg og kalvene deres i boreal skog, som vi deretter brukte til å estimere elgpopulasjonstettheten i et gitt område som et konseptbevis. Videre evaluerte vi om og ved hvilken observasjonshøyde elg ble forstyrret av dronen, og om elgens beitetrykk på barskogtrær kan identifiseres ved hjelp av droner. Vi brukte først dronen 'DJI Mavic 2 Enterprise Dual' for å teste oppdagbarheten til GPS-merkede elgekuer og deres kalver. Dronen ble programmert til å fly til den siste kjente GPS-posisjonen til elgen ved 100 m høyde. Hvis elgen ble oppdaget fløy vi dronen rett over den og senket deretter dronen gradvis til 70, 50, 30 og 20 m høyde og noterte ved hvilken høyde eventuelle kalver ble oppdaget. I tillegg kvantifiserte vi hvordan nærheten av drone påvirket elgens atferd (n = 24 GPS-merkede individer) sammenlignet med forsøk der personer nærmet seg GPS-merkede elgkuer på bakken for å oppdage elgkalver. Gjennomsnittlig tid brukt på tilnærmingsforsøk med drone var 17 minutter sammenlignet med 97 minutter for tilnærminger på bakken, med høyere oppdagbarhet for droner (95% av elgkuer og 88% av elgkalver) sammenlignet med tilnærminger på bakken (78% av elgkuer og 82% av kalver). Oppdagbarhet av elgkalver økte ved lavere dronehøyder (50-70 m), mens alle voksne elger ble oppdaget ved 100 m (unntatt to individer som hadde flyttet seg fra området før forsøket ble gjennomført). Elgkuer forlot stedet i 35% av tilnærminger med drone sammenlignet med 56% av tilnærminger på bakken. Vi klarte ikke å finne effekter av droneforsøkene på elgens områdebruk, men elgen beveget seg over 4 ganger større avstander og brukte større område i løpet av 3 timer etter bakkenærmingene sammenlignet med etter droneforsøk. Etter å ha fastslått at en flyhøyde på 100 m ga god oppdagbarhet av elg med minimal forstyrrelse, evaluerte vi deteksjonsforholdene for elg mer detaljert ved hjelp av dronen 'DJI Matrice 300 RTK' med et 'Zenmuse H20T' kamera. Totalt fløy vi 33 gridflygninger over 11 GPS-merkede hunnelger. I 26 av disse flyvningene (79%) var elgen innenfor rutenettet. Av disse 26 elgene oppdaget vi 20 elger, tilsvarende en deteksjonsrate på 77%. Sannsynligheten for å oppdage en elg tenderte til å være større i overskyet sammenlignet med solrike forhold, men ble ikke påvirket av andre faktorer (temperatur, skogtype, tetthet av tredekket). Deretter gjennomførte vi 34 gridflygninger om høsten for å finne elg som ikke var GPS-merket og estimere lokal elgtetthet. Vi oppdaget elg i 9 av de 34 flyvningene, totalt 20 individer, tilsvarende 1,24 elger per km2 basert på rå-observasjonene. Vi oppdaget sannsynligvis 75-90% av alle elger gitt at forholdene var mer gunstige på grunn av kaldere temperaturer og mindre solskinn sammenlignet med flyvningene over GPS-merkede elger. Dette tilsvarer en høsttetthet på 1,38 - 1,65 elger per km2 og en sommertetthet på 1,49 - 1,84 elger per km2. Disse estimerte elgtetthetene fra våre droneflyvninger stemte godt overens med elgtetthetsberegninger fra elgmøkktellinger gjennomført to år tidligere. Til slutt evaluerte vi mulige metoder for å estimere elgens beiteskader i unge barskogbestander, noe som vil være utfordrende å oppnå. Oppsummert var drone svært effektivt for å oppdage voksne elger og kalvene deres i den boreale skogen, og var raskere og mindre forstyrrende enn tilnærminger på bakken. Videre antyder resultatene våre at overvåking med droner kan gi svært pålitelige tetthetsestimater for elgbestander, i det minste i små områder, og kan være nyttige for å estimere beiteskader. Vi diskuterer hvordan funnene våre kan iverksettes på en større skala for forbedret elgforvaltning i hele Skandinavia.

Summary

Drones are a promising new technology for the monitoring of wildlife populations. In this project, we evaluated the use of drones as a tool to monitor moose (*Alces alces*) populations and browsing in the Scandinavian boreal forest. Specifically, we aimed to identify the most successful detection conditions for moose and their calves in the boreal forest, which we then implemented to estimate the moose population density in a given area as proof of concept. Moreover, we evaluated if and at which threshold height above ground moose were disturbed by drones, and if moose browsing on coniferous trees can be identified using drones. We initially used the drone 'DJI Mavic 2 Enterprise Dual' to test detection success of GPS-collared moose. The drone was programmed to fly to the last known GPS position of moose at 100 m altitude and – if detected – we flew the drone directly above the moose. The drone was then progressively lowered to 70, 50, 30 and 20 m altitude. Additionally, we quantified how these drone approaches affected moose behavior and space use (n = 24 GPS-collared individuals) compared to trials in which a person approached moose on ground (to detect calves). The average time used for drone approaches was 17 minutes compared to 97 minutes for ground approaches, with drone detection probability being higher (95% of adult female moose and 88% of moose calves) compared to ground approaches (78% of adult females and 82% of calves). The detection success of moose calves increased at lower drone altitudes (50-70 m), whereas all adult moose were detected at 100 m (except two individuals that had moved from the area before the flight was conducted). Adult female moose left the site in 35% of drone approaches compared to 56% of ground approaches. We did not detect effects of drone approaches on moose space use, but moose moved > 4-fold greater distances and used larger areas during 3-h after ground approaches. After establishing that a drone flight height of 100 m allowed for successful moose detection while minimizing disturbance, we evaluated the detection conditions for moose in more detail, using the drone 'DJI Matrice 300 RTK' with a 'Zenmuse H20T' camera. In total, we flew 33 grids over 11 GPS-collared female moose, with moose located within the grid in 26 flights (79%). Of these 26 moose, we detected 20 moose, corresponding to a detection probability of 77%. The probability of detecting a moose tended to be greater in cloudy compared to sunny conditions but was not affected by other factors (temperature, forest type, tree cover density). Subsequently, we conducted 34 grid flights during fall to detect moose that were not GPS-collared and estimate local moose population density. We detected moose in 9 of the 34 flights, totaling 20 individuals, equivalent to 1.24 moose per km^2 based on the raw observations. We likely detected 75-90% of all moose given that conditions were more favorable due to colder temperatures and less sunshine (compared to flights over GPS-collared moose), corresponding to a fall density of 1.38 - 1.65 moose per km^2 and a summer density of 1.49 - 1.84 moose per km^2. These predicted moose densities from our drone flights matched closely with moose density estimates obtained from pellet counts conducted two years earlier. Finally, we evaluated potential methods to estimate moose browsing damage in young conifer stands, which will be challenging to achieve. In summary, drone approaches were highly efficient in detecting adult moose and their calves in the boreal forest, being faster and less disturbing than ground approaches. Moreover, our results suggest that monitoring using drones can yield highly reliable moose population density estimates, at least in small areas. We discuss how our findings could be implemented on a larger scale for improved moose management across Scandinavia.

Content

1. Background

In Scandinavia's boreal forest zone, forestry and game harvest are economically and culturally important corner stones of rural societies (Wam *et al.* 2005). The largest and economically most important game species in boreal Scandinavia is the moose (*Alces alces*) (Storaas *et al.* 2001). Moose are browsers, i.e. adapted to forage on woody plants. In winter, when access to deciduous trees and shrubs is limited by snow, moose browse on young pine trees (Hjeljord 2003). Browsing pressure on pine can be considerable, depending on moose density, availability of other browse and winter severity (Sand *et al.* 2019). Young pine trees may be damaged to a degree that future timber production of young forest stands will be afflicted by slow growth and low timber quality (Bergqvist, Bergström & Edenius 2001; Wallgren *et al.* 2013). Moreover, while timber production has a long-term perspective caused by a slow turnover rate of commercial boreal tree species, game harvest is a year-to-year event with a more continuous distribution of effort and income. Due to these reasons, stakeholders have an ongoing conflict of interest regarding forestry and moose harvest (Ezebilo, Sandström & Ericsson 2012). Thus, the management of the Scandinavian moose population is characterized by trading off the two interests and aims at sustaining a highly productive moose population at a density that is sustainable for timber production (Wam *et al.* 2005). Other issues, such as the minimization of wildlife-vehicle collisions, the conservation of deciduous species for biodiversity, and tourism other than game hunting also have to be considered by management (Lavsund, Nygrén & Solberg 2003).

The regulation of the moose population by harvest to adapt to various management goals requires data on the status of the moose population density. Reproduction and survival determine population dynamics and are important parameters for wildlife management. However, this data is hard to assess from animals in the wild. Thus, current moose monitoring practices in Scandinavia primarily focus on monitoring population growth through relative indices rather than finding absolute densities. Among these relative indices are the annual changes in hunting bag statistics, the proportion of the quota that has been harvested, hunter efforts, and moose observations by hunters (Ueno *et al.* 2014). In addition, some moose management areas perform track or aerial counts during winter at regular intervals of one to several years. In Sweden, fecal pellet counts gain a growing attention and are performed by hunters in spring to assess relative winter densities and distribution (Rönnegård *et al.* 2008). None of these methods are used by the management to elaborate absolute densities but help to track the development of the moose population. However, absolute densities and more detailed information regarding reproduction would be very useful for more precise and adaptive management, at least on comparatively smaller spatial scales.

One method to monitor reproduction is the GPS-collaring of female moose (Stubsjøen *et al.* 2000; Rolandsen *et al.* 2017), and subsequent ground observations of these animals to detect calves. For example, the GRENSEVILT project GPS-collared moose over the last years to obtain more detailed information regarding space use and reproduction. Another novel and promising method for monitoring wildlife is the use of unmanned aerial vehicles, hereafter drones. Drones are increasingly used to monitor and study wildlife due to technological advancements, making them affordable and user-friendly (Linchant *et al.* 2015a; Schroeder *et al.* 2020; Iwamoto *et al.* 2022). Thus, they have a large potential to non-invasively monitor the abundance and reproductive success of wildlife. Considering their increasing use not only by researchers, but also managers, photographers, and recreationists, it is also important to understand their effects on animal behavior and movement (Mulero-Pázmány *et al.* 2017; Bennitt *et al.* 2019).

Apart from monitoring relative population changes, there are regular assessments of moose browsing damage. This is done using two partly different methods in Sweden (ÄBIN; assessing damaged stems (Rolander, Kalén & Bergqvist 2017)) and Norway (Solbraa-method; assessing browsing pressure on available shoots (Solbraa 2008)). In Sweden, these browsing assessments have recently become standardized and coordinated and are now scheduled regularly in all moose management areas. There is no such coordination in Norway, results are not stored in a common database, and they are not necessarily comparable among assessments. Furthermore, a study comparing the Swedish and the Norwegian method found that they can in some cases lead to very different assessments (Zimmermann *et al.* 2022). Browsing damage assessments are time-intensive and expensive due to intensive fieldwork requirements over large areas (Hellbaum *et al.* 2023). Thus, there is a need to develop a more cost-effective, coordinated method of browsing surveys.

Here, we evaluated the use of drone-borne cameras to monitor moose populations and young forest stands. Drones are still underused in Norway’s wildlife management, despite their wide range of potential applications (Koh & Wich 2012; Linchant *et al.* 2015b; Burke *et al.* 2019). Most trials to date using drone-mounted cameras to count animals were conducted for species that aggregate in open areas (e.g., birds, wild reindeer (Hodgson *et al.* 2018; Ruud & Hagen 2019)). So far, few trials have been done for wild ungulates in forested landscapes, e.g. for moose in North America (McMahon *et al.* 2021) and red deer, roe deer and wild boar in Poland (Witczuk *et al.* 2018). Drones have the advantage that they are cheaper than manned aircraft, they can be operated on spot and at lower heights, produce less noise, and their use is independent of daylight (when using thermal infrared cameras). As technology develops and the market increases, drones become affordable for wildlife managers, landowners and other stakeholders involved in moose management.

It is not the drones themselves, but rather the cameras mounted on the drones that determine the usefulness. For monitoring of homoeothermic animals, thermal infrared cameras (TIR) that register heat emitted from the body can be more successful than optical cameras (RGB) that record the light reflected by the body, especially if the species is elusive and hard to optically distinguish from the surroundings (Franke *et al.* 2012; Cilulko *et al.* 2013; Havens & Sharp 2015; Burke *et al.* 2019). Detection success using TIR depends on flight height, camera angle, temperature and humidity of the surroundings and the atmosphere, the skin/hair temperature of the animal, and its behavior and selection of habitat (Israel 2011; Cilulko *et al.* 2013; Havens & Sharp 2015). So far, the application of drones in forestry has been limited to forest inventories, to e.g. estimate timber volume (Goodbody *et al.* 2017). There is a large potential regarding the use of drones to extract forest parameters, such as the assessment of the horizontal and vertical structure, for wildlife management.

2. Aims

The overall aim of this project was to **evaluate the use of drones as a tool to monitor moose populations and browsing** in the Scandinavian boreal forest. We completed five working packages (WP):
WP 1: Investigating successful **detection conditions** for moose in the boreal forest (camera, flight parameters, weather, air temperature, habitat).
WP 2: Investigating if and at which threshold height moose are **disturbed** by drones.
WP 3: Quantifying if drones can be used to **monitor calving and survival** of calves of GPS-collared moose cows.
WP 4: Drone-based monitoring to **estimate the moose density** in a given area as proof of concept.
WP 5: Describe potential methods to quantify the degree of **moose browsing**, e.g., evaluation of forest recruitment and identification of stem breaking and browsing on top shoots.

3. Material and methods

3.1 Study area, moose captures, GPS collaring

Our project was conducted in southern Scandinavia, in the border region between Innlandet county in Norway and Dalarna and Värmland counties in Sweden (Fig. 1). The study area is dominated by boreal coniferous forest consisting of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) interspersed by bogs, dams, lakes, and deciduous trees mainly composed of, birch (*Betula pendula* and *B. pubescens*), aspen (*Populus tremula*), willow (*Salix spp.*), alder (*Alnus incana* and *A. glutinosa*) and rowan (*Sorbus aucuparia*). There is a large network of gravel roads used for forestry, making the area easily accessible (Zimmermann *et al.* 2014). The climate is cold, with snow cover for 3 to 6 months per year (mainly from November to April) during cold and dry winters (Zimmermann *et al.* 2015; Milleret *et al.* 2017). Winter moose densities range between 1 and 3 per km^2 (Zimmermann *et al.* 2015). Generally, from November (depending on snow depth) moose start to migrate to areas with less snow, often valley bottoms and forested lowlands (Gundersen, Andreassen & Storaas 2004). From April to May, they migrate back again to summer habitats at higher altitudes (Gundersen 2003; Zimmermann, unpublished data). All four large carnivore species of Norway (wolf (*Canis lupus*), brown bear (*Ursus arctos*), wolverine (*Gulo gulo*), and lynx (*Lynx lynx*)) are present in the area.

Twenty-four moose were darted from a helicopter with a CO_2-powered dart gun and equipped with a GPS collar (Vectronic Aerospace, either VERTEX PLUS with GSM-link, or SURVEY with Iridium-link). The immobilization and handling procedure is described in detail elsewhere (Evans *et al.* 2012; Lian *et al.* 2014; Græsli *et al.* 2020b). Captures were approved by the Norwegian Food Safety Authority (id 26431) and the Norwegian Environmental Agency. GPS collars were programmed to take one position every hour (VERTEX PLUS) or every two hours (SURVEY) throughout the day. On days with drone or ground approaches, all except 5 GPS collars were programmed to take one position every 10 minutes between 08:00-18:00 local time. The five exceptions were individuals equipped with VERTEX PLUS collars with built-in cameras. These collars were not re-programmed to save battery capacity. The positions from the GPS collars were sent every two hours to a server and displayed on a map within a web-application (www.dyreposisjoner.no), where the field team could obtain the latest moose locations.

3.2 Drone operations

All drone operations were conducted by licensed operators (open category A1/A3). We ran 4 different types of drone flights:

1. To measure moose detection success, calf presence, and disturbance effects (WP1, 2, and 3), we used the drone “DJI Mavic 2 Enterprise Dual” using a GPS+ GLONASS system with a ± 1.5 m horizontal and ± 0.5 m vertical accuracy range. The drone was programmed to fly to the last known GPS position of the moose (flight speed was 6 m/s) at 100 m altitude while the operator stayed ≥ 500 m away (but within the visual line of sight). When the drone arrived at the last known position, the operator manually searched for the moose using the video/image transmitted by the drone (hereafter referred to as search flights) and – if it was detected – flew the drone directly above the moose, where it hovered for two minutes while recording video, using a built-in RGB camera (1920 x 1080 resolution). If the moose did not flee from the site, the drone was progressively lowered to 70, 50, 30, and 20 m altitude with a 1-minute hovering time for each altitude interval. At each altitude, we noted the presence of offspring and moose cow behavior. Behavior was classified into 4 categories: (1) lying, (2) standing still, (3) walking, which often included foraging, and (4) running. If the moose started running at any time during the approach or when the drone had hovered for one minute at 20 m altitude, the trial was completed, i.e., the drone was flown back to 100 m altitude and returned to the original position. The speed for lowering or elevating the drone was set to 2 m/s. We conducted 42 search flights between May and December 2021.
2. To evaluate if we could detect moose using grid flights at a fixed altitude (WP1), we programmed a larger drone (DJI Matrice 300 RTK Combo), which featured longer flight times per battery pack. The drone was equipped with a multi-sensor camera module including a thermal camera, wide angle lens, a zoom lens, and a laser range finder (DJI Zenmuse H20T). Grid missions were programmed centering around the last known GPS position of the moose (Fig. 1). We programmed the drone to fly grids that were large enough to increase the probability of including the moose within them but small enough to allow for remaining battery life for a manual search after the grid flight. The drone was programmed to fly at 100 m height and a speed of 9 m/s and take pictures at a 90° angle with 50% frontal and 25% side overlap. These flights were conducted in May and June 2023.
3. We flew grid flights with the aim of covering the largest possible area (see results) based on battery capacity, topography, and visibility of the drone to estimate moose density in the area (WP4). Grid flights were programmed the same way as described above, but with the difference that we did not know of any GPS-collared moose in the area. These flights were conducted in October 2023.
4. We programmed the drone to fly grids at 50 m height at a slow speed (2 m/s), taking pictures at a 90° angle with 80% frontal and 70% side overlap. These grid flights were conducted in young forest stands (<2 m average tree height) to evaluate browsing damage of trees by moose (WP5). Flights were conducted in early winter (December) and will then again be conducted on the same grids in spring 2024 (to estimate differences in tree volume between fall and spring; see below).

3.3 Ground approaches

To compare disturbance effects of drones to other types of disturbances (WP2) and obtain a baseline measure of calf presence (WP3), we approached moose on the ground. Ground approaches were conducted by a single observer on foot to detect if female moose had calves. We approached the last known moose GPS position using a VHF-receiver (RX98, Followit AB, Sweden) to locate the moose. All approaches were conducted with headwind and the track was recorded (one position every 10 sec) with a handheld GPS unit. We approached each moose close enough to get a visual confirmation of the presence or absence of a calf/calves. We sneaked back downwind to minimize the risk of the female moose detecting us. We recorded the duration of approaches from the start (≥500 m from the last moose position) until the moose was detected or the approach stopped, using handheld GPS tracklogs for ground approaches and timestamps from drone videos.

We used a paired study design to compare calf detection success between drone and ground approaches. For comparisons of calf detection, we only used cases where the same individual was monitored using both a drone and a ground approach within one week (n = 44 approaches). To minimize the risk of calf mortality between approaches, we minimized the number of days between drone and ground approaches but left a minimum of one day between approaches to allow females to return to their baseline behavior after the potential disturbance. We randomized the order of drone and ground approaches.

3.4 Data preparation and statistical analysis

3.4.1 WP1 Moose detection

First, we tested different heights above GPS-collared moose based on search flights to find the optimum between detection probability (including calves) and the area surveyed. Because the detection success of adult female moose was very high (95%; see results), we could not formally analyze the probability of detecting moose based on search flights. Second, based on grid flights over the last known position of GPS collared moose, we analyzed the probability of detecting a moose using generalized linear models with a binomial distribution (0 = moose not detected versus 1 = moose detected). To check if a moose was in the area covered by the grid flight, we plotted the moose location at the time the flight was started as well as the two following locations (because flights lasted 15-20 min), visually confirming if a moose was within the grid or not. To define moose detection, we used 3 different definitions: (i) the drone operator verified moose detection during the flight, (ii) moose detection was verified by an independent observer (not present during drone flights) who visually checked all pictures taken by the drone, and (iii) the sum of detection obtained by the two previously mentioned methods. The observer was trained to detect moose in thermal images by viewing sample footage. In all 3 analyses, we included temperature, weather (sunny or cloudy), dominant forest type (pine, spruce, or deciduous forest), tree height, and tree cover density as independent variables. We obtained data regarding tree cover density in 2018 from the European Environment Agency (Tree Cover Density 2018; https://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density/status-maps/tree-cover-density-2018?tab=download), defined as the proportion of ground covered by trees. We extracted tree cover density at the GPS position of the moose during the flight and the following position (because drone flights lasted 15-20 minutes), and then estimated the mean tree cover density of these two positions. The dominant forest type, tree height, and tree crown cover were obtained from the 'Skogsressurskartet' SR16 data set (https://www.nibio.no/tema/skog/kart-over-skogressurser/skogressurskart-sr16; accessed in November 2023) and extracted for each moose GPS position at the time the grid flights were conducted. Tree cover density was highly correlated with tree crown cover (Pearson correlation coefficient > 0.6), so we excluded the latter from our analyses.

3.4.2 WP2 Moose disturbance

For all GPS positions, we estimated the distance to the closest road and extracted the tree cover density, using the r packages ‘rgeos’ and ‘raster’ (Hijmans *et al.* 2015; Bivand *et al.* 2018) because these factors might affect how much a moose reacts to disturbance. Moreover, we estimated step length (Euclidean distance) between consecutive GPS positions (separately for 2-h and 10-min fix rate) and estimated daily and hourly area use using 95% Kernel Density Isopleths (KDIs) using the reference bandwidth of the r package ‘adehabitatHR’ (Calenge 2006). Daily area use was estimated based on 2-h positions, only including approaches for which we had obtained at least 10 GPS positions during a 24-hour period after the approach had started (leading to the exclusion of 3 approaches). Hourly area use (three hours before and after approaches; see below) was estimated based on 10-min positions, only including approaches for which we had obtained at least 5 GPS positions per hour.

To analyze the potential disturbance caused by the approaches, we conducted three analyses at different spatio-temporal scales: (1) direct disturbance, analyzing the probability of a moose being flushed during an approach, (2) shorter-term disturbance effects on step length and area use comparing three hours before and after the approach started, and (3) longer-term disturbance effects comparing step length and area use 24 hours before and after the ground or drone approach started, or before and after a true control (no known disturbance). For analysis (1), we classified a moose as being flushed when we saw it moving away from the location where it was first detected during either the ground or drone approach. We used this behavioral response as a binomial response variable (0 = not flushed, 1 = flushed) in a generalized linear model (GLM) with a binomial error distribution and a logit link. As independent variables, we included the approach type (ground or drone), calf presence (yes/no), distance from the closest road, and tree cover density. For analyses (2) and (3), we used step length (log-transformed to normalize residual distributions) as response variable in linear mixed effects models of the R package ‘lme4’ (Bates *et al.* 2015). We included the time of the day, tree cover density, distance to the closest road, calf presence, approach type, period (before/after), and the two-way interaction of approach type × period as fixed effects, and moose ID and experiment ID as random intercept. To avoid higher-order interactions, we additionally conducted an analysis only including the period after the approach had started, to test if flushed moose moved greater distances depending on approach type and calf presence. We included calf presence, tree cover density, distance to the closest road, approach type, flushing behavior (flushed or not flushed), and the two-way interactions of approach type × flushing behavior and calf presence × flushing behavior as fixed effects, and moose ID and experiment ID as random intercept. Finally, we analyzed hourly and daily area use (log-transformed response variable to normalize residual distributions), including calf presence, approach type, period, and the two-way interaction of approach type × period as fixed effects and moose ID and experiment ID as random intercept. We initially tested if the linear or quadratic function of distance to the closest road and time of day fitted better (based on AIC). For the drone approaches only, we additionally analyzed the video recordings to quantify if moose behaviors changed during the drone approach at different hovering heights.

3.4.3 WP3 Moose reproductive success

We tested if the use of drone with a RGB and thermal camera is a more effective and less disturbing method to survey moose cows and their calves, using search flights. We analyzed the probability of successful calf detections (response variable; 1 = calf detected versus 0 = calf not detected) for the paired approaches (described above) of moose cows for which at least one approach type had confirmed calf presence (n = 32 approaches), using GLMs with a binomial error distribution and a logit link. We included the approach type and tree cover density as predictor variables. As our fall observations were limited to two paired approaches, we were unable to explore potential seasonal differences.

3.4.4 WP4 Moose population count

We used the findings regarding detectability from WP1 to estimate moose population density in our study area. To do so, we corrected for detectability when estimating the number of moose per km^2 (see results). We then compared this estimate to a predicted density estimate obtained from moose pellets counts in 2021 from the same area where we conducted our grid flights (including areas between grids).

3.4.5 WP5 Assessing relevant parameters of moose browsing

To quantify if moose browsing can be monitored using drones, we considered two methods. First, we tested if individual browsing marks and stem breaks could be identified directly on high-resolution RGB images. To achieve this, we conducted grid flights at 50 m altitude with high sideway and frontal overlap, resulting in each point within the grid mission being photographed several times from different angles. Suitable forest stands (young pine stands, on average < 2m high) were identified using aerial images and verified in the field. Initially, we manually checked images to identify potential browsing marks. If successful, those images could be used as training dataset for a machine learning algorithm automating further image processing.

As a second method, we aimed to quantify total available biomass for browsing within a forest stand before and after the winter browsing season. The difference in biomass represents the accumulated winter browsing. This involves utilizing high-resolution overlapping images to create orthomosaics, point clouds, and digital surface models (DSM). Deducting the ground surface (digital elevation model, DEM) from the surface including vegetation (digital surface model, DSM) results in a map with net vegetation height. Calculating the volume of this map provides us with the total biomass within the surveyed forest stand. Calculations of vegetation height and volume can be done using raster analysis. By calculating total standing biomass in autumn and spring (i.e., before and after winter browsing by moose) we aimed to calculate the total biomass browsed during winter. One challenge with this method is the relatively low resolution of the DEM. Since we conduct the two flights at the exact same location the error from the DEM is going to be identical for both flights and should therefore be negligible.

3.4.6 Model selection

For all analyses (WP1-4), we conducted model selection by successively removing variables that reduced Akaike's information criterion corrected for small sample size (AICc) (Burnham, Anderson & Huyvaert 2011) from the full model (described for each analysis above), using the r package 'MuMIn' (Barton 2016). There was no collinearity (Pearson's r < 0.6 and variance inflation factors < 3) between independent variables within the same model (Zuur, Ieno & Elphick 2010). Parameters that included zero within their 95% CI were considered uninformative (Arnold 2010). Model assumptions were verified by plotting residuals versus fitted values (Zuur & Ieno 2016) and performing dispersion and deviation tests, using the r package 'DHARMa' (Hartig 2021).

4. Results and discussion

4.1 WP 1 Moose detection

During search flights, the time used for drone approaches was 12 to 22 min (mean ± SD: 17 ± 2 min). For these approaches, we mostly used the RGB camera (as the resolution of the thermal infrared camera was too poor). The drone operator detected adult female moose in 40 of 42 approaches (95%). One of the individuals not detected during a drone approach moved >1.5 km from the last known GPS position for unknown reasons 20 minutes before the approach started. All adult moose were detected at 100 m height.

These findings indicate that drone approaches are highly useful for detecting GPS-collared female moose, consistent with previous studies using drones to monitor wildlife (Hui *et al.* 2021; Stander *et al.* 2021; Iwamoto *et al.* 2022). Both drone and ground approaches were successful at detecting adult moose, but drones performed slightly better than ground approaches in detecting moose. Moreover, drone approaches were more time-efficient in detecting moose, taking only ca. one sixth of the time used for ground approaches.

After establishing that a drone height of 100 m was suitable to detect adult moose, we conducted grid flights to quantify the factors affecting detectability in more detail (Fig. 1). In total, we flew 33 grids over 11 GPS-collared female moose (between 1 and 6 flights per individual; mean ± SD: 3 ± 1.8). The moose was located within the grid in 26 flights (79%). During flights, drone operators detected 15 of the 26 moose (58%), mostly using the thermal infrared camera. Similarly, an independent observer who was not part of the field team detected 15 moose, mostly from the thermal infrared images. However, the drone team and the observer did not always detect the same individuals, i.e., in total we detected 20 moose, corresponding to a detection probability of 77%.

Temperature during flights ranged from 9 to 23 °C (mean ± SD: 14 ± 4 °C), the weather was sunny in 14 flights and cloudy in 12 flights, and tree cover density where the moose was located ranged from 0-94% (mean ± SD: 65 ± 24%). Moose were in forest dominated by spruce in 17 cases, pine forest in 8 cases and outside forest in one case. The probability of detecting a moose based on all detections was best explained by the model including weather (sunny versus cloudy) and tree cover density (Table 1). However, both the effect of weather and tree cover density were uninformative, i.e., the 95% confidence interval (CI) overlapped zero, after excluding the one moose located outside a forest. The probability of detecting a moose based on the independent observer (i.e., based on checking images) was best explained by weather (Table 1), with moose more likely to be detected during cloudy conditions (Fig. 1). Finally, the probability of detecting a moose based on the drone operators (i.e., detections during fieldwork) was best explained by the intercept only model (Table 1).

Table 1: Overview of the best, full, and intercept only models for the analyses quantifying the effects influencing the probability of detecting moose. We separated the analyses into moose detections recorded by the drone operators during flights, by an independent observer checking drone images, and the combination of these two methods (i.e., all detected moose).

Analysis/model	Model parameters	df	logLik	AICc	delta AIC	AIC weight
Total moose detections						
Best model	Tree cover density + weather	3	-10.916	28.9	0	0.659
Null model	Intercept only	1	-14.045	30.3	1.33	0.338
Full model	Tree cover density + dominant forest type + tree height + temperature + weather	7	-9.73	39.7	10.76	0.003
Moose detection based on checking pictures						
Best model	Weather	2	-14.531	33.6	0	0.831
Null model	Intercept only	1	-17.713	37.6	4.01	0.112
Full model	Tree cover density + dominant forest type + tree height + temperature + weather	5	-12.97	38.9	5.36	0.057
Moose detection by drone operators						
Null model	Intercept only	1	-17.713	37.6	0	0.691
Second best model	Weather	2	-17.342	39.2	1.61	0.308
Full model	Tree cover density + dominant forest type + tree height + temperature + weather	7	-15.574	51.4	13.78	0.001

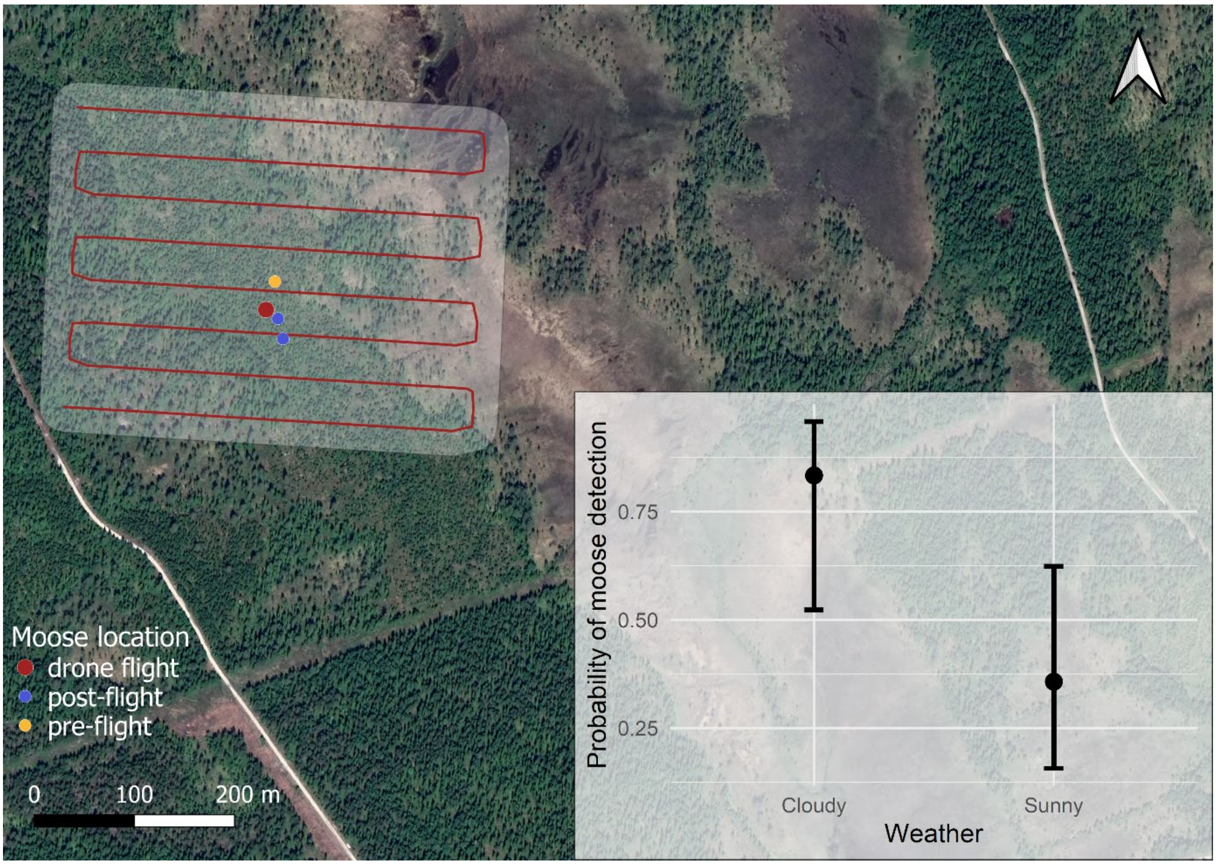

Fig. 1: An example of a grid flight centered on a moose's last known GPS position. The drone flight path is represented by the red line and the area covered by the drone images in shading (top left). The inset (bottom right) shows the predicted effect of cloudy versus sunny weather conditions on the probability of detecting moose on thermal images taken by the drone.

Previous studies showed that habitat structure, weather conditions, and image quality can affect detectability of animals by drones (Bonnin *et al.* 2018; Doull *et al.* 2021; McMahon *et al.* 2021). Here, we only found an effect of weather conditions, indicating that cloudy conditions are more favorable to conduct drone flights for moose detection than sunny days, similar to a previous study estimating the detectability of moose in North America (McMahon *et al.* 2021). It was somewhat surprising that we did not detect an effect of temperature and tree cover density. However, this finding must be interpreted cautiously due to our comparatively low sample size. Because the grid flights for this WP were all conducted during May and June, when temperatures are generally warmer and the sun is above the horizon for most of the day (heating up rocks etc.), there might still be a positive effect of lower temperatures on moose detection probability during colder times of the year (although this might be reduced by a thicker winter coat of moose at this time of the year). Moreover, moose were easier to detect from thermal infrared images compared to RGB images, highlighting that thermal infrared cameras are highly useful in detecting wildlife. Thermal infrared cameras have the advantage that they can be used during challenging conditions, e.g. during nighttime and when animals are partly covered by vegetation. Additionally, when conditions are sunny and the angle of the sun is flat, the RGB camera underexposes shadowy areas between trees making animal detection impossible in these images.

4.2 WP 2 Moose disturbance

4.2.1 Behavioral response to the drone

Adult female moose were flushed (i.e., left the site) in 14 (35%) of 40 drone approaches, compared to 23 (56%) of 41 ground approaches. The probability of being flushed was greater during ground compared to drone approaches (Estimate ± SE: 1.07 ± 0.48, 95% CI: 0.12; 2.02). Distance to the closest road was uninformative. Tree cover density and calf presence were not included in the best model.

During drone approaches, 30 moose were lying (75%), 7 were standing (17.5%), and 3 were walking (7.5%) when the drone hovered at 100 m height (Fig. 2). None of the 40 moose left the site at 100 m hovering height, one left the site at 70 m height (walking), 3 left at 50 m height (2 running, 1 walking), 2 left at 30 m height (both walking), and 8 left at 20 m height (1 running, 7 walking; Fig. 2). Of the 34 moose that were approached down to 20 m, 22 (65%) were still lying (Fig. 2).

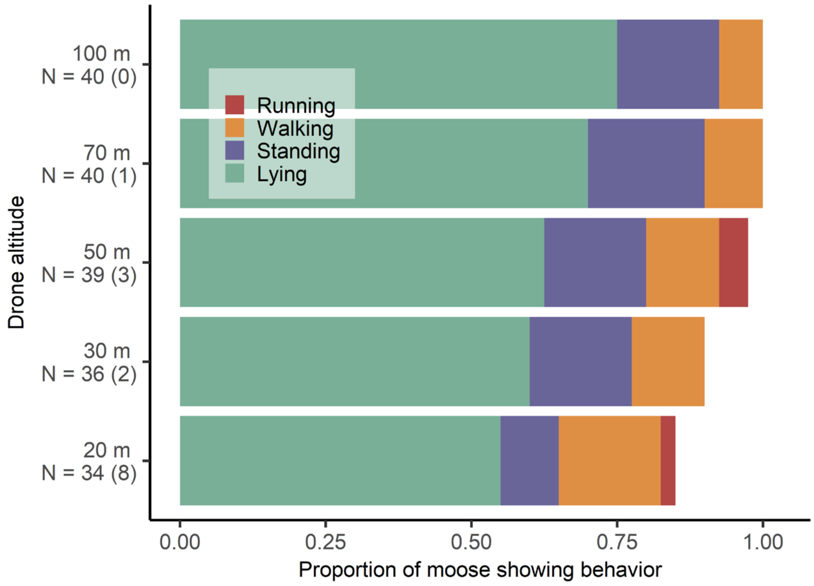

Fig. 2: The proportion of moose showing different behaviors in relation to the approach altitude of the drone. The number of drone approaches conducted is shown for each altitude. The number of approaches stopped (when the moose fled) for each altitude is indicated in brackets.

4.2.2 Short-term disturbance

When analyzing shorter-term disturbance, the interaction of approach type and period indicated that moose step length was larger in the 3-h after ground approaches had started, but not when drone approaches were conducted (Fig. 3A, Table 2). Moreover, moose moved larger distances when they had a calf (Table 2). Tree cover density, time of day, and distance to closest road were not included in the best model. The additional analysis of the 3-h after the approach had started indicated that moose moved greater distances when being flushed during ground approaches, but not during drone approaches (Fig. 3B). During drone approaches, there was little difference in distance moved between moose that were flushed or not flushed (mean ± SD: 26 ± 65 m versus 17 ± 17 m per 10-min), whereas moose flushed during ground approaches moved >4-fold greater distances compared to moose not flushed (111 ± 208 versus 24 ± 35 m per 10-min). Moose with calves moved greater distances than those without calves, but the interaction of calf presence × flushing behavior was not included in the best model. The analysis of area use showed that moose used larger areas during and after ground approaches, but not during drone approaches (Fig. 3C).

Table 2: Effect size, standard error (SE), and lower (LCI) and upper (UCI) 95% confidence intervals of explanatory variables for (1) 10-min step length and (2) hourly area use by adult female moose. Drone approaches were used as baseline level. We performed model averaging of best models (ΔAICc < 2) to estimate the effect size of each variable. Informative parameters are presented in bold (95% confidence intervals do not overlap with zero).

	(1) 10-min step length				*(2) Hourly area use*			
Parameter	Estimate	SE	LCI	UCI	Estimate	SE	LCI	UCI
Intercept	**2.33**	**0.24**	**1.86**	**2.81**	-2.57	0.75	-4	-1.1
Approach type (ground)	0.18	0.22	-0.25	0.61	0.07	0.70	-1.3	1.44
Calf presence (yes)	**0.44**	**0.22**	**0.01**	**0.88**	1.04	0.65	-0.2	2.32
Period (2h-pre)	0.06	0.11	-0.16	0.27	0.53	0.53	-0.5	1.57
Period (1h-pre)	-0.05	0.11	-0.26	0.16	0.41	0.52	-0.6	1.43
Period (1h-post)	-0.01	0.11	-0.22	0.20	0.83	0.51	-0.2	1.85
Period (2h-post)	-0.17	0.11	-0.38	0.05	0.18	0.52	-0.9	1.2
Period (3h-post)	-0.06	0.11	-0.28	0.15	0.31	0.53	-0.7	1.35
Period (2h-pre) × Approach type (ground)	0.14	0.18	-0.22	0.50	0.36	0.87	-1.4	2.08
Period (1h-pre) × Approach type (ground)	0.15	0.18	-0.20	0.51	0.02	0.85	-1.7	1.7
Period (1h-post) × Approach type (ground)	**0.52**	**0.18**	**0.17**	**0.87**	1.19	0.85	-0.5	2.87
Period (2h-post) × Approach type (ground)	**0.94**	**0.18**	**0.58**	**1.30**	**2.45**	**0.87**	**0.73**	**4.17**
Period (3h-post) × Approach type (ground)	**0.46**	**0.19**	**0.08**	**0.83**	1.35	0.90	-0.4	3.11

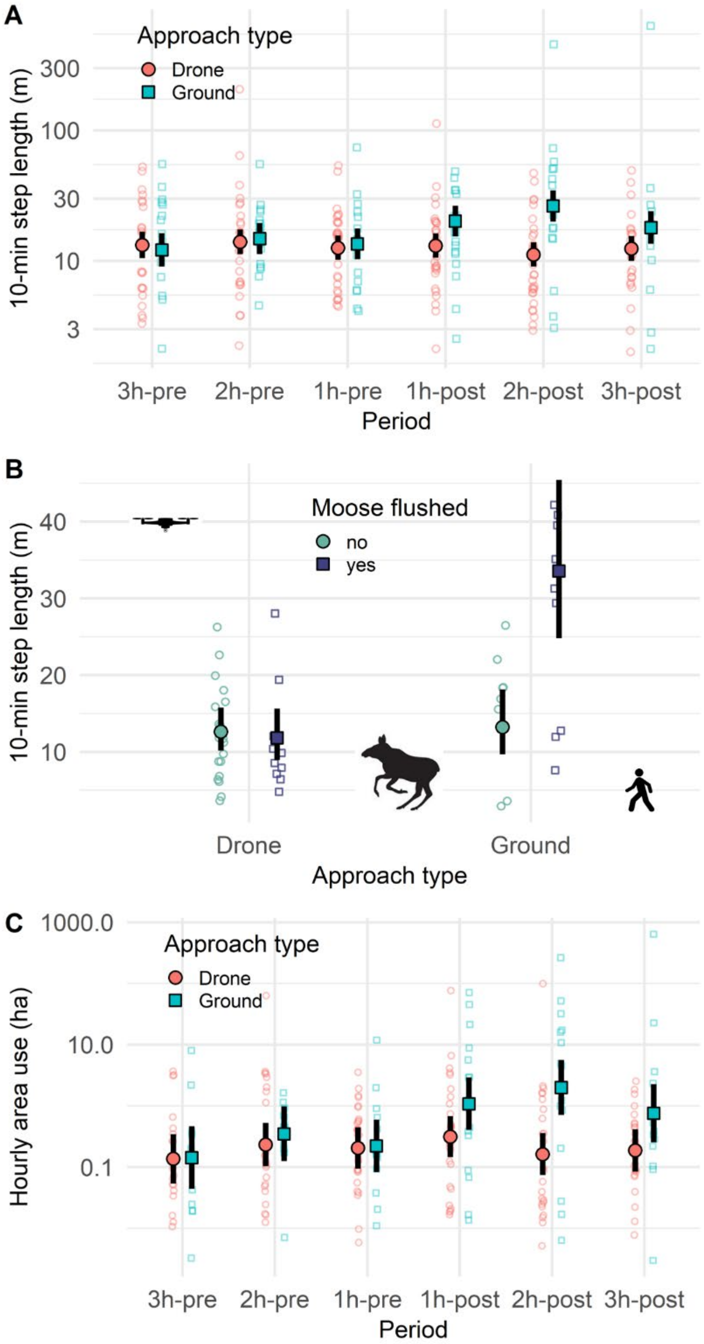

Fig. 3: The predicted effect of (A) approach type on step length by adult female moose in the period 3-h before and after approaches had started. Plot B shows the predicted effect of the interaction of flushing behavior and approach type on the distance moved for the 3-h after the approach had started. Plot C shows the predicted hourly area use by adult female moose 3-h before and after drone and ground approaches. Area use was estimated as 95% Kernel Density Isopleths from 10-min GPS positions. 95% confidence intervals are shown as bars. Small symbols represent median values per experiment, treatment, and period estimated from raw data. Note that the y-axis in plot A and C is log-transformed.

4.2.3 Longer-term disturbance

Step length of adult female moose 24-h before and after approaches were best explained by the time of day and distance to the closest road. Moose moved greater distances during nighttime, and when closer to roads (Table 3). The best model did not include tree cover density, the presence of calves, approach type, period, and their two-way interaction. The additional analysis of the 24-h after the approach had started indicated that moose with calves moved greater distances when being flushed, but not moose without calves (Fig. 4A). Approach type was included in the best model but was uninformative. The analysis of area use 24-h before and after approaches was best explained by approach type, period, and the presence of calves. Moose used larger areas in the 24-h after approaches had started (Fig. 4B) and used smaller areas when having calves (Table 3). The effect of approach type was uninformative, although there was a trend that moose used larger areas on days with ground approaches (Fig. 4B, Table 3).

Table 3: Effect size, standard error (SE), and lower (LCI) and upper (UCI) 95% confidence intervals of explanatory variables to explain the variation in (1) 24-h step length and (2) daily area use by adult female moose approached by a drone or a person on the ground. Control days (no approaches conducted) were used as baseline level. We performed model averaging of best models (ΔAICc < 2) to estimate the effect size of each variable. Informative parameters are presented in bold (95% confidence intervals do not overlap with zero).

	(1) 2-hourly step length				*(2) Daily area use*			
Parameter	Estimate	SE	LCI	UCI	Estimate	SE	LCI	UCI
Intercept	**4.89**	**0.08**	**4.73**	**5.06**	**4.38**	**0.35**	**3.68**	**5.07**
Approach type (drone)					-0.17	0.32	-0.81	0.47
Approach type (ground)					0.59	0.33	-0.06	1.23
Period (24-h post)					**0.34**	**0.17**	**0.01**	**0.67**
Calf presence (yes)					**-0.92**	**0.35**	**-1.62**	**-0.23**
Time of day	**-0.16**	**0.01**	**-0.18**	**-0.13**				
Time of day^2	**0.01**	**0.00**	**0.00**	**0.01**				
Distance to closest road	**-0.08**	**0.03**	**-0.14**	**-0.02**				

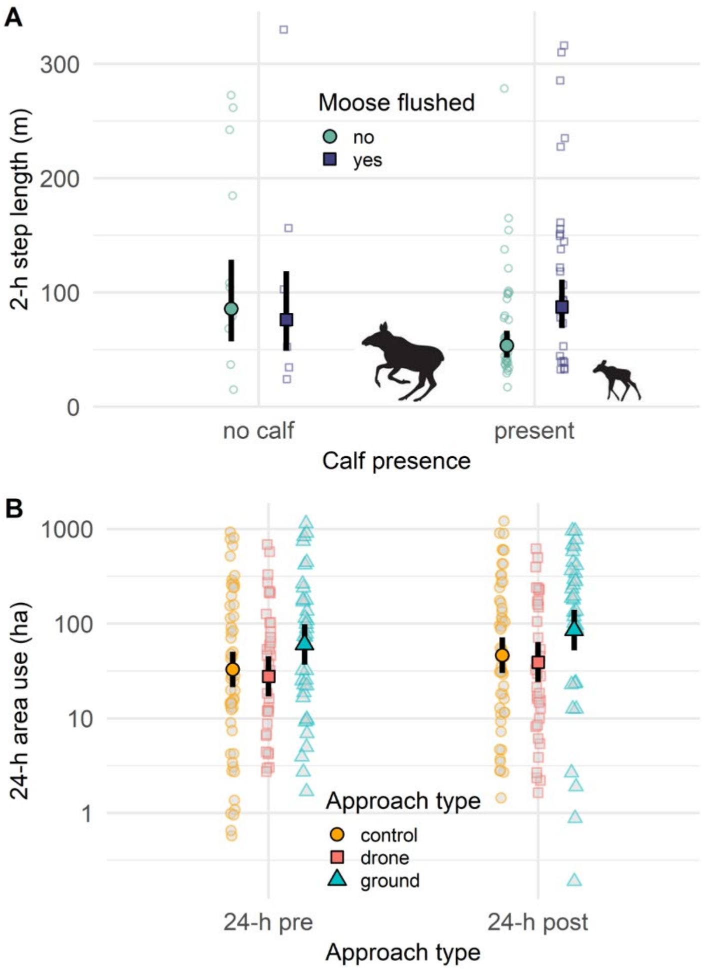

Fig. 4: Plot A shows the predicted effect of the interaction of flushing behavior and calf presence on distance moved for the 24-h after the approach had started. Plot B shows the predicted (large symbols) daily area use by adult female moose for drone and ground approaches, and control days. Note that the interaction of period and approach type was not included in the best model. Area use was estimated as 95% Kernel Density Isopleths from 2-h GPS positions. 95% confidence intervals are shown as bars. Small symbols represent median values for each experiment, treatment, and period estimated from raw data. Note that the y-axis in plot B is log-transformed.

4.2.4 Interpretation of findings

Compared to ground approaches, drone approaches resulted in fewer instances of moose flushing behavior, and in cases when flushing occurred, the affected moose exhibited shorter flight distances. Moose reacting less strongly to drone approaches could be attributed to the drone's resemblance to a large bird, as there are no avian predators of moose (although we acknowledge the possibility that moose associated drones with helicopters, which were used for captures). Conversely, humans (sometimes together with large carnivores) represent the primary cause of moose mortality in Scandinavia (Nilsen & Solberg 2006; Jonzén *et al.* 2013; Wikenros *et al.* 2020). This explains why moose moved > 4-fold larger distances during and after being flushed by ground approaches compared to drone approaches. A previous study conducting ground approaches to detect calves reported similar behavioral responses of moose than reported here (Johnsen 2013). Græsli *et al.* (2020a) investigated the effect of hunting dogs on moose behavior and found that moose moved on average 4.1 km longer on days when disturbed by baying dogs compared to the day after the disturbance, resulting in increased energy expenditure and resting time. This response was much stronger compared to our findings, indicating little evidence of longer-term (24-h) disturbance effects, especially for drone approaches.

The two drones used in this study differed in body size, rotor size and rotating frequency, resulting in different visual and acoustic disturbance. The lack of behavioral change to either drone indicates that the drones did not disturb moose at higher altitudes (70-100 m). Similarly, drone monitoring at 100 m altitude of African elephants (*Loxodonta africana*) (Vermeulen *et al.* 2013) failed to detect evidence of disturbance by drones. However, we cannot exclude the possibility of responses that are difficult to detect with GPS-positioning only, such as changes in heart rate or physiological stress. For example, American black bears (*Ursus americanus*) responded to drone flights with elevated heart rates but infrequent behavioral changes (Ditmer *et al.* 2015), and in eastern grey kangaroos (*Macropus giganteus*), drones elicited a vigilance response but kangaroos rarely fled from the drone if operated at an altitude > 60 m (Brunton *et al.* 2019).

4.3 WP 3 Moose reproductive success

During search flights, 15 of 17 known calves (88,2%) were found using the drone and 14 (82,4%) using ground approaches. The probability of detecting a calf was best explained by the intercept-only model, and both the effect of approach type (estimate ± SE: 0.93 ± 0.07 for drone approaches versus 0.76 ± 0.13 for ground approaches) and tree cover density (estimate ± SE: 0.18 ± 0.55) were uninformative in the full model.

Drone search flights (n = 40) detected 72% of known calves at 100 m hovering height and 92% at 70 m hovering height (Fig. 5 shows an example of a thermal image recorded of an adult female moose and her calf). At lower drone altitudes (50-20 m) moose were increasingly disturbed but calf detection success did not improve. Thus, a hovering height of 70 m (or 100 m for adults) appears optimal to ensure moose calf detection while minimizing disturbance, similar to a study on eastern grey kangaroos (Brunton *et al.* 2019). Importantly, we did not have complete information regarding moose calf presence (determined if a calf was seen throughout the study), which might have led to overestimating calf detection success (as calves that were never observed were counted as true absences).

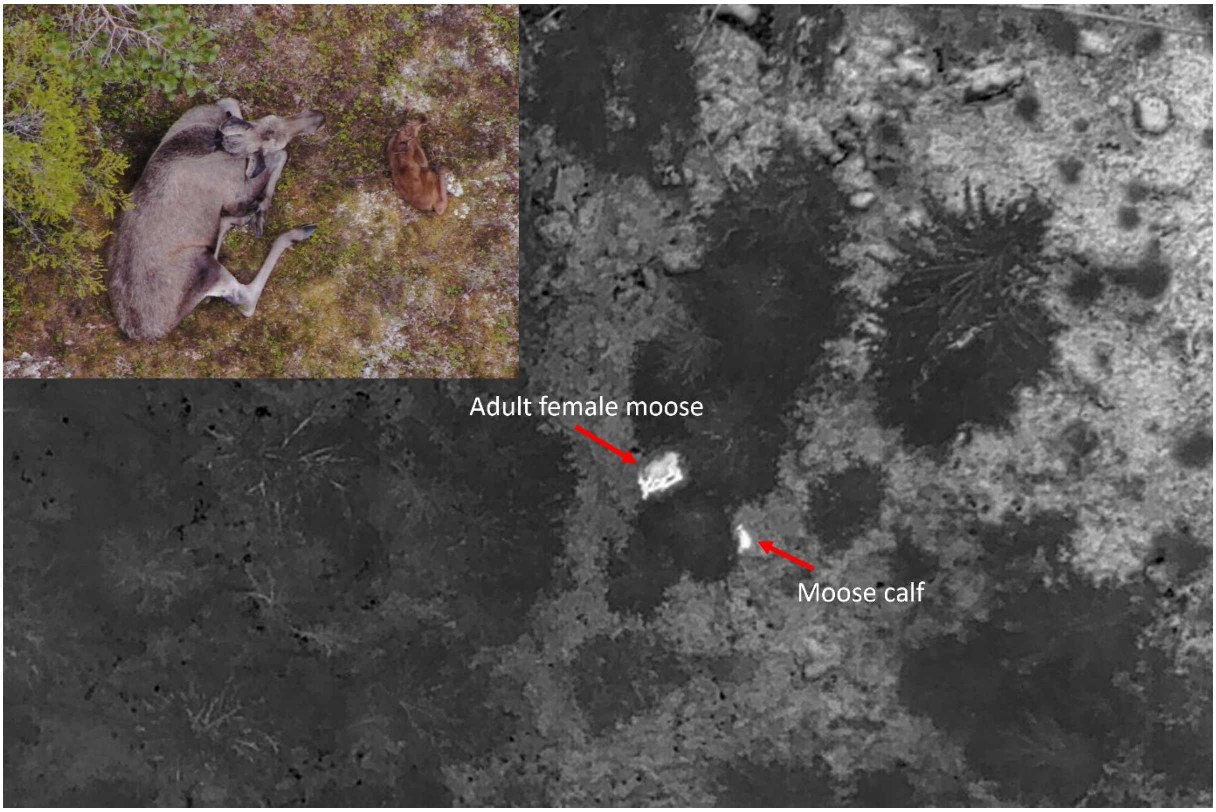

Fig. 5: Example of a thermal image taken by the DJI Matrice 300 RTK Combo drone equipped with a dual camera that recorded both thermal infrared TIR and color RGB (DJI ZenMuse H20T). The small image shows an image taken with the zoom camera (500 mm) from a different moose cow and calf. Pictures: Thomas Vogler.

Overall, drone approaches were less disruptive than ground approaches for detecting calves – a crucial aspect considering their susceptibility to predation (Swenson *et al.* 2007; Sand *et al.* 2008) Previous studies have highlighted the significance of disturbance on moose calf survival. For instance, DelGiudice et al. (2015) observed that 18.4% of calves were left behind by their mother within 48 hours post-capture for equipping calves with GPS or VHF collars. Similarly, disturbance of elk (*Cervus canadensis*) by ground approaches during the calving season decreased the calf-cow ratio (Phillips & Alldredge 2000). These findings highlight the critical impact of disturbance on the survival of calves, emphasizing the need for monitoring methods that reduce disturbance while maximizing calf detection success. Given the lesser disruption observed with drone approaches, their use presents a promising avenue for monitoring moose reproduction with minimal disturbance.

4.4 WP 4 Moose population count

We conducted 34 grid flights (Fig. 6) that covered between 21.2 and 56.8 ha (mean ± SD: 47.5 ± 6.2 ha) and recorded between 223 and 597 thermal images (mean ± SD: 504 ± 66) per flight. In total, we covered an area of 1614 ha and recorded 17,133 thermal images (and the same number of RBG images). These flights were conducted in fall, between the 2nd and 10th of October, which means that temperatures were lower compared to the flights conducted for WP1. Temperatures ranged from -2 to 12 °C (mean ± SD: 6 ± 4 °C). We detected moose in 9 of the 34 flights, totaling 20 individuals. This is equivalent to 1.24 moose per km^2 based on the raw observations. Based on WP1, we can assume that we likely detected 75-90% of all moose given that conditions were more favorable due to colder temperatures and less sunshine (and given that moose were still having their summer coat). Assuming that we missed 10-25% of moose, the true moose density during fall would correspond to 1.38-1.65 moose per km^2. Moreover, given that the flights were conducted during the second week of the moose hunting period, we likely underestimated true summer densities because some moose were already shot. Information from local hunting teams indicated that they had harvested between 25 and 50% of the quota during the first week of the hunt. Additionally, it was previously shown that wolves predate on ca. 4% of the summer moose population (Zimmermann *et al.* 2019). Thus, given that moose harvest reduces the overall population by 15% (Zimmermann *et al.* 2019), we can assume that the total summer density (before predation and harvest) was ca. 7.75-11.5% higher. After adjusting for hunting and predation, the summer moose population density was between 1.49 and 1.84 moose per km^2. We conducted fecal pellet group counts in the same general study area during the summer 2021 and predicted moose densities based on these counts across the study area. The predicted summer moose density in the study area where we conducted our drone flights was 1.71 moose per km^2. Average winter moose density was 1.3 ± 0.3 moose per km^2 (Zimmermann *et al.* 2019). Thus, predicted moose density from pellet counts and from drone flights matched closely, suggesting that the two measures yield comparable and highly reliable estimates. These promising results indicate that drones can be used to provide true density estimates, though we note that current technological limitations only allow us to apply this method on comparatively small areas.

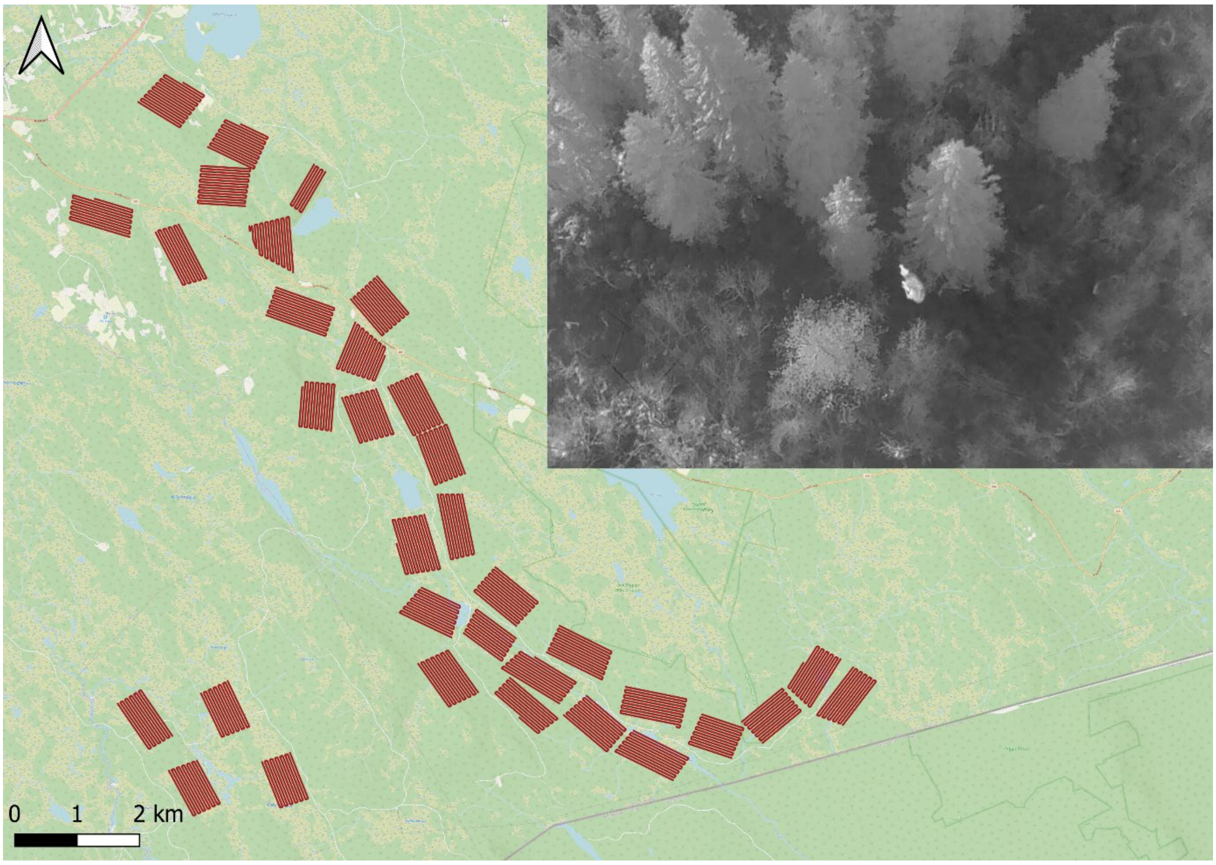

Fig. 6: Showing the 33 grid flights conducted during October 2023 to estimate moose population density. Picture: Martin Mayer.

Given that no habitat variables were retained in the best model, we could not integrate habitat variables into a population model. The 20 moose observations consisted of 5 adult (>1 year old) bulls, 8 adult cows, 4 calves, and 3 adult individuals of unknown sex. This sample size was unfortunately too small to estimate the sex ratio and calf-to-cow ratio but provides a proof of concept that drones can be used for this purpose. Age determination (calf versus individuals >1 year old) was possible from the thermal infrared images alone, but for sex determination of adults, we were flying over the moose after the grid flights were conducted, using the 500 mm RGB camera to get a detailed look of the moose without disturbing them. We could not do this for the 3 individuals of unknown sex due to battery limitations. Thus, it will be possible to determine calf-to-cow ratios from grid flights alone, whereas sex determination of adults will be challenging. A potential solution would be to conduct flights during spring/early summer when bulls are growing their antlers, which would allow visual detection in thermal infrared images.

4.5 WP 5 Assessing relevant parameters of moose browsing

Remote sensing has recently been successfully tested to estimate available moose browse using models that combine open source data from airborne LiDAR, aerial photography and optical satellite data, where structural information on vegetation provided by LiDAR was the most important component of the models (Kastdalen 2019). While LiDAR data is publicly available, national aerial LiDAR surveys are not conducted regularly. The last national survey was concluded in 2022 at which time the oldest datasets included in the survey were 13 years old (https://www.kartverket.no/geodataarbeid/nasjonal-detaljert-hoydemodell/status-hoydemodell, accessed 03.01.2024). Additionally, a one-time survey provides only a snapshot of available biomass at the time of survey. Because of the long intervals between surveys, it is challenging to draw conclusions on trends in biomass availability and browsing intensity. Drones present a promising alternative for generating high-resolution, up to date images suitable for the same purpose. Taking images with sufficient overlap allows for creating orthomosaics of the mission area. Moreover, using photogrammetry enabled us to generate a point cloud and high-resolution elevation models (Fig. 7).

In December 2023, we conducted grid flights at 50 m altitude over young pine forest stands (recording 1722 images; Fig. 7) with the goal of repeating those flight missions in spring 2024 to quantify winter browsing damage. However, our initial results indicate that we are not able to recognize browsing marks and stem breaks on individual trees from RGB pictures (Fig. 7). At 50 m altitude the ground sampling distance of the DJI Zenmuse H20T wide angle lens is 1.72 cm/pixel. Improving the resolution would require flights at lower altitudes or the use of a camera with a narrower field of view. Both solutions are impractical because they reduce the area covered by a single flight considerably. Also, even though drones are capable of following Digital Elevation Models (DEMs) for navigation, utilizing this method at low altitudes poses significant risks due to the DEM's limited accuracy in capturing small-scale elevation changes. We believe identifying individual browsing marks is possible by using the zoom lens but likely unsuitable as a management method.

Using images from low-altitude grid flights, we successfully generated a DEM and orthomosaics (Fig. 7). However, our current assessment of winter browsing-related biomass loss remains pending until the spring 2024 flight data becomes available. Nevertheless, we have encountered several challenges inherent in this approach. For example, the amount of browsed biomass compared to the total standing biomass may be so small that it is not identifiable among other factors impacting biomass estimates. Moreover, variation in snow cover and depth, along with differing light conditions, could compromise the accuracy of DSM measurements.

Conversely, active optical sensors like LiDAR, operating independently of sunlight reflectance, offer a potential solution to these challenges. LiDAR's ability to penetrate vegetation and snow, coupled with its ability to produce multiple returns and identifying different vegetation layers, enables the generation of high-resolution DEM and DSM. Modern, lightweight LiDAR systems can be mounted on drones like the Matrice 300, enabling the production of on-demand, high-resolution datasets. This technology promises more accurate estimates of available browse and, through repeated surveys, could be a valuable tool for assessing browsing intensity from a management perspective.

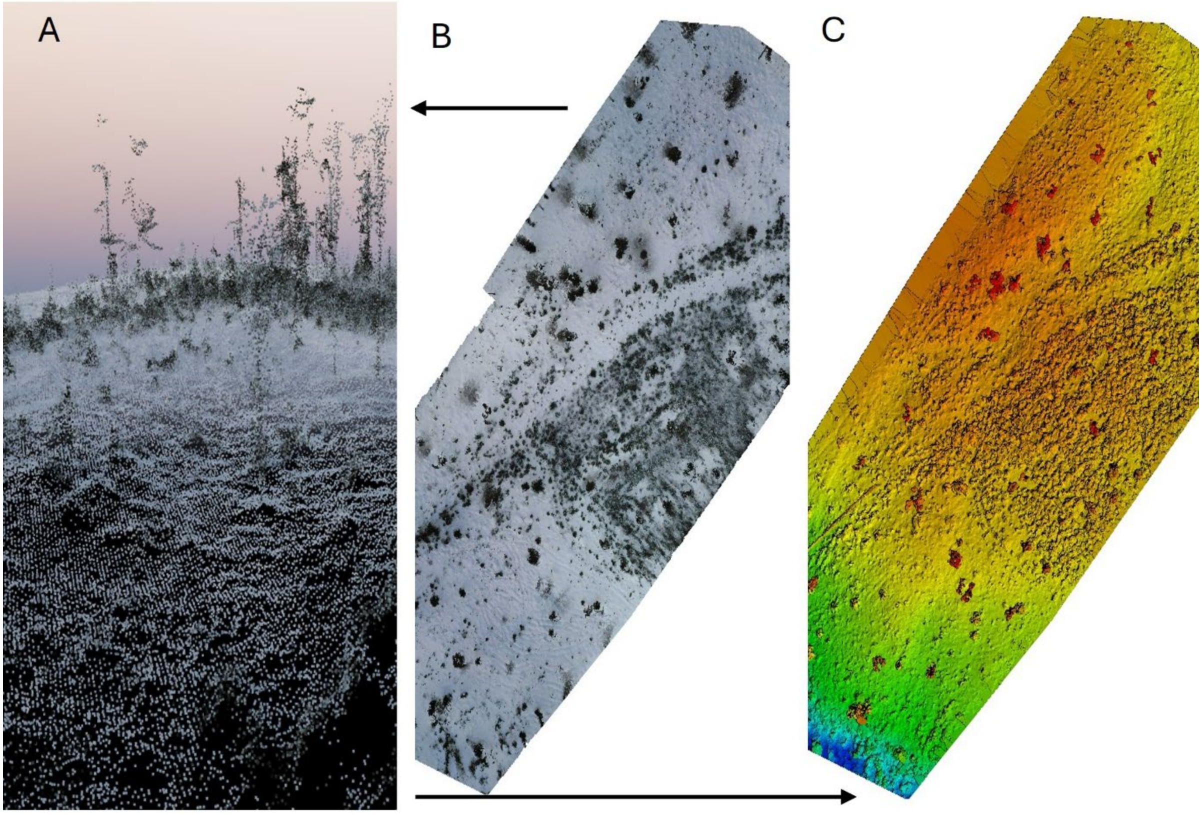

Fig. 7: The images from the grid missions were used to create a 3-D point cloud (A) based on an orthomosaic (B). The point cloud is the basis to produce the digital surface model (C).

5. Conclusions and future perspectives

This project was conducted over a period of 2-years and relied on a combination of GPS-tagged moose, moose fecal pellet group counts, and browsing surveys conducted by the Interreg-project GRENSEVILT and the regional moose project "Elg i endring". In line with experiences from other studies (Witczuk *et al.* 2018; Burke *et al.* 2019), we used a multi-use drone with a high-precision GPS (DJI Matrice 300 RTK Combo) equipped with a dual camera that recorded both thermal infrared and RGB images (DJI ZenMuse H20T). Results from the project are made available in this written technical report, scientific publications (Mayer *et al.* 2024; Mayer et al. in preparation), oral presentations (e.g., a talk at the 36th Congress of International Union of Game Biologists, Hjorteviltet 2024) and video clips and other information on social media (e.g., X and Facebook).

Our study highlights the applicability and time-efficiency of drones in monitoring moose while minimizing disturbance when flying at >70 m height. Moreover, drones prove valuable in detecting moose calves, which is useful for evaluating reproductive success and calf survival with minimal disturbance. To cover larger areas (i.e., for grid flights), an altitude of 100 m appears optimal (although we note that it might be possible to detect moose at higher altitudes). Grid flights over GPS-collared moose revealed that moose detectability was 77% in our study area and tended to be better on days with cloud cover compared to sunny conditions. No other variables were found to affect detectability, though this result must be treated cautiously given our relatively small sample size. After accounting for imperfect detectability, we estimated the moose density in fall to be 1.38-1.65 moose per km^2, which is in line with estimates from pellet group counts. Thus, we could demonstrate the usefulness of drones for estimating absolute moose densities. Obtaining absolute population density estimates has the advantage over other census methods, such as hunting bag statistics, that it is more robust to potential biases (e.g., hunter effort, reporting, etc.) thereby providing a better-informed foundation for wildlife management. However, there remain challenges for this method to be applied over larger areas. To address this, it would be advantageous to fly line transects rather than grids plots. However, this would require flying beyond the visual line of sight for which a special license is required.

We could unfortunately not yet fully evaluate if our method is applicable to quantify moose browsing in young forest stands. To do so, we will need to conduct additional flights in late winter. However, our initial findings indicate that the methods used in this study might lack the necessary detail to yield reliable data regarding moose browsing damage. As a recommendation, we propose exploring the use of drone-borne LiDAR modules to estimate moose browsing intensity.

Drones offer numerous other applications in wildlife research and management. For example, we saw that using the thermal infrared camera was highly successful in detecting animal tracks in snow. This could be used as an alternative method for estimating animal abundance of various species, given that we could identify species based on tracks. In line with this, drones might be useful for tracking injured wildlife that collided with vehicles. Future studies could also use drones for the monitoring of other species, such as identifying active beaver lodges and ant hills based on heat signatures. Moreover, it will be relevant to test if smaller-bodies species, such as hares and grouse species, can be identified using the same method.

6. Acknowledgements

We would like to thank all landowners for allowing us to conduct drone flights on their land and for providing us with valuable information regarding moose hunting.

7. References

Arnold, T.W. (2010) Uninformative parameters and model selection using Akaike's Information Criterion. *The Journal of Wildlife Management,* **74,** 1175-1178.

Barton, K. (2016) Package “MuMIn”: Multi-Model Inference. R package, Version 1.15. 6.

Bates, D., Mächler, M., Bolker, B. & Walker, S. (2015) Fitting Linear Mixed-Effects Models Using *lme*4. *J. Stat. Soft.,* **67,** 48.

Bennitt, E., Bartlam-Brooks, H.L., Hubel, T.Y. & Wilson, A.M. (2019) Terrestrial mammalian wildlife responses to Unmanned Aerial Systems approaches. *Scientific reports,* **9,** 2142.

Bergqvist, G., Bergström, R. & Edenius, L. (2001) Patterns of stem damage by moose (Alces alces) in young Pinus sylvestris stands in Sweden. *Scand. J. Forest Res.,* **16,** 363-370.

Bivand, R., Rundel, C., Pebesma, E., Stuetz, R., Hufthammer, K.O., Giraudoux, P., Davis, M., Santilli, S. & Bivand, M.R. (2018) Package ‘rgeos’. *R package v. 0.3–24*.

Bonnin, N., Van Andel, A.C., Kerby, J.T., Piel, A.K., Pintea, L. & Wich, S.A. (2018) Assessment of chimpanzee nest detectability in drone-acquired images. *Drones,* **2,** 17.

Brunton, E., Bolin, J., Leon, J. & Burnett, S. (2019) Fright or flight? Behavioural responses of kangaroos to drone-based monitoring. *Drones,* **3,** 41.

Burke, C., Rashman, M., Wich, S., Symons, A., Theron, C. & Longmore, S. (2019) Optimizing observing strategies for monitoring animals using drone-mounted thermal infrared cameras. *International Journal of Remote Sensing,* **40,** 439-467.

Burnham, K.P., Anderson, D.R. & Huyvaert, K.P. (2011) AIC model selection and multimodel inference in behavioral ecology: some background, observations, and comparisons. *Behavioral Ecology and Sociobiology,* **65,** 23-35.

Calenge, C. (2006) The package “adehabitat” for the R software: a tool for the analysis of space and habitat use by animals. *Ecological Modelling,* **197,** 516-519.

Cilulko, J., Janiszewski, P., Bogdaszewski, M. & Szczygielska, E. (2013) Infrared thermal imaging in studies of wild animals. *European Journal of Wildlife Research,* **59,** 17-23.

Ditmer, M.A., Vincent, J.B., Werden, L.K., Tanner, J.C., Laske, T.G., Iaizzo, P.A., Garshelis, D.L. & Fieberg, J.R. (2015) Bears show a physiological but limited behavioral response to unmanned aerial vehicles. *Current Biology,* **25,** 2278-2283.

Doull, K.E., Chalmers, C., Fergus, P., Longmore, S., Piel, A.K. & Wich, S.A. (2021) An evaluation of the factors affecting ‘poacher’detection with drones and the efficacy of machine-learning for detection. *Sensors,* **21,** 4074.

Evans, A.L., Fahlman, Å., Ericsson, G., Haga, H.A. & Arnemo, J.M. (2012) Physiological evaluation of free-ranging moose (Alces alces) immobilized with etorphine-xylazine-acepromazine in Northern Sweden. *Acta Veterinaria Scandinavica,* **54,** 1-7.

Ezebilo, E.E., Sandström, C. & Ericsson, G. (2012) Browsing damage by moose in Swedish forests: assessments by hunters and foresters. *Scandinavian Journal of Forest Research,* **27,** 659-668.

Franke, U., Goll, B., Hohmann, U. & Heurich, M. (2012) Aerial ungulate surveys with a combination of infrared and high–resolution natural colour images. *Animal Biodiversity and Conservation,* **35,** 285-293.

Goodbody, T.R.H., Coops, N.C., Marshall, P.L., Tompalski, P. & Crawford, P. (2017) Unmanned aerial systems for precision forest inventory purposes: A review and case study. *The Forestry Chronicle,* **93,** 71-81.

Græsli, A.R., Le Grand, L., Thiel, A., Fuchs, B., Devineau, O., Stenbacka, F., Neumann, W., Ericsson, G., Singh, N.J. & Laske, T.G. (2020a) Physiological and behavioural responses of moose to hunting with dogs. *Conservation Physiology,* **8,** coaa122.

Græsli, A.R., Thiel, A., Fuchs, B., Singh, N.J., Stenbacka, F., Ericsson, G., Neumann, W., Arnemo, J.M. & Evans, A.L. (2020b) Seasonal hypometabolism in female moose. *Frontiers in Ecology and Evolution,* **8,** 107.

Gundersen, H. (2003) Vehicle collisions and wolf predation: Challenges in the management of a migrating moose population in southeast Norway. *PhD Thesis, University of Oslo*.

Gundersen, H., Andreassen, H.P. & Storaas, T. (2004) Supplemental feeding of migratory moose *Alces alces*: forest damage at two spatial scales. *Wildlife Biology,* **10,** 213-223.

Hartig, F. (2021) Package ‘DHARMa’. *R package version 0.3,* **3**.

Havens, K.J. & Sharp, E.J. (2015) *Thermal imaging techniques to survey and monitor animals in the wild: a methodology*. Academic Press.

Hellbaum, P., Ampe, N., Carlomagno, E., Grimsgaard, A., Luksengård, S., Miltz, C. & Zimmermann, B. (2023) Elgbeitetakst 2022 i Våler og Åsnes kommuner.

Hijmans, R.J., van Etten, J., Cheng, J., Mattiuzzi, M., Sumner, M., Greenberg, J.A., Lamigueiro, O.P., Bevan, A., Racine, E.B. & Shortridge, A. (2015) Package 'raster'. *R package*.

Hjeljord, O. (2003) Ulv i Østfold 1999- 2003, et sammendrag av resultater fra forskningen. pp. 1- 21. NLH, Ås.

Hodgson, J.C., Mott, R., Baylis, S.M., Pham, T.T., Wotherspoon, S., Kilpatrick, A.D., Raja Segaran, R., Reid, I., Terauds, A. & Koh, L.P. (2018) Drones count wildlife more accurately and precisely than humans. *Methods in Ecology and Evolution,* **9,** 1160-1167.

Hui, N.T., Lo, E.K., Moss, J.B., Gerber, G.P., Welch, M.E., Kastner, R. & Schurgers, C. (2021) A more precise way to localize animals using drones. *Journal of Field Robotics,* **38,** 917-928.

Israel, M. (2011) A UAV-based roe deer fawn detection system. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* **38,** 51-55.

Iwamoto, M., Nogami, S., Ichinose, T. & Takeda, K. (2022) Unmanned aerial vehicles as a useful tool for investigating animal movements. *Methods in Ecology and Evolution,* **13,** 969-975.

Johnsen, S. (2013) To run or stay: anti-hunter behaviour of female moose.

Jonzén, N., Sand, H., Wabakken, P., Swenson, J.E., Kindberg, J., Liberg, O. & Chapron, G. (2013) Sharing the bounty—Adjusting harvest to predator return in the Scandinavian human–wolf–bear–moose system. *Ecological Modelling,* **265,** 140-148.

Kastdalen, L. (2019) Fjernmålt elgbeite: Utvikling av metodikk for kartlegging av elgens vinterbeiteressurser fra fjernmålte data. *Skriftserien Høgskolen i Innlandet*.

Koh, L.P. & Wich, S.A. (2012) Dawn of drone ecology: low-cost autonomous aerial vehicles for conservation. *Tropical Conservation Science,* **5,** 121-132.

Lavsund, S., Nygrén, T. & Solberg, E.J. (2003) Status of moose populations and challenges to moose management in Fennoscandia. *Alces,* **39,** 109-130.

Lian, M., Evans, A.L., Bertelsen, M.F., Fahlman, Å., Haga, H.A., Ericsson, G. & Arnemo, J.M. (2014) Improvement of arterial oxygenation in free-ranging moose (Alces alces) immobilized with etorphine-acepromazine-xylazine. *Acta Veterinaria Scandinavica,* **56,** 1-8.

Linchant, J., Lisein, J., Semeki, J., Lejeune, P. & Vermeulen, C. (2015a) Are unmanned aircraft systems (UAS s) the future of wildlife monitoring? A review of accomplishments and challenges. *Mammal Review,* **45,** 239-252.

Linchant, J., Lisein, J., Semeki, J., Lejeune, P. & Vermeulen, C. (2015b) Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges. *Mammal Review,* **45,** 239-252.

Mayer, M., Furuhovde, E., Nordli, K., Ausilio, G., Wabakken, P., Eriksen, A., Evans, A., Mathisen, K. & Zimmermann, B. (2024) Monitoring GPS-collared moose by ground versus drone approaches: efficiency and disturbance effects. *Wildlife Biology,* **in revision**.

McMahon, M.C., Ditmer, M.A., Isaac, E.J., Moore, S.A. & Forester, J.D. (2021) Evaluating unmanned aerial systems for the detection and monitoring of moose in northeastern Minnesota. *Wildlife Society Bulletin,* **45,** 312-324.

Milleret, C., Wabakken, P., Liberg, O., Åkesson, M., Flagstad, Ø., Andreassen, H.P. & Sand, H. (2017) Let's stay together? Intrinsic and extrinsic factors involved in pair bond dissolution in a recolonizing wolf population. *Journal of Animal Ecology,* **86,** 43-54.

Mulero-Pázmány, M., Jenni-Eiermann, S., Strebel, N., Sattler, T., Negro, J.J. & Tablado, Z. (2017) Unmanned aircraft systems as a new source of disturbance for wildlife: A systematic review. *PloS one,* **12,** e0178448.

Nilsen, E.B. & Solberg, E.J. (2006) Patterns of hunting mortality in Norwegian moose (Alces alces) populations. *European Journal of Wildlife Research,* **52,** 153-163.

Phillips, G.E. & Alldredge, A.W. (2000) Reproductive success of elk following disturbance by humans during calving season. *The Journal of Wildlife Management***,** 521-530.

Rolander, M., Kalén, C. & Bergqvist, J. (2017) Äbin: Skogliga inventeringsmetoder i en kunskapsbaserad älgförvaltning (version 1.0). (ed. Skogsstyrelsen). Jönköping, Sweden.

Rolandsen, C.M., Solberg, E.J., Sæther, B.E., Moorter, B.V., Herfindal, I. & Bjørneraas, K. (2017) On fitness and partial migration in a large herbivore–migratory moose have higher reproductive performance than residents. *Oikos,* **126,** 547-555.

Rönnegård, L., Sand, H., Andrén, H., Månsson, J. & Pehrson, Å. (2008) Evaluation of four methods used to estimate population density of moose *Alces alces*. *Wildlife Biology,* **14,** 358-371.

Ruud, H.-P. & Hagen, E. (2019) Drone som alternativ til flytelling. *Villreinen*.

Sand, H., Mathisen, K.M., Ausilio, G., Gicquel, M., Wikenros, C., Månsson, J., Wallgren, M., Eriksen, A., Wabakken, P. & Zimmermann, B. (2019) Kan forekomst av ulv redusere elgbeiteskader og øke tettheten av løvtrær? Utredning om ulv og elg del 4. *Skriftserien*, pp. 1-70. Høgskolen i Innlandet.

Sand, H., Wabakken, P., Zimmermann, B., Johansson, Ö., Pedersen, H.C. & Liberg, O. (2008) Summer kill rates and predation pattern in a wolf–moose system: can we rely on winter estimates? *Oecologia,* **156,** 53-64.

Schroeder, N.M., Panebianco, A., Gonzalez Musso, R. & Carmanchahi, P. (2020) An experimental approach to evaluate the potential of drones in terrestrial mammal research: a gregarious ungulate as a study model. *Royal Society open science,* **7,** 191482.

Solbraa, K. (2008) Elgbeitetaksering. Skogbrukets kursinstitutt, Biri.

Stander, R., Walker, D.J., Rohwer, F.C. & Baydack, R.K. (2021) Drone nest searching applications using a thermal camera. *Wildlife Society Bulletin,* **45,** 371-382.

Storaas, T., Gundersen, H., Henriksen, H. & Andreassen, H.P. (2001) The economic value of moose in Norway - a review. *Alces,* **37,** 97-107.

Stubsjøen, T., Sæther, B.-E., Solberg, E.J., Heim, M. & Rolandsen, C.M. (2000) Moose (Alces alces) survival in three populations in northern Norway. *Canadian Journal of Zoology,* **78,** 1822-1830.

Swenson, J.E., Dahle, B., Busk, H., Opseth, O., Johansen, T., Söderberg, A., Wallin, K. & Cederlund, G. (2007) Predation on moose calves by European brown bears. *The journal of wildlife management,* **71,** 1993-1997.

Ueno, M., Solberg, E.J., Iijima, H., Rolandsen, C.M. & Gangsei, L.E. (2014) Performance of hunting statistics as spatiotemporal density indices of moose (Alces alces) in Norway. *Ecosphere,* **5,** art13.

Vermeulen, C., Lejeune, P., Lisein, J., Sawadogo, P. & Bouché, P. (2013) Unmanned aerial survey of elephants. *PloS one,* **8,** e54700.

Wallgren, M., Bergström, R., Bergqvist, G. & Olsson, M. (2013) Spatial distribution of browsing and tree damage by moose in young pine forests, with implications for the forest industry. **305,** 229-238.

Wam, H.K., Hofstad, O., Nævdal, E. & Sankhayan, P. (2005) A bio-economic model for optimal harvest of timber and moose. *Forest ecology and management,* **206,** 207-219.

Wikenros, C., Sand, H., Månsson, J., Maartmann, E., Eriksen, A., Wabakken, P. & Zimmermann, B. (2020) Impact of a recolonizing, cross-border carnivore population on ungulate harvest in Scandinavia. *Scientific Reports,* **10,** 21670.

Witczuk, J., Pagacz, S., Zmarz, A. & Cypel, M. (2018) Exploring the feasibility of unmanned aerial vehicles and thermal imaging for ungulate surveys in forests - preliminary results. *International Journal of Remote Sensing,* **39,** 5504-5521.

Zimmermann, B., Mathisen, K.M., Ausilio, G., Sand, H., Wikenros, C., Eriksen, A., Nordli, K., Wabakken, P., Aronsson, M. & Persson, J. (2022) Elgvandringer i grenseland med følger for skogbruk, jakt og rovdyr. *Sveriges lantbruksuniversitet, Institutionen för ekologi.*

Zimmermann, B., Nelson, L., Wabakken, P., Sand, H. & Liberg, O. (2014) Behavioral responses of wolves to roads: scale-dependent ambivalence. *Behavioral Ecology,* **25,** 1353-1364.

Zimmermann, B., Sand, H., Wabakken, P., Liberg, O. & Andreassen, H.P. (2015) Predator-dependent functional response in wolves: From food limitation to surplus killing. *Journal of Animal Ecology,* **84,** 102-112.

Zimmermann, B., Wikenros, C., Sand, H., Eriksen, A. & Wabakken, P. (2019) Elg i ulverevir: predasjon og elgjakt. Utredning om ulv og elg del 2.

Zuur, A.F. & Ieno, E.N. (2016) A protocol for conducting and presenting results of regression-type analyses. *Methods in Ecology and Evolution,* **7,** 636-645.

Zuur, A.F., Ieno, E.N. & Elphick, C.S. (2010) A protocol for data exploration to avoid common statistical problems. *Methods in ecology and evolution,* **1,** 3-14.

Høgskolen
i Innlandet

Droner er en lovende ny teknologi for overvåking av viltbestander. I dette prosjektet evaluerte vi bruken av droner som et verktøy for overvåking av elg. Vi testet først oppdagbarheten til GPS-merkede elgkuer og deres kalver ved å fly dronen 'DJI Mavic 2 Enterprise Dual' til den siste kjente GPS-posisjonen til elgkyrne ved 100 m høyde, for deretter å senke dronen gradvis til 70, 50, 30 og 20 m høyde. Det var høyere oppdagbarhet, mindre tidsbruk og mindre forstyrrelse av elgene ved bruk av drone enn når en person nærmet seg elgkua på bakken. I neste forsøk evaluerte vi oppdagbarheten av elg mer detaljert ved hjelp av dronen 'DJI Matrice 300 RTK' med et 'Zenmuse H20T' kamera. Totalt gjennomførte vi 33 gridflygninger over 11 GPS-merkede elgkyr.

På denne måten oppdaget vi 77% av elgene. Sannsynligheten for å oppdage en elg var større i overskyet sammenlignet med solrike forhold, men ble ikke påvirket av andre faktorer (temperatur, skogtype, kronedekke). I det tredje forsøket estimerte vi lokal elgtetthet ved å gjennomføre 34 gridflygninger om høsten for å finne elg som ikke var GPS-merket. Vi oppdaget elg i 9 av de 34 flyvningene, totalt 20 individer. Ved å ta hensyn til oppdagelsessannsynlighet tilsvarer dette en høsttetthet på 1,38 - 1,65 elg/km2. Disse estimatene stemmer godt overens med elgtetthetsberegninger fra elgmøkktellinger gjennomført to år tidligere i samme område.

Til slutt evaluerte vi mulige metoder for å estimere elgens beiteskader i unge barskogbestander. Oppsummert var bruk av drone en svært effektiv metode for å oppdage voksne elger og kalvene deres i barskogen, og var raskere og mindre forstyrrende enn observasjoner på bakken. Videre antyder resultatene våre at overvåking med droner kan gi svært pålitelige tetthetsestimater for elgbestander lokalt, og kan bli nyttig for å estimere beiteskader. Vi diskuterer hvordan funnene våre kan iverksettes på en større skala for forbedret elgforvaltning i hele Skandinavia.