AIMS-THERMAL - A THERMAL AND HIGH RESOLUTION COLOR CAMERA SYSTEM INTEGRATED WITH GIS FOR AERIAL MOOSE AND DEER CENSUS IN NORTHEASTERN VERMONT

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ABSTRACT: This paper describes a simultaneously firing dual camera system that integrates a new generation radiometric thermal camera with a high spatial resolution natural color camera where all imagery is spatially indexed with local coordinates and managed by a GIS. A test of the system to estimate the moose population in northeastern Vermont found that the Airborne Imaging Multispectral Sensor (AIMS) Thermal system performed well under both overcast and sunny conditions; overcast conditions produced far fewer false-positive heat signatures than older systems. Tests for detection rates in hardwood stands indicated 100% accuracy. Tests to determine if camera lens parallax produced different probabilities of detection inside and outside of the image nadir due to the screening effect of trees indicated no such bias. The estimated moose density was 0.84 moose/km^2 based on a 20% sample (133 km^2) of the 682 km^2 study area, and was within 5% of the pre-survey estimate. Future analysis will include testing of sightability in coniferous habitats.

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Key words: Aerial infrared sensing, aerial color imagery, *Alces alces*, density estimate, GIS, moose, population density, remote sensing, Vermont.

The use of aerial thermal imaging technology for use in moose (*Alces alces*) surveys has a checkered history due to a variety of problems including marginal thermal technology, accurate and verifiable target recognition and counts, spatial sampling management, target geocoding, consumer-friendly data delivery formats, and expense. Early attempts to use thermal infrared imagery in the 3-14 micrometer spectrum for use in large game census (Croon et al. 1968, McCullough et al. 1969, Addison 1972, Graves et al. 1972, Parker and Driscoll 1972) were limited by relatively primitive scanner technology and a general lack of integrated mapping systems to support survey management and robust spatial modeling of animal locations and habitat characteristics. Dunn et al. (2002) used a videotape based forward-looking infrared radiometer (FLIR) system operating in the 8-12 micrometer spectrum at 300 m above ground level (agl) to nominally distinguish cattle, horses, deer (*Odocoileus spp.*), and elk (*Cervus elaphus*) in the southwestern United States with the aid of image processing. However, they ultimately found that thermal imagery was inadequate for improving elk surveys in wildland settings due to variability in topography and vegetation. Haroldson et al. (2003) found that white-tailed deer (*O. virginianus*) surveys in deciduous forests suffered from variable thermal contrast between deer and background objects, inconsistent sampling protocols, and sensor performance leading to unacceptably variable and unreliable animal counts.

Adams et al. (1997) used FLIR and color video tape systems in a series of orbital flight surveys at varying intensities to sample study areas. Each study site was subdivided into a set of 1.6 km diameter orbits, a portion of which was more intensely sampled as subsites. The survey was designed to be done in open hardwood stands in winter and their results indicated that density estimates of moose were acceptable. Bontaites et al. (2000) used thermal imaging from fixed-wing aircraft in a Gasaway-type survey (Gasaway et al. 1986) to estimate moose numbers and validate that fall hunter surveys accurately reflect changes in the moose population. They judged that their technique and technology were promising, although all objectives were not successfully met.

This project differs significantly from previous efforts in that a new generation of thermal imaging technology using spatially indexed photos is combined with high resolution color images managed in a GIS. This approach uses thermal imagery to detect warm targets on a cold background and high resolution color photos to identify specific heat sources. All data acquired by the system is integrated with a GIS, which allows robust spatial management and analysis of all imagery and related spatial data. The study objectives were: 1) an operational test of the thermal implementation of the Airborne Imaging Multispectral Sensor (AIMS-Thermal) hardware, software, and GIS interface installed in a Cessna 206 aircraft, 2) image quality and target recognition assessment from the FLIR and high-resolution color cameras, and 3) a moose population estimate based on a 20% sample of a 684 km^2 wildlife management district in northeastern Vermont.

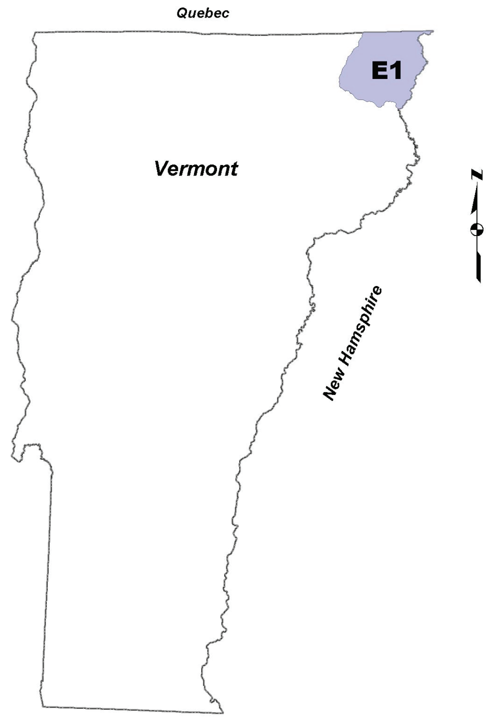

Fig. 1. Location of study area in northeastern Vermont used to test a GIS-managed, thermal and color camera aerial survey for moose and deer in winter 2010.

STUDY AREA

The study area was Wildlife Management Unit (WMU) E1, 682 km^2 located in the northeastern corner of Vermont and bordered by New Hampshire and Quebec (Fig. 1). The area is topographically expressive with several hills rising abruptly from a basin at 257-1,129 m above sea level. The area is heavily forested with expansive maple (*Acer saccharun, A. pensylvanicum*) and beech (*Fagus grandifolia*) hardwoods, and conifer stands of fir *(Abies balsamea),* spruce *(Picea rubens, P. glauca, P. mariana*), hemlock (*Tsuga canadensis*), and eastern white pine (*Pinus strobus*); timber harvesting activity was evident. The estimated moose density was 0.89 moose/km^2 based on a rolling 3-year average of moose sightings by November deer hunters in a regression equation developed in New Hampshire (Bontaities et al. 2000, Rines 2002).

METHODS

Hardware and Software System Design

The Airborne Imaging Multispectral Sensor (AIMS) was developed to provide a flexible technology to integrate a broad spectrum of multispectral imaging and associated GPS, LIDAR altimetry, and avionics instruments for deployment on light aircraft (Millette and Hayward 2005). The AIMS technology and software allow imaging cameras and scanners operating in a variety of spectral ranges to become plug-and-play devices in an aircraft; a software environment that automates geo-registration and orthorectification of imagery makes it available for use in GIS and image processing environments.

The AIMS-Thermal (AIMS-T) implementation paired a radiometric microbolometer-based thermal camera with 16-bit radiometric depth and a 640 x 480 detector array operating in the 8-14 micrometer spectral range, together with a 21.1 megapixel 8-bit natural color CCD with a 5616 x 3744 detector array (Fig. 2). The natural color camera lens has a 10% wider field of view than the thermal camera to insure that hot features on the edges of a thermal image would be captured in their entirety on the color accurate analysis. Thermal data are stored as TIF images to preserve full spatial and radiometric resolution of the 16-bit imagery, and color imagery is stored as JPEGs to reduce mass storage requirements of the larger color photos.

Both cameras were installed in a Cessna 172 fixed-wing aircraft operated by Research Aviation, LLC (Granby, Massachusetts) with a duplexed SCSI disk array built into a flight recorder, and a GPS driven navigation system with panel mounted pilot display for flightline management. Additional data recorded by the AIMS-T system included real-time differential GPS with Omnistar Satellite enrichment; pitch, roll, yaw attitude of the aircraft by means of an attitude-heading-reference system (AHRS); and LIDAR altimetry. All data recorded during flight was time-stamped in milliseconds by a Data-Stream-Synchronization-Module (DSSM) which allows it to be spatially organized and indexed in post-flight processing.

The software components used for post-flight processing of the AIMS-T data streams are illustrated in Fig. 3. All imagery exposure times, GPS, LIDAR, and avionics data are poured into a database engine that formats it into a GIS attribute table. The GIS attribute table supports creation of shapefiles contain-

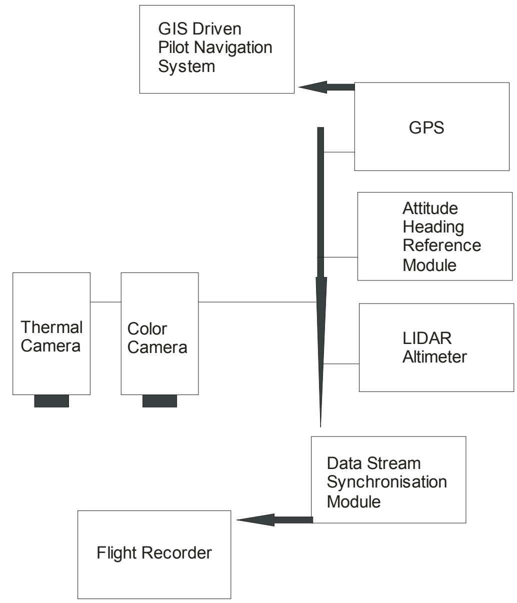

Fig. 2. Integration of components used in a GIS-managed, thermal and color camera aerial survey of moose and deer in Vermont, winter 2010.

ing photo centers for each exposure from the thermal and natural color cameras, as well as the flight path of the aircraft. This table also provides the framework for the integration of related spatial data such as sampling transects, flightlines, topography, and vegetation. Once the photo center shapefiles are created, a database link is created between each photo center feature in the GIS database and the appropriate image in the thermal or color image database. This image linking paradigm allows rapid access to images without the computational overhead of full orthorectification and registration of each individual image. Given that the study area required a combined total of 107,135 thermal and color images, this was a substantial reduction in processing effort. All GIS operations were performed with ArcGIS (ver. 10.0) software tools.

Survey Flights

The study area was sampled with 35 survey units (SU) distributed relatively evenly across the census area (Fig. 4). Each SU was laid out non-randomly in ArcMap to take

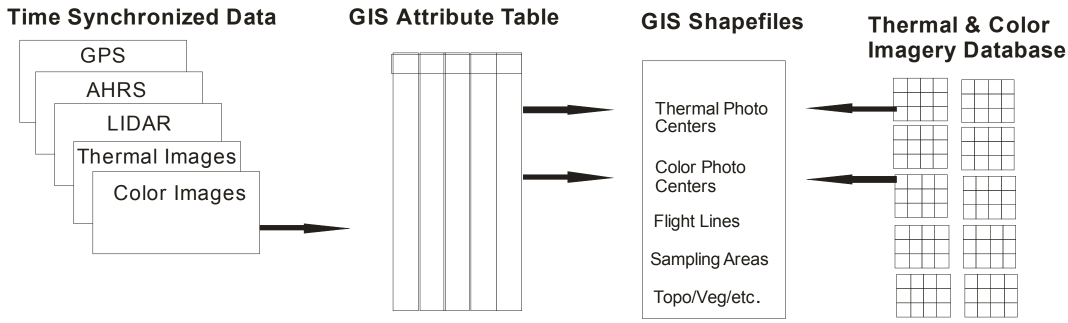

Fig. 3. Data and software system used in a GIS-managed, thermal and color camera aerial survey of moose and deer in Vermont, winter 2010.

advantage of relatively flat topography and/or along contours, avoiding major changes in elevation so that a constant agl and swath width was more easily maintained. Large water bodies, developed areas, agricultural lands, and elevations >900 m were considered unoccupied moose habitat and were not surveyed; a similar assumption was made in New Hampshire surveys (Bontaities et al. 2000). However, unlike the New Hampshire survey, we did not avoid "heavy" softwood cover.

Total linear distance of each SU was 19.36 km. Due to the size and topography of the study area, 13 SUs consisted of 2 parallel 9.76 km long transect legs; the remaining 22 SUs were comprised of 4 parallel legs 4.88 km long. Each leg was separated by a 129 m wide buffer zone to minimize multiple detections of the same moose within each SU. The IR swath width was designed originally to be 252.4 m with coverage of 4.87 km^2 in each SU, providing a sample area of 170 km^2 or 25% of the study area. After pre-survey trials and final lens selection, the total survey area was reduced to 132.69 km^2 or 20% of the study area; the relative proportion of habitat types in the actual surveyed area was similar to that in WMU E1 (Fig. 5).

Survey units were flown from a nominal altitude of 305 m agl, with a nominal horizontal image swath of 129 m, and a nominal vertical image swath of 96 m or 1.3 ha/image. Nominal instantaneous field of view (IFOV) of thermal images at 305 m agl is 20 cm, while nominal IFOV for natural color images is 1.8 cm. Airspeed of the aircraft was nominally 90 km/hr and frame rates of the thermal and color cameras were set to 500% and 30% overlap along the flight line, respectively. The 400% overlap on the thermal imagery was done to preserve the opportunity to conduct double counts on moose and deer observations should they be deemed necessary, and to provide a detailed imagery

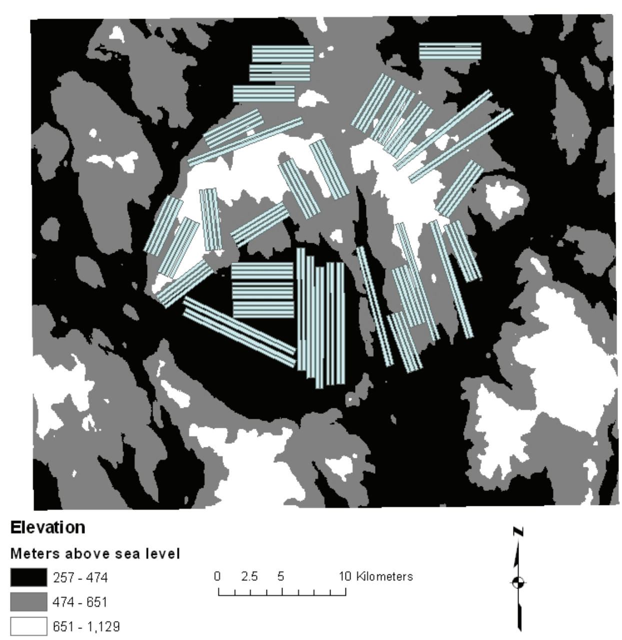

Fig. 4. Survey blocks in the digital elevation model used in a GIS-managed, thermal and color camera aerial survey of moose and deer in Vermont, winter 2010.

database from which to analyze false-positive heat signatures in future research.

The AIMS-T system was deployed in January and February 2010 over a 4-week period; 6 flights were flown between 0700 and 1100 h in SUs where there was a minimum ceiling of 610 m agl. Time spent was 24 h of data acquisition and an additional 32 h of transit between SUs, turns, fuel stops, and flight base. A total of 94,605 thermal images and 12,530 high-resolution color images were recorded with continuous snow cover, and a variety of sky illumination conditions ranging from heavy overcast to bright sunshine. Survey flights were cancelled when wind speeds were forecast to exceed 30 km/h. Snow cover never exceeded 45 cm and no restrictive crust layers existed.

Imagery Analysis

Image analysis was done with visual interpretation by the lead author, which required development of an integrated software environment that provides pan and zoom functionality for both 8- and 16-bit images. Given the large number of thermal images, it was necessary to have a 16-bit viewer that allowed rapid scrolling through images along a flight line rather than manually opening and closing individual images. The process involved scrolling through thermal images along each flightline looking for heat signatures. When candidate signatures were detected, the color photo center shapefile in the GIS was used to open the corresponding high resolution color photo which was then used to identify the actual source of heat. Examples of a portion of a thermal and corresponding color photo for a typical heat signature are in Fig. 6. Note that the radiometric resolution of the thermal image clearly indicates 2 hot targets, but that the spatial resolution is not adequate to identify the particular feature emitting the heat. Looking at the corresponding color image, it becomes obvious that the heat sources are moose. Differentiating between moose and deer in the

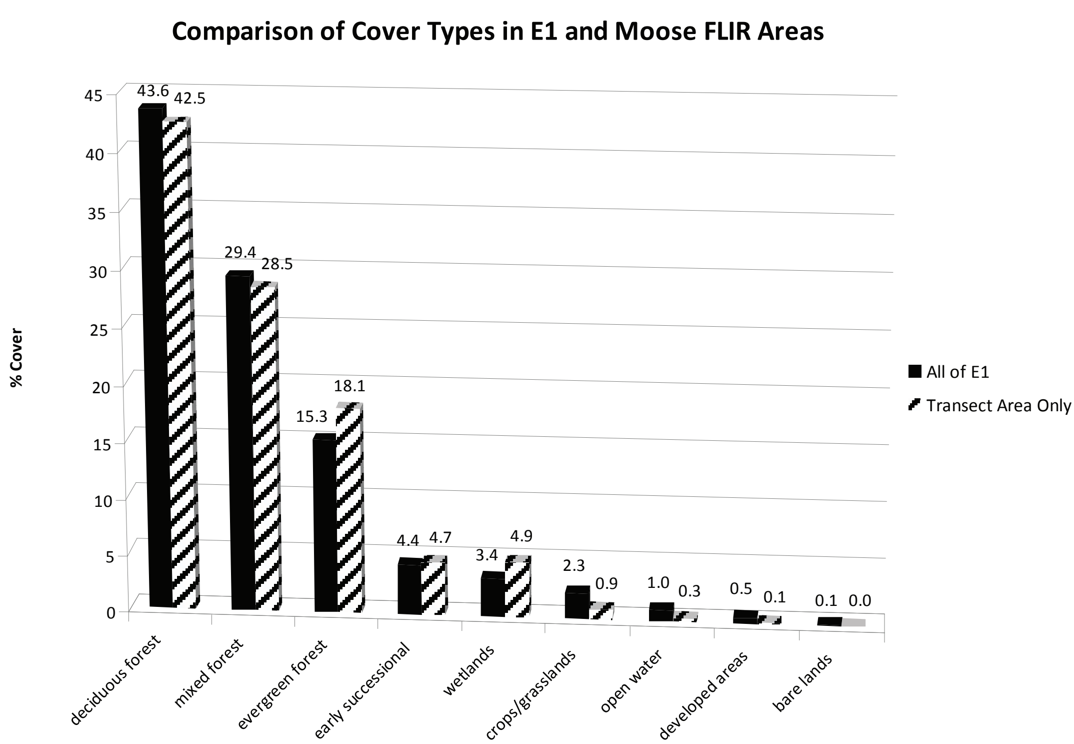

Fig. 5. Comparison of the proportion of available cover types in the study area and survey units used in a GIS-managed, thermal and color camera aerial survey of moose and deer in Vermont, winter 2010.

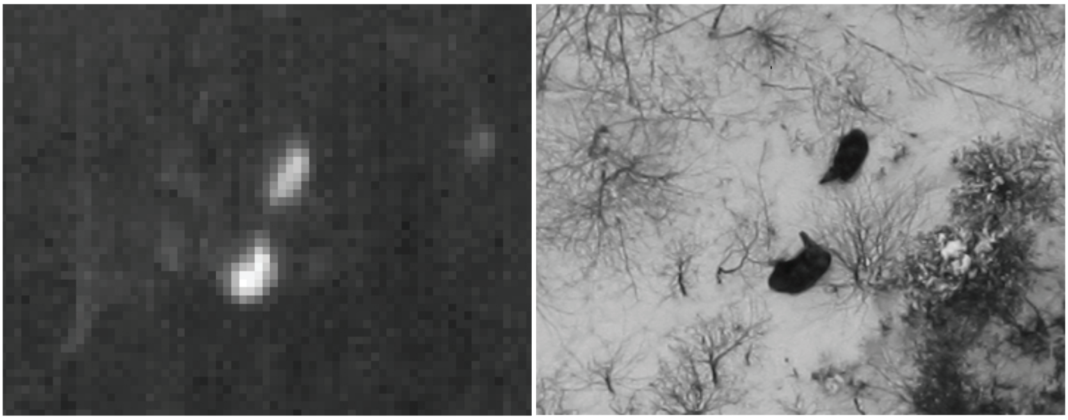

Fig. 6. Comparison of thermal and high resolution color images in a GIS-managed, thermal and color camera aerial survey of moose and deer in Vermont, winter 2010.

color images was not always obvious when the aircraft was above 400m agl due to rapidly changing topography. In these cases, the corresponding agl of the photo was noted from the GIS attribute table, pixel size was calculated, and the image was zoomed in to where pixels could be counted and body length calculated. Animals designated as moose generally had body lengths $\geq$2.7 m whereas deer had body lengths $\leq$1.8 m (Bubenik 1998). Experiments are presently underway testing the effects of increasing aircraft elevation and the use of wider field of view lenses on the quality of both thermal and color imagery.

Images verified to contain moose or deer had the thermal imagery attribute table in the GIS database updated to reflect the number and type of animal. Additionally, the corresponding color image had the location of each animal annotated directly on the JPEG to facilitate expedited photo verification of all animal classifications. Having the census animal locations included in the GIS database offers the potential for ecological assessments of moose population and habitat characteristics such as forest cover type, food availability, elevation, microclimate, and proximity to logging activity.

RESULTS & DISCUSSION

A total of 112 moose and 40 deer were detected in the 35 survey blocks; 66% contained moose and 26% contained deer (Table 1). The estimated moose density within the study area was 0.84 moose/km^2, and was within 5% of the pre-survey estimate. Detection rates of moose by the thermal imager may have been close to 100% in cut-over and hardwood forests, but was likely lower in coniferous habitats. To test for detection rates in hardwood stands, a GIS-driven analysis was done to review heat signatures in a total of 1078 thermal and corresponding color images. The USGS (NLCD-2001) land cover data (Homer et al. 2004) was used to identify hardwood stands in the study area and a total of 1000 thermal images were selected from these areas; 500 were selected due to the presence of conspicuous heat signatures and 500 were selected due to the conspicuous absence of heat signatures. Additionally, 78 of 93 images with identifiable moose and deer were added to these 1000 images, which together represented a 10% sample of all non-overlapping thermal imagery in homogeneous hardwood areas. Re-inspection of these images resulted in no additional moose or deer with conspicuous heat signatures, no additional moose or deer lacking conspicuous heat signatures, and no moose or deer added or removed from the 78 images originally identified with moose or deer in hardwood areas.

Sightability trials of visual helicopter surveys over radio-collared moose in British Columbia detected only 1 of 18 moose when

Table 1. Survey data from a GIS-managed, thermal and color camera aerial survey for moose and deer in winter 2010.

Survey Unit	# Flight Lines	Thermal images	# Moose	# Deer	Area Surveyed (km^2)	Survey Unit Area (km^2)
1	4	3476	0	0	4.44	4.875
2	4	3181	3	0	3.862	4.875
3	4	2782	4	19	3.891	4.875
4	4	3003	10	0	3.843	4.875
5	2	2377	4	0	3.632	4.875
6	4	2839	2	0	4.557	4.875
7	4	2338	1	0	4.039	4.875
8	4	2718	0	0	4.114	4.875
9	4	2981	1	0	4.531	4.875
10	2	2156	0	0	3.417	4.875
11	2	2164	0	0	3.296	4.875
12	4	2746	0	0	3.799	4.875
13	4	2897	1	0	4.036	4.875
14	4	2639	3	0	3.73	4.875
15	4	2369	1	0	3.968	4.875
16	4	2375	5	0	3.74	4.875
17	4	2595	2	0	4.05	4.875
18	2	2447	3	0	3.883	4.875
19	2	2304	10	5	3.121	4.875
20	2	2438	14	1	3.416	4.875
21	2	2173	5	1	3.082	4.875
22	2	2237	1	1	3.156	4.875
23	2	2788	1	0	3.898	4.875
24	4	3127	2	6	4.216	4.875
25	4	3221	10	0	4.322	4.875
26	2	2559	0	3	3.326	4.875
27	2	2707	5	3	3.506	4.875
28	4	3025	0	0	3.749	4.875
29	4	2863	0	0	3.581	4.875
30	2	2347	8	1	2.929	4.875
31	2	2539	4	0	3.285	4.875
32	4	3313	0	0	4.141	4.875
33	4	2790	0	0	3.92	4.875
34	4	2621	0	0	3.767	4.875
35	4	3470	0	0	4.446	4.875
Totals	**114**	**94605**	**112**	**40**	**132.689**	**170.61**

coniferous cover was >60% (Quayle et al. 2001), and sightability correction factors for dense forest cover in Newfoundland moose surveys have ranged from 2 to 4 (Oosenburg and Ferguson 1992, Gosse et al. 2002). Infrared detection has likewise been shown to be compromised by heavy coniferous cover (Garner et al. 1995, Dunn et al. 2002, Potvin and Breton 2005). Testing detection rates in the Vermont conifer stands poses some of these same challenges and is not yet complete.

To test if camera lens parallax produced different probabilities of detection inside and outside of the image nadir due to screening effect of trees, the 93 thermal images containing moose and deer were divided into 5 zones from west (zone 1) to east (zone 5), each representing 20% of the image area across the horizontal image swath. The zone locations of each moose and deer was recorded as follows: zone 1-13 observations; zone 2-27 observations; zone 3-13 observations; zone 4-31 observations; and zone 5-28 observations. Since there was not under-representation of moose and deer on the outer edges of images (zones 1 and 5), screening effects due to lense parallax didn't appear problematic, and application of double-count models (Potvin et al. 2004) was not pursued.

The project was successful in that it yielded both an accurate estimate of the moose population in the study area and significant advances in the technology and knowledge base about aerial thermal censusing. The most significant technical advance is the development of the dual thermal/color camera system integrated with a GIS. The combination of the radiometric sensitivity of the 16-bit thermal imager and the extremely high spatial resolution of the color camera optimized the opportunity to fly the largest image swath possible at safe elevations above the landscape, while at the same time providing imagery that is easy to interpret accurately. The spatial integration of the imagery databases by means of a GIS creates the opportunity for wildlife managers to have instant access to images of individual animals for interpretative validation and analysis (e.g., size, weight, age, sex). The GIS integration also provides the option to support ecological modeling of populations by taking advantage of a host of GIS data layers that may be available, or could be developed directly from the color imagery.

Particularly valuable was the knowledge base developed pertaining to IFOV characteristics and illumination effects on survey imagery. The original calculations for determining optimal flight elevations and camera lens options were based on estimates that a maximum IFOV of 20 cm for the thermal data would be required to detect heat signatures from moose and deer, and a maximum IFOV of 1.8 cm in the color imagery would be required to accurately identify conspicuous heat sources. Based on interpretation of some 90,000 images, the estimates proved to be quite accurate. The performance of the thermal detector exceeded expectations and could likely be flown 15-20% higher without an appreciable loss of heat detection. However, it is not yet clear that this would also be true for the color camera. Degrading the IFOV of the color imagery by 15% may increase misclassifications between moose and deer; additional testing is scheduled.

Illumination conditions during data acquisition affect the quality of thermal imagery significantly. Overcast conditions with diffuse illumination provide optimum data with relatively homogeneous cold surfaces upon which heat sources stand out with maximum contrast (Fig. 7a). Thermal data acquisition under clear skies (Fig. 7b) produces images with extremely high levels of emissive heterogeneity and bears little resemblance to images acquired under overcast skies. A detailed analysis of the clear sky thermal imagery was done to assess the source of the heterogeneity and its impacts on target detection and photo interpretation accuracy. This analysis indicated that high image heterogeneity is primarily the result of heating of the main boles of trees due to low sun angles. A secondary source of image variability resulted from shadows cast by trees on snowpack under bright illumination. The interaction of these 2 sources of emittance variability results in a complicated image scene that can be challenging to process visually. Despite this, even in images with the highest levels of heterogeneity (i.e., typically hardwood stands in direct sunlight with continuous snowpack) individual moose and deer were detectible as thermal features without exception. This was not the case with previous generations of thermal imagers and marks a major turning-point in the technology. However, the time to process these images increased 5-fold relative to overcast imagery since there were significantly more false-positives to be checked in the associated color photos. Future work will test the use of image processing to distinguish false positive heat signatures from moose signatures in images with high levels of heterogeneity.

The state of thermal imaging technology has developed to the point that modern 3rd generation microbolometer-based cameras have the radiometric sensitivity to be used successfully for moose and deer population surveys. The AIMS-T sensor system successfully integrates this type of instrument with a high resolution natural color camera, GPS, LIDAR, and avionics data together with a GIS to create a highly productive environment to conduct accurate moose and deer population surveys in relatively open and/or leaf-off hardwood-dominated landscapes. Research to quantify the detection rates of moose under heavier conifer canopies is not yet complete, however, due to the high spatial and radiometric resolution of the AIMS-T system and the 500% overlap of the thermal images, initial results are promising. Furthermore, the ability to integrate thermal and high resolution color imagery within an automated GIS environment creates the opportunity for detailed ecological and spatial modeling of wildlife habitat characteristics. Considering that the data acquisition and analysis for the

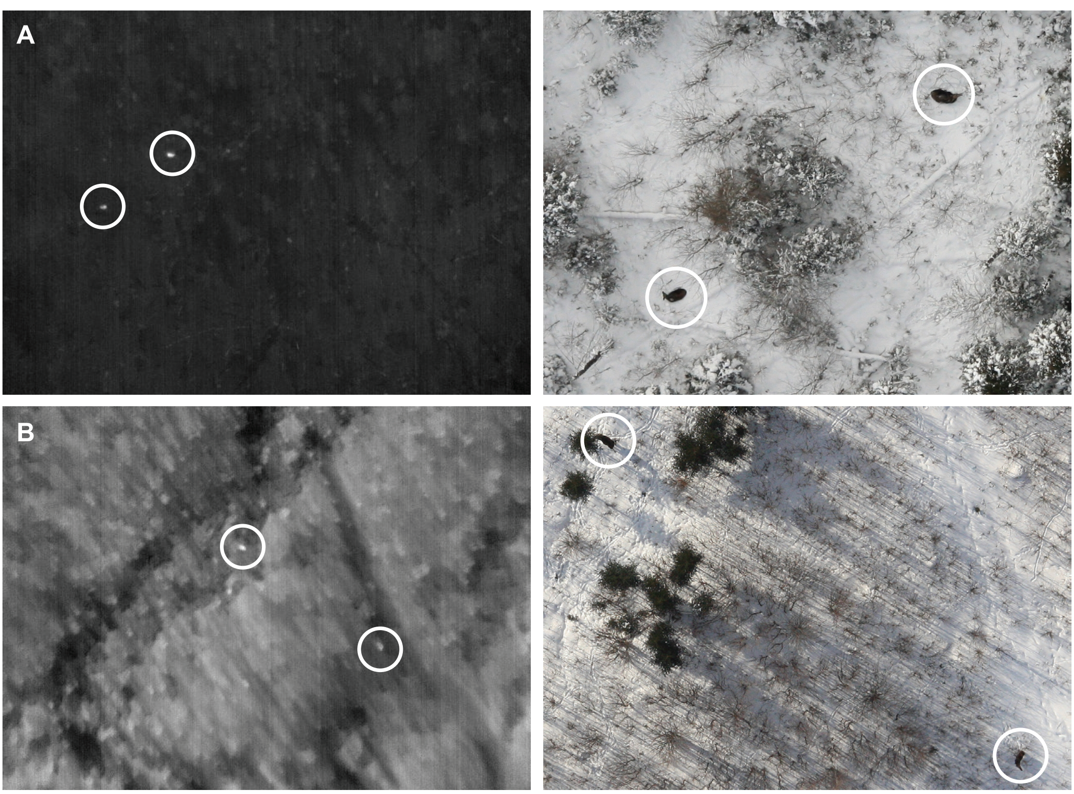

Fig. 7. Comparison of overcast (a) and clear sky (b) imagery in thermal and high resolution color in a GIS-managed, thermal and color camera aerial survey of moose and deer in Vermont, winter 2010.

Northeastern Vermont project cost less than $270/km^2, this type of thermal aerial survey has never been more cost effective.

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