Very Large Scale Aerial Photography for Rangeland Monitoring

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Abstract

Ecological assessment of ground cover by conventional on-the-ground point sampling is labor intensive, expensive, and biased by access. Historically, motion blur has prevented high-resolution aerial photography from being used for ground cover measurements. To reduce motion blur we used a fixed-wing, 225-kg (empty weight) airplane flown at 72 km/hr ground speed 100 m above ground level with both a modified Hulcher 70 mm camera (500 mm lens, Kodak Aerocolor HS SO-846 film, 1/4,000-second shutter speed), and a Canon 11. 1 -megapixel, automatic, digital single lens reflex, color camera (420 mm focal-length lens). The resulting very-large scale aerial (VLSA) photography had resolutions of 5.0 and 2.1 mm GSD (Ground Sample Distance) for the scanned film and digital-camera images, respectively. Motion blur was minimal. The cost for obtaining 450 VLSA photographs over a 70,800-ha watershed was $0.07 ha. We found our methods well adapted for extensive aerial surveys to monitor the ecological condition of rangeland watersheds.

Introduction

The world's rangelands are a vast and important resource, but one where the average value of goods and services derived per unit of land is low. Management inputs for monitoring rangeland ecological integrity have also been low and usually insufficient to accurately assess ecological status or to detect ecologically important degradation (NRC, 1994; Donahue, 1999). No land-management agency or enterprise has had, nor is likely to have, the budget and personnel needed for adequate on-the-ground monitoring (West, 1999). The need for cost-effective, statistically-adequate monitoring allowing unbiased measurements of key indicators of rangeland condition has motivated more than 30 years of research to develop methods for high-resolution aerial monitoring (Carneggie and Reppert, 1969; Carneggie *et al.*, 1971; Tueller *et al.*, 1972, 1988; Tueller and Booth, 1975; Hayes, 1976; Heintz *et al.*, 1978; Meyer and Grumstrup, 1978; Everitt *et al.*, 1980, 1987; Harrison *et al.*, 1987; Hinckley and Walker, 1993; Walker and De Vore, 1995; Harris *et al.*, 1996; Quilter and Anderson, 2001; Hansen and Ostler, 2002). Aldrich *et al.* (1959) introduced the Hulcher 70mm camera (Model 102) for monitoring natural resources. The camera allowed shutter speeds up to 1/2,000 second and for more than two decades it remained the preferred camera for obtaining large-scale (1:600 to 1: 10,000) photography for natural-resource assessments. With this camera Booth (1974) obtained 1:600 to 1: 1,000-scale photographs by triggering the camera at intermittent intervals to systematically, photographically sample western Nevada (USA) rangeland watersheds for soil-erosion evaluations. Abel and Stocking (1987) subsequently used intermittent aerial sampling to estimate sediment yield from Botswana rangelands.

The equipment and methods for obtaining large-scale aerial photography of rangelands from fixed-wing aircraft remained more or less static through 2000. Our objective was to develop a very-large scale aerial (VLSA) monitoring system for measuring bare ground with accuracy comparable to measurements made on the ground. Here we describe successive innovations leading to systematic acquisition of high-resolution aerial photography with minimal motion blur and the application of these methods to the economical measurement of bare ground over extensive rangeland watersheds, grazing allotments, and pastures.

Equipment

Platform

We acquired our photography using a Rans S12XL, two-seat airplane powered by a Rotax 582 water-cooled 66 hp engine (Fig. 1). With this engine the airplane has an empty weight of about 225 kg. The airplane was flown 100 m above ground level (AGL) at 72 km hour^{-1} ground speed, straight and level flight. Contract costs were under $150 hour^{-1} (plane and pilot).

Camera, Lens, Film, and Film Processing

At our request the Charles A. Hulcher Co. (http://www.hulchercamera.com/) modified a 70mm camera (Model 123)

E-mail: geocarto@geocarto.com
Website: http://www.geocarto.com

for shutter speeds in excess of 1/4,000 sec and equipped it with a Mamiya 500 mm, f/5.6 manual focus lens, including a non-standard support for the large lens. The camera's motorized film winder allowed photograph acquisition at 20 frames sec^{-1} and we triggered bursts of three to four photographs at that rate for each target. We used Kodak Aerocolor HS SO-846 negative film which was developed by Digi-Graphics (http://www. digigraphics. com/basics.html) and was pushed one or two f-stops during development. Selected scenes were then digitized (scanned) at 1 pixel per 25µm of negative by Precision Photo (no known website, Dayton, OH, USA).

Digital Camera

In 2003 we acquired an 11.1-megapixel Canon EOS 1Ds digital color (red, green and blue bands) single lens reflex camera. The 1Ds was connected to a vibration-resistant 24 gigabyte hard drive (Image Labs, http://www. imagelabs. com/contact. php) via an IEEE- 1394 (Fire Wire) interface cable for image storage. We equipped the camera with a Canon 300 mm, f/2.8 autofocus, autoaperture, image-stabilizing (IS) lens. A 1.4x teleconverter was added to give the equivalent of a 420 mm, f/4.0 lens. Shutter speed was manually set for 1/4,000th second and automatic override ("safety shift") was enabled. The camera is capable of 3 frames sec^{-1} up to 10 frames.

Camera Triggering and Navigation

To increase the safety of flying low and at close-to-stall speeds, we equipped the Rans with a Track'Air "Tracker" aerial survey system (http:// www.trackair.com/) specifically adapted for our application. An onboard laptop computer pre-programmed with geographic coordinates for desired sample (photographic) locations was interfaced with the system and with a global positioning system (GPS) receiver. The aerial survey system graphically showed the pilot, via a small screen in the cockpit, directions to the target area (ferry mode) and when in the target area, the nearest planned aerial transect ("track-up" mode) and targeted GPS coordinates along the transect. When the airplane was flown over targets, the system triggered the camera.

The Track'Air system allowed an adjustable threshold or deviation from programmed GPS coordinates in the detection of programmed flight lines and camera triggering. To facilitate acquisition of individual transect flight lines, we set the lateral threshold at 100 m to each side of the programmed line. While this made it easier to acquire transect flight lines, it also meant the camera would trigger at distances up to 100 m to the side of the line. We relied on pilot skill to keep the airplane on the transect flight line using 'Tracker's' graphic indication of the airplane's position relative to the programmed line. No deviation was allowed for the forward direction. The exact GPS coordinates, altitude, ground speed and time were logged each time the camera was triggered. We used a program called Didger 2 (http://www.goldensoftware.com/) to draw parallel lines over digital raster graphics to program our flight lines. Photo stations along each flight line were established using coordinates lifted off the map and pasted into the text-based flight plan editor to create the flight plans.

Laser Altimeter (Range Finder)

Altitude AGL was continuously monitored with a Riegl LD90-3 100VHS-FLP laser range finder (http://www.riegl.com/) mounted vertically on the bottom of the airplane. The instrument sent out a laser beam that was reflected off the ground and measured upon return to give a distance AGL measurement that was accurate within 25 mm. The unit had a range of 300 m and a refresh rate of 2000 Hz. The readout was displayed on a laptop screen within the cockpit giving the pilot a continuous readout of altitude AGL when below 300 m.

Camera Mount and Equipment Stowage

A camera mount and equipment rack was constructed of 4-mm-thick aluminum. The rack was bolted into the plane in place of the passenger seat using U bolts with vibration-absorbing rubber shims between the hardware (Fig. 1). Items stowed on the equipment rack are listed in Table 1. 'Velcro' and plastic ties were used extensively to secure equipment and cables.

Airplane Transport

We transported the Rans to study sites by trailer after removing wings and propeller. It required about 4 hours for 2 people to prepare

Table 1 List of very-large scale aerial (VLSA) equipment. All equipment was stowed on the equipment rack unless otherwise noted.

1. Camera and lens mounted over porthole #1 in the bottom of the airplane.
2. Laser altimeter (rangefinder) positioned over porthole #2 in the bottom of the airplane.
3. 'Tracker' hardware interface box and Garmin 25 GPS housing ("TECI" box).
4. Light meter controller and digital readout; sensor attached to airplane belly.
5. Laptop computer for laser altimeter readout on 5-cm cushion of rubber foam and positioned for pilot's ease in reading.
6. Laptop computer controlling 'Tracker' system, mounted on 5-cm cushion of rubber foam on the passenger-side floor in front of the equipment rack.
7. Two 24-volt batteries to power Hulcher camera and 'Tracker' system.
8. Inverter to power laptop computers.
9. Twelve-volt battery mounted in separate bracket to the rear of the equipment rack and connected to inverter.
10. Cables and cords. There are a number of these and all were neatly stowed and secured on or within the equipment rack.
11. Pilot's 8" LCD 'Tracker' display, mounted above instrument panel.
12. GPS antenna mounted on top of airplane.

the airplane for transport and another 3 hours to reassemble it at the job site.

Study Sites

Muddy Creek Study Site

Two public-land grazing allotments in the Muddy Creek watershed, southwest of Rawlins, WY, USA, were surveyed in May 2002 (41° 18' N, 107° 49' W). The study site covers 13,000 ha, with elevation ranging from 1,980 to 2, 100 m. The predominant plant communities are Wyoming big sagebrush [*Artemisia tridentata* Nutt. ssp. *wyomingensis Beetle* & Young] (46%) and saltbush [*Atriplex* L. spp.] (12%) with shrub-dominated riparian areas (16%). Annual precipitation is 256 mm. Soils are Torriorthents, Haplargids and Natrargids (Reiners and Thurston 1996).

Cottonwood Creek Study Site

The Cottonwood. Creek watershed, northwest of Casper, WY, USA, was surveyed in June 2003 (43° 15' N, 107° 1' W). The watershed contains more than 70,800 ha, includes all or part of 22 public grazing allotments and private pastures, has an elevation range of 1,620 to 2,590 m, and contains 9 vegetation types of which half is Wyoming big sagebrush/grassland. Allotment #10036 was selected as representative of the watershed and ground data were collected using a frequency-frame (ITT, 1996) and by acquiring 59 photographs from 2-m AGL using a camera stand and an Olympus E20 5-megapixel digital color camera with a 9-mm lens (Booth *et al.* 2004; Booth *et al.* 2005a). The frequency-frame method consisted of 2 transects, each with 25 plots 3 paces apart, with each plot having at least 5 points classified for basal cover, yielding a total of at least 250 points/transect. Two-meter AGL photography was paired with the 100-m AGL photography (± 20 m) by reference to the GPS coordinates used by the aerial survey system to trigger the airborne camera.

Bare Ground as a Key Indicator

Among the 60+ indicators identified for monitoring rangeland condition (Rowe *et al.*, 2002), ground cover and its inverse, bare ground, are among the most prominent (ITT, 1996; USDI BLM, 1997; Bonham *et al.*, 2004; Kaiser 2005). Bare ground is exposed mineral or organic soil that is susceptible to raindrop splash erosion (Morgan, 1986). It is considered a key indicator because soil conservation is a first-priority ecological concern (NRC, 1994; Society for Range Management, Task Group on Unity in Concepts and Terminology, 1995) and it has been consistently correlated with runoff and with increased grazing (see review by Booth and Tueller, 2003). We and others (Kaiser, 2005) infer that soil-stability-protecting land management can be legitimately supported by accurate bare-ground measurements. Species composition changes are closely related to rangeland condition; however, bare ground has greater utility than species composition for extensive, low-cost monitoring using remote sensing methods, thus the measurement of ground cover from aerial photographs offers a defendable path for adapting rangeland assessments to a remote sensing framework (Pickup *et al.*, 1994).

Image Analysis Software

Our image-analysis method has been previously described (Booth *et al.*, 2005a; 2005b;). We used "VegMeasure, " (Louhaichi *et al.*, 2001; Johnson *et al.*, 2003) which was designed to measure plant cover on rangeland by quantifying areas of specific color for large batches of digital photographs through rapid binary classification. The VegMeasure blue-band and brightness algorithms were used for bare ground because, in our experience, they more accurately separated bare ground from other parameters of ground cover.

Results

Navigation and Camera Triggering

Safe, systematic aerial sampling-consistent with sampling needs of watersheds and other large land areas-was greatly facilitated by our aerial survey system and by precise measurements of airplane altitude AGL from our laser range finder. Lateral deviation from programmed transect flight lines, as indicated by the 'Tracker' log of GPS coordinates for acquired photographs, was usually within 3 meters and at no time was greater than 10 m.

Muddy Creek - Hulcher Photograph Quality and Resolution

We obtained 172 nearly motion-blur-free, 1:200-scale, photographs - a significant advance over the 1:600 limitation (Figs. 2 & 3). The acquisition rate of 20 frames sec^{-1} during photographic bursts resulted in overlapping photographs that permitted stereo viewing. The nadir field-of-view of each photograph was approximately 12 x 12 m of ground from 100 in AGL. The digitized photographs had a resolution of 5 mm GSD. Light during the photographic missions ranged between 8 and 10 thousand lux.

Vignetting, a reduction in the intensity of exposure of film at the edges of the field-of view, is apparent in many of the photographs and is evident in Fig. 3 by comparing the hue of the soil and vegetation in the center versus the edge of the photograph. Vignetting made the photographs unsuitable for using image analysis software to measure percentage bare ground.

Cottonwood Creek - Canon Photograph Quality and Resolution

Upland sites were sampled with 460 photographs from 100 m AGL using the 420-mm focal length with the Canon 1Ds, shutter speed = 1/4,000th sec, f/4.0, ISO = 400. All photographs resulted from automatic camera triggering by the aerial survey system. The field of view in the photographs

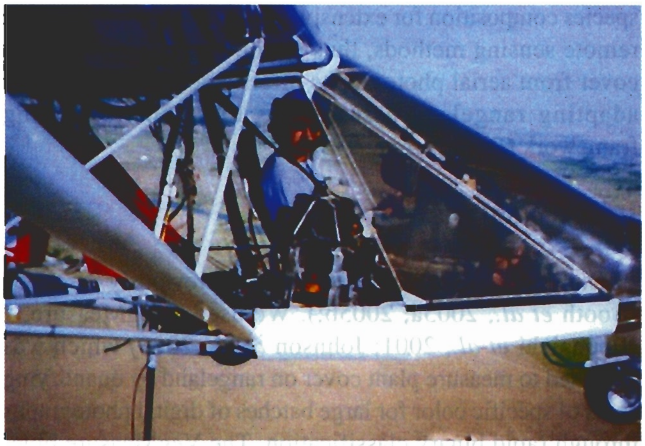

Figure 1 Camera and equipment stowed on equipment rack in airplane next to pilot Joe Nance.

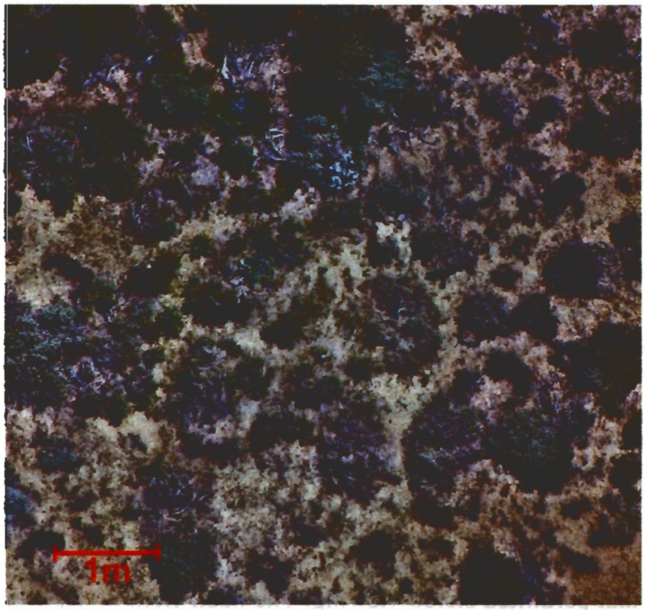

Figure 2 Digitized image from 70-mm film (1:200 scale) showing nadir view of a Wyoming big sagebrush plant community.

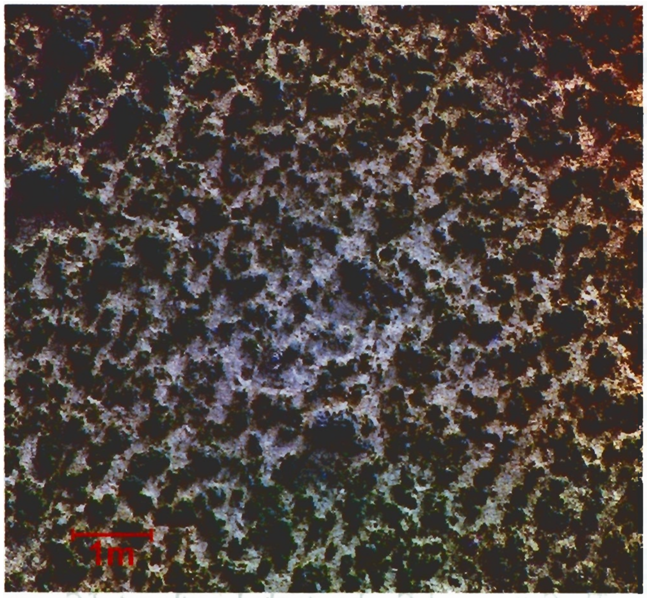

Figure 3 Digitized image from 70 mm film (1:200 scale) showing nadir view of a saltbush community. Note that this photograph contains more vignetting than is evident in Figure 2.

was 8.5 x 5.6 m, with a resolution of 2.1 mm GSD (Figs. 4 & 5). Light during the photographic missions ranged between 6 and 14 thousand lux. When used in conjunction with basic plant inventories, many species could be identified from the aerial photography, such as the *Tetraneuris acaulis* (Pursh) Green var. *acaulis* shown in Fig. 4. Wyoming big sagebrush was also easily recognizable. Note the presence of discernible detail in both shadowed areas and on the highly-reflective soil surface between the Gardner's saltbush [*Atriplex gardneri* (Moq.) D. Dietr] in Fig. 5. Sixty-one, 100-m AGL photographs were obtained over allotment # 10036. Bare ground measurements from the 100-m AGL photography tended to be higher, but not significantly different from measurements derived from 2-m AGL digital photography (Table 2). Image-derived measurements of bare ground were significantly greater than measurements obtained using the frequency frame (Booth *et al.*, 2005a). The cost for obtaining the aerial photography of the Cottonwood Creek watershed was about \$6,000 or \$0.07 ha^{-1}. This compares to a cost of \$800 (54 man-hours × \$15 hr^{-1}) or about \$0.12 ha^{-1}, to collect data from the 15 BLM transects in allotment #10036.

Discussion

Aerial and ground measurements

Ground-cover measurements are known to be affected by the diameter of the contact point used for sampling (Mueller-Dombois and Ellenberg, 1974; Cook and Stubbendieck, 1986; Booth *et al.*, 2006b), so the difference in our cover measurements could be related to the difference in contact point size (0.97-2.1 mm/pixel for imaging methods versus 3-4 mm for the tips of the frequency-frame ("range fork")). Also, image analysis methods may fail to account for litter, small rock, or other groundcover characteristics. The most important considerations are (1) the true value is not known, and (2) the key to evaluation of land management is change over time. Photographic methods allow a large number of photographic samples to be acquired, saved, and used for future reference to detect ecologically important change.

Advantages of Fully Automatic, CMOS, Digital Camera

At the start of our effort to develop a high-resolution aerial photograph acquisition system, there was no digital camera available to us that could equal the combination of shutter speed, color sensitivity, resolution, and frame rate of the 70-mm film camera. High resolution digital cameras required many seconds or even minutes to capture and store

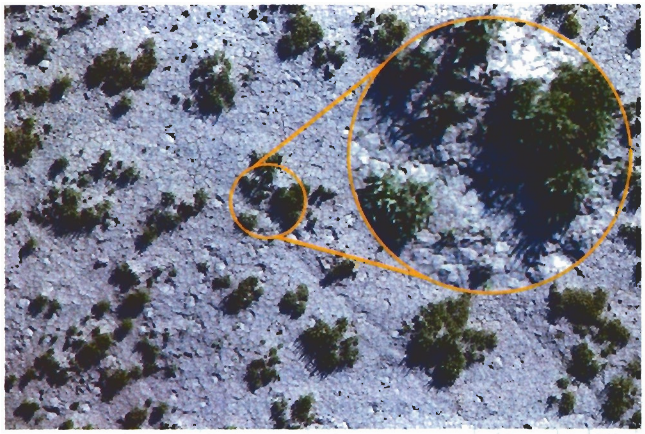

Fig. 4

Fig. 5

Figures 4 & 5 Aerial images from BLM allotment #10036 in central Wyoming, USA, acquired with the Canon IDS (λ = 420 mm, f/4.0). Image sensor resolution (maximum collected resolution) is 2.1 mm ground sample distance (GSD). Printed scale is 1:112. Inlay printed scale is 1:31.

photographs. Attempts to use available digital still frame or analog video cameras for VLSA-type applications were unsuccessful (Booth, unpublished report; Quilter and Anderson, 2001). Although our modified 70-mm camera surpassed the available digital systems for the characteristics noted, it lacked many of the benefits of automatic cameras. Film was often incorrectly exposed due to changing light conditions during a mission - changes due to weather and to different reflective surfaces, including differences in soils and plant communities (Fig. 3). The 500 mm F/5.6 lens required high-light conditions (5,000 lux minimum and 10 to 14 thousand lux for optimum exposure), wide apertures (reducing sharpness and depth of field), low grain (800 ISO) film (reducing sharpness), and special handling in development. Vignetting was a consistent problem. Use of film required developing and scanning, an added cost of about US $5.50 per frame and a delay of at least a week. The utility of digital technology for computer image analysis was needed to avoid the labor intensive microscopic examination of film for data extraction. Scanning resulted in loss of detail and color since the scanning process had a reduction ratio of 1:25 (length of 1 image pixel = 25 µm negative), which meant that each photograph pixel was actually an average of 625 μm^2 of negative. The digital camera used in this study has improved VLSA photograph collection by overcoming all of the above problems. Compared to scans of the Hulcher 70-mm photographs, the 1Ds photography delivers greater resolution (2.1 versus 5.0 11 mm GSD) and sharper color separation (compare Figs. 2 & 3 with 4 & 5). We attribute the lower 12 color saturation of the film primarily to the high ISO rating (800) which results in grainy, less color-saturated photographs. Color is a necessary part of differentiating among characteristics of a scene and sharper color separation is likely to enhance the accuracy of image analysis.

We found the image-stabilization (IS) feature of the Canon EF lens prevented noticeable motion blur at airplane ground speed / shutter speed combinations where a film camera would have shown pronounced motion blur (Figs. 4 & 5). Photographs were collected in RAW format, which allowed simple post-acquisition exposure compensation for dark photographs. The RAW format is lossless, but is only 1/3 the file size of a TIF file of equal dimensions.

Because of the advanced features of automatic digital cameras, the collection of unusable photographs is largely eliminated. ISO speed (gain) can be set anywhere from 100 to 1,600 ISO, trading light sensitivity for image "noise." Post-acquisition exposure compensation allows under-exposed photographs to be lightened without saturating key parts or losing color density of the photograph. Available lenses have wider apertures, and the IS technology of these lenses allows slower shutter speeds without incurring noticeable motion-blur. The improved light-handling capacity of the camera allows greater flexibility in light conditions suitable for attempting or continuing a mission and Al Servo auto-focusing accommodates rapid deviations in planned altitude that result from air turbulence or topography-forced changes in altitude. Our digital camera system had the capacity to acquire and store 2,000 photographs using a modest 24 gigabyte hard drive. This compares to a potential of 450 photographs per flight using a 70-mm film camera without special-order large film magazines. Digital photographs are ready for immediate analysis–a major advantage allowing adjustments to be made in flight or at the site, or targets re-flown before leaving the job site.

The speed of photograph acquisition is largely determined by the file format selected. RAW image files are 8-11 MB each, and can be captured continuously at 4 second intervals 13 without overloading the camera memory buffer. Medium-compression JPG files are around 1-2 MB, and can be continuously captured at 2 second intervals until the hard drive is almost full (transfer rate slows as hard drive approaches maximum capacity). Smaller numbers of photographs can be acquired at much greater frequency, for example, RAW format photographs can be acquired at 3 frames/second for up to 10 photographs (with bursts at 1 -

minute intervals), 1 frame/second for up to 15 photographs, at 2-second intervals for up to 18 photographs and at 3-second intervals up to 27 photographs. Stereo imagery can be acquired with the digital camera system within the parameters of memory and frame rate.

Another benefit of the automated camera is that it stores metadata for each frame. Metadata include date, time, shutter speed, aperture, ISO setting, shooting mode, lens focal length, extender types, drive mode, and parameters of 20 custom functions – including the safety shift that allows reduction of shutter speed in shutter-priority mode when light is insufficient at the widest aperture for acceptable exposure- and other information parameters. Since the Track'Air navigation system logs the GPS coordinates and time of every photograph triggered, having a corresponding time permanently associated with digital images allows rapid and almost fool-proof pairing of photographs to GPS locations and accurate mapping of ground locations. The date imprinted on each photograph ensures that job-site photographs are never confused or misidentified.

Table 2 Comparison of bare-ground by measurement method for BLM allotment #10036.

Method	% Bare Ground	S.E.	n
BLM Pace Transect	21.24	3.6	15
Ground Imagery (2m AGL)			
Digital Grid Overlay	31.47	4.91	15
VegMeasure	32.09	1.72	58
VLSA Imagery (100m AGL)			
Digital Grid Overlay	33.13	2.16	61
VegMeasure	36.30	1.73	61

Scale is the traditional description of film resolving power. However, scale has little meaning for digital photographs where resolution is better defined in terms of the GSD (Comer 1998). We recognize that VLSA digital products are more accurately described as "very high resolution" but we bridge the gap with past foundational work by using the VLSA designation.

Sampling Protocol

An aerial rangeland surveys needs sufficient number and distribution of photographs for an acceptable level of confidence that the data accurately represent the finite population (e.g., upland ground cover) sampled. Statistical level of confidence is related to sampling intensity and distribution with regard to topography, plant community, management, and other factors influencing the population sampled (Oosting, 1956, pages 48 to 51). Oosting (1956) held that a systematic sample distribution is preferable to a random distribution for ecological monitoring. VLSA aerial monitoring is a tool that facilitates systematic aerial sampling through preflight planning and programming, and automatic (unbiased) camera triggering.

Conclusions

In 1944, Ellison and Croft observed, "There are two levels of observation in range inspection: one extensive and the other intensive. ... Intensive observations on small areas are necessary to secure the detailed facts from which the only valid conclusions of range condition can be made."

Since the launch of Landsat in 1972, we have had amazing extensive views, but Landsat and other small-scale, low-resolution data sets (Table 3) have proved inadequate for identification, inventory and measurement of detailed rangeland features. VLSA methods make "intensive"

Table 3 Resolution from various sensors and platform combinations compared. The highest resolution bandwidths are reported for satellite data. Some bandwidths may have lower resolution. VLSA cameras listed include the Hulcher Model 123 70-mm film camera and the Canon EOS 1Ds 11.1-megapixel digital SLR. Ground imagery was acquired using an Olympus E20 5.0-megapixel digital SLR. To quantify image resolving capability in a way that allows comparisons among digital images, sensor resolution is given in terms of ground sample distance (GSD), defined as the linear dimension of a single pixel's footprint on the ground (Comer et al., 1998).

Platform	Sensor resolution (GSD)
Modis	250 m
Landsat 7 TM	15 m-Panchromatic 30 m-Multispectral
SPOT	2.5 m-Panchromatic 10 m-Multispectral
IKONOS	1 m-Panchromatic / 4 m-Multispectral
Quickbird	0.61 m-Panchromatic / 2.4 m-Multispectral
NAPP	1m
VLSA - Hulcher, λ = 500 mm, 100 m AGL	5.0 mm
VLSA - Canon,), λ = 420 mm, 100 m AGL	2.1 mm
Ground - Olympus, λ = 9 mm, 2 m AGL	0.97mm

observations economical. The application of VLSA methods to practical resource surveys and monitoring of extensive rangeland watersheds is greatly facilitated by the advent of the automatic, digital camera with a high data transfer rate. This technical advance is complemented by development of computer software packages to automatically measure bare ground from VLSA photographs in a fraction of the time that would be required to collect similar data using conventional ground methods. We conclude that VLSA equipment and methods described here are an advance toward practical, inexpensive acquisition of statistically adequate, unbiased, high-resolution, aerial photographs that facilitate objective monitoring of the ecological integrity of extensive areas of all the world's rangelands.

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