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Research Report

Remote sensing of heritage resources for research and management

By Alan P. Sullivan III, Kevin S. Magee, Philip B. Mink II, and Kathleen M. Forste

Abstract: Resource managers are responsible for anticipating the likely locations and characteristics of heritage properties in order to plan effectively for ground-disturbing projects. In many cases selection of the most appropriate remedies or treatments for affected cultural resources must be made with either little advance notice or incomplete information. This research report describes how the application of remote sensing may be effectively integrated with wilderness research and management planning. For instance, magnetometry and ground-penetrating radar can rapidly acquire information (without excavation) about the size, depth, and distribution of anthropogenic features. Similarly, at the regional level, satellite images can be analyzed to achieve high rates of accuracy in the direct prediction of heritage resources in unsurveyed terrain. The decision-making implications of these applied remote-sensing studies are discussed with respect to allocating heritage-management funds for programmatic planning and cost-effectively acquiring cultural resource data from remote or inaccessible reaches of wilderness.

Key Words: heritage resources, predictive models, terrestrial and satellite remote sensing

Introduction

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Figure 1. View of several hundred square kilometers of densely forested terrain along the eastern South Rim of Grand Canyon. Beneath this canopy are thousands of archaeological sites whose locations and characteristics are largely unknown to resource managers and scientists. This "hidden heritage" problem affects all units in the National Park System with significant human histories that are registered by highly variable concentrations of surface archaeological phenomena.

Draped like emerald-green bunting over the northeastern corner of the Coconino Plateau in north-central Arizona, the ancient coniferous forest that mantles Grand Canyon National Park and the adjoining Kaibab National Forest (fig. 1) camouflages thousands of archaeological sites. Bypassed by millions of visitors annually are hundreds of square kilometers of de facto wilderness, terrain that is rarely seen or traversed by humans though not congressionally designated as wilderness. Yet the area's abundant hidden heritage creates a number of problems for resource managers and researchers alike. (Heritage resources are by-products of prehistoric and historic human activities such as ruins, hearths, and artifacts that are potentially significant to various cultural groups.) First, without accurate knowledge of the regional distribution of heritage resources, managers are constrained in their decision making, particularly in responding to "stressor" syndromes (e.g., population growth, resource extraction, encroaching development) that affect visitor experiences (Bishop et al. 2011). Second, critical ground-disturbing projects, often intended for public safety (e.g., road widening) or experience enhancement (e.g., visitor services expansion), are delayed or become needlessly intrusive because even coarse-grained data, such as the presence or absence of heritage resources, are chronically unavailable in considering alternative land-modification options (Ahlstrom et al. 1993). Third, scientific projects related to understanding the human and natural histories of parks and surrounding areas are disadvantaged because regional-scale information is discontinuous and the significance of known data points is incompletely understood because of erratic sampling (Sullivan et al. 2007).

Here, we share the results of recent applications of remote sensing that show great potential for helping managers and scientists overcome the aforementioned problems from two different information settings. In some cases, prior knowledge is available about the surface archaeology of heritage resources that may be affected by a surface-modifying project, yet the information required to make an informed judgment regarding their disposition (e.g., preservation or long-term monitoring) is unavailable without additional, often expensive and time-consuming, archaeological excavation (Anderson and Neff 2011). Moreover, in most cases, no information is available whatsoever about the surface archaeology of heritage resources that may be threatened by park projects, visitor impacts, or operations of adjacent federal agencies (Fairley 2005). We intend to illustrate that remote sensing holds great promise in helping park managers—regardless of park size or annual number of visitors—meet their obligations within the letter and spirit of the Wilderness Act, as well as other federal heritage laws (e.g., National Historic Preservation Act). Our message is straightforward as well: current gaps in understanding the extent of the "hidden heritage" problem can be resolved with the broad and consistent application of the methods we discuss, which we believe ought to play a larger role in long-term management of and research planning for all units in the National Park System.[1]

What's down there? Terrestrial remote sensing of known archaeological phenomena

Terrestrial remote sensing (TRS) consists of noninvasive techniques that measure variations in Earth's physical properties, such as subsurface voids, magnetism, and electrical conductivity (Kvamme 2008). Our explorations of the archaeological potential of TRS in Grand Canyon National Park focus on validating surface-subsurface feature relations and resolving ambiguous surface indications, as the following examples illustrate.

Site B:16:105 holds the remains of a prehistoric stone-outlined pit structure and a stone-outlined surface structure. Prior to excavation, a ground-penetrating radar (GPR) survey over the pit structure was conducted (in approximately two hours). The GPR unit, which is designed to detect and record anomalies that are registered by differences in travel times of radar waves beamed directly below the ground's surface (Conyers 2004), consists of a near-surface antenna and receiver that are systematically drawn across the vegetation-free surface of an archaeological site without touching it. In this case, results (fig. 2) clearly show the outline and depth of the pit structure as well as a large, deep, centrally located hearth. Upon excavation it was determined that this feature had deliberately been filled with rock at the time of abandonment, and therefore, in all likelihood, was "ritually" abandoned. This discovery is a first-time finding in the history of Grand Canyon archaeology for which, however, we now have a digital record to use in planning future excavations that are guided by GPR applications.

In contrast, site MU 3617 is an amorphous scatter of prehistoric artifacts, daub fragments (pieces of dried mud that had been applied to formerly intact walls), and a linear rock alignment. To determine if the alignment was part of a buried structure and to explore the usefulness of another TRS method in a heavily vegetated area, a magnetic gradiometer (MG) survey was conducted over the entire site (in approximately four hours). MG measures variations in Earth's magnetic field that are attributable to anthropogenic activities (Aspinall et al. 2008). Results (fig. 3) strongly suggest that the rock alignment is unrelated to a buried structure and that the area where the daub was found appears to be the remains of a heavily burned structure. The significance of this finding is that burned sites, in contrast to unburned sites, have greater inferential potential because of the higher likelihood that they contain preserved carbonized remains.

TRS provides resource managers and researchers with nonintrusive methods for investigating the range of spatial patterning of buried and nonburied archaeological features. In addition, these culturally sensitive techniques provide nondestructive options for heritage managers who must assess the interpretive potential of sites and features that may be considered sacred by indigenous peoples. Conducting geophysical survey on sites slated for excavation for legal compliance purposes (as in the case of site B:16:105) provides a valuable set of baseline data that can inform future interpretations of sites that will not be excavated (as in the case of site MU 3617). Finally, the noninvasive nature of these techniques allows researchers to preserve sites while working to understand their significance within the larger regional context of park resources, whether they are associated with designated or de facto wilderness.

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What's out there? Satellite remote sensing of unknown archaeological phenomena

Satellite remote sensing (SRS) employs sensors on spacecraft to capture variation in light reflectance and absorbance at different spatial (pixel size) and spectral (electromagnetic bandwidth) resolutions (Parcak 2009). High-resolution sensors, such as the one carried on the QuickBird satellite (0.6–2.4 m [2.0–7.9 ft]), are required to differentiate abundant small-scale archaeological phenomena from their natural surroundings (fig. 4).

Our recent applications of SRS, both pixel-based and object-oriented[2] studies, have focused on developing direct predictive models of archaeological phenomena in the Grand Canyon area (Sullivan et al. 2006). Simplifying greatly, this approach has several steps. First, distinctive spectral signatures, which can be considered electromagnetic "fingerprints" of the pixels associated with different kinds of known archaeological phenomena, are extracted from geo-referenced satellite images. Next, these signatures are projected to the pixels and objects associated with unsurveyed terrain in the same images, a procedure that yields probability maps of the distribution of archaeological phenomena (Benz et al. 2004). Finally, model predictions are then checked for accuracy by intensive archaeological survey to ascertain the number of true positives (correct "presence" predictions), false positives (incorrect "presence" predictions), false negatives (incorrect "absence" predictions), and true negatives (correct "absence" predictions). Figure 5 graphically illustrates the output of such modeling for an area along the eastern South Rim of Grand Canyon National Park; each dot represents the predicted location of a heretofore unknown archaeological site. Even though verification of the model's accuracy is ongoing, provisional results indicate that the overall distribution of archaeological phenomena provides an empirically grounded basis for management planning at the regional level, especially with regard to where sites are clustered versus where they are not.

Another application was focused on predicting the presence of masonry structures, which are often obscured by vegetation that has recolonized long-abandoned ruins, from the attributes of their associated artifact scatters, which are commonly vegetation-free. The initial hypothesis was that the vegetationally unobscured scatters would register the highest contrast with the natural background because of unrestricted line of sight between the target (artifact scatter) and the satellite-borne sensors. Using several statistical satellite-image transformation and enhancement techniques and "fuzzy" classification procedures,[3] we discovered, however, that the highest percentages (around 80%) of true positives were achieved for partially obscured scatters. These results suggest that the most sensor-distinguishable signal may occur at the interface between archaeological remains and the forest margin, a finding that dramatically expands the range of application of SRS in densely forested ecosystems. Thus managers and scientists have greater latitude to evaluate alternatives of a proposed project that are likely to encounter archaeological sites and, more importantly, select the option that enhances preservation of the greatest number of cultural resources.

Implications and future directions

Of the many challenges that confront heritage resource managers, from short-term compliance to long-term planning, all are unified by the same issue that scientists face: access to reliable data upon which informed decisions can be made. Our central theme has been to illustrate the advantages of routinely incorporating TRS and SRS in any park endeavor to create information-rich digital databases. Actually, training in TRS has been a National Park Service priority, yet its application is spotty, which is largely attributable to the widespread lack of equipment and processing software. Nonetheless, TRS, like geographic information systems and global positioning systems, can no longer be considered technological gimmickry with limited applications but, instead, should be elevated to the status of integral tools of management practice and scientific method (Mink et al. 2006). In contrast, SRS applications in archaeology have barely advanced beyond the proof-of-concept stage; our modeling studies suggest, however, that the upside planning potential of SRS-based regional predictive models is considerable yet untapped. Unquestionably, the widespread availability of TRS and SRS images of different kinds of archaeological phenomena can be integrated seamlessly into planning because both managers and scientists need to be able to predict what is "down there" or "out there" with certain degrees of confidence.

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Notes

Note 1

For the two TRS methods discussed in this report, ground-penetrating radar and magnetic gradiometry, contracting expenses vary from $959 to $906 daily, respectively, for initial equipment setup and instrumentation calibration, and $859 to $806 per day thereafter. These estimates include costs of machine time, personnel, and software but do not include travel, report write-up, and institutional overhead. Considering that the purchase price for a magnetic gradiometer is about $20,000 and a ground-penetrating radar system is about $20,000–$50,000, depending on the number and sensitivity of the antennas selected, many smaller units of the National Park System may opt to partner with universities or other agencies whose large capital equipment budgets have enabled the acquisition of such devices.

Table 1 contains basic information about satellite image acquisition and processing costs. In many cases, special licensing "network" arrangements can be negotiated with software providers and, depending on location, scene size, and the image "tasking" problem, special federal pricing may be available as well.

When the costs of excavation, including perpetual curation of recovered materials, and the costs of time-consuming survey to cover large areas are compared with the estimates in table 1, what seem like significant upfront capital investments for either TRS or SRS are reasonably cost-effective (not unlike the start-up and maintenance expenses of any national park unit–specific GIS).

Note 2

Object-oriented methodology differs from pixel-based techniques because the intended unit of observation is not the pixel but rather segments of multiple pixels (i.e., objects). While the initial image segmentation uses low-level pixel-based information, it creates higher-level contiguous regions of pixel clusters called "objects" (Benz et al. 2004).

Note 3

A transformation called Minimum Noise Fraction (MNF) identifies extraneous "noise" in the image that can be excluded from subsequent analyses. A Normalized Difference Vegetation Index (NDVI) transformation captures vegetation responses in the proximity of anthropogenic disturbances. A Tasseled Cap Transformation (TCT) detects the preferential trapping of moisture within the rubble mounds of masonry ruins. Matched Filtration (MF) procedures "unmix" a pixel that registers both natural and cultural features with the intent of uncovering a single known anthropogenic spectral signature.

"Fuzzy" classification replaces the binary statements of "true" and "false" with a continuous range between 0 and 1, where 0 stands for "false" and 1 for "true." All values between 0 and 1, then, vary between true and false, representing a fuzzy range. In a fuzzy classification, an object can be considered to be in any class to a certain extent: final classification is based only upon the variables that make the strongest argument (i.e., that best match the training or "known" data).

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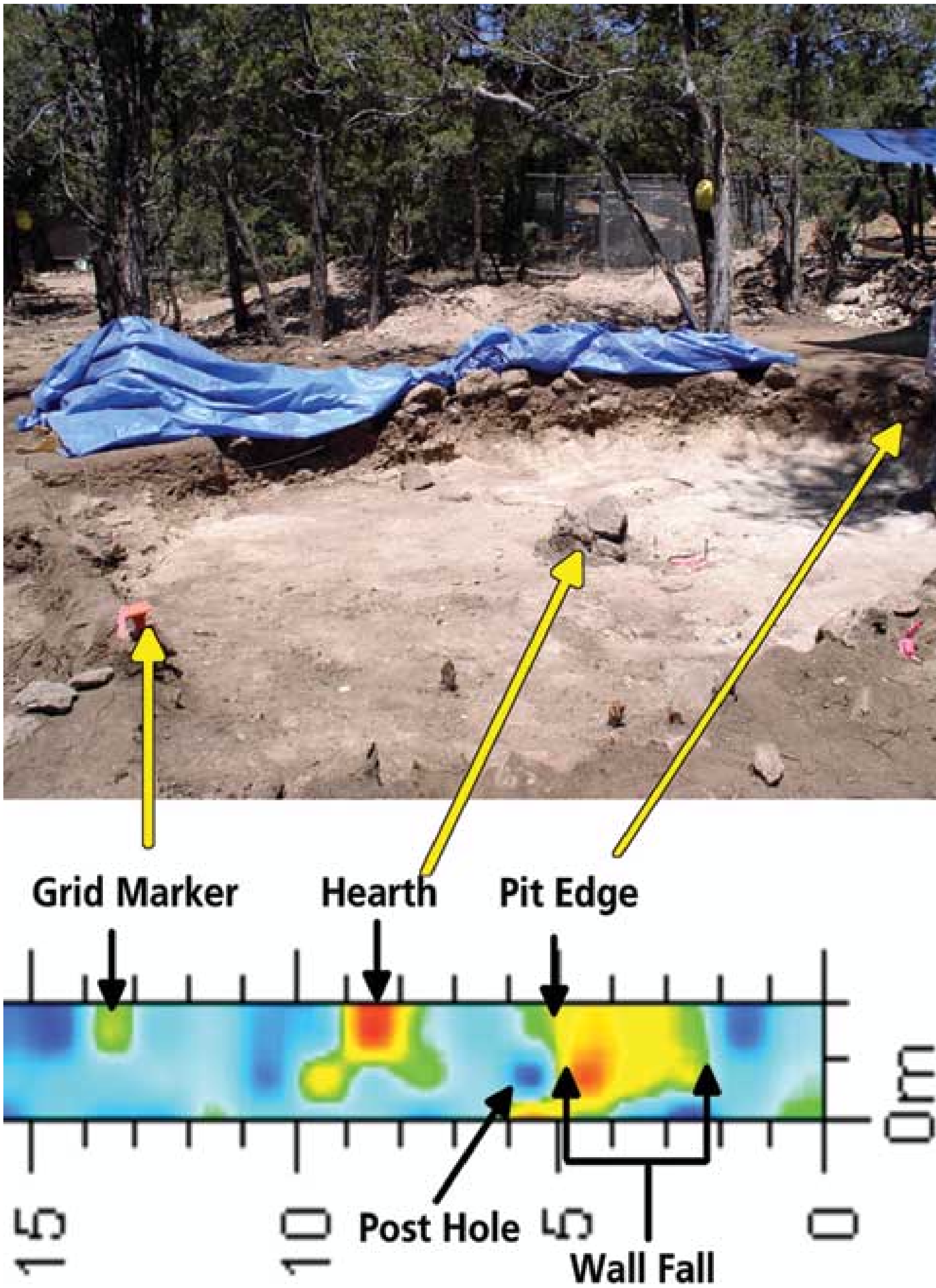

Philip B. Mink II

Figure 2. Correspondence between anomalies revealed by ground-penetrating radar (photo at top) before excavation and features disclosed after excavation (diagram at bottom) at site B:16:105, Grand Canyon National Park.

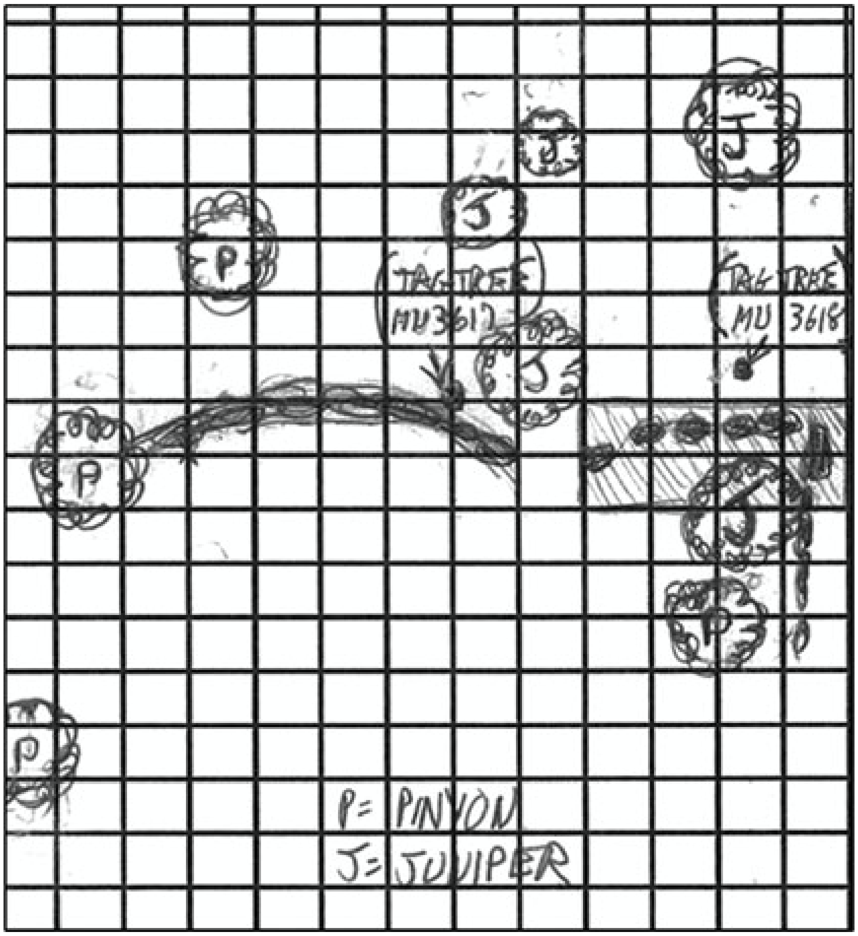

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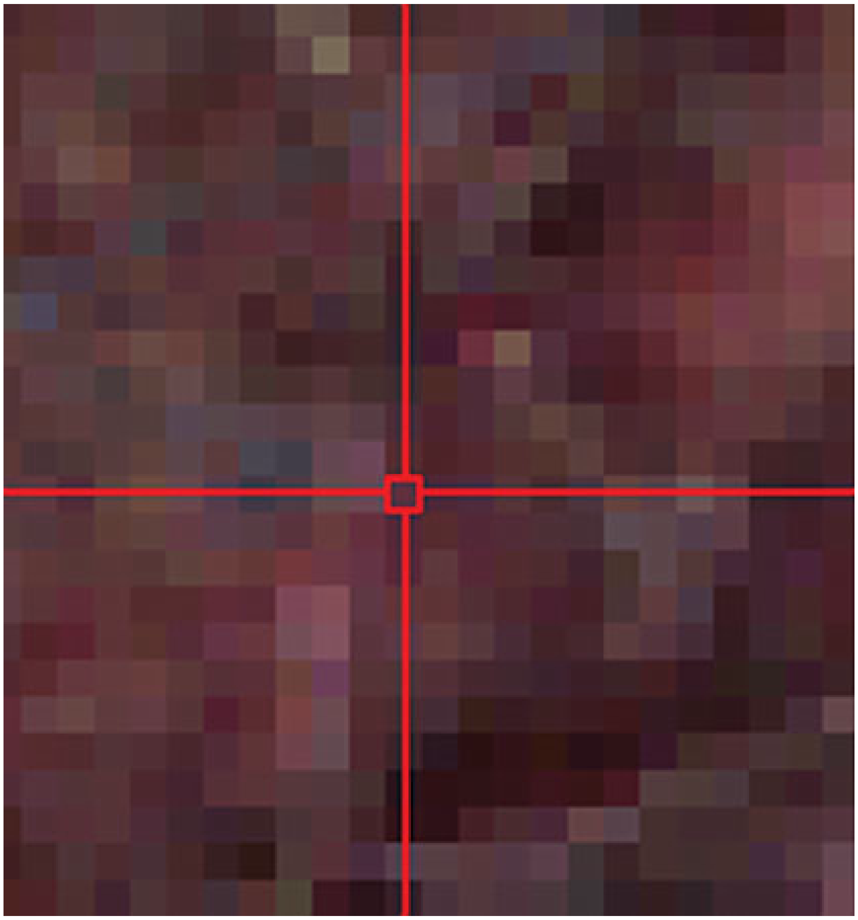
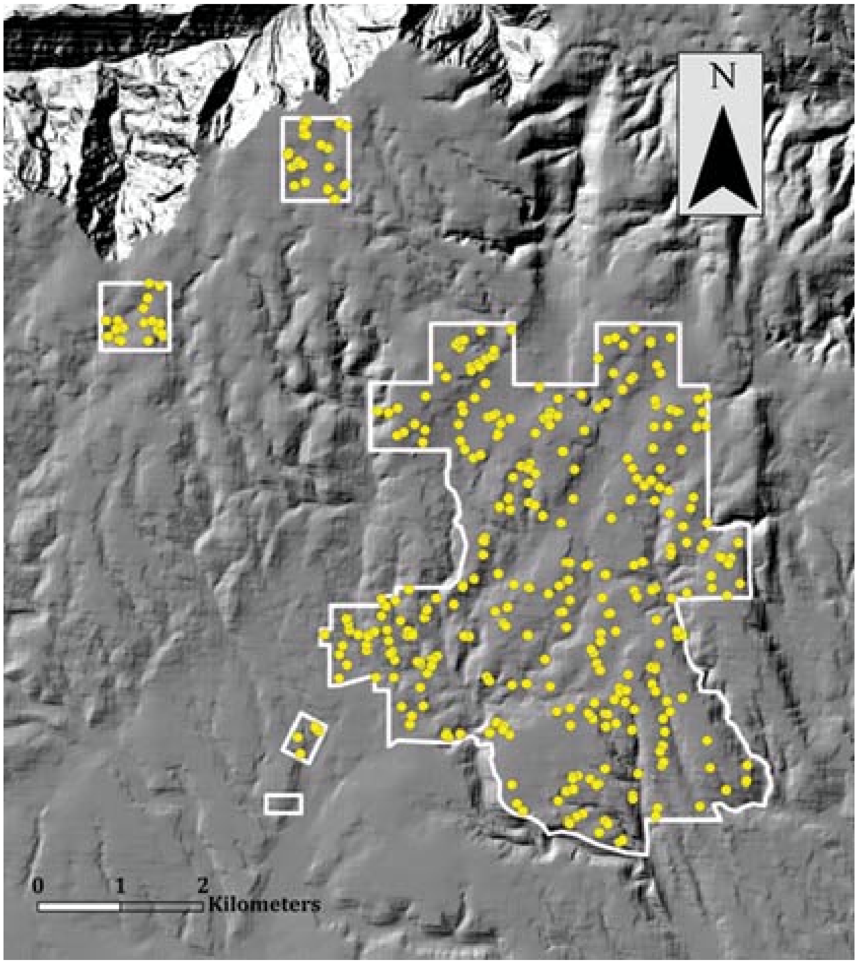
Figure 3. Field map (above) and corresponding magnetic gradiometer image (next image) of anthropogenic features at site MU 3617, Grand Canyon National Park. The results of this study indicated that the rock alignment (curved element in left center, this image) was not an architectural feature, and the concentration of daub (fragments of a hardened mud surface that had once adhered to walls before their collapse) and rocks (lightly hatched area, right center, this image) was the remains of a heavily burned structure (dark tone at right center, next image). Trees and concentrations of impenetrable vegetation are represented by purple polygons.



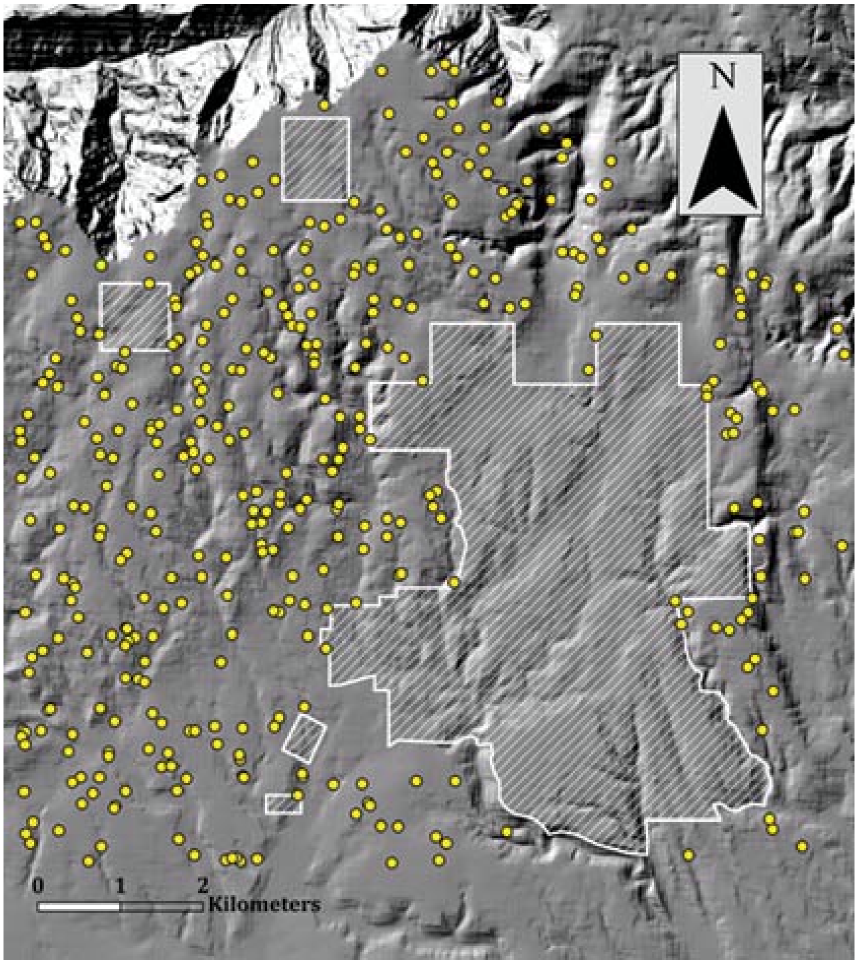
Kevin S. Magee

Figure 4. Tusayan Ruin in Grand Canyon National Park as it appears on a Landsat TM image (30 m [33 yd] pixels, this image) and a QuickBird image (1 m [3.3 ft] pixels, next image). Note that rooms, which appear as either individual quadrilateral spaces ("Kiva" in center, next image) or clusters of quadrilateral spaces ("Room Blocks" in left center and upper center, next image), can be distinguished from the tree canopy with QuickBird's fine-grained resolution.



Kathleen M. Forste and Kevin S. Magee

Figure 5. Geo-referenced and processed QuickBird satellite image showing the locations of known archaeological phenomena (i.e., “training data” for the “fuzzy” classification component of the direct predictive model) in this image and the predicted locations of previously unknown archaeological phenomena (next image) in an area south of Desert View, Grand Canyon National Park and Kaibab National Forest.



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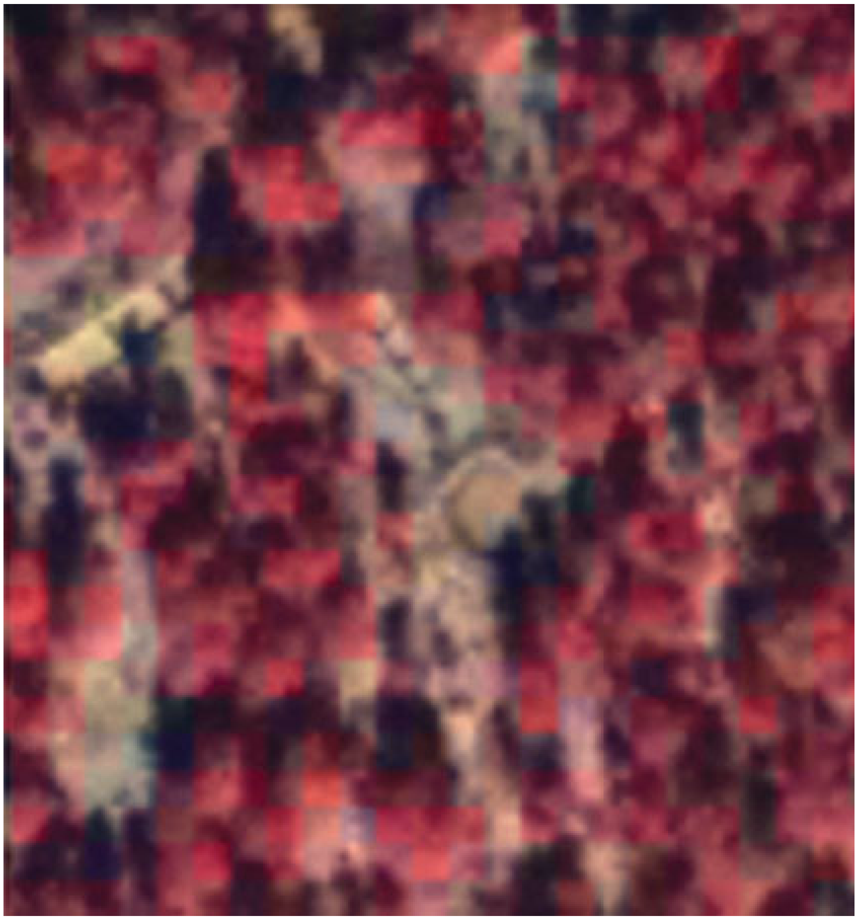

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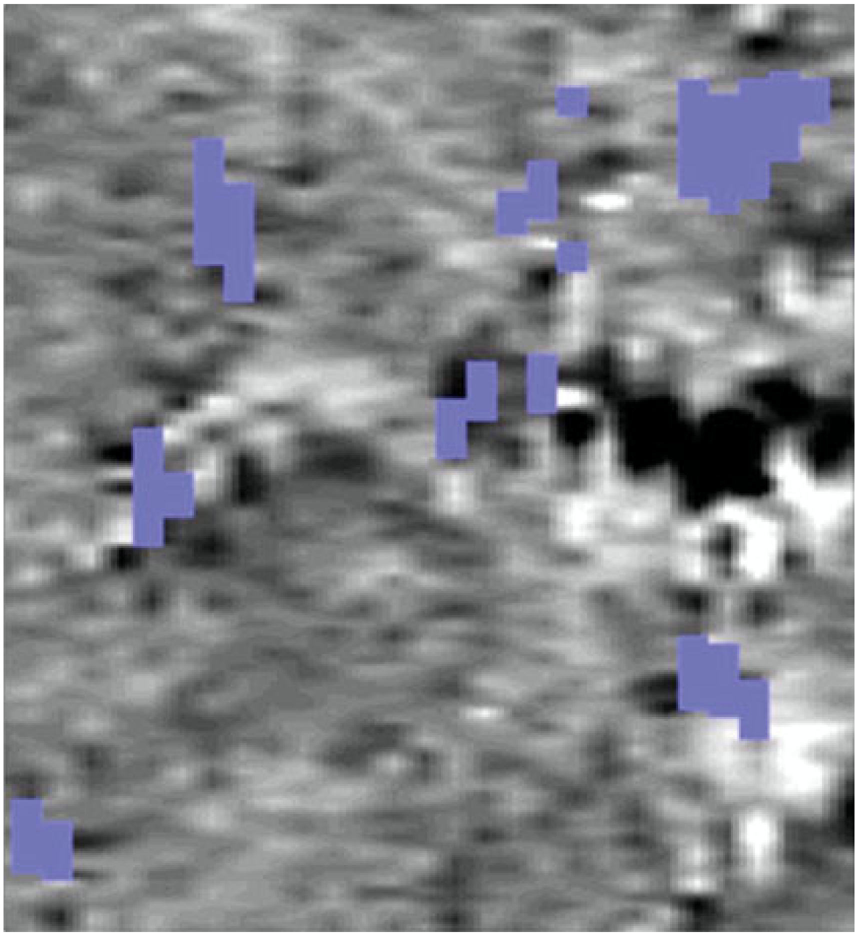

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Table 1. Basic costs of satellite image acquisition and processing

Satellite Imagery	Spatial Resolution	Cost for 100 sq km (39 sq mi) (archived)	Cost for 100 sq km (39 sq mi) (tasked)
4 band[1]	0.5 m–4.0 (1.6 ft–13.1 ft)	$1,000–$1,400	$2,000–$6,000
8 band[2]	0.5 m–2 m (1.6 ft–6.6 ft)	$2,900	$3,800–$7,800
Software			
Pixel-based	$750–$1,250[3]		

Object-based	$16,7044
Labor	
2 weeks' labor for imagery scientist	$3,600
Total Cost	
Minimum	$1,750
Maximum	$24,504

[1]IKONOS, QuickBird, GeoEye-1 Sensors
[2]WorldView 2 Sensor
[3]ITT ENVI, Erdas Imagine
[4]eCognition

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