Using Remote Sensing to Evaluate Environmental Institutional Designs: A Habitat Conservation Planning Example*

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Objective. Satellite-based remote-sensing analysis is a beneficial, yet underused, tool for environmental policy, planning, and evaluation. We identify its benefits and costs to encourage social scientists to consider the use of remote sensing as a tool for planning and evaluating environmental institutions. *Methods*. We analyze two multispectral Landsat Thematic Mapper satellite images to evaluate a habitat conservation plan (HCP) implemented pursuant to the Endangered Species Act. *Results*. Image analysis provides useful broad spatial scale information on HCP performance that is not discernible to the naked eye or through other methodologies. *Conclusions*. Satellite image analysis should be considered as a tool for planning and evaluating environmental institutional designs—despite the financial costs and requisite technical training. These images provide ecological and land cover change information that may not be available elsewhere. We provide lessons learned to help make analysts cognizant of some important issues surrounding the use of satellite-based imagery for environmental institutional analysis.

Remote sensing is the science of observation at a distance (Jensen, 2000; Campbell, 1996). Over the last 10–20 years, land cover inventories based on remotely sensed imagery have become commonplace. But the opportunity now exists to apply remote-sensing techniques toward the evaluation of environmental institutional performance. In our view, satellite-based remote

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sensing for this purpose is beneficial and currently underused. The reasons for underuse are clear. Many social scientists and environmental policymakers have no experience with remote-sensing technology. Moreover, image analysis can be expensive; it requires special computer hardware and software and skilled personnel.

Applications of remote sensing *are* expensive to undertake; we do not deny that. However, when major long-term environmental planning efforts are underway or when planning or policy outcomes must be evaluated, remote-sensing analysis can provide information that may ultimately lead to substantial cost savings and environmental improvement over the long term. To emphasize this point, we apply a remote-sensing analysis to evaluate the performance of a particular institutional design: a broad spatial-scale habitat conservation plan.

We begin with a brief overview of the traditional uses of remote sensing for habitat and biodiversity protection. We then describe the case study. After outlining the data collection, methods, and results, we provide some lessons learned from this experience to help environmental policymakers, planners, analysts, and scholars consider satellite-based remote sensing as a tool for evaluating or planning other environmental institutional designs.

Traditional Applications of Remote Sensing in Habitat and Biodiversity Protection: Land Cover Inventories and Change Analysis

Understanding the geographic distributions of biodiversity and its change over time is critical for environmental policy and management. Throughout the 20th century, traditional mapping used aerial photographs (e.g., USDA, 1988) or field samples (e.g., Cole et al., 1998) for mapping biodiversity. Over the last 30 years, airplane- or satellite-based technologies, such as panchromatic, multispectral, or hyperspectral sensors, have been used (Trotter, 1991; Nagendra, 2001).

Satellites with panchromatic sensors measure reflectance in one wide portion of the electromagnetic (light) spectrum and produce one black and white image of the landscape (SPOT, 2001). Multispectral satellites have not one but several sensors, each sensitive to a different location along the electromagnetic spectrum. In this study, we use Landsat Thematic Mapper (TM) imagery, which uses seven sensors sensitive to different sections of the light spectrum: blue (.45–.52 μm), green (.52–.60 μm), red (.63–.69 μm), near infrared (.76–.90 μm), mid-infrared (1.55–1.75 μm), thermal (10.4–12.5 μm), and mid-infrared (2.08–2.35 μm). Hyperspectral images measure many—sometimes hundreds—of locations along the spectrum (e.g., JPL, 2001).

There are a variety of remote-sensing platforms used in land cover inventory research, such as the high spatial resolution Airborne Data Acquisition and Registration data (Phinn, Stow, and Mouwerik, 1999), digital aerial photography and videography (Airola, 1996; Slaymaker et al., 1996; Brown and Arbogast, 1999), Landsat Multispectral Scanner (Schweik and Green, 1999), Landsat TM (this study; Adams et al., 1995; Sader, 1995; Walsh et al., 1999; Lunetta and Balogh, 1999), Indian Remote Sensing Satellite (Nagendra and Gadgil, 1999), the Advanced Very High Resolution Radiometer (Lambin, 1996), and others. Each platform has its own attributes (e.g., the number and types of sensors used, pixel size).

A variety of techniques exist to analyze images produced by these technologies, including (1) single-sensor (grey-scale) analysis (often a visual analysis); (2) color compositing, in which data from three sensors of an image are assigned to the primary colors of blue, green, and red and are reviewed visually; (3) band-to-band ratioing (such as the popular normalized difference vegetation index), in which information from two or more sensors is mathematically processed to emphasize a particular landscape feature; (4) principle component analysis, a technique sometimes applied to reduce noise in image data produced by sensor problems; and (5) supervised classification, in which field data are used to statistically assign pixels to various land cover types (Campbell, 1996; Jensen, 2000).

"Gap analysis" is probably the most well-known satellite-based remote-sensing application for studies of biodiversity protection. Gap analysis programs seek to identify native species or communities of species that are underrepresented in the landscape and to identify locations where additional measures could be put in place to help protect these species (Scott et al., 1991; Scott et al., 1993; Eve and Merchant, 1998; USGS, 2001a). Although Gap analysis programs have used many of the inventory techniques listed above (e.g., Scott, Tear, and Davis, 1996), most U.S. states have used supervised classification (Stoms et al., 1998).

In short, there is a substantial literature using remote sensing for mapping biodiversity. In addition, a smaller, but growing, literature examines how humans affect land cover change (Wood and Skole, 1998; Moran and Brondizio, 1998; Entwistle et al., 1998; Schweik, 1998; McCracken et al., 1999; Schweik and Green, 1999; Nyerges and Green, 2000). This article adds to this literature and to the broader environmental policy literature by making connections between satellite-based landscape change analysis and the evaluation of environmental institutions.

A Habitat Conservation Planning Example

The U.S. Endangered Species Act (ESA) requires individuals and organizations (other than federal agencies) to apply for a permit before they develop any part of an endangered species' habitat. To receive a permit, they must prepare and submit a habitat conservation plan (HCP) for approval to the U.S. Fish and Wildlife Service (FWS). These HCPs exhibit great variation in size, complexity, and institutional form.[1] In size, HCPs vary from less than an acre to more than a million acres. In complexity, they may cover a single species or many species. Permit applicants may also be a single organization (such as a timber company desiring to log some of its property) or a consortium of organizations (such as a council of local governments seeking a joint permit covering several local zoning ordinances). In institutional form, HCPs are limited only by the creativity of the applicants. Most large HCPs establish a core preserve surrounded by buffer zones, but there are numerous ways to acquire, regulate, monitor, enforce, or otherwise manage these areas. To a large extent, these decisions are made by the applicants, subject to FWS approval (Thomas, 2001).

The number and size of HCPs grew dramatically during the 1990s. The first HCP was completed in 1983, shortly after Congress amended the ESA in 1982 to authorize the FWS to issue permits for HCPs. Yet the FWS issued only 14 permits during the first 10 years (1983–1992). After 1992, the pace rapidly quickened. By July 2001, the number of permitted HCPs climbed to 358, covering tens of millions of acres (USFWS, 2001).

Case Selection

We selected the Coachella Valley fringe-toed lizard (CVFTL) HCP for study for two primary reasons. First, it is the second-oldest HCP—the plan was completed in 1985, with the permit issued in 1986—which means significant time has passed for humans to develop the habitat and for natural changes in land cover to occur. Second, it encompasses a relatively broad geographic region; at approximately 70,000 acres, it offers a better opportunity to demonstrate the utility of remote-sensing analysis for institutional evaluation over a broad geographic region than does the first HCP, which covers only 3,500 acres.

Endangered Species and Ecological System Processes

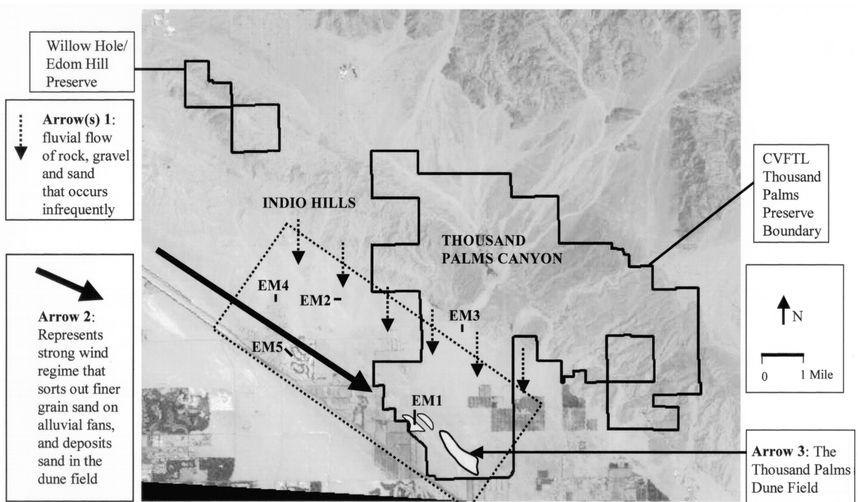
The HCP focuses on the protection of a single species, the Coachella Valley fringe-toed lizard (*Uma inornata*). The lizard lives in sand dunes that have been whittled away by rapid development in the Coachella Valley, home to several resort cities, including Palm Springs and Palm Desert. Central to designing an effective HCP was understanding the ecological system that supports the lizard's sand dune habitat. Figure 1 presents a diagram of the dune system at the HCP's main preserve (Thousand Palms), overlain on a Landsat TM image. The figure demonstrates the fluvial and eolian characteristics typical of Coachella Valley dune systems (Barrows, 1996). Sand is flushed out of hills to the north by major storm events that

[1] For current data on HCPs, see USFWS (2001).

occur infrequently (Figure 1, Arrow 1). Over time the sand is sorted from other materials by water and wind on alluvial fans. Sand of various grain sizes is transported and scattered by a southeasterly wind (Figure 1, Arrow 2) to the dunes (Figure 1, Arrow 3). The lizard prefers active blow sand in which the sand grains are small and loose enough for it to burrow into quickly with its fringed toes to escape predators and the sun, but not so small that the grains enter the lizard's ears and respiratory system. A successful HCP design for the lizard must protect the active blow sand system, including the sand source areas and the unobstructed wind corridors that replenish the dunes.

FIGURE 1

Ecological Model of Sand Transport for the CVFTL HCTP Thousand Palms Preserve (Overlaid on June 6, 1986, Landsat TM Image, Band 1 [Visible Blue]); Adapted from Barrows (1996)



Note: Vegetation (darker) reflects less light and sand (whiter) reflects more light at this wavelength. Dark lines outline the main preserve (large boundary in eastern portion of image) and smaller Willow Hole/Edom Hill preserve to the northwest. EM#s represent 1986 image endmember locations for input to Matched Filtering analysis. Dashed box indicates approximate subset area for Matched Filtering analysis. The preserve boundary GIS layer was provided by the Coachella Valley Association of Governments.

The CVFTL HCP Institutional Design

The institutional design is composed of (1) preserve areas, (2) managed areas, (3) zoned and regulated areas, and (4) fee areas (Figure 2). Many HCPs have preserve areas, which provide core habitat for targeted species. The CVFTL HCP has three: a main preserve (Thousand Palms) and two smaller "back-up" preserves (Willow Hole-Edom Hill and Whitewater).[2]

[2]In the original plan, the specified sizes of the three preserves were 13,030, 2,469, and 1,230 acres, respectively (CVFTL HCP Steering Committee, 1985). As of 2000, however,

The main preserve is particularly important for the lizard because it encompasses the largest active dunes in the region and also protects some of the presumed sand source areas and wind corridors. But the HCP designers were unsure of the sand source. Was the active blow sand primarily flushed through the Thousand Palms Canyon (Figure 1) during flood events? Or did it come from the alluvial fans of the Indio Hills? The preserve director described the uncertainty this way:

> Experts in aeolian sediment transport estimated that the two identified sand sources each contributed about 50% of the total sand delivered to the Thousand Palms dune field. The Thousand Palms Canyon sand source was largely in a single ownership and would be a relatively simple acquisition. The western Indio Hills sand source and transport corridor was made up of hundreds of small parcels, each with separate ownership. The acquisition of this sand source would be difficult and extremely costly. This situation posed a dilemma to the architects of the HCP and the preserve system. Without quantitative data there was no way to determine whether protecting just one of the sand sources would be sufficient. Nevertheless, a decision was required; the architects of the HCP decided to protect just the Thousand Palms Canyon sand source through direct acquisition. (Barrows, 1996:889)

Thus, the shape and placement of the main preserve was largely determined by reducing transaction costs in the face of scientific uncertainty. A secondary benefit of preserving the Thousand Palms Canyon was that it contained unique palm oases, which would also be protected.

Managed areas (Figure 2) are public lands on which human uses compatible with habitat maintenance are allowed. Unlike the preserve areas, managed areas were designated for multiple uses, whereas the preserve areas were designated off-limits to most human uses. The plan also designates private land to be zoned or regulated (Figure 2). As with the managed public lands, the primary planning criterion for these private lands was sand transport. Much of this private land lies in unincorporated areas of Riverside County, where the HCP planners assumed that county planners would subsequently revise zoning ordinances for compatible uses. This was a major assumption, particularly given the uncertainty of the actual sand source locations and related wind corridors. If the sand came from the Indio Hills and their alluvial fans, which lie outside and upwind from the main preserve (see Figures 1 and 2), then the success of the HCP would largely ride on future zoning by Riverside County.

Fee areas comprise more than half of the HCP's total acreage. The HCP allowed development without restrictions on these lands provided that developers paid a $600/acre mitigation fee, which would be used to acquire

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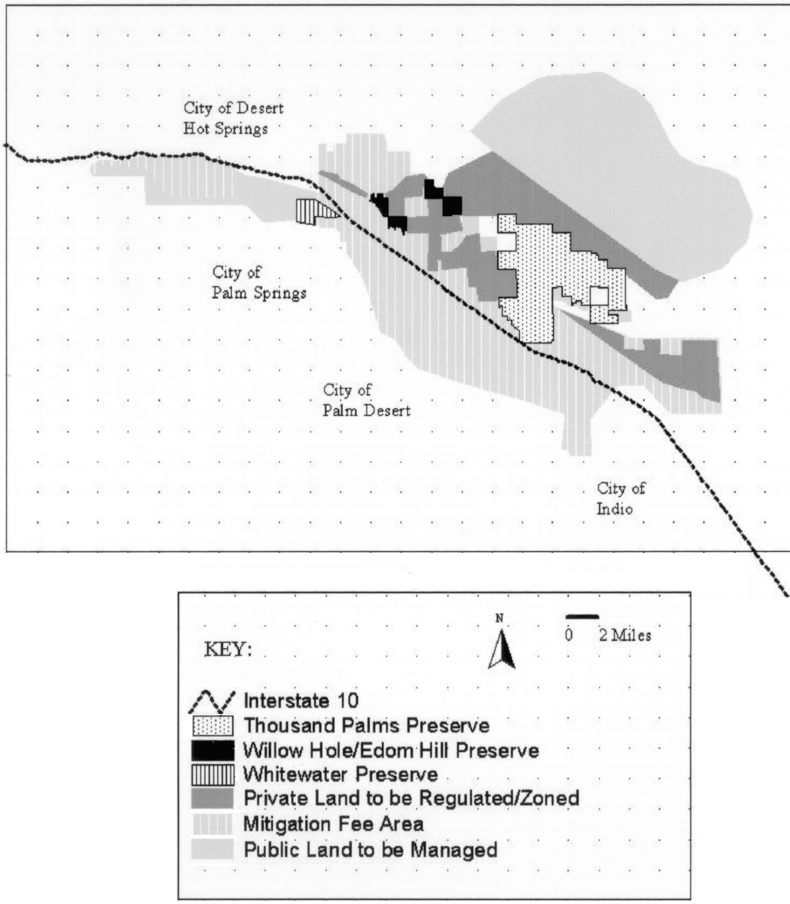
the main preserve was significantly larger, at 17,359 acres, while the other preserves were smaller, at 1,994 and 1,175 acres, respectively (Center for Natural Lands Management, 2000).

and manage the preserve areas. The cities and Riverside County collected

FIGURE 2

Institutional Design of the CVFTL HCP



this fee from developers, along with other assessed development fees, before issuing grading permits. They then forwarded the fees to the Nature Conservancy, which administered the fund for purchasing and managing the preserve lands.

Research Procedures

The uncertainty of the sand source, combined with the varying levels of protection in each of the four types of designated areas in the HCP, suggest the importance of evaluating three rival hypotheses:

Hypothesis 1: Active blow sand in the main preserve comes mostly from the Thousand Palms Canyon.
Hypothesis 2: Active blow sand in the main preserve comes mostly from the Indio Hills region.
Hypothesis 3: The sand source is a relatively equal combination of the two regions.

Given that aeolian sand transport happens continuously, we expect to see patterns in the multispectral images coming from its source. If Hypothesis 1 is supported, then we can assume that the preserve design is effective in preserving the ecological system, provided that people comply with the plan. If evidence supports Hypothesis 2, then additional efforts may be needed to ensure that alluvial fans from the Indio Hills are protected. If the evidence supports Hypothesis 3, then the findings are ambiguous in terms of the appropriateness of the current HCP design.

Satellite Image Processing

Because movement of sand across the Coachella Valley floor is gradual, two time points should provide sufficient information to evaluate institutional performance. We selected one image taken just after the HCP was issued (June 6, 1986) and one taken as close to the time of our fieldwork as possible (July 9, 1998). These two time points allowed us to analyze how the HCP affected land cover during its implementation. Minimal cloud cover and seasonal control were also image selection criteria. We ordered Landsat TM data of the region using the U.S. Geological Survey's (USGS's) EarthExplorer (USGS, 2001b) and conducted georeferencing, radiometric calibration, and atmospheric correction procedures to make the data from the two images comparable (see <http://www.masspolicy.org/schweik/ /hcp/cvftl.htm> for more information). Figure 1 displays the data from the visible blue light sensor for the northeast portion of the 1986 image. Darker areas represent lower levels of visible blue light reflectance, whiter areas, higher levels of visible blue light reflectance.

The choice of appropriate image analysis method depends on the research question, the particular characteristics of the habitat of interest, and the attributes of land cover disturbances created by human actions. For example, traditional supervised image classification is best used when land cover exhibits discrete qualities at the pixel level. In this case study, however, we were interested in the relative abundance of active blow sand within each pixel, which would allow us to more accurately measure sand movement across the valley. Assigning pixels to one category would likely lose valuable information regarding the relative abundance of active blow sand within each pixel because, with the exception of the dunes, active blow sand is not a dominant land cover feature.

For this reason, we turned to "matched filtering" (MF),[3] a technique that can estimate relative abundances of land cover types *within* pixels (ENVI, 1997). The analyst must first identify a set of important land cover types, referred to as "endmembers," that, in various combinations, can characterize the contents of all (or most) image pixels. The analyst must locate homogeneous areas in the field that represent these endmembers and measure their spectra, using a field spectrometer or the satellite image itself. We used the latter.

An analytic challenge is that the number of sensors limits the number of endmembers that can be used (ENVI, 1997). In the case of Landsat TM, the analyst is limited to five endmembers. One way to reduce the number of endmembers required is to "clip" the images so that only areas important for the research question are included. We needed to analyze only the valley floor from the alluvial fans of the Indio Hills to the southeast edge of the Thousand Palms preserve, so we clipped out this subregion (the dotted rectangles in Figure 1). Using a "pixel purity index" procedure (ENVI, 1997), along with field information supplied by local scientists and our own field-based observations, we identified five important land cover types (endmembers) for analysis:

EM1: Active blow sand (primary habitat for the fringe-toed lizard)
EM2: Packed silt (very fine sand and silt that is stabilized like dry clay), with scattered creosote bushes
EM3: Unsorted/poorly sorted alluvial sands, gravel, and rock, with scattered creosote bushes
EM4: Development (within the town of Thousand Palms)
EM5: Bright live vegetation (primarily golf course fairways)

Endmember pixel locations are identified in Figure 1.

ENVI's MF module uses the endmember spectral data and a linear unmixing equation[4] to generate material-abundance estimates for each pixel. Pixels are usually assigned a number between zero (endmember not present) and one (pixel comprised entirely of that endmember) but can exhibit numbers below zero or above one if the endmembers chosen do not model the material well (ENVI, 1997). Figures 3 and 4 show grey-scale representations of MF output for each of the endmembers for the two time points. Dark locations for EM5 have low abundance values for bright live vegeta-

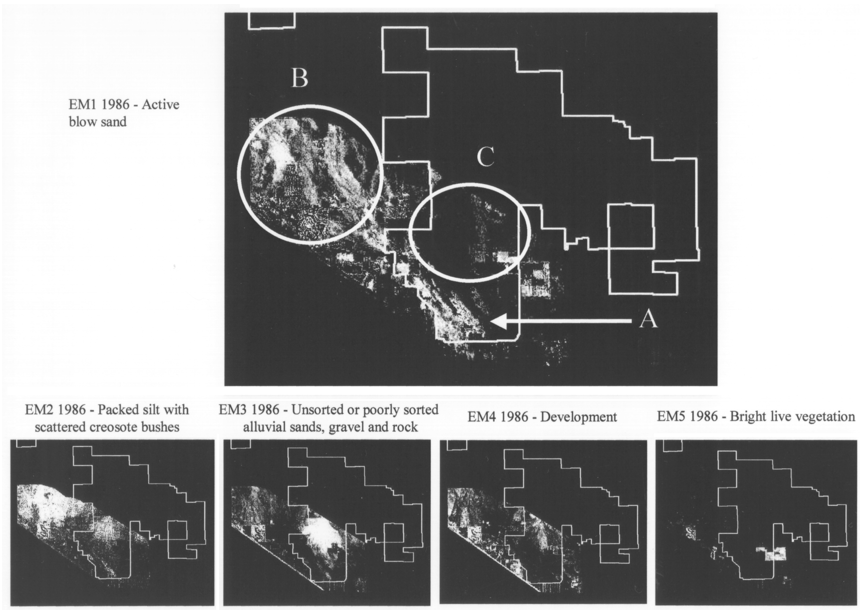
[3] MF is available in the software "Environment for Visualizing Images" (ENVI). Recently, another major image analysis software, ERDAS Imagine, has introduced an MF-like module called "subpixel classifier." Although these techniques have been around for years, it is only very recently that commercial software has provided this functionality.

[4] The general form of this equation, in matrix form, is: $\mathbf{R}^{[mx1]} = \mathbf{EM}^{[mxn]} * \mathbf{X}^{[nx1]} + e^{[mx1]}$, where $\mathbf{R}$ = original image values calibrated to surface reflectance; $\mathbf{EM}$ = endmember spectra matrix; $\mathbf{X}$ = vector of unknown abundances or fractions; m = number of image bands used; n = number of endmembers used (must be $m - 1$ or less); and e = root mean-squared error in the fit of the model (see ENVI, 1997; Boardman, Kruse, and Green, 1995).

tion. Bright white areas have high values for this endmember. A comparison between EM5 in Figures 3 and 4 reveals the expansion of golf course fairways around the preserve as allowed by the HCP. Similar interpretations can be made with the other EM results in these figures.[5]

FIGURE 3

Landsat TM June 6, 1986, Matched Filtering Results with CVFTL Thousand Palms Preserve Boundary Overlaid



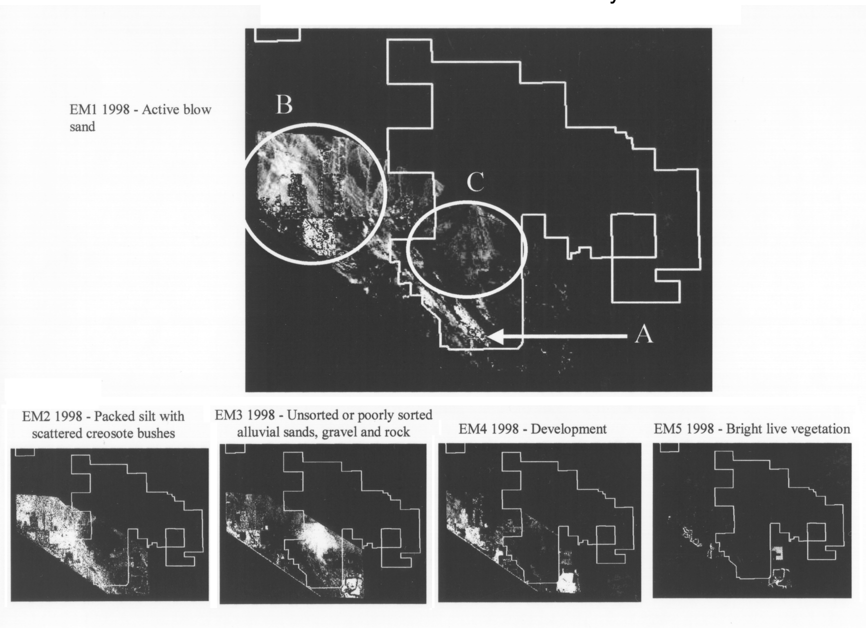
Validation of Results

We validated the MF results at two spatial scales. We first reviewed the output at a broad scale to see if endmember abundance patterns made sense based on what was previously published, what we witnessed in the field, and what we heard during field interviews. Each endmember output matched our general expectations. The only noticeable problems were some slight discrepancies in development areas, where higher than expected levels of EM1 (active blow sand) and EM3 (unsorted sand, gravel, and rocks) appeared, and in EM4, where "development" appears in the alluvial fan of Thousand Palms Canyon. In the former, these estimates could be correct,

[5] For more detailed images, see <http://www.masspolicy.org/schweik/hcp/cvftl.htm>.

FIGURE 4

Landsat TM July 9, 1998, Matched Filtering Results with CVFTL Thousand Palms Preserve Boundary Overlaid



because the soil in developed areas may be made up of EM1 and EM3 material and because active sand blows into developed areas. In the latter, it is entirely a modeling artifact, because there are no housing developments on this alluvial fan. The term "development" represents many different and spectrally distinct materials; finding one representative pixel that models all kinds of development is difficult. Although ENVI (1997) provides procedures to deal with these problems, we did not pursue them because development can be reasonably well identified by analyzing combinations of EM1, EM3, and EM4 results and because we were primarily concerned with modeling active blow sand (EM1).

Several readers of earlier versions of this article raised the important question of whether the spatial and spectral resolution of Landsat TM is adequate to capture the movement of active blow sand. We investigated this fine-scale question by collecting field data (prior to MF analysis) at 13 locations at which we visually estimated the percentage of various EM components and used Differential Global Positioning Systems to identify our location. For each site, the relative EM abundance values in the 1998 model results matched (in a relative sense) the visual percentages recorded in the field. Given this finding, and that the MF results captured very well the patterns in existing sand dunes in 1998, we are confident that Landsat TM spatial and spectral resolution at the subpixel level picks up the reflectance of sand movement across the valley. Although we did not think it necessary to pursue it for this study, techniques described by Atkinson and Curran (1997) could further validate these findings.

Results

Examination of EM1 results in Figures 3 and 4 suggest, quite dramatically, that large amounts of active blow sand with similar spectra to the homogeneous dunes lie upwind of the main preserve in the alluvial fans fed by the Indio Hills. In both time points, the sand dune areas in the preserve are strikingly high valued and bright (Pointer A in Figures 3 and 4), and significant levels of active blow sand spectra appear in the alluvial areas fed by Indio Hills runoff (circle B in Figures 3 and 4). Thousand Palms Canyon (circle C in Figures 3 and 4) reveals substantially lower levels of active blow sand spectra in both time points.[6] This analysis supports Hypothesis 2, because it suggests that the majority of the active blow sand in the main preserve comes from the alluvial fans of the Indio Hills (Figure 1), which are outside the current preserve system and subject to zoning by local governments.

The CVFTL HCP planners assumed that Riverside County would protect much of the area west and north of the main preserve through zoning (see Figure 2). But some development has already occurred in blow sand areas north and west of the existing preserve, which can be seen by comparing the MF output for EM4 (development) and EM5 (bright live vegetation) for the two time points. Whether this development will radically alter the sand transport system is an open question, but it is certainly a threat, because houses, buildings, and tree rows impede the movement of wind-blown sand into the main preserve. Currently, many of the local actors who planned and implemented this HCP are developing a new multispecies HCP that will cover a larger area around the CVFTL HCP. It remains to be seen, however, whether this new HCP will address the unprotected sand source area, though we provided these actors with our Landsat images and results to aid them in identifying and protecting the sand source area.

Lessons Learned

The CVFTL HCP case provides a striking example of how the multispectral data provided by Landsat images can assist in habitat conservation planning and evaluation. The CVFTL HCP designers did what they could in the early 1980s to infuse scientific information into the planning process, and, throughout the late 1980s and 1990s, they conducted field studies to

[6] Notice that there is significant change between 1986 and 1998, with more active blow sand in 1998. This is consistent with a major storm event that occurred between these time points.

learn more about the sand source issue (Barrows, 1996). For example, they used aerial photography and field inventories to map land cover, but multispectral satellite images were not used, even though Landsat images were available (although appropriate software to process the images may not have been). Although methodologists from the planetary sciences were just beginning to develop the foundational tools for MF and spectral mixture analysis (Adams, Smith, and Johnson, 1986), a visual inspection of color composite maps of the 1986 image reveals some of the blow sand patterns that are so prominent in the MF results. These patterns are detected by the infrared sensor data but are not easily detectable in traditional aerial photographs. Thus, an investment of perhaps $20,000–$30,000 in the mid-1980s would have provided information that could have dramatically influenced the design of the HCP and perhaps improved the long-term viability of the dunes in the main preserve. In sum, this case provides an example of how multispectral satellite imagery can provide broad-scale information to environmental managers and planners that is not readily available or easily gathered through traditional means (e.g., aerial photography or on-the-ground field studies).

Some readers may ask: What broader lessons does this case provide related to the application of remote sensing for environmental policy, planning, and evaluation more generally? In the context of the ESA, with 358 HCPs already approved and many more under development, covering tens of millions of acres, satellite-based multispectral data can provide a mechanism for capturing a baseline inventory of the land cover when each HCP starts. The large and growing repository of Landsat TM images available at the Earth Resource Observation System (EROS) data center (USGS, 2001b) provides land cover data for almost any terrestrial location during any year and season since the early 1970s. The remote-sensing techniques we presented here—and the broader HCP evaluation methodology we have developed elsewhere (Thomas and Schweik, 1999)—should be of interest to many HCP planners and evaluators and, more generally, to anyone studying environmental institutions that manage land cover, particularly those covering large areas. Further, the techniques presented here work in other ecological contexts, such as forested environments. For example, we applied the same techniques to map the changing geographic configuration of rules or the "institutional landscape"[7] of a national and a state forest in south central Indiana over the 1972–1992 time period (Schweik, 1998; Schweik and Green, 1999).

Based on these experiences, we have identified four important questions that researchers should consider before proceeding with a satellite-based remote-sensing analysis. First, can multispectral satellite images measure the land cover phenomenon of interest (Cao and Lam, 1997)? Although this

[7] The phrase "institutional landscape" comes from Schweik (1998) and is used to describe the geographic composition of rules put in place to manage a particular natural resource.

may seem like an obvious question, it is a crucial one, related to appropriate spatial, spectral, and temporal scales (Quattrochi and Goodchild, 1997; Grove et al., 2001). Spatial scale is defined by resolution (pixel size) and extent. Spectral scale has to do with whether the number of sensors or cameras sensitive to various portions of the electromagnetic (light) spectrum provided by a particular satellite platform (e.g., the United States' Landsat TM or multispectral scanner, France's SPOT) provides enough information to distinguish between land cover features of interest. In this study we checked spatial and spectral resolution empirically, by comparing model results to field inventory locations. In addition, the analyst must also make sure that the image used captures the study location (spatial extent). This can easily be accomplished by reviewing online images at EarthExplorer (USGS, 2001b) prior to ordering. Temporal scale is defined by duration and time step. The central question here is: How many image time points are required to capture the phenomenon of interest? In this study we had to ask ourselves whether two time points would be sufficient to capture sand source movement or development across the valley. Similarly, if an analyst wants to understand institutional relationships related to deforestation in Amazon rain forests, she would probably require more time points over a 30-year period than a researcher conducting a similar study of deciduous forests in the Midwest United States, because forest vegetation grows much more quickly in the Amazon.

Second, what kind of topography is being studied? The CVFTL case is in a relatively broad and flat valley, so shadowing in Landsat images was not a problem. In some areas, however, shadowing from hills or mountains will be significant, which adds another layer of analytic complexity. Technical methods are available to deal with the effects of shadow in images, including mathematical removal (Jensen, 2000), comparison of similar topographic regimes using a digital elevation model and Geographic Information System (GIS), and modeling shadow as an endmember (Adams et al., 1995).

Third, what is needed to make satellite images readily comparable? Comparative analysis of multispectral satellite images requires preprocessing prior to any cross-time analysis to remove noise in the images not attributable to land cover. Water vapor and aerosol composition in the atmosphere vary from day to day and affect the way light is reflected and captured by satellite sensors. Any change detection studies that use a time series of satellite images should undertake radiometric calibration and atmospheric correction procedures to remove this noise (Schweik and Green, 1999). In some instances, image rectification or normalization will be required when the noise removal techniques are not sufficient (Hall et al., 1991).

Fourth, what are the geographic attributes of the institutional landscape? Most environmental management regimes—as well as monitoring and enforcement mechanisms—have geographic properties. It is important for analysts to understand the geographic configurations of rules that permit, require, or prohibit human actions. One great challenge is that these institutional landscapes are usually not well mapped. Progress in GIS mapping will help future studies connect remote-sensing change analyses with institutional designs, such as the rules embedded in a planning document or regulatory regime. But in many instances, GIS maps depicting institutional boundaries (such as Figure 2) are not available. Work will be needed to develop the needed institutional GIS layers. In sum, it is important that a researcher consider how these issues will be dealt with before undertaking a remote-sensing analysis.

We also learned from this effort that satellite-based image analysis can assist environmental policy analysts, planners, and land managers in monitoring institutional compliance. Are actors complying with HCP rules? Does the enforcement regime ensure compliance? Multispectral image products, such as those in Figures 1, 3, and 4, can help answer these questions. For example, by comparing bright live vegetation in 1986 (Figure 3) with that in 1998 (Figure 4), we can see agriculture move outside the preserve boundaries, as the CVFTL HCP requires. This type of analysis could be particularly helpful in settings where the land cover type (e.g., forests) and the topography make ground-based monitoring methods difficult and time consuming. Similarly, from an enforcement perspective, if satellite image analysis provides evidence of noncompliance with rules, then the enforcement system is presumably inadequate. For broad geographic areas, a time series analysis of satellite images may identify particular regions where rule breaking is prevalent and enforcement is inadequate.

But the use of remote sensing to monitor compliance also may raise concerns over privacy and the issue of "big brother" watching overhead. We were concerned about this as we undertook our fieldwork. The issue is too broad to cover here, but let us mention one surprising discovery. A building industry representative we interviewed strongly *supported* the application of remote sensing for habitat conservation planning. Like public officials and environmentalists in the Coachella Valley, he wanted better information regarding the location and condition of habitat. Developers want to know that the location where they plan to develop will not later be subject to a zoning reversal or be the subject of some lawsuit after investments have been made. In this developer's view, if satellite image analysis could increase the certainty of safe investments, then all the better to use it. Still, in the CVFTL HCP case, we found no problems related to compliance. A future application of remote sensing might run into resistance in locations where rule breaking is prevalent. Constitutional questions such as personal privacy may hinge on whether it is a government or a private actor doing the analysis (Schweik, 1995). One possible solution would be to identify the acceptable uses of remote sensing as a monitoring tool in HCPs, to which important stakeholders would add their signatures of agreement.

Of course, satellite-based image analysis does have limitations. Earlier we described important technical challenges and scale-related issues that must be considered. And we must emphasize that satellite image analysis is not cheap. USGS prices vary, with recent Landsat images ranging from around \$4,800 for the general public to as little as \$425 per image for a recognized U.S. government or affiliated user. Remote-sensing software varies in price and functionality from free packages like Multispec (Biehl, 2001) to high-end packages like ERDAS Inc.'s Imagine (ERDAS, 2001). Image analysis can now be conducted on PC platforms with a reasonable amount of memory (e.g., 128MB or higher) and hard disk space. The greatest challenge may be finding capable remote-sensing analysts. Finally, remote sensing cannot substitute for field work; indeed, it requires ground truthing to interpret the images.

The study reported here required three weeks of image processing by a skilled analyst and two weeks in the field by two researchers. We completed this study at a cost of under \$10,000, not including the costs of hardware, software, and personnel time. These costs may seem high, but for the developers, public officials, and environmentalists who planned and implemented this HCP, even a cost of \$50,000–\$100,000 for remote-sensing analysis would have been low compared with the \$7 million collected in development fees for the main preserve, which was used to purchase land that, from this analysis, appears not to include a significant portion of the primary sand source. In short, satellite-based image processing is expensive to apply, but as this case shows, in certain circumstances, a multispectral image analysis may provide crucial information for planning or evaluation of environmental institutions that is well worth the cost.

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