Long-Term Ecosystem Monitoring and Change Detection: The Sonoran Initiative

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Abstract—*Ecoregional Systems Heritage and Encroachment Monitoring (ESHEM) examines issues of land management at an ecosystem level using remote sensing. Engineer Research and Development Center (ERDC), in partnership with Western Illinois University, has developed an ecoregional database and monitoring capability covering the Sonoran region. The monitoring time horizon will extend from the 1970s to at least 2020. The driving issues behind the design of ESHEM are military installation sustainability and encroachment. This paper describes the data in ESHEM as well as "beyond the fence-line" issues that public land managers must now face. It is realized that Federal lands management in the 21st century must occur in cooperation with neighbors. Past experience has shown us that ignoring realities "beyond the fence-line" is an invitation to land use conflicts*

Background

The Ecoregional Systems Heritage and Encroachment Monitoring (ESHEM) initiative examines issues of land use change and land management at an ecosystem level. The longstanding relationship between the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC) and military installations, and recent technological advances have made this feasible only within the last few years. The Sonoran Initiative is the second prototype out of ERDC. The first focused on the Sandhills region in the Southeastern United States. This paper will discuss the Sonoran components and examples of applications in the region (figure 1).

Grounded in requirements for managing or tracking entire ecoregions (or a sensible focus on ecosystem sub elements), ESHEM incorporates ecoregional databases and monitoring capabilities from multiple data sources. Potential applications will include regional characterization, change detection, habitat fragmentation for biological species of concern, development encroachment, eco-monitoring, or Base Realignment and Closure (BRAC) support. ESHEM integrates multi agency (USGS, NASA, EPA) data and state-of-the-art scientific capabilities and is intended to cover many land monitoring concerns over a temporal horizon from the 1960s to at least 2020. It is expected that cooperation with other land managers will become part of the process as this research matures.

The military has good reason to be involved in regional ecosystem monitoring. Mission sustainability and encroachment are important issues in the military. In the last decade questions of habitat and urbanizing development have emerged that have the potential to affect an installation's military training and readiness mission. However, neither of these issues can be adequately managed solely within the installation boundaries. They are by their character issues "beyond the fence line." For example, should a species, such as *Gopherus polyphemus* (gopher tortoise) be listed as a threatened or endangered species (TES) in the Eastern United States because of increased urbanization and/or changes in forestry management practices, then off road training at several military bases will be severely curtailed. The military, however, is trying to cooperate with other land managers. Particularly in the Sonoran region, Federal and other non-private lands dominate the face of the country. Within this region the military has one of its best opportunities to cross-manage. In general, Federal lands management agencies must cooperate with their neighbors, and political and local interest groups.

The current support by the military for addressing habitat and urban encroachment concerns emanates from the need to develop and deploy the "Objective Force," that is the new Army configuration, intended to be in place by about the year 2010. It is increasingly clear that questions of habitat and urban encroachment have the potential to limit the effectiveness of the "Objective Force" vision. Another important driver for looking at regional issues is found in DoD Directive 4715: Range Infrastructure. This Directive deals with concerns about sustainable ranges, land management processes, and range "health" or status. If the military has to set aside lands for species protection, particularly Threatened and Endangered Species (TES), that land is not fully available for support of the installation's training and readiness mission. Similarly, if land that was once adequate for heavy weapons ranges is now adjacent to civilian residential housing, it becomes more difficult for the military to carry on its training and readiness

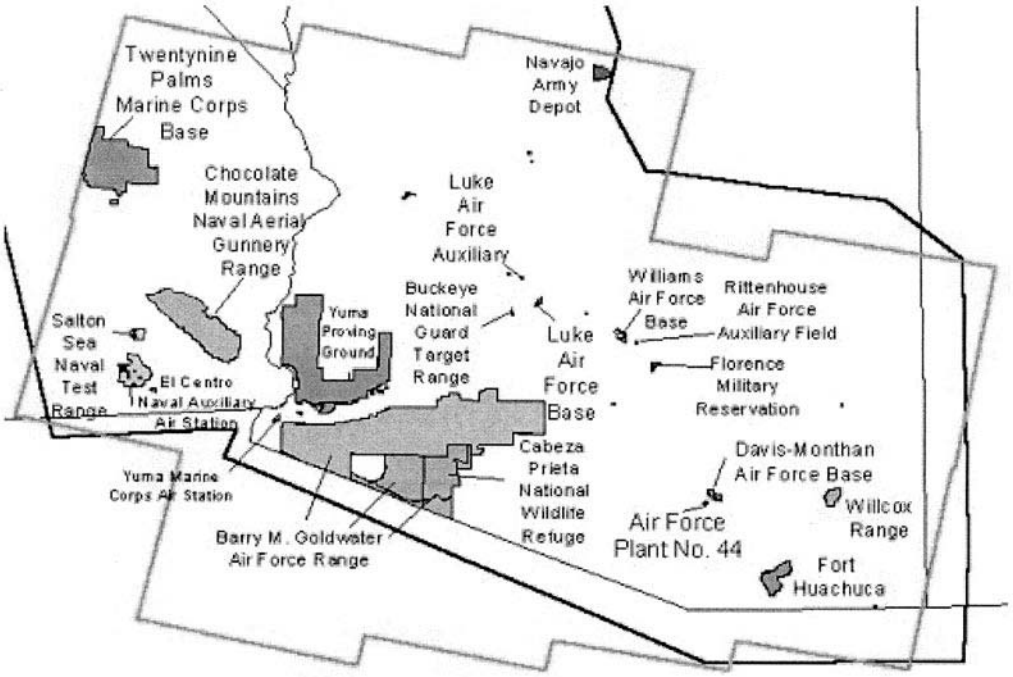

Figure 1—Military ownership within Sonoran Imagery coverage. From Federal Lands distribution in the National Atlas. The military has a high presence in the Region.

purpose without alienating those individuals that live along the installation boundary. The result of this is that the range becomes less useful over time. In most cases, installations will not gain additional lands; they are now rarely available. At the same time, the vision of the "Objective Force" is to establish weapons systems and training techniques that will require more land than is available at most current installations. Thus the double edged sword of more restrictions on current lands and the requirement for even more land means the military needs to manage its current resources even more intensely (including for conservation purposes) and no longer has the option of worrying only about it's own land. Ignoring realities beyond the "fence-line" is an invitation to land use conflicts.

ERDC is now focusing on issues of habitat and TES management. The purpose of this portion of the research is to support the ability to identify ecosystem wide critical habitats and habitat fragmentation. It also is intended to provide the basis to efficiently and cooperatively partition the TES habitat management responsibilities among agencies within a region. Within the Army conservation pillar research program, Environmental Requirement A (4.6c) is concerned with Threatened and Endangered Species Inventory, Survey, and Monitoring Areas of Concern in terms of habitats and populations. It specifically states, "... recognizing that military actions may result in or contribute to more subtle longer-term land and ecosystem changes, research and investigation is needed on TES in a larger ecosystem context."

Purpose of Sonoran ESHEM Initiative

The purpose of Sonoran ESHEM Initiative is to provide the framework for land management and monitoring at the ecosystem level for Southwest ecosystems in the United States (in a manner similar to the research already accomplished in the Southeast Sand Hills area). The focus is the dry desert and scrub domain in the United States Southwest that includes a high concentration of military installations and Federal lands. The product is in three parts:

1. A historic land cover data set at high-resolution (60 meters) covering a large portion of the Sonoran Ecosystem.
2. A cost effective monitoring ability to give near real time information about potential significant changes
3. Applications of the system to show usage and payback.

Development of the Historic Land Cover Data

The U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC/CERL), Champaign, IL, has engaged in several research projects investigating tools for encroachment risk assessment. The concept of following the trend of urbanization within a region and the prediction of how that might continue into the future has been developing for several decades (Steinitz 1967). ERDC/CERL has engaged in several research projects that investigated risk assessments from increased development near installations. The conceptual framework for the approach has been investigated (Rose et al. 2000). Some regions that include military installations have been studied for the alternatives that are available to policy managers (Steinitz et al. 1996). Some studies have focused on the restrictions resulting from resource depletion (Steinitz et al. 2002) more than from the development issues. These studies have helped formulate the establishment of a military-specific predictive tool (Deal 2001) for evaluating future alternatives.

Several advances have occurred that now make possible a more defensible illustration of developmental growth. The integration of remote sensing techniques into a single coordinated Geographic Information Systems (GIS) framework is primary. Our long term land change data base takes advantage of the opportunities remote sensing present. Two standardized sources of data form the backbone:

- The National Land Cover Data is the result of a project to generate land cover data derived from images acquired in the early 1990s by the Landsat satellite's Thematic Mapper sensor.
- The North American Landscape Characterization is a project to provide complete Landsat Multispectral scanner (MSS) coverage of the conterminous United States and Mexico in the years 1973, 1986, and 1991 for the purposes of mapping land cover and land cover change.

In a series of CERL development contracts, one of the authors, Dr. Ehlschlaeger, formerly at the Department of Geography, Hunter College (CUNY), has developed a unique procedure called "CellPicker" that uses the NLCD to derive historical land cover maps from the images in the NALC data (Lozar et al. 2003). It consists of a series of steps using a suite of image-processing tools GIS manipulations, and Java applications to generate land cover maps for the 1970s, 1980s, and 1990s. A version was used to generate map coverage for the entire Sonoran Ecoregion in the Southwestern United States. The "ground-truth" data are considered to be the 1990s NLCD, which are classified raster grids based on 30-m Landsat TM data. The 1980s and 1970s Land Use Data are grids derived from the NALC images. The CellPicker process attempts to find grid cells in the NALC images that have the same appearance over all three decades. Grid cells with the same appearance over three decades are considered "ground truth" and are given the NLCD category at the same location. The classified grids are developed via a supervised classification technique using ground-truth cells from the CellPicker process (Cox 2003).

Near Real Time Monitoring Ability

Once you have a long-term land use base in place, the next issue is, "What is the most cost effective means of monitoring the region covered?" NASA has had a long history of developing satellite instruments that provide remote sensing imagery for civilian purposes beginning in 1972. The Landsat series provided high-resolution multi-spectral images of the Earth's surface. The Multispectral Scanner (MSS) instrument provided detail at roughly 60- x 80-meter pixel size in four broad spectral bands. Beginning in 1982, the Thematic Mapper (TM) instruments were launched. The TM images continue to provide detail at about 30-meters resolution in seven spectral bands. Though highly useful, the Landsat series of instruments have some shortcomings:

- They are too detailed and slow to cover the entire Earth in a short period.
- They are surface sensing instruments without collateral atmospheric instruments to provide corrections for atmosphere and sensing angle effects.

In response to the scientific investigation of global climatic change, NASA developed a program to use remote sensing capabilities to study the Earth from space. As part of the EOS, the Terra mission (also called EOS AM-1) is part of NASA's ESE. The Terra satellite was successfully launched from Vandenberg Air Force Base, CA, on December 18, 1999. The second in the series, Aqua, is now also providing products. Several of the instruments aboard Terra provide data and products of interest to military land managers.

The Terra platform and its products represent cutting edge science as applied to remote sensing (Eos Data Web site). Specifically, products derived from the EOS are physical process based, meaning that they are:

- Based on "first principle" physical processes.
- Objectively derived.
- Calculated and repeatable.

Though these objectives may seem obvious to most scientific disciplines, Terra products come closest to obtaining this goal in the remote sensing discipline. Most remote sensing products require subjective analysis and expert knowledge to be useful in scientific analysis.

Land managers have a need for the products from Terra. Most of the instruments generate a suite of products, some for atmospheric or oceanographic studies and some for land monitoring. Of particular interest to land managers are those products of greater detail (high resolution) that dependably cover their installations. Though the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument (Aster Web site) has high resolution (15 meters), coverage is spotty. MODIS and Multi-angle Imaging Spectraradiometer (MISR) instruments sense the entire globe every 2 days; some of the spectral bands are at roughly 250 meters resolution. Though this scale is gross for most management purposes, it still provides some unique advantages over other sources of imagery. Further, products derived from the images are:

- Available at no cost.
- Available on a dependable schedule (daily, monthly, yearly; planned for at least the next 15 years).
- Built through a series of steps using data from other instruments on the Terra satellite that correct for atmospheric, directional, and seasonal effects. This unique benefit of Terra is not available with other existing satellites.
- Based on the most advanced scientific understanding (still in development).
- Based on objective "first principle" physical science of the objects being derived (e.g., vegetation characteristics are based on the physical response of chlorophyll to radiation).
- Developed for environmental monitoring purposes (for land managers, land/habitat/monitoring and change detection).
- Standardized and comparable through time.
- Spatially stable. On a Terra product, the location and size of a single pixel will be the same in March 2001 as in December 2018 to within 10 meters for a 250-meter pixel.

- Coordinated with legacy products in some cases. The Normalized Difference Vegetation Index (NDVI) product is coordinated with a 20-year-older National Oceanic and Atmospheric Administration (NOAA) product1. Together, these characteristics provide an excellent potential base for land and ecological monitoring over a nearly five-decade horizon.

The MODIS instrument2 is of particular interest to land managers. The MODIS hyperspectral sensor is the key instrument aboard both the Terra and Aqua satellites. MODIS views the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands. These data will improve the understanding of dynamics and processes occurring on the land (as well as in the oceans and the lower atmosphere). The series of MODIS instruments will play a vital role in the development of validated, interactive Earth system models able to predict change accurately enough to assist policymakers in making sound decisions concerning the protection of our environment. To do this, not only are the raw spectral band data made available, but also many calculated (level 2 and 3) products, some of which are of interest and use for regional ecosystem monitoring and management.

We translated useful and existing MODIS Land Products from the NASA Unique HDF format to a standard GIS (ESRI GRID) format. CERL now has more than 280 Gigabits of MODIS data—all the indicated MODIS LAND data that was available in CY2003 in an easy to use format. To provide some idea of the significance of this data:

The western region's coverage:

- Is over one million square miles.
- Covers 16 States and Mexico.
- Includes 112 ecosystems.
- Covers 300 military installations.

The idea behind ESHM is that the MODIS products can be easily integrated with Historic Trend Data of the Sonoran land cover data sets within the MODIS monitoring region. The dozen imagery areas that make up the Sonoran land cover data can be directly compared with the grosser MODIS Vegetation Indices and Land Use Types. Thus a set of temporally consistent trends can be derived for both the natural and man-made environment. By this method we have the ability to use NASA instruments within the Sonoran to help monitor and manage lands, particularly in this case military lands.

Applications to Show Potential Paybacks

Although the spatial detail is low in the MODIS images and products, the temporal coverage is very high. As an example for the area around the Imperial Valley of California (where several military installations exist in the region), from the Landsat images the NLCD are generated once a decade (maybe). From the NALC Triplicates, we were able to generate three decades of land cover for the region at 60 meters resolution. But that was a long and costly process. Looking at a region only once a decade really isn't monitoring and you likely shouldn't try to use such infrequent snapshots to proactively manage the landscape. However, the MODIS Land Cover product is generated once a year for the entire globe and preliminary products are produced quarterly. Most land managers will ignore the MODIS Land Cover product because it is at a kilometer resolution. Yet, if you ask these same land managers two critical questions, the usefulness of the MODIS Land Cover is immediately put into perspective. The questions are:

- How long ago was your current land use map generated?
- How much did it cost?

Most answers indicate the land cover maps are about a decade old and they cost tens of thousands of dollars. Compare that to the MODIS Land Cover every 90 days and no cost for acquisition (there may be some minor cost for analysis and formatting for use respectively. MODIS products offer the potential to manage lands and land use changes in near real time.

The current work is being done as one thrust of a TES habitat fragmentation project. Fire is a significant and continuous factor in the ecology of savannas, boreal forests, and tundra. It plays a central role in deforestation and habitat change and fragmentation. Important habitat impacts of fires include changes of physical state of vegetation, release of soot and other particulate matter during fires, and changes in plant community development and soil nutrient, temperature, and moisture. One of the MODIS Products is the Fire Occurrence Product that is generated daily (or more often) because a MODIS instrument senses each location on earth four times a day. (The Terra platform senses at 10:30 a.m. and 10:30 p.m., while the Aqua platform senses at 2:30 p.m. and 2:30 a.m. Near real time fire products can be acquired from the MODIS Rapid Response Team at NASA GSFC or through a product that is summarized as an 8 day composite. For example, in the MOD14a2 Summarized 8 Day Composite Fire Product for the period ending May 8, 2001, we found a fire that covered more than 13 square kilometers at the west edge of the Goldwater Range and less than 5 kilometers south of Yuma MCAS. Such data can temporally monitor potential large and small changes in the habitat of Endangered Species as they relate to management of lands on or near military installations. This concept has lead to ERDS's most recent thrust.

ERDC and Western Illinois University are currently working on relating MODIS products to Threatened and Endangered Species (TES) monitoring. The objective of this work is to investigate and develop examples of Space-Time modeling of Threatened and Endangered Species Habitat from the MODIS data. MODIS data provide scientifically measured products available on a regular time scale. Traditional habitat modeling, for example, landscape pattern metrics, has assumed static land cover maps defined at a nominal scale. However, species live a dynamic life requiring different resources at different portions of their life cycle. Species' life cycles often correspond to the seasons of the year. MODIS' temporally specific and ratio scale data combined with detailed land cover data using the latest spatial statistic techniques that can organize three dimensional data (latitude, longitude, and time) can potentially provide a superior model for species, especially TES habitat modeling.

To do this, specific TES lifecycles will be associated with MODIS data. The project will identify space-time data products (geographic and temporal dimensions) necessary to model the seven TES of greatest concern to military installation land managers. Then a sample of space-time products will be conflated from multiple sources for a target date in the year 2002. For example, the MODIS Land Cover data can be combined with vegetation information to create biomass values at specific space-time locations. This space-time data would be useful for space-time habitat fragmentation analysis. For example, NDVI values from MODIS data at specific vegetation type locations can provide a good measure of biomass for a particular TES during its mating season.

Results and Conclusions

The Ecoregional Systems Heritage and Encroachment Monitoring (ESHEM) initiative has begun to put together the ability to examine issue of land use change and land management at an ecosystem level. Recent technological advances have made this feasible only within the last few years. The Sonoran Initiative is the second prototype out of ERDC. This paper discusses the development of historic land cover data, remote sensing components to the ESHEM initiative, cost effectiveness, and applications.

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