B Appendix B: Selected Remote Sensing Applications

Data produced by remote sensing have intrinsic value because they carry information that can be displayed pictorial y for the worlds of sc ience, resource management and commerce. When properly interpreted, “pictures” produced by remote sensing, whether from satellites, aerial photography, ground-based radar, or other sources, can show the location of a hidden bunker, a caravan route used a thousand years ago, ancient stream beds, or the relative health of agriculturally significant crops. Remote sensing can also be combined with other techniques to produce additional kinds of information for decisionmakers. Geographic information systems (GIS) and the global positioning system (GPS) are two technologies often used to add value to remotely sensed data.

Remotely sensed data are increasingly accessible to users. Potential data users can also purchase a wide array of geographic information systems of varying levels of sophistication that run on inexpensive desktop computer platforms to process and interpret those data. Similar advances in GPS technologies have assisted in making remotely sensed data much easier to use and more affordable.

As noted in chapter 2, GIS are computer-based analytical programs that can run on the full range of computer platforms, from main frames to laptops. Their output are maps that portray any data that can be spatially arrayed. The power of a GIS lies in its ability to combine different kinds of spatial information and display them on a single map in combined or overlapping layers.

Imagine, for example, that you are a Red Cross administrator concerned with planning relief efforts following a major hurricane. You start with a map of the southeastern United States. Remotely sensed data provides you with the path of the hurricane and updates this information regularly. But you need other data, which may not depend on remote sensing, and you especially need to know the relationship of this information to the storm path and to the level of destruction along its path. What areas are likely to suffer the greatest damage? Where are your existing service centers? What are their human and materiel resource levels and how do these relate to the anticipated destruction of the storm? What is the strength of other services in the area? These are the kinds of overlapping information that can be portrayed with a GIS. Remotely sensed data are just one source of information for such a system, and they are easily combined with other sources, such as the manning levels of Red Cross relief centers.

GPS provides latitude, longitude, and elevation information-for example, for ships lost at sea or hikers lost in a forest (box 2-6). Depending on the system, such information may be provided to the subject (the lost ship or hiker) or transmitted to someone searching for them. Thus, GPS is of value in its own right. GPS also helps provide verification on the ground, or "ground truth" for analyses with geographic information systems. GPS anchors remotely sensed data with map coordinates.

Examples of the value of remotely sensed data, GIS, and GPS for a variety of applications follow. These examples provide a sense of the diversity of applications of these new technologies. People using these methods provided the material that is the basis of what follows; the names of the organizations that employ them appear in the summaries. [1]

MONITORING AGRICULTURE AND VEGETATION

Environmental satellites provide day-to-day monitoring of agricultural crops, changing weather patterns that affect agriculture, and the condition of noncrop vegetation, such as forests and rangelands. Information from satellite monitoring is valuable to national economies, private organizations, and individuals whose success or 1ivelihoods are determined by agricultural and other types of renewable resources.

Within-season and post-season agricultural information is especially important to subsistence economies, such as those in Africa, Asia, and Latin America. Information derived from satellites can be used to anticipate regional food grain shortages or surpluses and to help with real-time planning for labor and marketing. Since environmental satellite data are directly available to all nations, information derived from such data can help promote more efficient agricultural commodity markets.

Agricultural and vegetation monitoring can be carried out with low-resolution environmental satellite data obtained from Russian, Japanese, European, and especially U.S. satellites.[4] While somewhat lacking in spatial detail and geometric accuracy, they provide daily coverage, immediate availability, and comprehensiveness. Environmental satellite images cover north-south swaths 3,000 kilometers wide or whole continents at spatial resolutions of 1 to 8 kilometers. Dozens of new images are obtained for every location each day and night. These data are broadcast directly to

[1] Other authors might have been used. These descriptions should not be construed as an endorsement by the Office of Technology Assessment of the technology used or the expertise found in any particular firm.

[2] Tom Wagner, Environmental Research Institute of Michigan, Ann Arbor, Ml.

[3] Such satellites are often termed weather satellites because they were originally designed to gather and transmit weather data. Increasingly, the data collected by these satellites find use in a much broader array of environmental tasks.

[4] See U.S. Congress, Office of Technology Assessment, OTA-I SC-588, *The Future of Remote Sensing from Space: Civilian Satellite Systems* (Washington, DC: U.S. Government Printing Office, July 1993).

low-cost ground receiving stations established in most countries around the world. By international convention, in most cases no licenses, fees, or special permissions are required to receive and use these data.[5]

For agricultural purposes, data from the Advanced Very High Resolution Radiometer (AVHRR) aboard three U.S. polar orbiting NOAA (TIROS) satellites are of particular interest. The AVHRR data are routinely processed by private and public agencies (including the National Weather Service, the U.S. Department of Agriculture, and the U.S. Geological Survey) to produce multi-date, composite vegetation index (VI) images. These composite VI images are produced using multiple NOAA satellite passes obtained over periods of several days to several weeks and show large areas with little or no cloud cover.

Vegetation index images provide direct evidence of the greenness of terrain, a good indicator of vegetation health and density during the growing season. To knowledgeable interpreters, such quantitative measurements of greenness provide objective, up-to-date evidence of crop or rangeland conditions. From such data, image analysts can deduce planting and harvesting times, areas affected by drought, disease, or flood, and the stages of crop development.

The Foreign Agricultural Service (FAS) of the U.S. Department of Agriculture routinely obtains AVHRR VI data from the National Weather Service. These data, in turn, are reformatted and processed to provide pictures of vegetation conditions in major agricultural regions outside the United States. To the FAS analysts these pictures, when combined with their knowledge of local crop calendars, growing conditions, and the weather, provide direct evidence of current crop status and early warning of possible problems that even local agricultural officials may not suspect.

For the past six years, with the help of such images, within-season small grain estimates in South Asia have been within 5 percent of final production figures. Analysts have accomplished this despite the general lack of crop progress reports from these countries during the growing season. Such information contributes to world crop forecasts and influences USDA policies and strategies.

In fiscal year 1994, FAS will spend $3 million to upgrade its satellite image monitoring system and develop strategies to integrate it with GIS and statistical data anal ysis methods. FAS sees emerging GIS technologies as key to integrating soil and rainfall data and historical production information.

The crop damage assessment conducted after the flood in Bangladesh in 1988 provides an example of the use of environmental satellite data for agriculture. In late August and early September of that year, the Ganges and Bhramaputra rivers flooded to record levels and inundated large areas of the country, including much of the emerging fall rice crop. Figure B-1 shows an AVHRR Vegetation Index image obtained with a United States Agency for International Development (USAID) supplied ground station in Bangladesh. This image was made about a month after the flood waters had receded. Damaged rice crop areas are light gray. They are primarily adjacent to the two major rivers, which appear dark. The areas affected and the level of damage can be estimated from images such as this one. Combining such information with local data enabled forecasts of the production for each administrative district and estimates of shortfalls. The total production estimate came within 5 percent of the official total estimate that was published six months after the harvest. (While some areas of Bangladesh were heavily damaged by the flooding, other areas had record harvests, and the total shortfall was not as great as originally feared.)

Historically, donor countries provide emergency food grain assistance based on rough estimates of anticipated needs. With communications and transportation disrupted and available govem-

[5] See, however, ch. 5,

FIGURE B-1: AVHRR Vegetation Index Image of Bangladesh

This image was made about a month after the 1988 flood Damaged rice crop areas are light gray

SOURCE Foreign Agricultural Service, 1988

ment resources directed at emergency relief operations, such estimates are often guesses based on hearsay and anecdotal evidence. If too little emergency food is received, people starve, while if too much is received, the local markets become saturated and prices for local farmers fall. Satellite data provide objective information that complements traditional means of forecasting crop production.

MANAGING CROPS[6]

Since 1984, Cropix, Inc. has used satellite imagery to estimate potato production in the Columbia River Basin of Oregon and Washington.[7] Unfortunately, two to four weeks typically pass from the time of satellite overpass to the time image data were delivered. The delay means stress patterns were detected too late in crops to aid the farmer, which frustrated both farmers and researchers. This situation will soon improve. With funds from NASA's Earth Observation Commercializtition Applications Program (EOCAP), Cropix is investigating the utility and economic feasibility of providing a crop monitoring and management service based on rapid delivery of satellite data.

Potatoes are the region's main cash crop, and consequently are the primary crop being monitored. Image data from SPOT, Landsat, and Marine Observation Satellite (MOS). a Japanese Space Agency satellite, are delivered within 24 to 48 hours after satellite overpass, enabling detection of field problems in time for farm managers to take corrective action.

The project is in its second of three years. With four customers who operate large farms, a prototype operation is underway for a region of rough] y 250,000 acres of irrigated farmland, an area that is covered by a single SPOT scene. Plans for the 1994 crop season include expansion of the service to monitor more than 300 fields, which will create a customer base large enough to demonstrate economic viability on a commercial basis. Once proven with the prototype, expansion of the service area to the entire Columbia Basin, southern Idaho, and California would be pursued.

Project success depends on the ability to receive satellite data within 24 to 48 hours. Through

[6] George R. Waddington, Cropix, Inc., Hermiston, OR.

[7] Lamb, F. G., "Agricultural Uses of Low-altitude Aerial Photography", *Remote Sensing for Resource Management*, C.J. Johannsen and J.L. Sanders, Editors. Soil Conservation Society of America, Ankeny, IA (1982). Waddington, G. R., Jr., C.F. Chen, and L.J. Mann, "Estimating Potato Acreage and Yield in the Columbia River Basin of Oregon and Washington Using Landsat: A Commercial Application," *Advances in Image Analysis*, Y. Mahdavieh and R.C. Gonzalez, Editors. SPIE, Bellingham, WA (1992). Waddington, G. R., Jr., and F.G. Lamb, "'Using Remote Sensing Images in Commercial Agriculture", *Advanced Imaging*, vol. 5, pp. 46-49 (Sept. 1990).

the combined efforts of Cropix, Oregon State University, SPOT Image Corp., EOSAT, and the Canada Centre for Remote Sensing, most image data turnaround times are just under 48 hours, using commercial courier services. However, limited courier services out of Prince Albert, Saskatchewan, the ground receiving station location, result in Friday and weekend satellite acquisitions being delivered in three to four days. To alleviate this problem and secure 24-hour turnaround, Cropix is investigating alternate data delivery methods, including the Internet, and ANIK, a Canadian-based satellite communications link. A full SPOT scene has been successfully transferred from SPOT Image Corp. 's Reston, Virginia, office to Oregon State University via Internet in 133 minutes.

Sub-images covering each customer's farm are extracted from the full scene image data. Commercial products include an "Early Warning Report," issued by 5:00 pm on the second day after each satellite image acquisition, and a "Temporal Analysis Report," issued monthly during the crop season. The Earl y Warning Report provides satellite views of each customer's field with subtle variations in the crop canopy enhanced and comments on possible causes for the apparent anomaly. This report is being upgraded in 1994 to include a statistical comparison of field performance versus the average for fields in the survey area, displayed below the imagery. The Temporal Analysis Report provides a visual record of a customer's field as it appeared on each image acquisition date during the crop season, and a detailed graphic showing field performance plotted against average performance for all surveyed fields. An example of this report is shown in figure B-2.

During the 1993 crop season, the four test customers received both Early Warning and Temporal Analysis reports on a regular basis. The experience of Glenn Chowning, president of Terra Poma Farms, provides an example of the power of this technology. Chowning pointed out an interesting occurrence within his field No. P2. As shown in the figure a dark patch appeared in the July 12 SPOT image at the right edge of the circle, and spread to engulf the entire right half of the circle by July 28. The dark patch was the result of late blight, a disease common to potatoes (the same disease that caused the Irish potato famine last century). The July 7 SPOT image shows a possible inoculation point, a small dark spot below and slightly to the right of the field center. Glenn said that harvest on the left half of the circle produced above average yields, whereas when the right half of the field was harvested, the potatoes showed signs of rot and yields were lower. Had the field been harvested a few days later, the rot would have progressed to the point that the balance of the potatoes would have been lost, at a cost of $200,000. Glenn did not base his decision on when to harvest on the imagery. However, in retrospect, he realized he could have prevented any loss if he had verified that late blight was infesting the field at the earliest signs of the dark patch in the imagery and sprayed at that time.

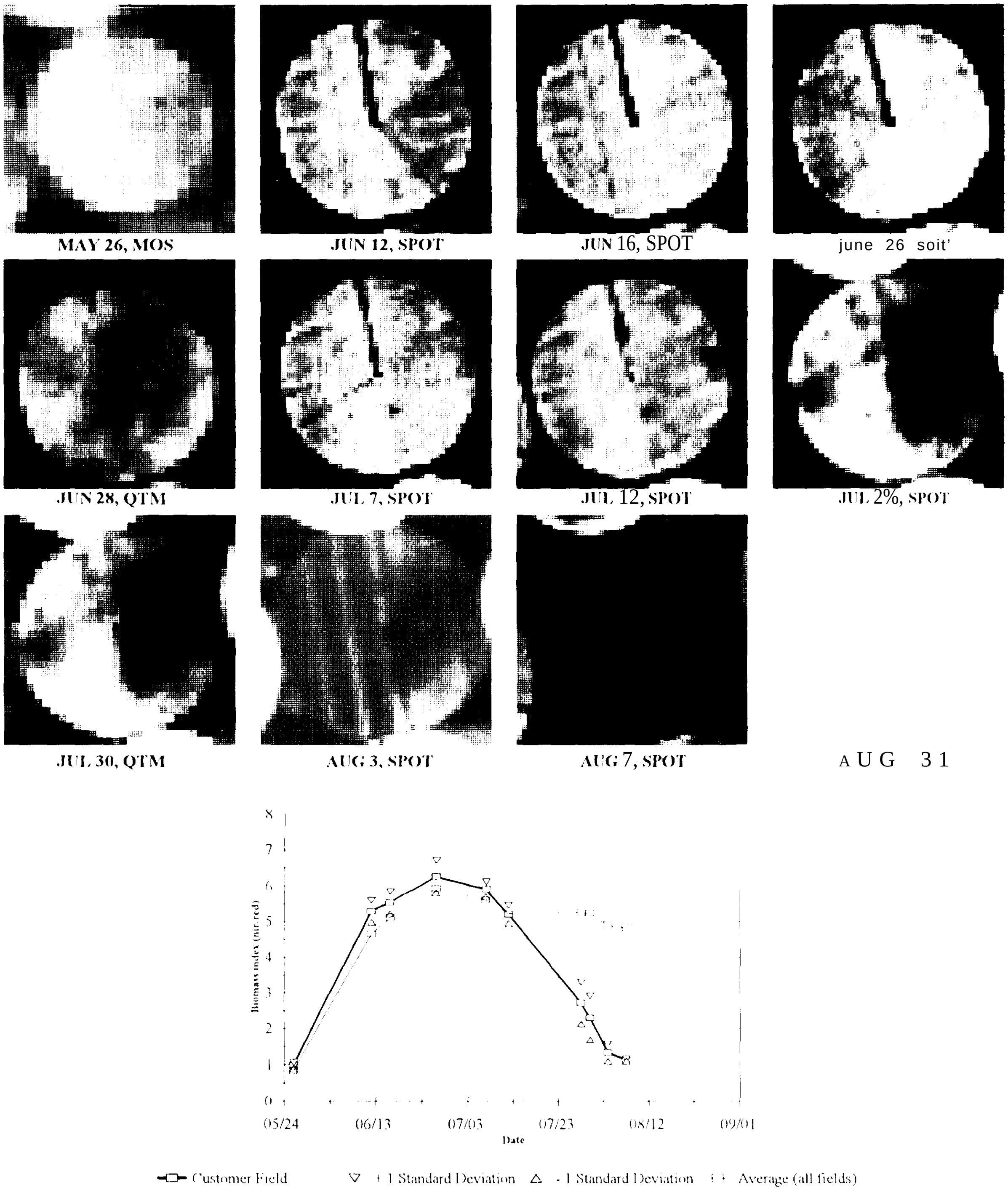
The cost of the service for the entire crop growing season is $7 per acre. The farming cost for potatoes is approximately $1,800 per acre with an additional cost of $400 per acre to store and deliver the crop to market. Average returns for a good crop can be anywhere from $3,000 to $4,000 per acre depending on market conditions, resulting in profit margins of $800 to $1,800 per acre. With such a large investment at stake, the service is an inexpensive insurance policy. Timely information regarding potential crop problems can help the customer take corrective action and adjust farming plans as needed.

MANAGING PIPELINE RIGHTS-OF-WAY[8]

Pipeline companies are faced with ever-increasing regulatory and operating pressures. New regulations are proposed or enacted each year that require mapping, facility inventories, pipe inspec-

[8] Mark A. Jadkowski, James W. Sewall Co., Old Town, ME

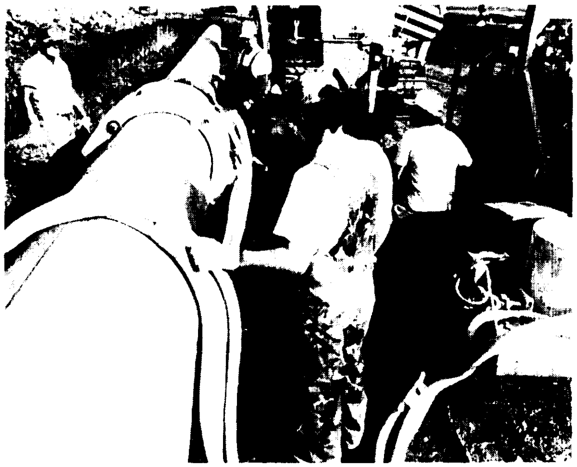
FIGURE B-2: Temporal Analysis Report on Terra Poma Farms, September 20, 1993



SPOT: SPOT Image Corporation Data © CNES 199320m pixel (O 1 acre) TM: Landsat-5 Thematic Mapper Data suppled by EOSAT, 30m pixel (O 2acre) MOS:Japanese MOS Datavia Canadian Center for Remote Sensing 50m pixel (O 6acre) QTM:Quick Delivery Raw TM Data corrected by CROPIX, 30m pixel (O 2 acre)

SOURCE CropIx, Inc 1993

FIGURE B-3: Pipeline Rehabilitation



SOURCE James W Sewall Co , 1993

(ions, rehabilitation, and environmental reporting (figure B-3). These pressures are compounded by the need to stay competitive in today's rapidly changing marketplace.

Automation has long been an answer to the problem of having to do more work with less people, and Automated Mapping/Facilities Management Geographic Information Systems (AM/FM/GIS) solutions are being proposed and implemented at a number of pipeline companies. The U.S. pipeline industry, which operates over 453,000 miles of gas, crude, and refined products lines, is expected to be a significant growth segment of the AM/FM/GIS market.

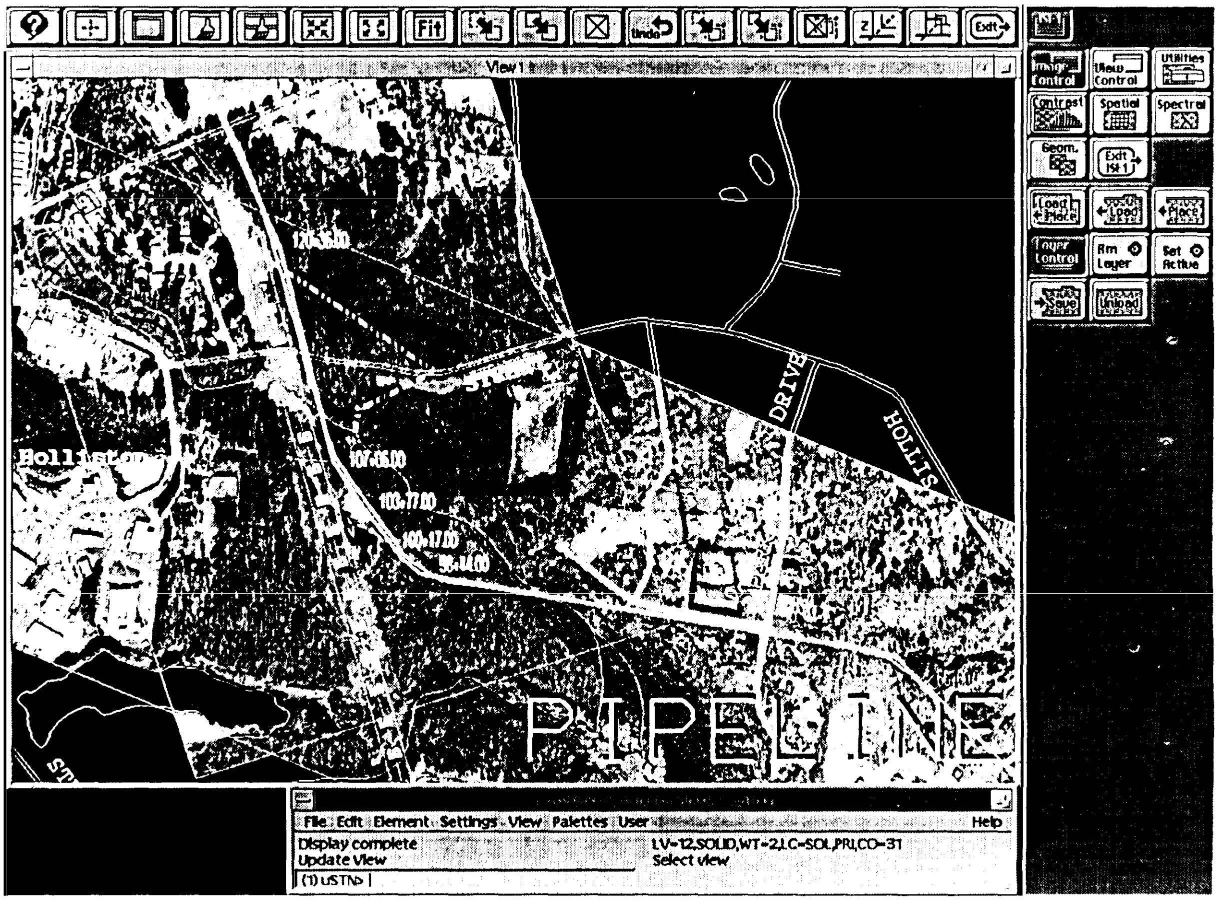
Pipeline companies index and track the location of their facilities using a system of survey stations that can at times baffle even the most seasoned professional. A small pipeline system can cross three or four state boundaries and map coordinate systems. A medium-sized company can have as many as 50 district offices that may require online AM/FM/GIS accessibility. A large company might operate over 30,000 miles of pipeline and manage 15,000 miles of rights-of-way and associated parcel easement records. These and other technical issues suggest the need for new and innovative mapping techniques, database design and management strategies, and approaches to providing system accessibility.

Until development of digital aerial photographic imagery, the ability to acquire and incorporate up-to-date land information cost-effectively into an AM/FM/GIS was out of reach for most pipeline companies. Alignment sheets, the most common pipeline facility maps, are almost always out of date. New photogrammetric mapping is cost-prohibitive in most cases. County maps and U.S. Geological Survey 7.5 minute quadrangle maps are not detailed enough. Resolution of satellite imagery is at present too coarse. The two commercial Earth observation satellite systems operating today, SPOT and EOSAT, offer 33-foot and 100-foot spatial resolutions, respectively, whereas optimal image resolutions for most pipeline applications range between one and three feet. Manual handling of hundreds or thousands of hardcopy aerial photographs is unmanageable.

Digital aerial photography provides an economic and versatile alternative. Photographic images can be scanned at resolutions of 1 to 3 feet, providing important land detail. The images provide the location of roads, hydrography, wetlands, cleared rights-of-way, structures, and other cultural features. Image processing is a mature technology that has been made affordable through competition in the desktop publishing industry. Disk storage capacity and laser printers capable of producing sharp images are relatively inexpensive. Today, major vendors of AM/FM/GIS systems provide the capability to integrate computerized aerial images with a facilities database (figure B-4). With these developments, it is possible to perform rapid online query and display of aerial photography for day-to-day operations of pipeline emergency management.

Many monitoring applications of digital aerial photography exist for pipeline rights-of-way, including general map updating, marketing, pipeline planning, and wetland delineation. Pipeline companies that handle crude and refined products are concerned with environmental damage from pipe rupture. They can use the imagery for locat-

FIGURE B-4: Pipeline Route Overlaid on Digitized Aerial Photograph



SOURCE James W Sewall Co 1993

ing sensitive areas and for planning access and placement of cleanup equipment in case of emergencies.

Gas pipeline companies are required to perform annual dwelling surveys, mandated by the U.S. Department of Transportation, which has jurisdiction over pipeline safety issues. In the surveys, dwelling densities within 660 feet of each pipeline are assessed. Four density classifications are used to set the operating stress level for the pipeline. The higher the dwelling or population density, the lower the allowable stress level in the pipeline. It is common for a company to decrease the movement of gas or replace pipeline at a cost of mil1ions of dollars because of the construction of a few dwellings. Digital aerial photography in an AM/FM/GIS can greatly add to the efficiency with which pipel ines are monitored and the accurac y of these regular safety-related surveys. However, the cost of flying, processing, and then scanning conventional aerial photography can still be cost-prohibitive for a large pipeline company. The technical solution to this economic problem is to cut costs drastically through the use of low-cost and easily operated digital camera systems for monitoring pipeline rights-of-way.

In 1992, Algonquin Gas Transmission Co. and James W. Sewall Co. initiated a project with the National Aeronautics and Space Administration to develop an aerial photography-based system that can be used commercially for pipeline management. A third partner in this development effort is NASA's John C. Stennis Space Center. Stennis Space Center's role in the project is to provide access to NASA technological resources, Sewall is the prime contractor, and Algonquin and its parent, Panhandle Eastern Corp., are responsible for defining all operational parameters. The project was funded by NASA's EOCAP, which commercializes remote sensing technology originally developed to support scientific and space exploration missions.

The technical objectives of this EOCAP project are threefold. First, the Project Team has developed a computerized system for storing and retrieving digital aerial photography of pipeline rights-of-way. The computerized system provides an accurate inventory of rights-of-way locations and pipeline surroundings for engineering, maintenance, and regulatory purposes. The system also provides very rapid access to much-needed information in case of emergencies. The second technical objective is to adapt a digital camera system for more routine aerial pipel ine rights-of-way monitoring. The Digital Aerial Rights-of-Way Monitoring System (DARMS) was designed and assembled for this purpose from commercially available components and specialized software. The third objective of the EOCAP project is to unite the digital aerial images described above with a working pipeline AM/FM/GIS system. This involves development of a series of specialized computer programs that facilitate pipeline-specific applications.

The project, now in its final stage, has succeeded in bringing to the pipeline industry a set of new and innovative remote-sensing tools for pipeline monitoring and management.

THREE ENVIRONMENTAL APPLICATIONS

The use of remote sensing for environmental applications has grown continuously since digital satellite imagery became available. Its growth is driven by the increasing number of environmental concerns and new knowledge and technology developed by the scientific community. The field includes such diverse topics as identification and mapping of endangered vegetation communities, monitoring and modeling animal habitats, and monitoring the effects of natural disasters. Purposes of the work include pure scientific exploration, environmental preservation, resource management, and regulatory activities. The following describes three specific application projects, including their purposes, methods, and results.

Protecting Endangered Animals

Wildlife biologists use satellite data to study animal populations that are at risk. In the Upper Peninsula of Michigan, habitat destruction and over-(rapping exterminated the fisher and marten populations. The U.S. Forest Service and the Department of Natural Resources of Michigan reintroduced both species, but little was known about the status of the new populations. Thomas maetal. used satellite imagery in conjunction with radio location data to evaluate the preferred winter habitat characteristics of fishers and martens. [10]

Animals trapped in the fall were fitted with radio callers and tracked from an airplane through the winter. Researchers recorded the geographic location of the animals on board the plane. They then referenced Landsat Thematic Mapper satellite data of the study area to precise geographic

[9] Janice L. Thomson, The Wilderness Society - Washington State Region, Seattle, WA.

[10] L. E. Thomasma, R. O. Peterson, and T. D. Drummer, 1991. "An Ecological Study of Fishers and Martens in the Upper Peninsula of Michigan." *Annual Report - Year 2 (1991-1992)* to the Michigan Department of Natural Resources (Houghton, MI., Michigan Technological University), 24 pp.

coordinates. The satellite data were classified using digital image processing software to generate a forest cover map delineating the different forest types available to the fisher and marten. The animal location data were overlaid on the forest cover type map using computer algorithms. The resulting data showed that fisher and marten both prefer conifer forest for their winter habitat. However, monoculture pine plantations, a less desirable habitat to the animals, have begun to replace the natural coniferous groves in the region. The same authors are now using Landsat satellite imagery to assess varying conifer patch size and shape on habitat preference.[11] Studies such as these provide important information that can guide forest management policy to preserve animal habitats. Similar studies are ongoing with other species around the country.

Locating Ancient Forests

Endangered ecosystems are being mapped using remotely sensed data. The ancient forest ecosystem of the Pacific Northwest is a dwindling resource that both the timber industry and a host of plant and animal species depend on. Morrison et al. demonstrated how Landsat Mutispectral Scanner data and aerial photographs can be used to locate groves of ancient forest across 12 national forests of the western Cascade Mountains of Washington, Oregon, and California.[12] Basic satellitc image classification techniques generated maps of both ancient forest and old-growth forest. Twelve national forest maps highlighted the stands of ancient forest and old growth. The results were input into a GIS to calculate the acreage of ancient forest in each national forest. The data set became a valuable source of information for subsequent studies, including a critique of President Clinton's Forest Plan for the Pacific North-West.[13] Because these data were in GIS format. they were ideally suited for analyzing the forest plan, which also was generated and distributed as GIS data. The ancient forest data allowed rapid analysis of 3.8 million acres of forest to determine how much of the ancient forest ecosystem would be preserved under the different options in the forest plan. The combination of vegetation maps generated from remotely sensed data, plus the geographic data processing capabilities of GIS, make possible rapid review of government land management policy and give nongovernrnent organizat ions a means to check and r-nonitor the government's use of public resources.

Enforcing Fishing Limits

Monitoring and enforcing fisheries harvest limits are important to maintaining marine fish populations. Yet enforcement agencies are taxed beyond their resources trying to monitor violators of fishing harvest limits and harvest in off-limit waters. Between 1983 and 1989, the number of over-exploited fish stocks more than doubled.

Freeberg et al.[14] developed a method to monitor ship tracks in the North Pacific and Bering Sea using Advanced Very High Resolution Radiometry (AVHRR) satellite data. The researchers found that moisture condenses around particulate material from stack emissions of ships. The resulting cloud lines can be detected in processed satellite data. Multiple data sets over a short time period allow the determination of ship direction and speed. Currently, Freeberg and his coworkers (1992) are designing a system complete with satellite ground receiving station, computing hardware, and soft-

[11] L. E. Thomasma, personal communication, 1993.

[12] P. H. Morrison, D. Kloepfer, D. A. Leversee, C. M. Socha, and D. L. Ferber, 1991. "Ancient Forests in the Pacific Northwest: Analysis and Maps of Twelve National Forests," The Wilderness Society, Washington DC, 14pp.

[13] The Wilderness Society, 1993. "A Critique of the Clinton Forest Plan," The Wilderness Society, Washington, DC, 47pp.

[14] M. H. Freeberg, E. A. Brown, and R. Wrigley, "Vessel Localization Using AVHRR and SAR Technology," Marine Technology Society Annual Meeting, Washington DC. Oct. 19, 1992, 18pp.

ware for data processing that w ill support the rapid turnaround time necessary for fisheries enforcement agencies.

MAPPING BIODIVERSITY IN PAPUA NEW GUINEA[15]

The island of New Guinea is considered one of only three major tropical wilderness areas left on Earth (the other two are the Amazon Basin and a large rain forest in Africa's Congo Basin). Papua New Guinea (PNG), the eastern half of the island, has large expanses of relatively undisturbed coral reefs, mangroves, and tropical forests. Within the forests, PNG highly varied geography and the island's isolation have led to the evolution of many species found nowhere else in the world. Nearly a quarter of the nation's mammalian species are endemic, as are 77 species of birds, and half of the amphibians. Species unique to PNG include such unusual animals as the world's largest pigeon, butterfly, and grasshopper and 34 species of birds of paradise.

Over 80 percent of the country is covered by forest. Today these forests are seriously threatened by high population growth, which adds some 100,000 new inhabitants every year, and by rapid economic development. Foreign companies, attracted to PNG's large reserves of timber, oil, and minerals, are a particular threat to the forests and their many species of plants and animals. Landowners, who once relied exclusively on subsistence farming, are increasingly tempted to sell rights to their land for cash from these companies.

However, conservationists are also taking an interest in PNG, and the government has decided to intensify efforts to protect the nation's biodiversity, an important future economic resource. In choosing where to focus its resources, the government of PNG will consider a variety of factors including social, cultural and economic conditions throughout the country. Because both time and funds for conservation are limited, deciding precisely and quickly where to work is the first logical step in any sensible conservation plan.

In April 1992, at the invitation of the PNG government, Conservation International organized and led a workshop in Madang, PNG, in which biologists and government representatives reached consensus on areas that are most important for protecting PNG's vast biological wealth.[16] The approach used was first applied at a workshop held in Manaus, Brazil, in January 1990, where experts on Amazonian ecosystems came to a consensus on biological priorities for conservation within the vast Amazon Basin.[17] So far, results of that workshop have led to the establishment of six new forest reserves in the Brazilian state of Arnazonas, as well as new protected areas in Colombia. The methodology used in Manaus was refined during the workshop in PNG.

The methodology relies on biological information. Field biologists who are the world's leading experts on a region's species and ecosystems are assembled. Each of these scientists may be an expert on only a few species or geographic areas, but together their knowledge and experience provide the best possible understanding of the region as a whole, GIS technology plays a key role in the process, for it provides the means to synthesize the scientists' knowledge.

Before the workshop, Conservation International prepared a set of base maps for the entire country using a GIS. These base maps brought together on one piece of paper for the first time a variety of basic geographic data needed to set conservation priorities: political boundaries, coast-

[15] Laura Tangley and Andy Mitchel, Conservation International, Washington, DC.

[16] Alcorn Janis, ed. 1993 "Papua New Guinea Conservation Needs Assessment." The Biodiversity Support Program, Washington, DC. Conservation International, BSP and PNG Dec. 1993. "Biodiversity Priorities for Papua New Guinea."' Map, Conservation International, Washington, DC.

[17] Conservation International, IBAMA and INPA. 1991. "Workshop '90, Biological Priorities for Conservation in Amazonia." Map, Conservation International, Washington, DC.

lines, rivers, lakes, roads, topography, vegetation type, population centers, protected areas, and Timber Rights Purchases.[18] The maps would have been even more useful if they had included such important data as land use and forest cover, but this information was not available for PNG at the country-wide level. In most cases such information must be derived from remotely sensed data, often from satellite imagery. The expense of acquiring and processing these data was beyond the means of the PNG workshop. Nonetheless, the base maps enabled by GIS technology were of great value.

To help them prepare for the workshop, the base maps were sent to key scientists in each of several disciplines: mammalogy, botany, ornithology, and others. These "'team leaders" used the maps to plot biological information they had collected from other scientists in their field. When the scientists arrived in PNG, they had a set of maps that not only captured the experience of dozens of experts, but also were compatible with one another. They could then immediately begin working to achieve group consensus on the areas most important for conserving PNG's biodiversity.

At the workshop in Madang, the researchers began a long, give-and-take process that led to a consensus within the group several days later. Working on large transparent Mylar sheets that could be overlaid on the base maps, group members focused on priority areas one by one, filling out a detailed data sheet for each of them and arguing over what the area's size, shape, and exact borders should be. During this stage the maps were critical to making tiny progress. By focusing on maps, the biologists bypassed disagreements over definitions and theory and focused on practical questions about the location of biologically important areas.

The borders the biologists drew on the Mylar overlays were digitized into the GIS and output as new maps, providing instant feedback to the scientists. This GIS analysis was critical to identifying the final set of biologically significant areas. During the deliberations, for example, the GIS was used to combine the initial borders the biologists had drawn with data sets of elevation and vegetation type. The result showed that only 8 percent of the country remaining lowland rain forest had been included within the borders of the biologically important areas; most of the low-lying lands that had been included were either mangrove forest or savanna. The botanists had grossly under-represented lowland rain forest, by far the most endangered ecosystem in PNG. They went back to the Mylar overlays and further discussions.

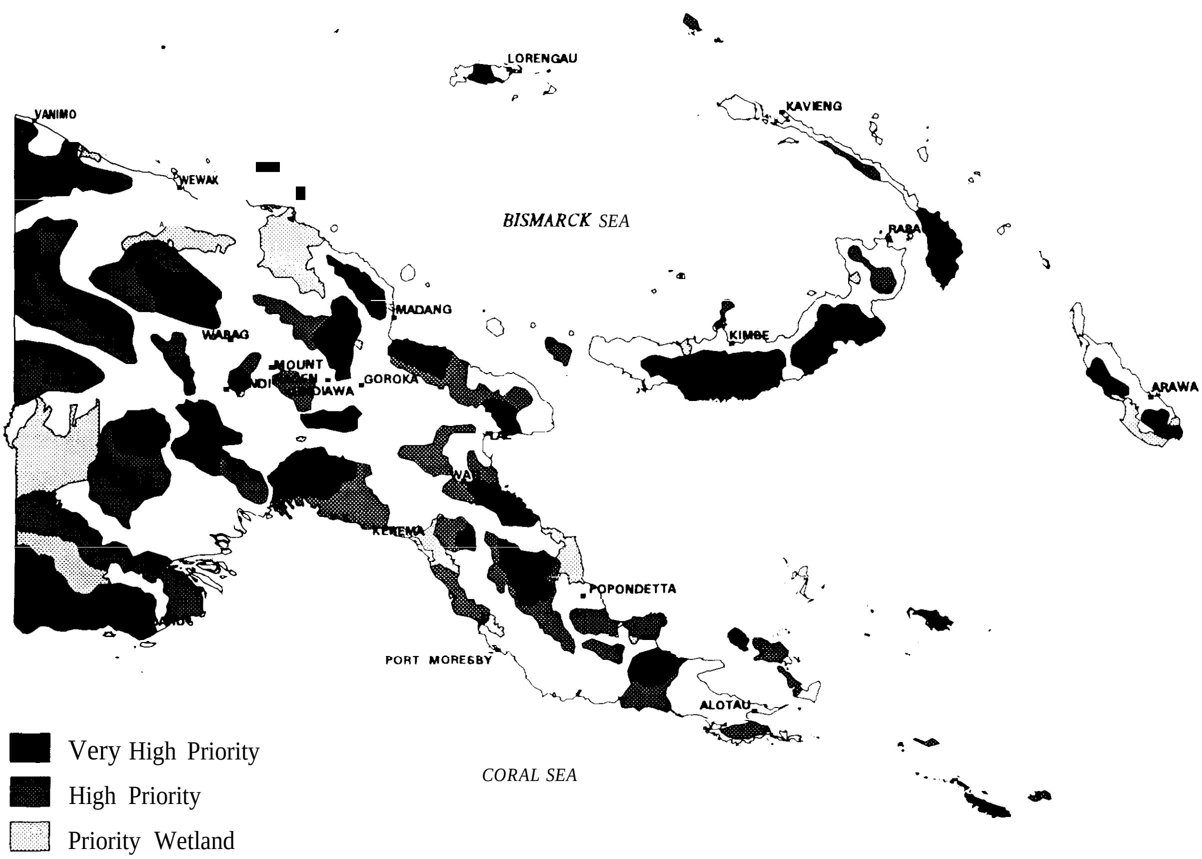
After several days of correcting such errors, arguing over the relative importance of certain areas, and agreeing on precise borders of priority areas, the biologists finally agreed on a map (figure B-5) identifying PNG most biologically significant areas. The final boundaries were then digitized into the GIS. A few months after the workshop ended, a final report and wall-size map of the biodiversity priority tireas were published tind distributed to scientists and government officials in PNG and throughout the world.[19]

The PNG Department of Conservation (DEC) is using the biodiversity map in a variety of land planning activities, including selecting new sites for protected areas, targeting environmental education programs, financing sustainable development projects, and negotiating with logging and mining companies over the select ion of sites for new resource extraction schemes. The map has also helped DEC convince international aid agen-

[18] Timber Rights Purchases are areas that have been identified for leasing to logging companies and thus face the greatest risk of deforestation.

[19] Tangley, Laura. 1992. "Computers and Conservation Priorities, Mapping Biodiversity". Lessons From The Field 1, Conservation International, Washington, DC.

FIGURE B-5: Papua New Guinea Map of Significant Biological Areas



SOURCE Conservation International, 1992

cies to fund conservation projects in PNG. Early in 1993, south New Ireland province, one of the areas identified as highest priority during the workshop, was chosen as the site of the first Global Environmental Facility (GEF) funded project for PNG.

In addition to building consensus among local and international scientists and government officials, a key element of the workshop approach is in building local capacity within the country to continue conservation efforts. In PNG, Conservation International left behind the entire GIS database generated by the workshop as well as the hardware and software needed to use it. In addition, Cl provided GIS training to both government and university technicians. Thus, PNG scientists can add new information to the database as it becomes available, including land cover data derived from satellite images. and can conduct more detailed analyses. The workshop left PNG better prepared scientifically to study and protect its own biodiversity in the future.

HELP FOR VICTIMS OF HURRICANE ANDREW[20]

Hurricane Andrew struck southern Florida in late August 1992, wreaking enormous damage and leaving many without homes. As the rain and wind subsided, federal, state, and local agencies, corporations, and individuals gathered resources to support those who were in the storm's path. Two questions needed to be answered quickly.

- Where should relief centers be established and how can people be notified of their locations?
- How much destruction occurred and where?

Science Applications International Corp. (SAIC) donated its geographic information system (G IS) services and computers to help find the answers. The GIS technology was immediately useful for keeping track of a variety of relief efforts, and later, as data became available. for evaluating the extent of destruction.

A digital database of the area was created and continually updated as reports came in from individuals in various sectors of the hurricane area. The location and status of Red Cross Service Centers, U.S. Army kitchens, bum sites, FEMA Disaster Application Centers, HRS Centers, tent cities, portable toilets, hazardous waste sites, and other facilities were maintained as digital information. When users needed updated maps, the digital data were printed in the form of a large hardcopy color map. Relief workers could use the maps to direct people to the proper facility to handle their needs.

After a few days, aerial photographs were taken. The hardcopy aerial pictures were converted to digital form and combined with the previously created digital line map database to provide an up-to-date pictorial view of the area, which was then used to begin evaluating the extent of the damage. The value of high-technology digital map information in a crisis situation quickly became clear. The database became a depository for field reports. As the information received was validated and integrated, it was redistributed in a graphic format easily interpreted by the user.

An important question that was difficult to answer during the Hurricane Andrew crisis support effort was, "How did the area look before Andrew?"' In some cases, only scattered debris remained of what had been trailer parks or subdivisions a few hours earlier. A reliable up-to-date record of what occupied land parcels prior to the hurricane did not exist. but such information is, of course, essential in assessing damage, in determining what aid is needed, and in establishing who is eligible for aid.

SAIC is currently developing technology called orthorectification to help satisfy this need. The technology creates digital image maps, precisely positioned to a worldwide coordinate system, from aerial photography and satellite imagery. The maps are stored on small cassette tapes or CD-ROM disks that are easily input to a computer and viewed. Image maps being produced for a national program have single elements (pixels) that cm-respond to one square meter on the Earth. Although higher resolution images could be used, maps with one-meter resolution offer an attractive cost compromise. These digital image maps are rapidly becoming popular with users, since they offer data that are more precise, more current, and less costly than the conventional line map paper products. Such digital image maps would have been very valuable in support of the Hurricane Andrew relief effort, as well as in estimating damage from the Mississippi floods.

I Other Mapping Activities

The U.S. Geological Service in Menlo Park, California, is currently creating a national image map database. The effort is supported by a multitude of agencies at the federal, state, and local levels, as well as private utilities, architectural and engineering firms, and individual property own-

[20] Jerry A. Maupin, Assistant Vice President, Science Applications International Corp., Melbourne, FL.

ers. Keying information to a precisely positioned image map is essential to being able to manage and digest the massive amounts of data generated today.

New remote sensing technology is making the collection of image map information even more practical and less costly. Airborne synthetic aperture radar (SAR) systems with onboard GPS now return digital SAR images that have been processed in real time onboard the aircraft. These images can be acquired under almost any weather conditions, and thus are ideal for supporting crises where poor weather conditions and atmospheric haze are likely. Satellite images from systems such as Landsat and SPOT offer data that cover broad areas and are easily processed. New commercial satellites will soon be launched that promise resolutions an order of magnitude finer than those offered by Landsat and SPOT.

It appears a major thrust over the next few years will be improving U.S. infrastructure. Much of the cost will be in planning and coordinating the projects and documenting the results. Remotely sensed photographic information can contribute to the success of these projects. Image maps will be useful in planning and controlling urban sprawl, transportation routes, utility routes, land use, watershed analysis, public land inventory, wetlands documentation, and many other applications. GIS/image maps can save millions of dollars compared with conventional land survey techniques. In addition, results will be consistent and well documented.

ECOSYSTEM MANAGEMENT USING BIOPHYSICAL LAND UNITS (BLU)[21]

Management of natural resources and the ecosystems they comprise is becoming increasingly complex. In particular, the resources and systems contained in public lands are subject to escalating competition and conflict over their use. For example, the public has expressed heightened concerns for conservation and preservation of lands histori-cal] y considered only for "disposal ." Because ecological change is continuous and inevitable it is crucial to understand and predict natural processes, as well as the interplay of cultural (human-induced) uses and impacts. Quantifying, monitoring, predicting, and subsequently protecting "natural" change, or directing "desired" change, must be scientifically evaluated to help resolve conflicts of ecosystem management and use.

The Albuquerque District of the Bureau of Land Management is responding to these needs by using geographic technologies, including GIS and satellite remote sensing. The Albuquerque District has developed a management tool using these technologies called Biophysical Land Units (BLU), which are spatial (geographic) representations of the location, extent, and dynamics of multiple ecological components. These components are the biological and physical (biophysical) attributes of an ecosystem or ecot ype. The attributes may include: soils grouped by texture or erodability, geological type, terrain features such as a limited elevation range or degrees of aspect or slope, vegetation/landcover types, surface water—in short, whatever characteristic is pertinent to the geographic location. For example, in New Mexico, some of the ecosystem attributes may consist of stands of conifers on steep slopes of volcanic cinders, or shrubs and forbs on low-slope, highly erodible soils, which are subject to violent storm runoff. In comparison, a coastal ecosystem may include attributes such as geological type, vegetation, water depth in an estuary, or tidal flow dynamics. In simple terms, BLUS are a graphic representation of ecological responses (condition) in a single map layer.

Historically, land managers have described the existing environment of regions or administrative units (wilderness areas, range allotments, etc.) by extrapolating from field surveys that cover only small percentages of the ecological components. By contrast, GIS technology allows a manager to develop BLUS from a matrix or cross-reference of

[21] Christa Carroll, Albuquerque District, Bureau of Land Managment, U.S. Department of the Interior.

ecological attributes, without regard to administrative or ownership boundaries-or personal hunches. The GIS sets no limitations on the number of ecological component layers that can comprise the BLU model matrix, and is intentionally exploited to represent hierarchical ecological structure. Further, if the programmed matrix combination of ecological components doesn't exist, it simply leaves a blank space in the model. Beyond minimizing human preferences, BLU model "drop out" is beneficial because it can define a previously unknown ecological response, or draw attention to an area that is a unique or potential "hot spot."

For example, when the BLU model was first developed for the El Malpais National Conservation Area in New Mexico, parts of the project area had been subject to extensive previous study. This known information was combined with intensive field verification of the BLU model, resulting in a high degree of confidence in the use of BLUS. Furthermore, through BLU modeling, parts of the project area that were previously little known were found to be different and more complex ecologically than expected. Once these "surprise" areas were identified, they were the focus of additional field verification.

Satellite remote sensing data, (specifically Landsat Thematic Mapper data) are being used in the BLU model for vegetation/landcover and surface geology/soils. It is well known that satellite data provide total spatial coverage of a large area in a "snapshot in time." But satellite data alone are not sufficient for resource analysis and modeling. Vegetation/landcover is only the *surficial* expression of ecological systems. The BLU model incorporates ecological components to understand the *dynamics* of systems. Using satellite images from different times, changes in the system can be detected and analyzed.

An initial iteration of "core" BLUS is usually a matrix combination of vegetation/landcover, soils, surface hydrology, and terrain characteristics. This initial iteration of BLUS is sufficiently flexible to provide "common ground" resource information to a wide spectrum of resource specialists. More detailed BLUS can be tailored for specific questions or conflict analyses by adding layers of biophysical or cultural information and/or site-specific data. Data collected from a particular site might include observed assemblages of flora and fauna, rain gauge or other climatic data, or a particular localized use or management practice.

So why go to all this trouble to model ecosystem dynamics? Ecosystem management requires understanding of energy exchanges and processes, which are constantly moving targets. GIS technologies can measure, track, and repeat ecosystem anal yses through time. The GIS never tires of repeating the processes at different points in time, or trying a different scenario. For instance, to track the rehabilitation of a riparian zone, changes in vegetation/landcover or availability of surface water can be measured and compared to changes in pasture rotation, weather variations, or the relationship of an additional stock and wildlife watering site. Further, a management alternative of improving an access road or establishing a trailhead can be analyzed for predicting the potential amount and direction of visitor use patterns and impacts.

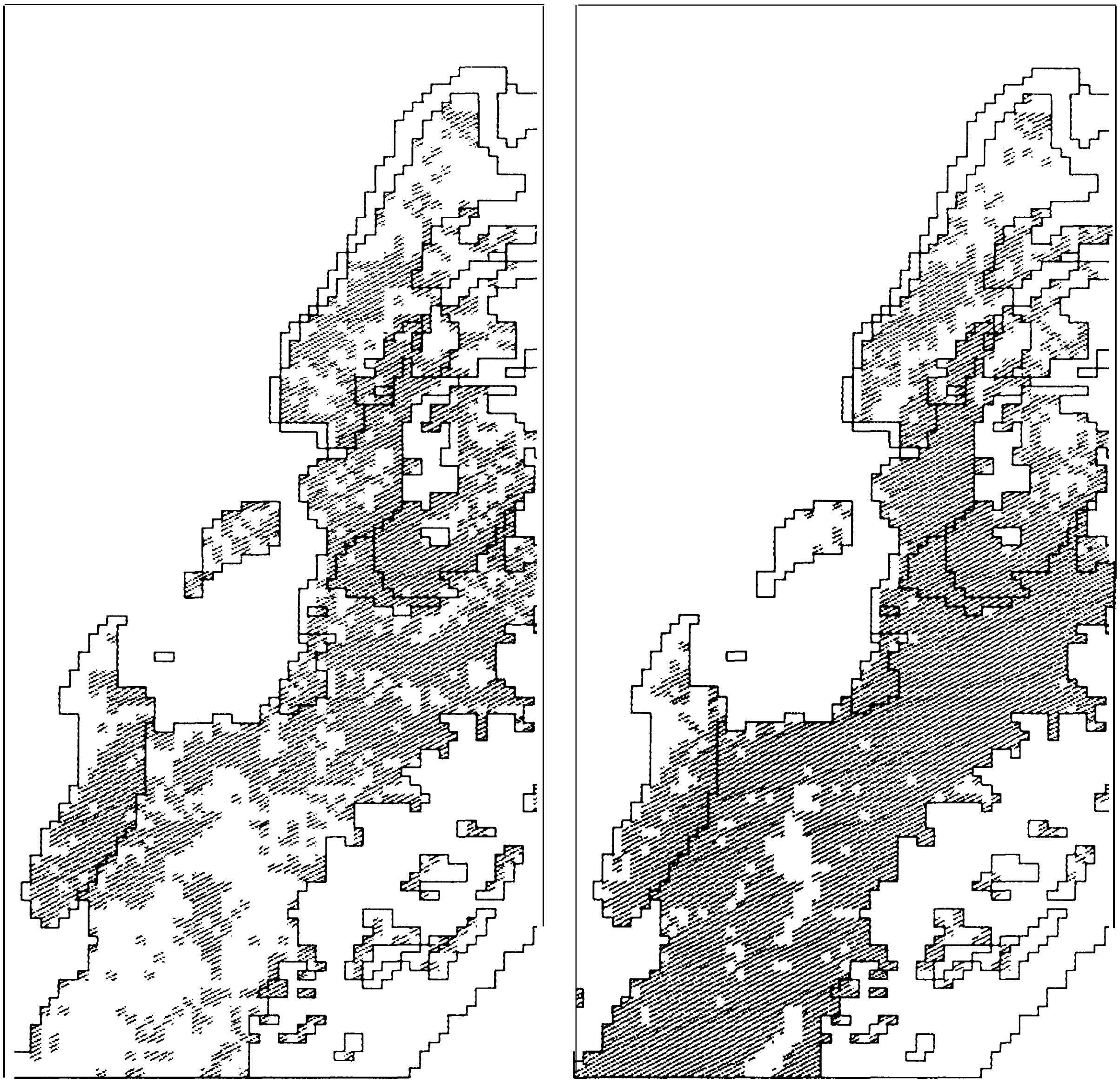
Additionally, BLUS are designed to be hierarchical in structure, representing three dimensional surfaces. They are thus flexible in scale, or resolution. When the element of *time* (satellite data snapshots-in-time, and/or other historic information) is added, they also become four-dimensional. This facet of the BLU concept provides a method to link past and present datasets with predictions of future landscape behavior. Improving methods of relating historic and current environmental data is crucial to identifying past patterns and developing analytic models for predicting change.

Spatial change detection and analysis of ecological responses in BLUS are key to ecosystem monitoring. BLUS can be used to track and evaluate the amount, direction, and rate of responses. The spatial distribution and location of BLUS has been shown to document trends from a patchy to more homogeneous landscape—a measure of *bio - diversity.* Detailed site data within BLUS help to identify the reasons for change, and to show if they are related to dramatic impacts or slow trends.

The BLU approach is providing land/ecosystem managers with practical information for day-to-day decisions. There are many data sources now going unused, simply for lack of a frame of reference. GIS and satellite remote sensing can provide such a framework. The Albuquerque office of the BLM expects to expand the four-dimensional concept of BLUs to a global scale to accomplish "global change monitoring" spatially.

Figure B-6 illustrates how BLU monitoring can assist in understanding the relationship between "potential plant communities" and use of

FIGURE B-6: Geographic Information Systems Comparison of Potential Plant Communities in El Malpais National Conservation Area in 1984 and 1988



SOURCE Albuquerque Off Ice of the Bureau of Land Management, 1993 the landscape. A potential plant community is the biotic community that an undisturbed site is capable of supporting, based on the site's physical characteristics. The GIS plots in figure B-6 show outlines of potential plant communities derived in GIS from soils and terrain data. The hatched areas depict a comparable BLU. The left plot displays the BLU in a "snapshot in time" in June 1984. The right plot displays the same BLU in June 1988. There has been a change in the location and size of the BLU indicating a change in ecological response or condition. A larger portion of the site's potential for supporting plant life has been achieved in 1988, the result of less vehicular travel, good vegetation growth in a wet year, and subsequent reduced grazing pressure. With BLUS in GIS we can quickly compare the actual condition of acres of vegetation to their theoretical potential, and determine what may be the "desired" state under various conditions of use. Additionally, proposed land uses can be compared with each other for potential conflicts. The causes of change can then be analyzed in GIS by overlaying specific "natural" layers and "cultural" layers such as roads, oil and gas wells, or range allotments. This simple example shows the power of GIS and satellite remote sensing as a framework and "common ground" for resource analysis.

GIS provides extensive modeling capabilities. All that is required is the desire to think and model spatially—not just in two dimensions, but in three or four dimensions. Dealing with these basic concepts of "space" (geography) includes taking full advantage of Earth-observing space platforms.