REMOTE SENSING FOR THE NATIONAL PARKS

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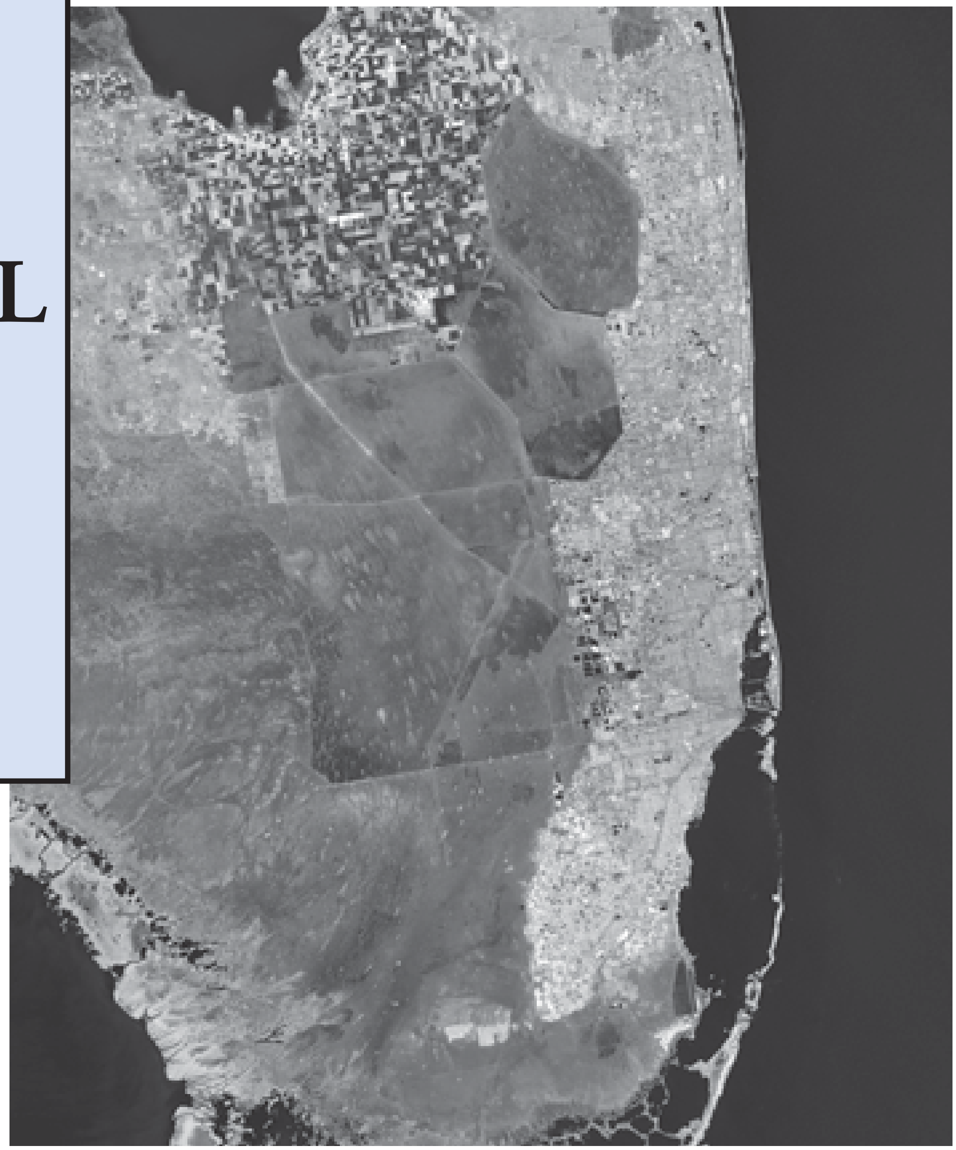

Figure 1. This January 2002 Landsat 7 image of South Florida reveals a variety of land uses and infrastructure in and around Everglades and Biscayne national parks and Big Cypress National Preserve, including farming, water conservation and control, residential development, roads, levees and canals, and the coastal metropolis of Miami-Dade counties. Analysis of a time series of images from sensors on board this and other satellites can assist park managers in detecting changes in land use and ecosystem conditions. LANDSAT 7, OBTAINED FROM THE NATIONAL PARK SERVICE REMOTE SENSING IMAGE ARCHIVE

Remotely sensed data are well established as valuable sources of information for natural resource managers. Now, the accumulation of multi-decadal historical records, implementation of new sensors, and developments in analytical techniques are driving a rapid expansion in the application of remotely sensed data. Time series of images are used to analyze landscape-scale changes in natural resources, while data from high-resolution sensors can be used to detect and quantify small changes in topography, map plant species or even individual plants, or measure flows of nutrients and energy that alter plant growth and affect fire risk (fig. 1). Several recent reviews document the broad range of applications of remotely sensed data to support conservation of biodiversity and ecosystem management, and to evaluate broader issues of land use change (Kerr and Ostrovsky 2003; Turner et al. 2003; Hansen et al. 2004). Some of these applications can directly support monitoring and management needs in units of the National Park System, including high-priority areas of monitoring landscape dynamics, invasive species, and other disturbances.

Remotely sensed data.... can directly support monitoring and management needs in units of the National Park System.

Evaluating landscape dynamics

Habitat loss and fragmentation are continuing threats to biodiversity in parks (GAO 1994). For more than 30 years, Landsat satellites have recorded images of Earth's surface from space, and these images provide a unique decades-long, moderate resolution (at scales of 100–260 ft; 30–80 m) record of land cover change in and around national parks. Hansen et al. (2002) and Parmenter et al. (2003) used LandSat data from 1975 to 1995 to document changes in land cover types in the area of Yellowstone National Park (Wyoming, Montana, Idaho). This multi-decadal record permitted the evaluation of land cover changes caused by natural and human-related processes, including increases in exurban development adjacent to the park and widespread changes to forest structure resulting from the 1988 Yellowstone fires. Development occurred in and near high-quality, low-elevation wildlife habitats that are used by species that also inhabit Yellowstone. Associated field research showed that this development resulted in greater densities of avian brood parasites and predators, leading to diminished reproduction in these "source" habitats (Hansen and Rotella 2002). Similarly, Narumalani et al. (2004) used a combination of aerial photography and satellite imagery to map land cover in and near Effigy Mounds National Monument (Iowa) from the 1940s into the 1990s. This time series revealed periodic changes in the structure and composition of habitats outside the national monument, such as conversion of forest to pasture, while habitats inside it remained relatively unchanged.

With existing data sources, similar analyses could be conducted for most parks. The National Park Service is a member of the Multi-Resolution Land Characteristics Consortium (MRLC) and contributed to the purchase and processing of Landsat imagery of the conterminous United States from about 1992 and of the United States (including Alaska and Hawaii) and Puerto Rico for 2001 (http://www.mrlc.gov/index.asp). MRLC processed the imagery and applied algorithms to classify each pixel and thereby create maps of derived products. These products—including maps of vegetation type, impervious surface, and forest cover—are available for all national parks via the Natural Resource GIS Program (http://science.nature.nps.gov/nrgis/). A separate collaboration by NASA and the U.S. Geological Survey (USGS) purchased global sets of Landsat imagery (the GeoCover dataset) from multiyear periods around 1975, 1990, and 2000. More than 15,000 of these images have been geographically corrected (orthorectified) to allow users to overlay images from different dates and thus simplify the detection of land cover change. These images are available from http://edc.usgs.gov/products/satellite.html. Though they have not been converted into maps or other derived products (as in the case of the MRLC), they nonetheless represent a unique global data set spanning three decades of change. Landsat images provide managers with a tool to place current park land cover in historical context, one that can sometimes be further extended by incorporating historical aerial photography and ground-based photos in the analysis.

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High-resolution commercial satellite images, with pixel sizes of 2 to 13 ft (60 cm to 4 m), provide a similar resolution, less-expensive alternative to aerial photography for some uses. Goetz and collaborators (2003) used Space Imaging Corporation's IKONOS satellite imagery to determine the percentage cover of impervious surfaces, trees, and riparian buffer zones for a large area (507 sq mi; 1,313 sq km) near Washington, DC. Using a combination of manual and automated ("unsupervised") classification techniques, they achieved mapping accuracies that exceeded 80%, equal to maps produced by more costly manual classification of aerial photographs. Because the mapped landscape characteristics were functionally and statistically correlated with water quality in small watersheds (Snyder et al. 2005), these maps also are suitable for evaluating landscape characteristics that directly influence the quality and quantity of water that enters units of the National Park System in the Washington, DC, area.

A future use of high-resolution satellite imagery may be to survey animal populations. Initial studies have demonstrated the feasibility of this approach (Laliberte and Ripple 2003), and in 2006 NASA is supporting a field evaluation of the use of QuickBird imagery from Digital Globe, Inc., imagery to count elk and bison adjacent to Grand Teton National Park (Wyoming).

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The NPS Inventory and Monitoring networks identified landscape-scale disturbances as a high priority for monitoring, but resources often limit the ability of the networks to deploy a ground crew to measure even the most basic attributes, such as area, of a major disturbance. Remotely sensed images are routinely used by news media to report on national and international disasters like the 2004 tsunami in Indonesia or the 2005 flooding of New Orleans. Parks are regularly affected by small and large disturbances and, in these situations, "emergency" requests for data acquisition can be submitted to obtain no-cost ASTER (45-ft or 15-m resolution) imagery. The procedure for emergency acquisition of imagery varies among commercial vendors. QuickBird satellite images, for example, can be requested at any time, and if the satellite is not allocated to a conflicting task, the images will be archived and made available for purchase in the future. High-resolution IKONOS images also can be acquired by making a more detailed request to Space Imaging Corporation.

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Because fires are a common source of disturbance and are an important driver of vegetation state and condition, an interagency project is drawing from the archive of Landsat images to create a fire atlas for all major fires (greater than 500 acres [202 ha] in the East, and 1,000 acres [404 ha] in the West) that have occurred in the

United States since 1982. The project collaborators will use these Landsat images to develop maps of fire severity and to more accurately map fire perimeters in national parks. This information is necessary to report burned area by severity class and to evaluate current land condition, and as a step toward achieving land health goals of the U.S. Department of the Interior. On a much finer time scale, the USDA Forest Service uses data from the MODIS instrument to map active U.S. fires each day. Current maps can be viewed on the Internet at http://activefiremaps.fs.fed.us/activefiremaps.php.

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Finding and mapping invasive plants

A huge potential exists for remote sensing data to contribute to monitoring and managing invasive plants, and the National Park Service and its collaborators are slowly accumulating successes such as identifying and mapping the widespread invasive plant cheatgrass (*Bromus tectorum*). Cheatgrass has invaded and threatens many national parks in the West, creating major ecosystem-level impacts through competition with native species and by changing fuel loads and fire patterns. The timing of green-up and senescence (the period of maturity to death) for cheatgrass differs from that of native vegetation, and cheatgrass is therefore easily detected using remotely sensed data (Peterson 2005).

Individual plant species have been most successfully identified from data collected by hyperspectral sensors—sensors that measure a high number of contiguous spectral bands. Usually mounted in aircraft, these sensors have both a high spectral and spatial resolution (variable, but typically 1–100 ft; <1–30 m)—and a high cost for data acquisition and analysis. An exception is the Hyperion hyperspectral sensor, which is satellite-borne and generates data with a moderate (100 ft; 30 m) resolution. Hyperion data were used to successfully detect small infestations, and even individual trees, of the invasive species Chinese tallow (*Triadica sebifera*, fig. 2), a pest in many parks in the Southeast (Ramsay et al. 2005). Use of this technique for other species would greatly enhance the ability of the National Park Service to economically use moderate resolution hyperspectral data to detect new plant infestations.

Most invasive species work focuses on locating, mapping, and managing invasive species. However, researchers and resource managers also need to understand how invasive plants impact and alter the functioning of natural ecosystems. Gregory Asner of Stanford University, working with data collected by the NASA AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) hyperspectral sensor in Hawaii Volcanoes National Park, estimated leaf area and levels of plant water and nitrogen in a 3,360 acre (1,360 ha) area near the summit of Kilauea Volcano in Hawaii Volcanoes National Park. These plant attributes allowed for the remote detection of stands of the invasive Canary Island tree *Myrica faya* and of patches of the invasive herb Kahili ginger (*Hedychium gardnerianum*) that exists in the understory (Asner and Vitousek 2005). Understory vegetation is normally invisible to conventional remote sensing techniques; however, detection of both invasive plant species was possible due to their effects on water and nitrogen levels in the forest canopy, which were observed by remote sensing. Thus, the remotely sensed data and associated model identified the locations of both the invasive canopy and understory species. This method also enabled the assessment of the impacts of these exotic species on forest water and nitrogen cycles.

Figure 2. Highly invasive Chinese tallow trees, pests in many national parks in the southeastern United States, can be distinguished from native vegetation using economical, satellite-borne sensors. The strong spectral contrast of tallow trees (appears red in original but is shown by arrow here) permits the use of moderate resolution (98 ft; 30 m) sensors, such as Hyperion, to identify trees or infestations. See Ramsey et al. 2005. COURTESY OF CHERYL MCCORMICK, UNIVERSITY OF GEORGIA

Ecosystem models help with management

A powerful use of remotely sensed data is to generate and test predictions of ecosystem dynamics through models. Examples of such synergism include dynamic predictions of snowpack, streamflows and water temperatures, soil moisture, fuel loads and fire risk, and nutrients in pristine and polluted watersheds (White et al. 1998; Fagre et al. 1997). Models are excellent tools for mitigating environmental risks and evaluating management decisions in an uncertain ecological setting. Models allow resource managers to assess the behavior of ecosystems in response to a variety of factors that are internal (e.g., fire, tree blowdown, erosion) and external (e.g., interannual, decadal, and long-term climate change) to a park. Ecosystem models that rely heavily on remotely sensed data have traditionally been retrospective, intended for use in understanding how various pieces of ecosystems fit together (Tague and Band 2004). With the advent of new technology, many of these models can now be run in both near real-time and forecast modes that use present conditions to initialize simulations that evolve from one week to as much as a century into the future (fig. 3) (Nemani et al. 2003).

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Scientists at the NASA Ames Research Center and their collaborators have created the Terrestrial Observation and Prediction System (TOPS, http://ecocast.arc.nasa.gov). This data and modeling software system brings together technologies in information technology, weather and climate forecasting, ecosystem modeling, and satellite remote sensing to inform management decisions related to floods, droughts, forest fires, human health, and crop, range, and forest production. TOPS automatically integrates and preprocesses remotely sensed data from a variety of sensors so that land-surface models can be run in near real-time to provide ecological forecasts.

TOPS incorporates ecosystem models that predict vegetation growth and standing biomass, snowpack dynamics, nitrogen and phosphorus cycling, fire behavior (e.g., FARSITE model), and soil moisture. This software can access, process, and convert imagery from MODIS, Landsat Thematic Mapper, ASTER, and IKONOS satellite sensors into biophysical variables such as canopy cover, leaf area index, and fraction of absorbed radiation, and use these variables to perform ecosystem simulations

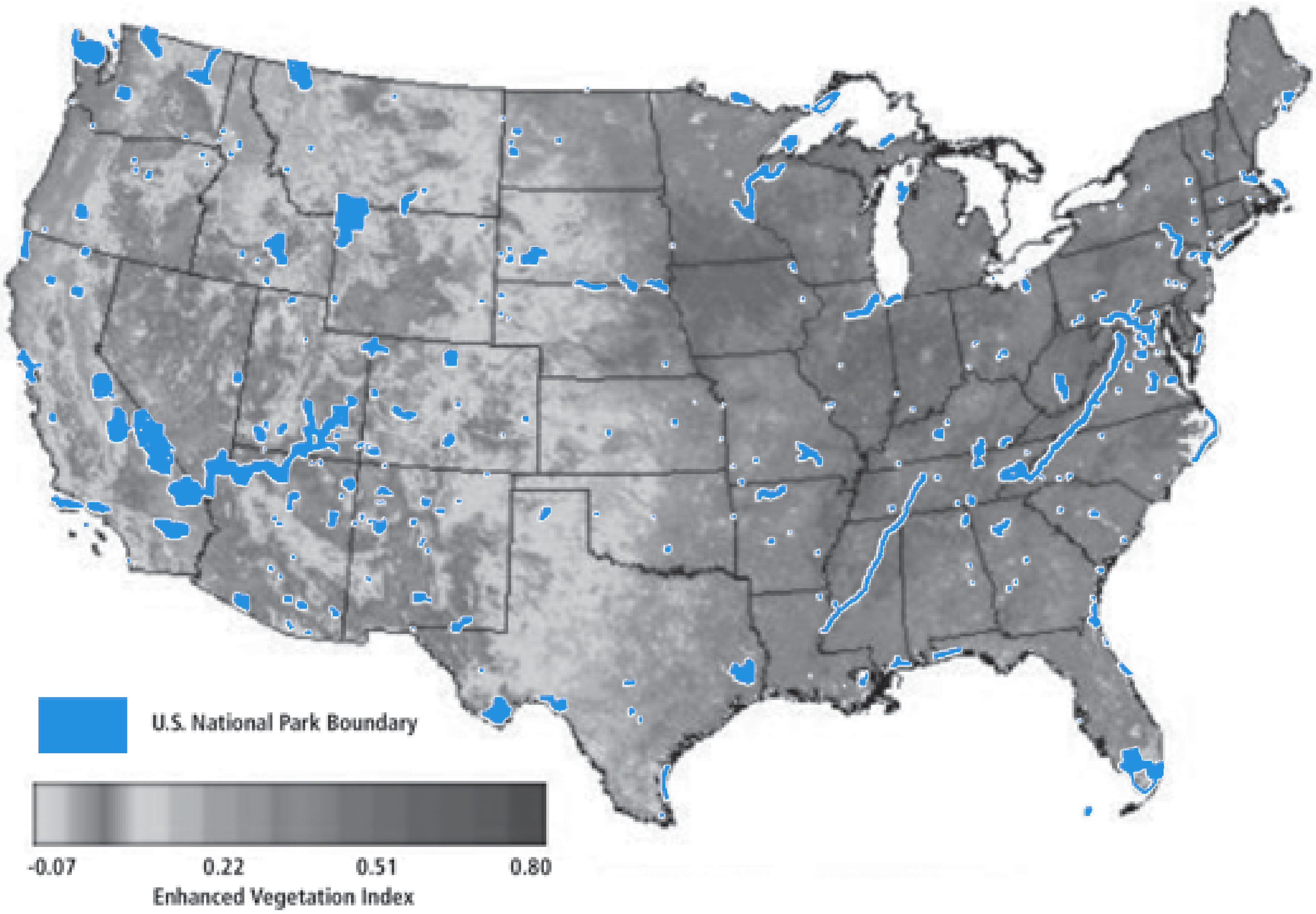

Figure 3. Ecological models allow data from satellite, suborbital, and ground sensors to be integrated to provide continuous monitoring of ecosystem conditions within all U.S. national parks. For example, this 8-km- (5-mi) resolution enhanced vegetation index (EVI) dataset from 22 August 2005 can easily be subset for each of the park boundaries to provide near real-time assessments of vegetation conditions within each park. A full-color version of this figure is available from the *Park Science* Web site. COURTESY OF FORREST MELTON, NASA AMES ECOLOGICAL FORECASTING LAB

at spatial resolutions ranging from 12 ft (4 m) to 3,300 ft (1,000 m) (fig. 4). Similarly, TOPS modeling software also provides ready access to a variety of standard MODIS products (table 1) such as fire occurrence, snow cover, and vegetation productivity.

Through a NASA-NPS collaboration, TOPS is used at Yosemite National Park (California) at 30-m and 1,000-m resolutions to produce real-time measures of conditions and forecasts of ecosystem variables including snowpack, soil moisture, and streamflows (fig. 5). Hydrologic models, such as the Regional Hydro-Ecologic Simulation System (RHESSys), have been used with TOPS for a subset of watersheds in Yosemite. Retrospective analyses conducted to date have accurately modeled peak streamflows in the upper Merced River watershed, and may provide another means of forecasting floods in the park. Thermal anomaly data (MOD-14) from the MODIS instrument are also processed by TOPS to provide a real-time monitoring capability for wildfires that occur within and adjacent to park boundaries. Future plans at Yosemite include using the TOPS framework to explore the impact of invasive species on biogeochemistry, and the impacts of climate change and variability on species distribution and fire risk. The successful implementation and routine use of TOPS products at Yosemite could serve as a model for integrating ecosystem models with satellite data for decision making in national parks throughout the country.

NASA-NPS partnerships

NASA and the National Park Service signed a memorandum of understanding in January 2005 to enable interagency partnerships using NASA's imagery and technological expertise to help the Park Service better address its management goals. Under this agreement the National Park Service and NASA have cosponsored a workshop focused on park resource monitoring needs (http://science.nature.nps.gov/im/monitor/meetings/StPetersburg_05_rs_pa/rs_pa_wrkshp_proc.cfm), begun to implement TOPS in prototype national parks, and completed a NASA-sponsored intern program that used Landsat images to monitor postfire vegetation change in Yosemite. In addition, NASA is funding several large studies specifically focused on NPS needs. These studies will use remote sensing information to identify burned areas at high risk to invasive plants, improve monitoring of land cover change in and around national parks, and improve our understanding of the consequences of land cover change on energy and water cycles. NASA also will assist park education and interpretation specialists by developing dynamic visualizations and means to communicate results of its research.

The trend for the future is clear: park managers will increasingly use remote sensing data. This trend will be driven by improved remote sensing technology and decreased costs, improvements in

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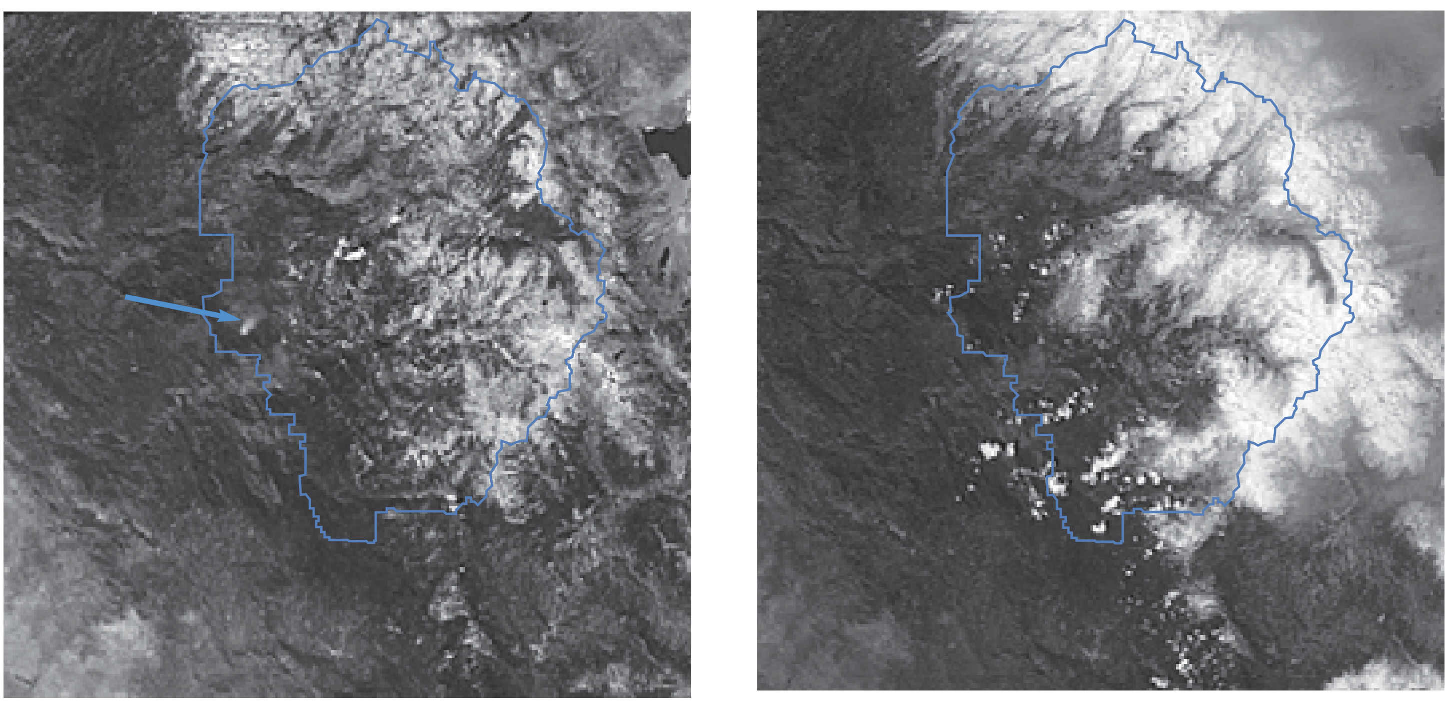

Figure 4. Satellite and suborbital sensors provide information on ecosystem conditions at a range of resolutions and scales. Using systems like TOPS, these 250-m (820-ft) resolution MODIS Direct Broadcast images of Yosemite National Park in California can be delivered to park personnel within hours of data capture onboard the satellite, providing an immediate snapshot of parkwide conditions for use in monitoring events such as the 14 September 2005 fire (left, arrow) and the extent of snow cover on 4 June 2006 (right).

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Table 1. Examples of satellite sensors most commonly used for ecological studies, and typical applications that are useful to protected-area managers

Application	Sensor / Cost[1]	Resolution[2] (m)	Description	Example application
Land cover, vegetation types, water quality	QuickBird $$ IKONOS $$ SPOT $ ASTER * TM/ETM $	<1–3 1–4 2.5–20 15 30	Directly measure surfaces in black and white (panchromatic) or multi-spectral images. Panchromatic images are higher resolution but without color needed to distinguish many features.	Hansen et al. 2002, 2004. Goetz et al. 2003, Homer et al. 2004, Peterson 2005
Individual species or species composition	IKONOS $$ QuickBird $$ Hyperion $ AVIRIS $$$	1–4 <1–3 30 <1	High spatial or high spectral resolution is necessary to distinguish small or unique objects. AVIRIS is airborne and is very expensive. Hyperion and AVIRIS are hyperspectral sensors.	Asner and Vitousek 2005, Ramsey et al. 2005
Phenology, land condition, snow cover, current fires, seasonality	MODIS * AVHRR * SPOT Veg $	250–1,000 1,000 1,000	High revisit frequency is most suitable for near real-time monitoring of phenological changes, fires, and similar events.	Reed et al. 2003, Justice et al. 1998
Water quality—chlorophyll, turbulence, color	MODIS * AVHRR * SeaWiFs *	250–1,000 1,100–4,000 1,100–4,500	Very high revisit rates permit daily or more frequent monitoring of sediment or smoke plumes, red tides, upwellings, dust storms, etc.	Warrick et al. 2004, Justice et al. 1998
Topography	Lidar $$$ QuickBird $$ IKONOS $$ SPOT 3D $$	<1 vertical <1–3 1–4 16	To create high-resolution digital elevation maps. Lidar is an active radar with a vertical resolution of <1 ft (30 cm).	Lefsky et al. 2002

Note: The table illustrates only a few typical applications. See Turner et al. (2003) or Faundeen et al. (2004) for more complete reviews of sensors and their uses.

[1] * = some or all products available at no cost, $ = inexpensive (<$2/sq mi), $$ moderate cost, $$$ very expensive.

[2] Higher resolutions are generally panchromatic (black and white) and lower resolutions are multi-spectral.

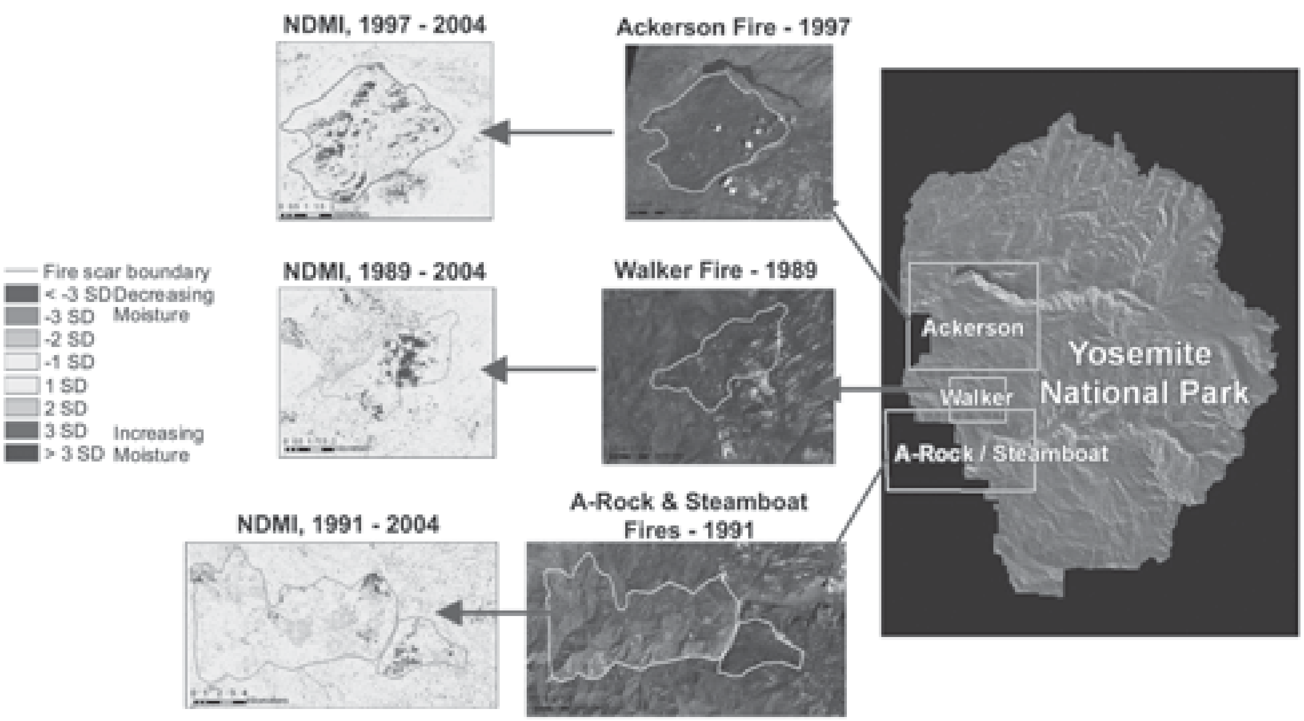

Figure 5. Satellite data can be used to monitor long-term ecosystem response to disturbance. For example, Landsat data have been used to monitor ecosystem conditions following three major fires in Yosemite National Park, revealing a consistent increase in vegetation moisture following fire occurrence. Fire boundaries are determined using Landsat scenes collected after the fire in which the fire scars are clearly visible. The normalized difference moisture index (NDMI) was calculated using a time series of Landsat scenes, and the cumulative change in NDMI from the date of fire occurrence through 2004 is shown for each fire. A full-color version of this figure is available from the *Park Science* Web site.

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