

Landsat's Role in Ecological Applications of Remote Sensing

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Remote sensing, geographic information systems, and modeling have combined to produce a virtual explosion of growth in ecological investigations and applications that are explicitly spatial and temporal. Of all remotely sensed data, those acquired by Landsat sensors have played the most pivotal role in spatial and temporal scaling. Modern terrestrial ecology relies on remote sensing for modeling biogeochemical cycles and for characterizing land cover, vegetation biophysical attributes, forest structure, and fragmentation in relation to biodiversity. Given the more than 30-year record of Landsat data, mapping land and vegetation cover change and using the derived surfaces in ecological models is becoming commonplace. In this article, we summarize this large body of work, highlighting the unique role of Landsat.

Keywords: remote sensing, Landsat, spectral vegetation indices, vegetation mapping, change detection

The discipline of ecology has undergone tremendous growth and diversification over the past century. These advances were driven by a variety of sociological, political, environmental, and technological developments that fostered new theory as well as new applications. Public concern over the state of the environment, which had been increasing over the decades leading up to the 1960s, led to landmark sociopolitical action. The Clean Air Act of 1963, later amended in 1970 and 1990, was perhaps the most important initial legislative action. Another major legislative event was the Endangered Species Act of 1973. Emerging environmentalism led to the establishment of an annual event known as Earth Day, first celebrated in 1970 and continuing today.

With regard to technology, the foundations were laid in the 1960s and 1970s for what would become widely known as geographic information systems (GIS). Electronic computing, revolutionized with the development of microprocessors in the early 1970s, ushered computing into the realm of environmental research, which ultimately enabled GIS to pervade environmental modeling.

On the theoretical forefront at the time was the development and appreciation of what by the 1990s was to become perhaps the dominant concept in ecology: scale. With respect to advancement in applications of spatial (and to a lesser extent temporal) scaling theory, there has been perhaps no greater catalyst than remote sensing. At the core of developments in remote sensing has been the Landsat program.

Launch of the Sputnik satellite in 1957 ushered in the Space Age. In 1962, John Glenn became the first human to orbit the Earth. During the manned Gemini and Apollo programs from 1965 to 1972, numerous pictures were taken

of Earth from space, and a discipline known as remote sensing was born. With the launch of the first Landsat satellite in 1972, scientists could suddenly view tangible human impacts on the whole Earth system on a regular basis. By necessity, field measurements and experiments focused (and have continued to focus) mainly on plots with sizes up to several square meters (m^2). Remote sensing enabled scientists to spatially reference their plots to images showing the land-cover and landform context of their data. Because Landsat data were digital, they could be used with other, thematic data sets in cartographic modeling schemes using GIS. This enabled spatially explicit ecological models to expand from local into regional applications.

For regional monitoring applications relying on temporal data sets, Landsat has several advantages. First, with more than 30 years of Earth imaging, it offers the longest-running time series of systematically collected remote sensing data. Second, the grain size (or spatial resolution) of the data facilitates characterization of land cover and cover change associated with the grain of land management. Third, Landsat Thematic Mapper (TM) and the later Enhanced Thematic Mapper Plus (ETM+) acquire spectral measurements in all major portions of the solar electromagnetic spectrum

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(visible, near-infrared [NIR], shortwave-infrared [SWIR]), providing Landsat TM and ETM+ significant advantages over less capable sensor systems. Fourth, in recent years Landsat data have become more affordable, as have the computers needed to process these data, making it possible to acquire and analyze large volumes of observations.

In the remainder of this article we give a brief historical overview of the Landsat program, paying particular attention to the initial vision for the program, the quality of its sensors, its role in the evolution of remote sensing, and its current status. This is followed by a discussion of the importance of Landsat to the development of spectral vegetation indices and to the emergence of the power of SWIR reflectance in ecological applications of remote sensing. We then present a section highlighting various ecological applications of Landsat data, including their integration with ecological models. We finish with a summary of the importance of remote sensing to ecology today, describing how Landsat has been—and will continue to be for the foreseeable future—a key contributor to spatiotemporal scaling in ecology.

Historical overview of the Landsat program

The tradition of taking the high ground to get a better perspective on landscapes and ecosystems is probably as ancient as human curiosity. The technology to support such efforts took a major step forward in the mid-1800s, when cameras were first taken aloft in hot air balloons to better record spatial variations in the land surface. At the end of World War II, scientific understanding and several emergent technologies came together to produce the type of systematic, global land-monitoring observatories that are available today. Landsat was the first spacecraft system deployed to conduct terrestrial monitoring, and it remains the preeminent observatory for monitoring regional land dynamics.

The scientific basis for Landsat originated from the understanding that photosynthetically active vegetation produces a unique solar reflectance spectrum, with low reflectance in visible wavelengths and high reflectance in NIR wavelengths. There are early reports on the use of NIR photography in ecology, but it was only during and shortly after World War II that remote sensing systems began to fully take advantage of the potential for multispectral measurements in terrestrial research.

The unique vegetation reflectance spectrum served as the basis for color-infrared (CIR) photography, which was used for camouflage detection by the military. Such photography also began to be used for high-altitude acquisitions from the US U-2 spy planes, because, by avoiding the shorter-wavelength (blue) visible wavebands, the imagery was less contaminated by haze, giving a clearer view of the land surface from these high altitudes (approximately 18 kilometers [km]). Similar significant success was achieved from space in the Apollo/Gemini program. This imagery proved valuable for land-cover assessments, agricultural surveys, and forest inventories. Thus, the CIR approach was deemed optimal for unmanned, spaceborne imaging systems.

Technical components of the Landsat concept consisted of Earth-orbiting spacecraft, electronic sensors, and electronic computers. All of these components primarily emerged following World War II. The late 1950s found the United States and the Soviet Union in a cold war battle to achieve primacy in these areas. The efforts to orbit television cameras for gathering weather information represented a US success in this direction. By the early 1960s, the US military was beginning to declassify these technologies and encourage government and university scientists to more fully explore their value for civil uses. Research teams at institutions, including the University of Michigan, the University of California–Berkeley, Purdue University, and the US Department of Agriculture (USDA) research laboratory in Weslaco, Texas, began to explore the details of how to exploit the new electronic, multispectral measurements.

By the mid-1960s, the National Aeronautics and Space Administration (NASA), primarily through the Apollo program, had encouraged the US Department of the Interior and USDA to consider the value of a dedicated land observation mission. The head of the US Geological Survey (USGS) at that time, William T. Pecora, took a particular interest in this concept, producing the initial proposal for an Earth Resources Observation Satellite. Ultimately, NASA was given the lead to develop the Earth Resources Technology Satellite (ERTS, later renamed Landsat). The first observatory was launched in 1972. USGS was given the archival responsibility to capture and distribute these data at the new Earth Resources Observation System Data Center in Sioux Falls, South Dakota. From 1972 to date, there have been seven Landsats launched—one launch approximately every 3 years through Landsat 5, which was launched in 1984, followed by two more launches in the 1990s. Landsat 6 was launched approximately 9 years after Landsat 5, in 1993, but failed to achieve orbit. Interestingly, this was the only satellite in the series that did not involve NASA oversight. Landsat 7 was launched in 1999, 6 years after Landsat 6.

When ERTS was under construction, the primary observation instrument was considered the three-band (red, green, NIR) return beam vidicon (RBV) instrument. In simple terms, this was a shuttered television camera that imaged a 185-km by 185-km land area. The assumption was that the radiometry and mapping geometry of this system was the best that could be achieved at the time, at least with electronic systems in which the data were transmitted to the ground. In addition, a proposal to fly a four-band multispectral scanner sensor (MSS), with green, red, and two NIR bands, originated out of the multispectral work being pursued at Michigan, Purdue, Berkeley, and elsewhere. The goal of the MSS system was to explore the potential of numerical multispectral imaging, particularly as analyzed by electronic computers. Ultimately, both systems were flown to provide an opportunity to compare them. Shortly after launch, electrical problems with the RBV camera resulted in its being shut down. The MSS system became the sole source of imagery from near the beginning of the mission. Interestingly, comparisons of the

early RBV and MSS image pairs demonstrated that the MSS system provided better imagery. The three-band RBV system was flown on Landsat 2 but not used nearly as much as the MSS system. For Landsat 3, the RBV was converted to a panchromatic system at higher spatial resolution (30 m), in an effort to complement the MSS system. Unfortunately, analog transmission of the RBV data made them quite noisy when compared with the digitally transmitted MSS data. The RBV system was discontinued after Landsat 3.

In the early 1970s, NASA researchers were assigned the task of developing a more advanced MSS system, in the view that it would produce considerable advances in land evaluations based on its enhanced performance characteristics. This system, which ultimately became Landsat TM, was deployed on Landsat 4 in association with an MSS system that duplicated the sensor used on Landsats 1, 2, and 3. The TM instrument is similar to the original MSS system in that it is a multispectral scanner. However, the technical capabilities of the TM instrument are a substantial enhancement over those of the MSS. Whereas the MSS instrument had a four-band, six-bit radiometry and a nominal 80-m instantaneous field of view (IFOV, the area viewed on the ground, which was technically 79 m by 56 m), the TM instrument is a seven-spectral-band sensor (one of which is thermal and has a 120-m IFOV) with eight-bit radiometry and a 30-m IFOV. Although the MSS was continued on Landsats 4 and 5, interest quickly shifted to the science and applications of the TM instrument after its first deployment in 1982 on Landsat 4. Landsat 7 introduced ETM+, which included a 15-m IFOV panchromatic band, two radiometric sensitivity ranges, and a 60-m IFOV thermal-infrared band. Also, for Landsat 7, an automatic, systematic acquisition scheme was introduced to ensure that clear scenes for most of the globe were acquired seasonally. With a 16-day return time, this scheme made it possible to obtain clear views of the greater part of the terrestrial surface one or more times per year.

In many ways, the politics and varying management approaches that have surrounded Landsat are as interesting and significant as the scientific and technical accomplishments of the mission. From the beginning, budgetary administrators in Washington have had concerns about NASA (or any other federal agency) taking on major new operational obligations, such as the weather satellites or agricultural surveys. Ultimately, NASA was given approval to pursue the Landsat concept as an "experiment." This justification lasted through Landsats 1, 2, and 3 and the launch of Landsats 4 and 5. In the early 1980s, the White House took initial steps toward commercializing Landsat by moving mission management to the National Oceanic and Atmospheric Administration (NOAA). The Reagan administration sped up the process and called for industry bids. A consortium of Hughes Aircraft Company and RCA Corporation formed the Earth Observation Satellite Company, or EOSAT, and won the bid to commercialize the mission. This was a bumpy road for everyone involved and was brought to an end in 1992, when Congress acted to bring the mission back under direct

government management. Landsat 6 was lost on launch shortly thereafter, and a major effort, under the direction of NASA and the Department of Defense (DOD), was undertaken to quickly construct Landsat 7.

During the development of Landsat 7, DOD dropped out of mission management because the instrument the department had planned to add was not funded. By presidential directive, Landsat was turned over to NASA, NOAA, and USGS. NOAA dropped out in 1998, when its requested budget for Landsat was also denied. Today, the mission operations for Landsat 7 (as well as Landsat 5) have been turned over to USGS, with NASA supplying technical support. NASA also undertook development of possible advanced sensor technology designs and orbited the Earth Observer-1 (EO-1) satellite with the Advanced Land Imager and the Hyperion hyperspectral sensor to test these possible future directions for continuation of Landsat beyond Landsat 7.

On the political front, there continues to be considerable pressure, under the 1992 public law and other congressional directives, to identify a mission approach that would involve private industry in the continuation of Landsat. From 2001 to 2003, NASA and USGS pursued a government-industry partnership to provide Landsat continuity, involving the release of a request for proposals in November 2002 for the Landsat Data Continuity Mission (LDCM). However, no satisfactory proposal was received and the LDCM procurement was canceled in late 2003. At the time of this writing, other options for the continuity of data beyond Landsat 7 are under consideration, as required by the 1992 law. It should be noted that in May 2003 the operation of one component of the Landsat 7 ETM+ sensor malfunctioned, resulting in a loss of 20% to 25% of the data in every full scene. Compositing approaches to fill in the gaps in the data are being implemented. For most applications, composited products should meet observation requirements.

The Landsat mission is remarkable in many ways. It is an exceptionally successful outgrowth of the US space program, derived primarily from the effort to place a man on the moon (the Apollo program). It has defined a new way of monitoring Earth's land areas, particularly the condition and seasonal dynamics of the vegetated land cover. It has stimulated much international interest in such observations, both through international ground stations and through the development of similar observatories by countries such as France, Russia, Japan, India, Brazil, and China. The Landsat program has now achieved a record of these measurements for more than 30 years and appears to be headed toward at least another decade of measurements, thus surviving despite the turmoil and chaos of Washington politics. One should expect, when looking back on the 50th anniversary of these measurements, that recognition will be given to the remarkable innovation that was developed in the United States in the mid-20th century and permitted scientists to begin truly monitoring life on Earth.

Landsat and the development of spectral vegetation indices

A few years before the launch of ERTS (i.e., Landsat 1), Birth and McVey (1968) evaluated the color of grass turf using a ratio of NIR (750-nanometer [nm]) to red (650-nm) reflectance, which they called the turf color index. Shortly thereafter, Jordan (1969) used a similar index to relate the quality of light on the forest floor to the leaf area index (LAI). This NIR-red ratio is now commonly referred to as the simple ratio and represents an example of the now-numerous algebraic combinations of multispectral measurements that have come to be known as spectral vegetation indices (SVIs). SVIs have been at the heart of ecological applications of remote sensing, and this section briefly describes their development and Landsat's seminal role in the process.

SVIs were originally applied to satellite remote sensing using the first Landsat MSS system. A precursor to what is now called the normalized difference vegetation index (NDVI, defined as $[\text{NIR} - \text{red}]/[\text{NIR} + \text{red}]$, or the difference divided by the sum of reflectances in the red and NIR spectra), was used by Rouse and colleagues (1974) to track what they called the "greenwave effect" over the growing season in grasslands of the Great Plains. Others soon followed with a demonstration that the phenology of various vegetation types could likewise be monitored with an SVI of MSS data, and that SVIs were more sensitive to phenology than were individual spectral bands (e.g., Blair and Baumgardner 1977).

The simple ratio and NDVI represent ratio-based SVIs, using visible and NIR reflectance, that result in a single index. Given their simplicity and use of commonly acquired spectral ranges, these SVIs have been widely applied over time to numerous data sets from a variety of sensors. However, Landsat data were also key to the development of algebraic combinations of spectral bands that result in related sets of SVIs, including those that utilize SWIR bands.

Consideration of the spectral development of crops or open-canopy vegetation over a growing season invariably leads to a consideration of soil spectral properties. One of the original conceptual models for this was the "tasseled cap" (Kauth and Thomas 1976). Recognizing that all four spectral channels of MSS data contain useful information, Kauth and Thomas statistically rotated the full MSS data space into a physically meaningful set of SVIs, the primary ones being brightness and greenness. The key point here is that soil reflectance is variable and that it is desirable to have an SVI that responds to amount of green vegetation irrespective of soil reflectance, which, as demonstrated by Kauth and Thomas, exists as a plane in multidimensional MSS space (at the base of what formed a tasseled cap). This was quickly followed by a simplification of the plane of soils to a conceptual soil line, with new MSS SVIs as spectral measures of the amount of vegetation independent of soil conditions.

With the launch of Landsat 4 and the wide availability of TM data, a new index was added to the tasseled cap to account for new information available from SWIR. In a model dubbed the "TM tasseled cap," a new series of indices—brightness,

greenness, and wetness—was derived. Brightness and greenness were reformulated to account for new sensor characteristics, and wetness was designed to contrast the SWIR bands against the visible and NIR bands in an effort to express the water content of soils and other scene components (Crist and Cicone 1984). With the addition of wetness, it was now possible to fully express the tasseled cap model in three spectral dimensions, which together formed the plane of vegetation (brightness and greenness), the plane of soils (brightness and wetness), and the transition zone (wetness and greenness).

Whereas the weighting of the different bands in the original tasseled cap was based on maximizing contrasts for a single Landsat MSS image from Illinois, the TM version was based on three TM scenes, one from the Midwest (Iowa) and two from the South (covering portions of Arkansas, Tennessee, and North Carolina). Although this facilitated a greater exploration of features other than soils and crops, forests remained largely unexplored. This changed with Li and Strahler (1985), who used brightness and greenness to identify the spectral properties of scene components for use in their geometric-optical model of forest structure, and with others who used these SVIs to evaluate forest succession. Cohen and colleagues (1995) examined the three main TM tasseled cap indices, finding that wetness was essentially unaffected by topographic variation in closed conifer stands and thus more powerful than brightness and greenness for predicting forest structural attributes, given that both brightness and greenness responded more to topographic variation than to forest condition.

Landsat-based SVIs also played a large role in the development of methods to detect changes in vegetation condition. Numerous approaches to change detection have been developed, but one of the more conceptually interesting and enduring ones, change vector analysis, was based originally on MSS data (Malila 1980). Change vector analysis describes two-date pixel spectral changes in two dimensions (namely brightness and greenness) in terms of a vector with both direction and magnitude. Later, the conceptual framework was developed to extend change vector analysis into three spectral dimensions to accommodate TM data. Collins and Woodcock (1994) used a different conceptual model to derive change information from TM data, defining both stable and changing components of brightness, greenness, and wetness.

Although it is convenient to give spectral indices names that conjure up visions of what in the Earth system they are sensitive to, it must be kept in mind that spectral data are not that well behaved. As already described, the NDVI responds to both vegetation greenness (or amount) and soil reflectance. Furthermore, brightness and greenness can be more sensitive to topographic variation than to soil or vegetation properties, in which case they can also be very highly correlated to each other.

Emergence of the power of shortwave-infrared reflectance

The previous section indicated that Landsat was the first Earth-observing satellite system to include SWIR channels and

to emphasize the importance of the TM tasseled cap index of wetness (which contrasts SWIR against all other spectral channels) in characterizing vegetation environments. At this point, we turn our attention to demonstrating the importance of Landsat TM and its successor, ETM+, to ecological applications of remote sensing, precisely because these systems contain SWIR channels. The importance of SWIR is most widely recognized in the study of forest vegetation.

Horler and Ahern (1986) conducted the first detailed examination of the forestry information content of TM data. They discovered that the SWIR bands contained more information about conifer and hardwood forests of western Ontario and Arkansas than the other bands. Later, it was found that TM SWIR was an important spectral region for estimating forest volume and LAI in conifer forests (e.g., Eklundh et al. 2001). In the greater Yellowstone ecosystem, Jakubauskas (1996) found that SWIR bands explained most of the variance in TM data associated with forest structure. This is similar to the finding that wetness was the most important tasseled cap index for assessing forest structure in western Oregon (Cohen et al. 1995, 2001). Working in Australia, Lymburner and colleagues (2000) reported that SWIR (in addition to visible) bands were the most important TM bands for characterizing variations in specific leaf area across diverse forest and crop types. In the Amazon, Steininger (2000) found the SWIR bands to be the most important TM bands for mapping age and biomass.

Considering the importance of SWIR bands for characterizing forest conditions, it is not unexpected that SWIR bands are also important for assessing forest changes. Using TM simulator data, Williams and Nelson (1986) found that SWIR bands enabled more accurate and detailed characterizations of insect damage in conifer and hardwood forests of North Carolina. Rock and colleagues (1986) likewise found with TM simulator data that a ratio-based SVI that included SWIR was able to detect stress associated with acid rain in Vermont forests. With TM data, the SWIR region has been identified as important for characterizing fire scars, windfall, thinning, and deforestation (e.g., Skole and Tucker 1993, Olsson 1994). Landsat's SWIR capabilities were a central reason that Coppin and colleagues (2001) proposed the system for operational monitoring of the forests of Minnesota.

The importance of SWIR reflectance has also been noted for nonforest applications. Lee and colleagues (1988) reported that the SWIR was the best spectral region for broad soil classification in leaf-off conditions because of its sensitivity to surface texture, organic matter content, and moisture. May and colleagues (1997) found TM to be better than other satellite multispectral data for mapping in a shrub-meadow complex because of its SWIR advantage.

Ecological applications of Landsat data

Landsat data have been translated into useful ecological information for more than 30 years, with both the methods and the applications growing increasingly sophisticated. In this section, we summarize Landsat applications in ecology, high-

lighting (a) the diversity of the uses of Landsat data to characterize the state and dynamics of ecosystems and (b) the increasing complexity of Landsat's integration with ecological models.

State and temporal dynamics of ecosystems. Ecosystems can be described by their condition (i.e., their state) and by how they are changing (i.e., their temporal dynamics). Since Landsat data became available, they have been regularly used for both purposes across a number of ecosystem types. Numerous studies have evaluated relationships between Landsat data and a number of attributes of vegetation, with some studies using derived maps in environmental applications. Analyses of Landsat have involved both the spectral and the spatial domains of the data, and Landsat data now figure prominently in large-area, operational mapping and monitoring.

Thematic classification. Forest classification (figure 1) has been a popular use of Landsat data for assessing such things as timber volume, wildlife habitat, successional stage, forest fragmentation, invasive species, rare and endangered plant species, biodiversity, and (with multirate data from a single growing season) characteristics of species (e.g., Gluck and Rempel 1996, Poole et al. 1996, Cohen et al. 2001, Dymond et al. 2002, Hansen et al. 2002). In other ecosystem types, classifications derived from Landsat data have been used to model wetland fish productivity, to map bird habitat in mixed cover types, to assess the cover density and productivity of coral reefs, to conduct fire risk assessment in shrublands, and (using multirate, single-season imagery) to map crop types in agricultural regions (e.g., Maselli et al. 1996, Oetter et al. 2001). The usual approach involves identifying spectral properties associated with classes of interest and then assigning class labels to image pixels with those properties.

Biophysics. While spectral-based classification of landscapes into discrete cover types is a prominent application of Landsat data, the use of these data for deriving continuous estimates of vegetation biophysical characteristics has been equally important (figure 2). Inversion of spectral models for isolated vegetation characteristics such as LAI, specific leaf area, biomass, canopy moisture content, and canopy cover has been used across a variety of vegetation types (e.g., Kanemasu et al. 1977, Lymburner et al. 2000, Steininger 2000). In forests, continuous representations of stand age have been derived (Cohen et al. 2001). Model inversions for simultaneous estimation of basic ecosystem component fractions such as soil, vegetation, and shade have been accomplished using mixture modeling approaches (Smith et al. 1990). Continuous surface properties not directly related to vegetation have also been studied with Landsat. Notably, the thermal band of Landsat TM has been used to characterize surface temperature (Holifield et al. 2003), and soil properties such as organic carbon content, phosphorus concentration, and pH have been estimated as continuous variables with Landsat data (e.g., Skidmore et al. 1997).