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THE IMPACT OF LANDSAT SATELLITE MONITORING ON CONSERVATION BIOLOGY

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Abstract. Landsat 7's recent malfunctioning will result in significant gaps in long-term satellite monitoring of Earth, affecting not only the research of the Earth science community but also conservation users of these data. To determine whether or how important Landsat monitoring is for conservation and natural resource management, we reviewed the Landsat program's history with special emphasis on the development of user groups. We also conducted a bibliographic search to determine the extent to which conservation research has been based on Landsat data. Conservation biologists were not an early user group of Landsat data because a) biologists lacked technical capacity – computers and software – to analyze these data; b) Landsat's 1980s commercialization rendered images too costly for biologists' budgets; and c) the broad-scale disciplines of conservation biology and landscape ecology did not develop until the mid-to-late 1980s. All these conditions had changed by the 1990s and Landsat imagery became an important tool for conservation biology. Satellite monitoring and Landsat continuity are mandated by the Land Remote Sensing Act of 1992. This legislation leaves open commercial options. However, past experiments with commercial operations were neither viable nor economical, and severely reduced the quality of monitoring, archiving and data access for academia and the public. Future satellite monitoring programs are essential for conservation and natural resource management, must provide continuity with Landsat, and should be government operated.

Keywords: conservation biology, Earth resource monitoring, global change, Landsat, Landsat history, satellite monitoring

1. A Satellite's Demise

On May 31, 2003, the sensor onboard the Landsat 7 satellite spacecraft began to malfunction, sending a warning throughout the global user community about the imperiled future of the Landsat program (USGS, 2003b). The sensor in question, the Enhanced Thematic Mapper plus (ETM+), is the latest in a series of data-capturing components of the Landsat program, initiated in 1972. This program provides the longest continuously available space-based environmental monitoring data for Earth, at a 30–65 m spatial resolution (Draeger *et al.*, 1997). While some of Landsat 7's problems have been mitigated by adaptive changes in the processing of ETM+ data, this sensor transmission crisis has proven only a foreshadowing of other troubles to come for this longstanding program.

In April 2004, Landsat 7, though compromised, completed its originally planned 5-year mission life (USGS, 2004), but no replacement satellite or sensor has been deployed, or even developed. In fact, the future of the Landsat program appears very doubtful. While the National Air and Space Administration (NASA) and the United States Geological Survey (USGS) claim that Landsat 7 still produces data that are useful though restricted in coverage area, plans for a future Landsat-like mission seem to have been shelved indefinitely. In September 2003, NASA's Landsat Data Continuity Mission (LDCM) scuttled one attempt at securing a private operator for the monitoring program, withdrawing its Request for Proposals (RFP) for the LDCM's development and implementation phases after insufficient commercial sector response. NASA announced it would evaluate other options for ensuring continuation of the Landsat data (http://ldcm.nasa.gov/). During 2004, NASA sent a Request for Information (RFI), seeking new continuation ideas, to the federal and non-federal research sectors (http://prod.nais.nasa.gov/cgi-bin/eps/sol.cgi?acquid=111775#Other%2001). Considering the time and effort it takes to develop a new sensor and platform and to deploy them, it may require several years to replace the Landsat satellites, meaning that data continuity for the longest-standing global satellite-monitoring endeavor may become seriously compromised.

It is difficult to assess all the consequences of these circumstances. Still, policy makers, environmental and conservation biologists, and natural resource managers may ask, what is most at risk? On a general level, that question is easily answered. Satellite monitoring has become one of the most powerful tools for monitoring global change, and yet we seem to be losing Landsat coverage, a benchmark tool, without replacement. The last decade of Landsat use has demonstrated the program's importance for global change and Earth observation sciences (Goward and Williams, 1997; Goward *et al.*, 1999, 2000), with Landsat data revealing rapid, dramatic and far-reaching changes in land cover and land use patterns. These changes, without doubt, will have significant impact on the future management and conservation of Earth's natural resources. Similarly, the near-certain loss of Landsat data continuity will itself have a deleterious effect on future natural resource conservation and management efforts. No other satellite monitoring program has produced a global data set with comparable accuracy or spatial and spectral resolution. Derivative Landsat products such as a global wall-to-wall coverage of orthorectified Landsat images for the late 1970s, circa 1990 and circa 2000, are now readily accessible via the Internet to academia and the public (Tucker *et al.*, 2004). Most other satellite monitoring programs do not provide low-cost imagery covering the entire globe (SPOT, IRS), or their sensor data are lacking spatial resolution (AVHRR, MODIS).

2. Global Change and Satellite Monitoring of Earth

Human-induced global changes in the 21st century may have tremendous impact on the survival of our natural world and of the human societies that depend on it. Human-induced changes include much of the world's deforestation (Skole and Tucker, 1993; Steininger *et al.*, 2001; Sanchez *et al.*, 2001) desertification (Jackson *et al.*, 1975; Otterman, 1976), and climate change (Lawton *et al.*, 2001; Weart, 2003, 2004), as well as massive species extinctions and rapid loss of intact natural ecosystems (Pimm *et al.*, 1995). Many of these changes to the environment start subtly and occur at spatial and temporal scales unfamiliar to conventional human thinking. From an Earthbound perspective, they can go undetected and unmonitored for years. For example, sea-level rise resulting from the melting of polar ice caps brought on by global warming initially may not be devastatingly perceptible, with the consequence that some interest groups can dispute the reality of global warming (Weart, 2004).

Programs for the acquisition of pertinent Earth science information from orbital satellites have dramatically altered our ability to monitor global changes and assess their impact (O'Neal, 1990; Skole and Tucker, 1993). A number of different satellite sensors, including Landsat, have been used to demonstrate and quantify: i) deforestation (Skole and Tucker, 1993; Steininger *et al.*, 2001); ii) increases in fire frequencies (Nepstad *et al.*, 1999; Cochrane, 2001); iii) changes in coral reef communities (Dustan *et al.*, 2001); iv) melting of the polar ice caps and glaciers (Doake and Vaughan, 1991), and many other global changes.

Most satellite sensors employed for these important assessments, however, were not originally designed with the intention to monitor global environmental changes. Satellite Earth sensors often were experimental and principally oriented towards development of advanced new technology and hardware; they were not designed with specific global change monitoring schemes in mind (Mack, 1990). But lack of such design intent doesn't necessarily eliminate a satellite's potential for global change monitoring. In discussing Landsat, historian Pamela Mack (1990, p. 122) points out:

> Technological systems are often used in ways not anticipated by their designers, both because users may find ways of using a new system not predicted during the development and because users may resist the intentions of the designers.

On Earth, environmental data collection procedures and protocols are usually determined by monitoring objectives and goals. However, frequently, science teams have found themselves actively developing new environmental applications for sensors already in orbit. As a consequence, sensor characteristics have been the primary drivers for identifying monitoring goals, instead of the reverse. An example of this is National Oceanographic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR), orbiting on board the Television Infrared Observation Satellite (TIROS) series and other NOAA satellites. This instrument was developed to be a meteorological sensor, measuring weather conditions via radiometric reflection in four spectral bands (Koffler and Spayd, 1990). However, the characteristics of the sensor's spectral bands and the fact that it could take a complete image of Earth every 12 h, made it also suitable for extensive fire and vegetation biomass monitoring – even leading to an online Internet resource providing near real-time data on fire occurrences globally (Goward and Williams, 1997; http://www.gvm.jrc.it/tem/wfw/wfw.htm).

The Landsat program is no exception to this tendency towards adaptive applications, as the Mack quotation above indicates. Many applications became apparent only after the program was well underway (Mack, 1990). Landsat's most unique feature, and greatest source of applications potential, is its longevity. Landsat provides the longest data record to address land use and land cover changes and their environmental impacts globally (Roughgarden *et al.*, 1991; Lauer *et al.*, 1997; Goward and Williams, 1997). NASA launched Landsat 1 (originally called Earth Resources Technology Satellite, or ERTS-1) in 1972, initiating the now more than 30-year Landsat mission (USGS, 2003a). Over time, the Landsat program would come to consist of a succession of six satellites (Landsat 6 never achieved orbit, due to problems with its launch platform) circling the Earth on polar orbits, collecting and transmitting satellite data and pictures covering the globe. These pictures and data today collectively constitute the largest consistent satellite database available for natural resource management (Draeger *et al.*, 1997).

Throughout the past decade or longer, the Landsat program has been at the core of global change research programs internationally (Goward *et al.*, 1999, 2000). Global change research has been mostly focused on Earth sciences. Our paper attempts to quantify the importance of the Landsat program for applied and basic research in conservation biology, and ultimately for management and conservation of natural resources and biodiversity. Natural resource managers and conservation biologists were not a defined target audience for NASA's satellite monitoring programs, but nonetheless the data produced by these programs may have had a significant effect on conservation biology research, or at least on the emergence and development of broad-scale ecological disciplines such as conservation biology and landscape ecology.

To evaluate the importance of Landsat monitoring in this regard, one needs to understand something about the evolution of the Landsat program and the context within which it has developed, and consider how the data produced have affected the development and practice of conservation science. We address these topics by:

1. briefly reviewing the history and evolution of the Landsat program, including the role different user communities have played in development of the sensors as well as in use of the data;
2. determining how the data have been used in conservation biology and ecology;
3. assessing the influence of Landsat data on science in these areas;
4. evaluating what other technological developments were needed to enable the effective use of Landsat data by this conservation science community.

3. Landsat Origins, Development, and Users

Throughout most of its existence, the Landsat program did not target ecologists or biologists as end-users. Its data collection was aimed initially at agricultural and geological uses and, to a lesser extent, at forestry. This orientation reflects the roles the Departments of Interior and Agriculture played in the program's early history. From its initial conception in the early 1960s, Landsat program development was problematic (Mack, 1990). NASA's Earth applications division, which developed weather, communications, and earth resources satellites, was always small and relatively weak, dwarfed, then as now, by space-oriented divisions. A central issue in planning of the Landsat program concerned the degree of involvement in sensor design and development NASA would cede to expected users. NASA always tended to restrict outside input into development of application satellites. Nonetheless, a few user groups did insert themselves into Landsat's development process, mainly because as government agencies with large budgets they could do so (Mack, 1990). The Department of the Interior (DOI), especially its Geological Survey (USGS), was intent on remote sensing for oil and mineral exploration, and the Department of Agriculture (USDA) was concerned with improving crop yield forecasts and crop disease monitoring. NASA's experimental focus favored the development of sophisticated new technology and hardware over simple, reliable, and quickly operational satellite sensors, just the opposite of the inclinations of these proactive future users. These collaborating government agencies sought cheap, reliable, quickly operational data collecting to fulfill their monitoring needs. The Department of Defense (DOD) also weighed in, ensuring that Landsat resolution would never equal that of the spy satellites DOD controlled. Eventually the scanner system first proposed by the USDA was chosen, but, ironically, at reduced resolutions that left Agriculture largely dissatisfied, while proving very useful to USGS (Mack, 1990).

DOI's acute concern over NASA delays led to DOI's unprecedented September, 1966 unveiling of a plan to launch its own "Earth Resources Observation Satellites" (EROS), forcing NASA to speed up its development and launch timetable (Johnson, 1998). Soon after, Interior, through its USGS division, refocused the EROS program on Landsat data processing and distribution. The acronym now stands for Earth Resources Observation Systems, a primary processor and distributor of Landsat images and data (Mack, 1990; Johnson, 1998). EROS has also played a pivotal role in creating a user market for Landsat by providing straightforward training in the most basic Landsat applications to both U.S. and foreign scientists and administrators (Johnson, 1998).

Other early Earth resources satellite interest groups included urban and regional planners, hydrologists, and geographers (Mack and Williamson, 1998). At the outset, the technology attracted few biologists or ecologists, and not only owing to NASA's neglect. Few had yet self-identified as prospective remote sensing users, nor were they – or their departments or professional societies – generally thinking on a global scale or about global change issues.

The first major U.S. symposium on Remote Sensing of Environment had been convened in February 1962 by the University of Michigan's Institute of Science and Technology, with a grant from the U.S. Office of Naval Research (Anonymous, 1964). Its three working groups focused, respectively, on remote sensing research needs in meteorology and oceanography, in geology and geophysics, and in agriculture, forestry, and botany. Agricultural production and crop concerns dominated the third working group's report; ecological topics were effectively absent (Shay, 1964).

This meeting was the first in a series of yearly – now biannual – symposia devoted to remote sensing topics, today coordinated by the independent non-profit International Center on Remote Sensing of the Environment (ICRSE) (O'Neal, 1990; http://www.icrse.org/). Ecological and conservation-oriented presentations began to appear in the proceedings of these symposia in any significant numbers only in the late 1980s. Similarly, a major 1967 National Research Council (NRC) study on "Useful Applications of Earth-Oriented Satellites," convened 13 separate panels; one covered forestry-agriculture-geography; another focused on geology, but none specifically addressed ecology, field biology or conservation (Landgrebe, 1997).

This stands to reason. In the 1960s "ecology" was barely evident as a discipline, and conservation biology was not yet even an imagined subdiscipline (Wilson, 1994; Christen, 1995; Bowler, 1993). Even in the 1970s, the first biologists concerned with conservation and park-building activities were usually locally motivated, primarily when their own field sites were threatened with development (Christen, 1995). These individuals tended to consider their own "conservation-mindedness" as a professional liability, a peripheral, non-scientific pursuit likely to be discounted by colleagues, and possibly held against them by tenure committees. Few extrapolated from these local "moonlighting" experiences to consider the potential of satellite Earth resources sensing for scientific conservation studies. During the course of the 1970s the International Biological Programme would do much to bring "big science" and large-scale thinking to practitioners of field biology, but this program was only in its early enactment stages at the time of Landsat design (Worthington, 1975; Christen, 1995).

As discussed above, the Landsat satellite system was developed mainly in the user context of federal government agencies charged with natural resource management (Mack, 1990). The environmental movement had not fully developed as a political force, and few feedback mechanisms existed to convey conservation interests, whether of scientists or lay people, at the time of the Landsat 1 launch. Still, the germ of the idea – Earth monitoring to benefit resource conservation, not just resource exploitation – was already on some minds, probably including that of Interior Secretary Stewart L. Udall (Mack, 1990; Johnson, 1998). One former USGS official, interviewed by Pamela Mack, suggested that Udall, a longtime conservationist, was especially interested in promoting a fast-moving DOI EROS satellite program in the mid-1960s specifically because he believed more government money should go to protecting natural resources and undeveloped areas (Mack, 1990).

Bureaucratic as well as conceptual hindrances may also have played a part in the late arrival of ecologists and conservation scientists to Landsat data. In the 1970s, NASA had trouble attracting some interest groups to Landsat information, partly because of the project's status as experimental, not operational, which placed in question the long-term utility of its data set (Mack, 1992). By 1979, Landsat was officially on its way to becoming an operational program, as asserted in Jimmy Carter's Presidential Decision 54, which also stipulated a long-term goal of Landsat's eventual private-sector operation (Mack and Williamson, 1998). Speeding things up, President Reagan abruptly impelled the 1985 transfer of Landsat's operational control to private industry, specifically to the Earth Observation Satellite Company (EOSAT) (Johnson, 1998). The intention was to subsidize EOSAT's Landsat operations until the data market itself paid Landsat's bill, but the government failed to produce a coherent subsidy package. Customers, lacking confidence in the system's long-term operation, consequently became scarcer, and for a time, data use dropped (Mack and Williamson, 1998).

President George H. Bush reversed Landsat's operational commercialization when he signed the Land Remote Sensing Policy Act of 1992. Landsat operational control returned to NASA, jointly with the DOD. In 1994, the Clinton administration amended this arrangement, assigning Landsat jointly to NASA, NOAA, and DOI. NASA was in charge of satellite procurement, NOAA would manage and operate the spacecraft and ground system, and DOI would again archive and distribute the data at cost (Mack and Williamson, 1998; Sheffner, 1994). The Land Remote Sensing Policy Act of 1992 also directed NASA and USGS to undertake jointly the Landsat Data Continuity Mission (LCDM).

As we explore below, by the 1990s, despite the program's roller-coaster development, Landsat data were being used far more for conservation-oriented purposes. For example, by 1992 the global change community had become very interested in Landsat data coverage of 20 years of Earth changes (Mack and Williamson, 1998). With global change becoming an important environmental topic in the 1990s, the research based on Landsat data also moved towards investigating patterns, processes, and effects of land cover changes on the biosphere and atmosphere. The obvious implications of land cover changes for biodiversity conservation contributed to increasing the numbers of Landsat users in the conservation biology community.

4. Landsat Uses in Conservation and Natural Resource Management

Despite conservation biologists not being a target audience, Landsat has had some impact on basic and applied scientific research in conservation biology, as well as in natural resources management. A bibliographic search focusing on keywords "Landsat," "conservation," and "biodiversity" reveals 179 published articles between 1975 and 2002 that addressed conservation or biodiversity issues using Landsat satellite imagery (Table I; for search methods, see Appendix). These papers

TABLE I

Journals having two or more articles found using the search term ("Landsat" or "ERTS" and "conservation" or "biodiversity")

Journal	# Articles
Conservation Biology[a]	17
International Journal of Remote Sensing[a]	15
Ecology[a]	14
Science[a]	13
Landscape Ecology[a]	12
Ecological Applications[a]	11
Bioscience[a]	10
Journal of Applied Ecology[a]	9
Biological Conservation[a]	7
Nature[a]	7
Environmental Management	6
Biodiversity and Conservation[a]	3
Cunninghamia	3
Environmental Conservation	3
Journal of Environmental Management	3
Agriculture, Ecosystems & Environment	2
Biotropica	2
Photogrammetric Engineering and Remote Sensing[a]	2
Remote Sensing of Environment	2
Soil Science Society of America Journal	2

[a] These journals were specifically targeted. See Appendix for description of methods used in bibliographic search.

were printed in 57 scientific journals ranging from *Conservation Biology* to the *Wildlife Society Bulletin*. We found 20 journals that published more than one article; these journals accounted for 80% of all the publications on the topic. The range and type of journal varied widely but several high-impact journals are included in the list, such as *Science*, *Nature*, and *Ecology*. The last two are also present in our list of the top seven journals that published 10 or more articles on the use of Landsat in conservation in this 27-year period. These seven journals present over 50% ($n = 92$) of all publications on the topic and include, in descending order of numerical importance, *Conservation Biology*, *International Journal of Remote Sensing*, *Ecology*, *Science*, *Landscape Ecology*, *Ecological Applications*, and *Bioscience*.

Landsat sensor characteristics, stemming from developments targeted at agricultural and geological uses, have had a strong impact on the nature of the sensor's utility for conservation biology. The majority of the published Landsat-based research we found in our bibliographic search focused on terrestrial ecosystems ($n = 156$, 90%). Only about 10% dealt with applications in marine or aquatic ecosystems combined ($n = 17$, 10%) (Figure 1a). To some extent, however, this may also reflect the limited focus in conservation activities on marine and aquatic ecosystems throughout the 1980s and 1990s. Only since the late 1990s has this focus started to change.

Similarly, when broken down into major habitat types, published conservation research is heavily biased towards forest habitats, accounting for 60% ($n = 103$) of papers (Figure 1b). As with the biome focus of Landsat-based research, the forest bias may largely be attributed to the radiometric, spectral and spatial resolution and characteristics of the data collected by the various Landsat sensors. The red, near-infrared and mid-infrared spectral bands especially have proven useful for detecting changes in forest canopies. Published studies on grasslands and agricultural areas are the next important group of research papers, though with 24% ($n = 41$), they are much smaller in number. The remaining 16% ($n = 28$) of the publications are focused on a diverse array of habitats, including mountainous areas, wetlands and even polar ice shelves.

Among forest habitats the focus has been on temperate forests, about 47% of the published papers (Figure 1c). This is followed by research on tropical rainforests (37%). All other forest types seem to be little monitored or studied using Landsat satellite imagery. That temperate edges out tropical by such a margin is a bit surprising considering that NASA had a special research program – the Landsat Pathfinder Program – that focused largely on changes in humid tropical forest ecosystems in the Amazon basin and Southeast Asia. However, the U.S. Forest Service and its university extensions were probably among the largest users of Landsat imagery, and clearly focused their efforts on temperate forest ecosystems in the continental U.S. In addition, one component of the Pathfinder program was actually focused on North American forests. Much of this work found easy access to the scientific journals, many of which are published in the United States.

We identified 10 major subject areas that were addressed in conservation biology through analysis of different aspects of Landsat imagery (Table II). The list of subjects is lead by research on land cover change, but also addresses more specific areas such as gap analysis, a method developed in the U.S. to identify gaps in the protection of biological diversity on a state-by-state basis (Scott *et al.*, 1993). Most of the publications address biological changes, ranging from broadly-addressed land cover changes to, more specifically, deforestation, habitat loss and fragmentation, fire monitoring, erosion and climate change. The biodiversity monitoring and gap analysis research are targeted especially towards using land cover types identified from remote sensing analysis of Landsat imagery to approximate biodiversity across the landscape and determine its current status and potential future threats. Lastly, the landscape ecological studies generally pertain to research that assesses effects on ecological processes of heterogeneity in the spatial arrangement of ecosystems or habitat types.

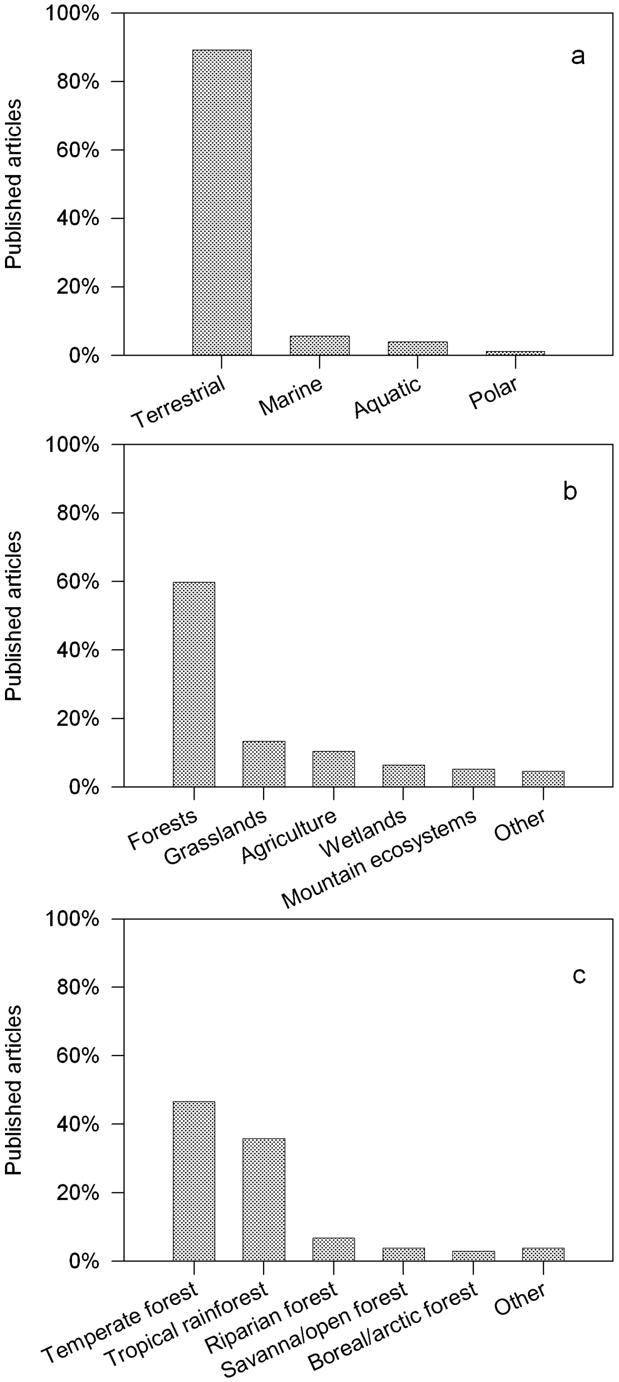

Figure 1. Biomes (a), habitat (b) and forest categories (c) covered by published conservation biology research utilizing Landsat satellite imagery.

TABLE II
Subject areas addressed by published articles using Landsat imagery for conservation and biodiversity science

Subject Area	Number of Articles
Land cover change	57
Biodiversity monitoring	32
Landscape ecology	32
Deforestation	31
Habitat loss	24
Habitat fragmentation	24
Fire monitoring	16
Erosion	10
Climate change	5
Gap analysis	5
Other	44

5. Factors Encouraging the Increasing Use of Landsat Imagery in Conservation Biology

Even in light of this range of publications, the use of Landsat in conservation biology really only began in the 1990s. Initially, this use of Landsat data was very restricted. While the first three papers on Landsat use in conservation biology were published in 1975, few research projects and articles followed in the subsequent decade (Figure 2). A cluster of papers in 1986, in *Bioscience* ($n = 6$), *Science* ($n = 1$), and *Ecology* ($n = 1$), represents the first increase in attention to the utility of Landsat-based remote sensing in conservation science. Only in 1995 did the number of published studies further increase, to at least 10 publications a year. A more noticeable boost occurred in 2000 and 2001, with publications based on Landsat satellite imagery almost doubling each year.

Factors that explain the prior infrequent use of these Landsat-derived data by conservation biologists include (Figure 2):

1. lack of affordable and appropriate analysis technology such as Personal Computers (PCs), fast microprocessors, adequate storage media, and of appropriate software, which hampered data utility during Landsat's early years;
2. high cost of the imagery, which for some years also helped place it out of reach of the moderate budgets of conservation biologists;
3. belated development of a broad-scale environmental science framework that would expand conservation science from species-based to ecosystem-based research and applications.

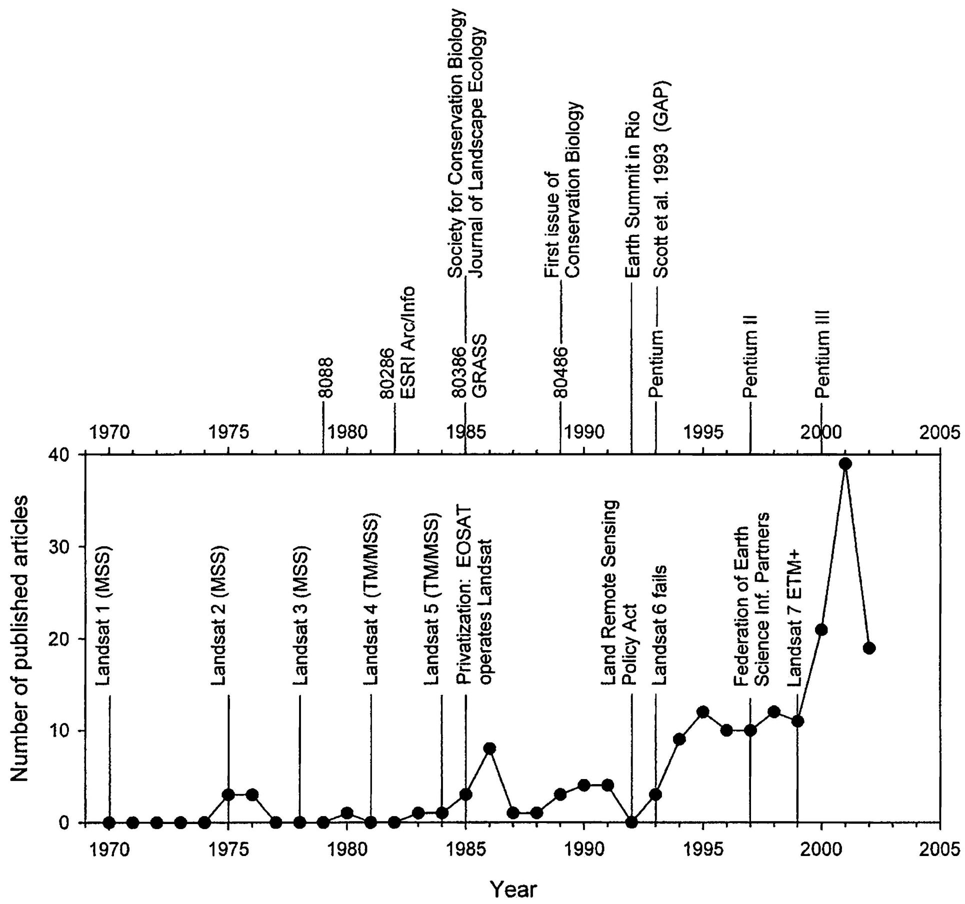

Figure 2. Timeline of Landsat data use in conservation biology publications as it relates to parallel developments in computer technology, Landsat pricing and administration, and development of broad-scale approaches in conservation biology.

5.1. THE DIGITAL REVOLUTION AND LANDSAT USE

The history of Landsat use in conservation biology parallels the digital revolution, i.e. the development of desktop digital analysis technology for the processing of large data sets (Figure 2). While sufficient computational power became available as the Landsat program unfolded, this was restricted to workstations and mainframes that biologists often could not afford. By the mid-1980s personal computers (PCs) were starting to become standard tools for biologists and were being used for data storage, database management, data analysis and modeling. Increased processing power and speed, as well as affordable pricing, allowed the spread of desktop PCs throughout the field. In October 1985, the first 386 microprocessor was released and, in April 1989, the first 486 was introduced. While these processors and the available

PCs had neither acceptable processing power nor analysis space to handle full Landsat satellite images, nonetheless with their advent working with data derived from the imagery did become more feasible. In the mid-1990s, with the emergence of the faster Pentium microprocessors, and PCs equipped with hard drives >1 GB and with CD drives, researchers without access to workstation or mainframe computing environments could endeavor to work with and analyze Landsat satellite images.

Concurrent with these developments, and equally important, was the development of geospatial analysis tools that provided software to import, store, display, and analyze satellite images and other spatial data, especially Geographic Information Systems (GIS) – a computer-supported spatial analysis environment. Today's most prominent GIS software provider – Environmental Systems Research Institute (ESRI) – developed its first GIS software, ArcInfo, in 1981 (http://www.esri.com/company/about/history.html). Along with other software packages, such as the Geographic Resources Analysis Support System (GRASS), which was developed by the U.S. Army Corps of Engineers, most of these tools were workstation or even mainframe based, although early on ESRI also provided a PC-based ArcInfo package. PC ArcInfo, however, could only process line-based spatial data and could not handle the Landsat-type digital raster data. These technological developments have significantly contributed to the steady increase in the use of Landsat data in conservation biology, though parallel developments in the field of biology were also required to account for the increases in publications.

Since the late 1990s, less than 20 years after the debut of GIS, workstations are no longer required for processing most satellite imagery. Processing multiple Landsat scenes using computationally complicated procedures has become an easily accomplished task for analysts and researchers using high-end desktop PCs.

5.2. Pricing policies: Landsat imagery cost reductions for users

Another likely reason for the adoption of Landsat data by conservation biologists during the mid-1990s was the significant reduction in Landsat data image pricing at that time. During the 1980s through mid-1990s, Landsat data were very high-cost (Draeger *et al.*, 1997). The number of publications seems to track nicely major policy changes that affected pricing for Landsat imagery (Figure 2). When Landsat data were "commercial," and being marketed by EOSAT in 1985, a single 185 by 170 kilometer "scene" typically cost as much as $4,400. Though the pricing was multi-tiered – allowing users in Federal agencies to purchase the data at much lower rates – this steep price increase eventually led to a reduced use of the imagery across the board. It appears the high price influenced many researchers to use AVHRR satellite imagery that was available for free (Hemphill, 2001), despite that sensor's much lower spatial resolution and fewer spectral bands. Finally in 1992, the Land Remote Sensing Policy Act allowed for cheaper prices (as low as $800 per scene) by charging the USGS with returning to its earlier responsibilities of management and sales of Landsat imagery (Johnson, 1998). With the newly available computational power and new lower prices, the number of publications in conservation biology using Landsat imagery started to increase (Figure 2). Because there is no copyright extant on satellite scenes, prices for archived images – images that have already been processed for another user, available at government or non-government data depositories – have dropped from $2,000 to $50 or even no cost. The new pricing for Landsat 7 ($475–$600 per scene) and the details of the Landsat 7 image acquisition plan – guaranteeing at least one satellite image for every place on Earth each year – means the new Landsat 7 program operation allows conservation biologists and non-governmental environmental organizations greater access to these images, despite their limited budgets. Multi-tiered pricing has been eliminated (Reichhardt, 1999; Sheffner, 1994).

5.3. Broad-scale approaches to ecology and conservation

Roughly concurrent with improved data access and better analysis technology, the late 1980s and early 1990s saw the development of biological research areas focusing on broad-scale issues – i.e. landscape ecology, gap analysis, and ecosystem management. Along with these research areas evolved new journals and institutions. One notable new journal, *Landscape Ecology*, was first published by Kluwer Academic Publishers in 1987. In 1986, the Society for Conservation Biology (SCB) was established to represent an ecological subfield focused on application and management-related ecological questions and devoted to "provid[ing] principles and tools for preserving biological diversity" (Lewis, 2004, p. 156). The first issue of that society's journal, *Conservation Biology*, also was published in 1987. In 1988 SCB held a seminal conference to identify "major, compelling research priorities" in conservation biology (Soulé and Orians, 2001, p. xiii). Number one among the five areas of highest priority was to "conduct a crash program of extensive surveys and mapping to identify areas that are critical for the protection of natural and genetic resources because of their high biotic diversity, or high levels of endemism, or because of imminent destruction of critical or unusual habitats and/or biotas" (Soulé and Orians, 2001, p. xiv). Item number three called for conducting studies at all spatial scales. Since that meeting, conservation biologists have increasingly recognized the importance of such research "especially at spatial scales larger than those that have typified ecological field experimentation" (Soulé and Orians, 2001, p. xv).

This parallel development of technology and theory provided the combination that in the 1990s made satellite data truly useful to conservation biologists and conservation organizations. Notable examples of resultant projects include the Gap Analysis project by Scott *et al.* (1993), which measured gaps in U.S. biodiversity protection by utilizing Landsat MSS and TM imagery.

Many projects took place outside the U.S., including that reported in another heavily cited paper, by Skole and Tucker (1993), measuring Amazonian deforestation and habitat fragmentation using Landsat TM data from 1978 to 1988, demonstrating the utility of comparative data. NASA and USGS have themselves supported some of the new global change-focused programs in this era, such as the Landsat Pathfinder Program, with its resultant data set, which NASA initiated in 1991. Under this program NASA has actually reconfigured selected portions of the global Landsat data archive to optimize Landsat data use for global change research. This program has several subcomponents, including broad-scale deforestation of humid tropical forests, characterization of North American landscapes and the "Land Cover Test Site Project," designed to improve data measurement. This last project developed Landsat data into a multi-epoch/multiseasonal data set for a selected group of test sites around the globe (http://www.ciesin.org/TG/RS/landsat.html; http://edcdaac.usgs.gov/pathfinder/pathpage.asp).

Many comparable efforts have been carried out without NASA's direct involvement or sponsorship, and many of them have utilized data from other sensors because Landsat data were too expensive to acquire or analyze. These projects include the first global forest map created largely from satellite imagery by the World Conservation Monitoring Centre, using AVHRR images from the 1980s and early 1990s (http://www.unep-wcmc.org/index.html? http://www.unep-wcmc.org/forest/fp_background.htm~main). A more recent non-NASA sponsored activity is the World Resources Institute's Frontier Forest Report, which used AVHRR data to measure measuring global deforestation and map key intact forests (Bryant *et al.*, 1997).

In the 1990s, environmental and conservation groups increasingly moved from species-centered, localized research approaches into regional, continental and even global approaches to their conservation research and conservation planning. Examples of these broad-scale conservation approaches are: "coarse-filter/fine-filter" analysis developed by Noss in the later 1980s (Noss, 1987); Gap Analysis (Scott *et al.*, 1993); Conservation International's biodiversity hotspots (Myers *et al.*, 2000); the World Wildlife Fund U.S. study of the "Global 200", a "science-based global ranking of the Earth's most biologically outstanding terrestrial, freshwater, and marine habitats," (Olson *et al.*, 2000); and Frontier Forests mapped by the World Resources Institute (Bryant *et al.*, 1997). This broadening of perspective and increasing awareness of the regional and global changes affecting biodiversity conservation and natural resource management required access to consistent and repeatedly collected global data on the condition of the environment. However, while government-associated groups were able to access Landsat data for free or at rates greatly reduced from the list prices for scenes, non-government environmental organizations initially relied entirely on available free data such as AVHRR data. Only with greater opportunities to use free or cheap Landsat data has the environmental community been able to gain full access to the utility of Landsat.

The 1992 United Nations Conference on Environment and Development (the "Rio Earth Summit") and the U.S. Government's Global Change Initiative, introduced during the 1990s, further expanded the end-user base for Landsat. NASA data purchases associated with the Global Change Initiative, especially, have resulted in extensive free access to satellite information for science and conservation organization researchers. Also of note in this regard has been the importance of the International Human Dimensions Programme on Global Environmental Change (IHDP), initially launched in 1990 by the International Social Science Council. The IHDP, in turn, collaborates with several international partner programs on global environmental change (Lambkin, 2003).

Today, Landsat satellite imagery and comparable products clearly belong in the toolboxes of landscape ecologists and many conservation biologists. Many of these researchers are probably relying on free or cheap Landsat data that is being distributed by various universities and conservation organizations via the Internet. Purchase of larger numbers of images for conservation biology research is probably mostly restricted to government agencies and U.S. universities. Surprisingly, these user communities have not yet widely voiced concerns about the future of the Landsat program and what this might mean for their applied and basic conservation research.

6. Conclusions

From our analysis of published research, it appears that over time Landsat data have become more widely available and utilized throughout the conservation biology community. However, even allowing for the existence of a considerable amount of gray literature, which was not included in our bibliographic search, the use of Landsat-derived data in conservation biology publications is not as extensive as we had expected. This may reflect the difficulties in developing scientifically rigorous ways for linking ecological processes across scale, i.e. linking the behavior of an organism or patterns in biodiversity at the local scale to changes in the biosphere at the regional, continental or even global scale. Glimpses of these scale issues become apparent in recent reviews of ecological and conservation applications of satellite remote sensing (Kerr and Ostrovsky, 2003; Turner *et al.*, 2003). Significant advances have already occurred, and, as conservation biologists continue to tackle scaling issues, it is clear Landsat use in conservation research will continue to expand.

Many of these conservation uses of Landsat-derived data occurred in the early 1990s, almost 20 years after the launch of the first Landsat satellite. While they paralleled NASA's and the U.S. government's recognition that Landsat data were truly useful for Earth system science and global change research (Goward *et al.*, 1999, 2000), applications of Landsat data for conservation biology received little attention. Considering the pattern of use in light of the early evolution of the Landsat program explains some of this imbalance:

a) The satellite system was developed for use mostly by federal government agencies charged with natural resource management. Conservation biology as a science had not yet developed and few feedback mechanisms existed that could convey conservation interests at the time of the Landsat 1 launch.

b) Rushed commercialization put program success at risk and resulted in the opposite of the intended outcome – less use of data and lower return on investment.
c) Use of Landsat data by non-government organizations or the wider public was of little concern during most of the development phase for Landsat and much of its operational life. During that time, also, few private users could purchase and operate computer and analysis equipment required for effective use of Landsat-derived data.

For Landsat to become a major research tool in conservation biology, many parallel and external developments had to occur. The most significant of these were:

a) Development of powerful and easy-to-use desktop PC and GIS software.
b) Reversal of the failed attempted commercialization of the Landsat program, eventually providing satellite imagery to conservation biologists who had no access to NASA and government agency budgets.
c) Rise of new research areas in the biological sciences that focused on conservation and landscape ecology, with their respective journals providing a platform for research into how land changes affect the conservation of species, communities and ecosystems.

Clearly the environmental community has a need for consistent global satellite coverage of the Earth's ecosystems. However, this community has not yet managed to become a major, consulted constituency of any of the satellite-operating government agencies. The renewed drive to commercialize Earth resources satellites will likely further restrict rather than enhance open access for environmental communities.

Based on our research, we believe operational Earth monitoring systems are needed to provide the environmental community, academia, and the public with critical information for research on major global conservation issues and to develop management strategies for the mitigation of global changes and their potential negative impact on Earth and human societies. This imperative gains heightened importance in a world where environmental policy decisions are no longer just a matter of local and national concern but have far-reaching impact on the global scale.

Concluding from these observations, we suggest there is a justified need for global satellite monitoring of Earth resources that provides rapid, inexpensive and consistent access to this type of information. Existing data, already increasingly accessible via the Internet, represent historical records of our natural heritage and should be made even more easily available to the public just as is being done with the holdings of major libraries and archival collections. Maintaining such accessible data repositories will not only be invaluable for short- and mid-term environmental policy decisions; by complementing other varieties of historical records, including natural history museum collections and land tenure data, these satellite-derived data repositories will provide future generations with accurate evidence of changes in human culture and value systems. Ongoing satellite monitoring programs need to be developed to create a consistently comparable record extending indefinitely the lineage of this historical resource. Data continuity should always be a major consideration in the development of future programs.

Much of the Landsat program's success can be attributed to a) its 30-m spatial resolution that allows for enough detail to detect land use changes; b) its long data continuity, providing records of how the Earth's land has changed over two to three decades, and c) recent Landsat data acquisition strategies permitting cloud-free images and seasonal assessments while providing global coverage. Calls for a new Landsat satellite should be formulated as calls for a guaranteed continued operational Earth resource satellite program with similar or even improved attributes. New, and different, satellites and sensors launched since the late 1990s, as components of NASA's new Earth Observing System (EOS), may provide data continuity fulfilling the basic requirements for such a program. However, so far these data are not as accessible as Landsat data. The imagery comes from newly developed and hence still largely experimental sensors. Currently most of these data seem not to be collected with the goal of global environmental monitoring. Although it may be technically possible, regular and complete coverage of Earth is not presently achieved by these satellite-based monitoring systems. In those cases where coverage is global, the spatial resolution is much lower than with Landsat. For example, the Moderate-Resolution Imaging Spectroradiometer (MODIS) offers only a spatial resolution of between 250 and 1,000 m. No clear plans have been communicated to a broader user community detailing a) how these sensors may fill the Landsat gap; b) whether the data acquired will adequately cover the entire globe and c) how, and at what cost, the data will be provided to end-users or archived for future use.

Finally, the U.S. government might recognize and support its land monitoring abilities in equal measure with its excitement about its endeavors in outer space and its proposed new mission to Mars. Congress's Land Remote Sensing Policy Act of 1992 clearly directs NASA and USGS jointly to undertake the LCDM. Additionally, these "Landsat equivalent" data are supposed to be available to all – "civilian, national security, commercial, and foreign policy interests" – at affordable costs, so that all sectors of the population have realistic access. The LCDM is also supposed to put the capstone on "operationalizing" by creating a system "less expensive to build and operate, and more responsive to users" than the present EROS system (lcdm.nasa.gov, July 2003). Unfortunately, the Act was formulated with the belief that this could be achieved via commercialization, or at least through dependent partnerships between U.S. agencies and private corporations. In a country with some of the world's best public museums and libraries, ensuring the inclusion of recent and historic Earth satellite data in public collections seems an important part of preserving the country's environmental legacy for future generations. Landsat and, hopefully, future continuing programs are providing huge opportunities in this direction that should not be missed.

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Appendix: Methods for Bibliographic Search

We searched four online bibliographic databases, including AGRICOLA (http://agricola.nal.usda.gov/), Zoological Record (http://www.biosis.org/products/zr/), Fish and Fisheries (http://www.nisc.com/), and Wildlife and Ecology Studies Worldwide (http://www.nisc.com/). Within each database we searched for [("Landsat" or "ETS") and ("conservation" or "biodiversity")]. Additionally, we searched the following journals for ("Landsat" or "ERTS") in the full text of all articles: *Biodiversity and Conservation*, *Biological Conservation*, *Bioscience*, *Conservation Biology*, *Ecological Applications*, *Ecology*, *Journal of Applied Ecology*, *Landscape Ecology*, *Nature*, and *Science*. We also searched for the term [("Landsat" or "ERTS") and ("conservation" or "biodiversity")] in the *International Journal of Remote Sensing* and in *Photogrammetric Engineering and Remote Sensing*. Our search covered the years 1972–2002. All searches were conducted in April of 2003; a small number of 2002 publications may not have been indexed in the search engines at that time.

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