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Earth Observations in Social Science Research for Management of Natural Resources and the Environment

Identifying the Contribution of the U.S. Land Remote Sensing (Landsat) Program

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RESOURCES FOR THE FUTURE

Earth Observations in Social Science Research for Management of Natural Resources and the Environment: Identifying the Contribution of the U.S. Land Remote Sensing (Landsat) Program

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Abstract

This paper surveys and describes the peer-reviewed social science literature in which data from the U.S. land remote sensing program, Landsat, inform public policy in managing natural resources and the environment. The Landsat program has provided the longest collection of observations of Earth from the vantage point of space. The paper differentiates two classes of research: methodology exploring how to use the data (for example, designing and testing algorithms or verifying the accuracy of the data) and applications of data to decisionmaking or policy implementation in managing land, air quality, water, and other natural and environmental resources. Selection of the studies uses social science-oriented bibliographic search indices and expands results of previous surveys that target only researchers specializing in remote sensing or photogrammetry. The usefulness of Landsat as a basis for informing public investment in the Landsat program will be underestimated if this body of research goes unrecognized.

Key Words: natural resources policy, environmental policy, Landsat, social science, environmental management

JEL Classification Numbers: Q0, Q2, O3

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Earth Observations in Social Science Research for Management of Natural Resources and the Environment: Identifying the Contribution of the U.S. Land Remote Sensing (Landsat) Program

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Introduction

From the first handheld cameras on the Gemini space missions to the sophisticated satellite instruments used today, Earth observations from the vantage point of space have enhanced understanding of humankind's relationship with the environment and natural resources. The Landsat program began in 1972 and continues today, serving as the longest, continuous source of remotely sensed resource data. This paper surveys the peer-reviewed social science literature in which data collected from space under the U.S. Landsat program are used to inform public policy in managing natural resources and the environment.

The paper seeks to identify the benefits of Landsat by differentiating articles in which methodology is designed to determine how to use Landsat data (for example, developing and testing algorithms or demonstrating the accuracy of the data) and articles in which data are applied for decisionmaking or policy implementation. The studies surveyed in this paper are selected from a wide range of publications within the social sciences using social science-oriented bibliographic search indices. Searching the social science literature leads to the identification of applications of these data by a community of experts unlikely to be identified by surveys of the Landsat program.[1] If this body of research is not recognized, the usefulness of Landsat data as a basis for public investment in the Landsat program will be underestimated.

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[1] For example, the American Society of Photogrammetry and Remote Sensing (ASPRS) recently surveyed "remote sensing professionals," a large community, but one that would not necessarily include the social scientists who have authored the papers identified in this review. The ASPRS survey is described at http://www.asprs.org/news/fli/Summary_of_Final_Results-ASPRS_Moderate_Resolution_Imagery_Survey.pdf (accessed June 2008); see slide 6 for description of the surveyed experts. Other recent surveys include Mitretek

The paper extends and updates previous discussions of social science applications of Landsat data (for example, see National Research Council [NRC; 1998] and Blumberg and Jacobson [1997]). These previous studies cite a wide range of applications, from archaeology and land use to public health. However, the sources are almost exclusively research papers on methodology development and demonstrations of the use of data rather than papers that use the data as an off-the-shelf research input as a basis for making decisions or implementing policy. Examples of the methodology-oriented literature cited in the NRC (1998) report include Green and coauthors (1994), who demonstrate the use of remote sensing to detect and monitor changes in land cover and use; Cowen and coauthors (1995), who demonstrate the design and integration of geographical information systems (GIS) for environmental applications; Hutchinson (1991), who shows the uses of the data for famine early warning; and Brondizio and coauthors, (1996), who show the link between thematic mapper (TM) data and botanical and historical data. Blumberg and Jacobson (1997) describe the promise and likely limits of observations for social science research and cite one social science application of Landsat data, a study of urban development in the San Francisco Bay and the Baltimore–Washington metropolitan regions (Acevedo et al. 1996).

The social science applications of Landsat are among the relatively recent uses of the data for several reasons discussed below. The earliest applications of Landsat data were in large-scale federal government demonstration programs and, later, in state and local government urban planning projects. Many of these applications served as experiments to determine how to use the data and tests of their limitations—precursors to more recent use in the social sciences. The newest generation of applications—those advancing the use of the data to enable innovation in public policy governing the management of environmental and natural resources—is represented by a body of literature largely of social science approaches to policy design. Examples of these innovations include the use of these data to provide essential information to underpin monetary estimates of ecosystem services and the development of "credit" programs for these services. These kinds of programs represent some of the most recent approaches to U.S. and international environmental management. Another example of a new approach, participatory resource

Systems (see Stoney et al. 2001) and a customer satisfaction survey by the U.S. Geological Survey ([USGS] in 2007; available from USGS by contacting Holly S. Stinchfield, Policy Analysis and Science Assistance Branch, USGS at stinchfieldh@usgs.gov). For an overview of the Landsat program and general discussion of communities using Landsat, see Lauer and coauthors (1997).

management, is significantly facilitated by Landsat data. The main contribution of this article is to describe and report results from a systematic literature search to identify these applications, summarize broad themes within the literature, and illustrate some of the policy innovations.

This article seeks to show that the usefulness of Landsat data is underestimated if this body of social science and policy research is not recognized. In addition, several factors influence the use of Landsat data in this research. For example, the use of data from advanced instruments that may be included on future Landsat missions will progress from technical validation, verification, and algorithm development to policy-related research. This literature review shows that this last step has taken as long as a decade. Technological innovation in computing and software capabilities and the cost of these complementary tools also influence the usability of data for policy.

Background and Context

The use of space-derived Earth observations has evolved through several generations of applications. Early research projects—the first generation—centered on government demonstration programs. Subsequent research—the second generation—built on the experiences and lessons from first-generation efforts and included the initial adoption of Landsat data for routine use. The most recent research and the focus of this paper—the third generation—has benefited significantly from the legacy of the earlier generations. This section briefly discusses the early applications of Landsat data to provide a context for the articles surveyed later in the paper. Figure 1 depicts these generations.

The First Generation—Foundational Research

The first generation of the use of Landsat sought to introduce and exemplify the potential of this new information. These activities provided a foundation for subsequent uses of these data by developing methods, protocols, and other complementary, supporting techniques to manipulate, store, and interpret the data. This period began in the 1960s with the successful launch of moderate spatial resolution imaging instruments on the Earth Resources Technology Satellite, later called Landsat.

Demonstration programs led by federal government agencies and some projects undertaken by private geologic exploration companies were among the major activities during this period. The government programs focused on the agricultural sector. The Large Area Crop Inventory Experiment (LACIE), jointly sponsored by the National Aeronautics and Space

Administration, the U.S. Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration from 1974 to 1978, demonstrated the potential for satellite observations from the Landsat series of multispectral scanners to make accurate, extensive, and repeated surveys for global crop forecasts. The Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS) program followed LACIE and extended the use of satellite observations. These extensions included systems for early warning of changes in forecasts of seasonal food production resulting from extreme weather or other events; the inventory and assessment of resources, such as water storage capacity in river basins (which affects irrigation); and related activities (Congressional Research Service 1983).

Companies conducting geologic resource exploration also were exploring the use of Landsat data at this time. The wide field of view of these data enabled identification of various land forms to map a region's structural features—essential for geologic research (for additional discussion, see Richers [n.d.]). These companies already had extensive experience in the sophisticated use of aerial remote sensing capabilities and also had the necessary tools in the form of both the facilities (computers and other equipment) and the expertise required to use Landsat data.

The Second Generation—Routine Use

During the 1980s, an increasing number of federal and, later, state and local agency decisions related to resource assessment and environmental management began to routinely incorporate Earth observations. Much of this well-established community of Landsat data users is identified by surveys such as those carried out by membership organizations of remote sensing specialists. The surveys find that public agencies use Earth observations as data inputs to computerized decision support systems; many agencies use these systems as part of the basis for carrying out their statutory mandates.

The growth in the breadth of communities in this second generation of applications of Landsat data is partly related to improvements in spatial resolution and other technical capabilities of the instruments (see Table 1). Additionally, important contributors to more widespread use include the decreasing cost and increasing capability of hardware and software (computers and other information technology as well as GIS and related software); the growth in the number of personnel trained to use remote sensing data; and the spread of information about Landsat data, which has allowed their use to percolate among new communities.

Federal Agencies

Several federal agencies began or expanded their use of Landsat and other remote sensing data during this period. A recent report from the U.S. Climate Change Science Program ([U.S. CCSP, 2008) describes in detail federal agency use of remote sensing, including Landsat data. The report shows that USDA has continued to build on the AgRISTARS and LACIE accomplishments by using Landsat and other remote sensing data in its Production Estimate and Crop Assessment Division and its Crop Condition Data Retrieval and Evaluation system (PECAD/CADRE), which evaluate worldwide agricultural productivity, to support activities of the Foreign Agricultural Service.[2]

Also documented in the U.S. CCSP report are several other examples of Landsat use. For example, to fulfill regulatory responsibilities in regulating air quality, the U.S. Environmental Protection Agency (EPA) uses several large computer models of industrial location, air emissions, atmospheric conditions, and other information. EPA's Community Multiscale Air Quality (CMAQ) modeling system uses Landsat in the modeling and measurement of multiple pollutants at multiple scales for air quality regulations and standards.[3] In CMAQ, Landsat data provide land-use and land cover change information as a basis for understanding surface exchange and biogenic emissions, both of which are determinants of air quality.

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) has also incorporated the use of Landsat and other Earth observations in its Hybrid Optimization Model for Electric Renewables (HOMER). A model for designing small-scale power systems, HOMER is used throughout the world to optimize deployment of renewable energy technologies. Landsat data provide information on tree use cover and density, which influence both solar and wind resources.

Another decision system, RiverWare, is used by the U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Tennessee Valley Authority to model and manage river basin systems. RiverWare requires data for multiple locations throughout a river system.

The federal government also uses Landsat data to facilitate tracking and assessment of public health issues. For example, the U.S. CCSP (2008) documents a model of the Centers for

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[2] In May 2003, USDA began to use land data from the Indian Remote Sensing Advanced Wide Field sensor instead of Landsat data because of problems with the scan line corrector on Landsat. See Reynolds (n.d.) and Mueller (n.d.).

[3] A detailed description of CMAQ is at http://www.epa.gov/asmdnerl/CMAQ/

Disease Control and Prevention (CDC) and Yale University, the Decision Support System to Prevent Lyme Disease. This system seeks to prevent the spread of the most common vector-borne disease, Lyme disease, of which tens of thousands of cases are reported annually in the United States. Landsat data provide information about tree cover, which influences the location and density of tick populations.

State and Local Agencies

Taken together, these federal agency models demonstrate a variety of applications of Landsat. As noted earlier, other levels of government now make use of these data as well. Recent NRC reports document the use of Landsat data by state and local agencies (NRC 2002, 2003). NRC found that the use of these data—although now increasing—was slow to develop in these agencies for several reasons. Many jurisdictions had been using high-resolution aerial imagery and found the Landsat resolutions to be less useful. In addition, budgetary constraints limited the ability of agencies to hire new personnel trained to use Landsat and to purchase the required hardware and software.

By the late 1980s and early 1990s, however, the institutional and technical capabilities changed to better enable the use of moderate-resolution data. The many examples of such use, some of which are noted by NRC (2002, 2003), include the following.

- The state of Maryland uses Landsat to create a "greenprint" to identify the state's forested areas. Baltimore City uses the data to create land-use maps of urban areas. The city also plans to use the data to map flood plains, plan watersheds, and identify viewsheds.
- Boulder County, Colorado, uses Landsat data in addition to data from the French Système pour l'Observation de la Terre, the Indian Remote Sensing Satellite, and aerial photographs to maintain and upgrade tax maps. The county also uses these data to identify wetlands, parks, and other open space; maintain roads; and redraw precinct boundaries as the population distribution changes.
- The Missouri Department of Natural Resources uses Landsat data to monitor state wetlands, map land use for tax purposes, and assess the health of forests.
- The Washington Department of Natural Resources uses Landsat data to manage federal lands within the state and to map changes in land use for the state's fire protection program.

NRC also cites the use of Landsat data by large, multijurisdictional regional governments. For instance, Portland Metro, which includes 24 city governments, three counties, and several special-purpose management districts, uses the data for planning land use and transportation. The Regional Land Information System for Portland Metro had initially used aerial imagery to acquire and maintain land records; in 1998, Landsat data were added to the system.

These examples are just a few of many cases of Landsat data use among public agencies and illustrate a second generation in which the data have come to play a role in public resource management.

A New Generation—Revolutionizing Management

The legacy of the applications described above has benefited social science researchers and policy analysts involved in the design of new approaches to resource and environmental management. These experts extend the application of Landsat data directly to policymaking by building on the earlier generation of demonstration programs and other pathfinding work.

This community is unlikely to be included in surveys typically used to identify Landsat users. The researchers are usually in social science departments and are not necessarily involved in remote sensing or photogrammetry. Rather, their uses are farther downstream.

The peer-reviewed social science research demonstrates the evolution of Landsat use. Table 2 outlines the steps taken in a bibliographic search to identify these applications as well as the search terms used. This search used two widely available citation indices, the Social Science Citation Index (SSCI) and EconLit. The search initially yielded 450 articles.

A large number of these articles focus exclusively or largely on comparing the performance of Landsat and other types of data, however, and make no link to the use of data specifically for public policy recommendations. Eliminating the methodologically focused articles reduced the number of policy-related publications to 139 articles. Of these articles, 130 appear in peer-reviewed publications (omitting 9 working papers and non-peer reviewed conference proceedings).

The next step selected only articles that use Landsat or other moderate-resolution imagery. Many articles use higher-resolution imagery, radar data, “night lights” data from the Defense Meteorological Satellite Program, or other non-Landsat, nonmoderate-resolution data.

This step identified these articles based on whether the author(s) specifically identify Landsat or other moderate-resolution imagery as the data source. These criteria led to 82 articles.

This search method has several limitations that could lead to an underestimate of Landsat data applications. For example, in 24 additional articles the title and abstract include the search terms, but the author(s) do not indicate whether data were Landsat or other moderate-resolution data. In other cases, neither the title nor the abstract include the terms but the article involves the use of Landsat data. An example is Gatrell and Jensen (2002), who use Landsat and field data to estimate tree canopy coverage in two Florida cities to study the relationship between urban forestry policy and economic development. Additionally, the two indices, SSCI and EconLit, although considered the most comprehensive social science indices, may not include all journals in which social science applications of Landsat appear. An example could be the field of public health.[4]

The first of the peer-reviewed articles identified in the search was published in 1988; most are much more recent, from about 2000 and later. Table 3 shows the distribution of these articles over time. The distribution suggests that a time period of about 20 years has elapsed between data validation, verification, and other methodology development and the use of the data as a basis for social science applications in public policy. Of course, as discussed above, these intervening years also include the adoption of the data for federal and other government agency use. And the intervening years also brought technological and cost-saving improvements in computing and software capability, as well as greater availability of training in the use of GIS as a complementary tool. All of these factors influence the capacity of public policy scholars to ask and answer the question, what policy innovation might these data enable?[5]

The literature represented by this set of articles centers on applying Landsat or other moderate-resolution imagery to the management of environmental and natural resources—approaches that the authors of these articles find to be enhanced or enabled by Landsat. The articles fall into several categories of environmental and natural resources. These include land

[4] Problems in the Landsat program, such as uncertainty of program continuity when the federal budget is constrained as well as technical failures in instruments, as noted earlier, probably reduce overall the adoption of Landsat data for many applications. The bibliographic search used in this review could not document these reductions, but their analysis is important to understand why Landsat may be underused.

[5] It would be misleading to assume that another 20 years will be required before future applied uses of new Landsat instruments were realized. Today's low-cost, highly capable computing power and the availability of spatial analysis software provide a stronger foundation for the rapid assimilation of new data than was available 20 years ago.

and forests, air, energy, habitat, and archaeological resources. The preponderance of articles addresses land use or forest resources. Table 4 shows the percentage of articles focusing on each type of resource (the total exceeds 100% because some articles address more than one type of resource). Table 5 lists the articles by publication date and resource topic.

Within these resource categories, the subjects of the articles are diverse; they address the following topics:

- deforestation in Mexico, the Amazon, and southeast Asia;
- other types of land use and changes in land use in geographically diverse countries, including the Philippines, Mexico, Africa, China, the United States, Vietnam, Madagascar, Indonesia, Nepal, India, Australia, Taiwan, Estonia, Uganda, Ecuador, Hong Kong, Albania, Cameroon, Puerto Rico, Mali, Peru, Zimbabwe, Belize, and Ghana;
- agricultural production;
- urban growth;
- wildfires;
- hydrological resources;
- air pollution;
- soil erosion;
- wildlife habitat;
- aquaculture; and
- watersheds.

The discussion below highlights 20 of these articles, selected to show the breadth of these applications.

Using "Credits" to Manage Natural Resources

Alvarez and coauthor (2003) link national agrarian policy to deforestation in the Peruvian Amazon and illustrate the role of moderate-resolution imagery in informing future programs that will provide tax-like credits for environmental management.

Responding to Deforestation, Reforestation, Forest Rehabilitation, and Afforestation

Apan and coauthor (1998) use Landsat TM data to define the appropriate size of forest rehabilitation plots depending on the steepness of slopes in Mindoro, Philippines. Dennis and coauthors (2005) compare the relative effects on land use of government-sponsored transmigration programs, commercial logging concessionaires, and forest fires as contributors to forest degradation in Indonesia. In related research, Dennis and Colfer (2006) link social science and remote sensing to explore additional causes of Indonesian forest fires. Foster and Rosenzweig (2003) analyze an increase in demand for forest products as a factor that increases forest cover in India, offsetting the expansion of agriculture and rising wages that usually decrease forest cover.

The Influence of Community Coalitions and Landholder Sizes on Tropical Deforestation

Harwell (2000) studies differences among government managers, international donors, environmental activists, and local citizens in their uses of remote sensing data to depict the extent and causes of forest fires in Indonesia. Alix-Garcia and coauthors (2005) observe greater deforestation in communities that form coalitions to cooperate in forest clearing; the authors identify a threshold size for these communities. To improve the management of deforestation, Aldrich and coauthors (2006) use imagery to distinguish the relative magnitudes of forested land conversion to agriculture by small and large landholders.

Participatory Resource Management

Brown (2006) examines the extent to which remote sensing data in Senegal influence participatory rural appraisals, in which villagers themselves have access to data for natural resource management.

Quantifying Neighborhood Satisfaction with Commercial and Residential Zoning

Ellis and coauthors (2006) show for urban planners the role of moderate-resolution imagery to measure neighborhood satisfaction with the use of trees and shrubs as buffers between residential and commercial areas.

Wildlife Habitat and Vehicle Collisions

Finder and coauthors (1999) use imagery to identify site and landscape conditions at white-tailed deer vehicle collision sites in Illinois and to recommend policy responses.

Monetary Estimates of Environmental Quality as a Neighborhood Amenity

Jensen and coauthors (2004) relate land cover to monetary estimates of neighborhood characteristics including income and housing values. Reginster and Goffette-Nagot (2005) use imagery to demonstrate the effects of environmental quality on residential location choices and land values.

Monetary Estimates of Ecosystem Services

Zhao and coauthors (2004) use remote sensing data to assess land-use change specifically as an indicator of the value to tourists of ecosystem preservation and maintenance.

Economic-Induced Changes in Agricultural Practices

Tsai and coauthors (2006) apply imagery to show how the practice of aquaculture responds to changes in land use, exports, and other economic, environmental, and demographic factors.

Advances in River Basin (Cachement) Management Practices

Adinarayana and coauthors (1994) demonstrate new approaches for hydrological management enabled by combining Landsat data with GIS.

Valuing Land

With the time series enabled by Landsat, Dai and coauthors (2005) are able to measure changes in the monetary value of land with respect to changes in land use over more than a decade. Braimoh and Vlek (2005) measure changes in land values as influenced by population growth and the development of markets for agriculture and other goods and services; the authors point out the implications of their observations for agricultural practices to maintain soil fertility.

Urban Development

Burchfield and coauthors (2006) study the relationship among ground water availability, climate, terrain, employment, and transportation infrastructure as determinants of various measures of “sprawl.” Grove and coauthors (2006) examine urban land use in relation to neighborhood characteristics (such as property ownership and income) and measures of neighborhoods’ propensity to care for their local environment and natural resources.

Conclusions

The use of Landsat data has a long and wide-ranging history. Foundational applications in federal demonstration programs such as LACIE and AgRISTARS, as well as private sector activities undertaken by geologic exploration companies, set the stage. An increasing number of federal, state, and local agencies began to adopt the use of these data during the next two decades as part of routine decisionmaking. Throughout this period, many of these applications were characterized by data validation and verification together with software and algorithm development.

Some of the most recent applications, during the past decade, are the focus of this report. These applications advance Landsat and Landsat-type data as a basis for social science research to enhance public policy. This community of researchers has not been typically included in user surveys or other measures. Yet the changes enabled by the data apply to the management of zoning, river basins, ecosystems, wildlife habitat, and deforestation/reforestation. This community is also difficult to identify, as it is not organized as a conventional trade association or professional society. The usefulness of Earth observation data could be underestimated if this body of research is not recognized. Demonstrating a full range of applications of Landsat is critical for the future of Earth observations when policymakers ask whether societal benefits exceed the costs of investing in the systems (for example, see discussion in Future Land Imaging Interagency Working Group [2007]).

The paper also notes the duration of the lag between the initial use of Landsat data in demonstration programs and their later use in policy applications. The lag time appears to be as long as two decades, although in the case of growth in the use of Landsat, these intervening years also brought technological advances in computing capability (exogenous to the Landsat community). The implication for applications of data from future Landsat series—if they include new instruments, for example—is that some time may be required before data from new instruments become integrated into public policy and their fullest socioeconomic benefit is realized. This observation lends support to concerns expressed by many experts about the desirability of continuity and stability in any series of data collection efforts.

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Tables and Figures

Table 1. Developments in the Landsat Series

Landsat series	Year	Sensors	Approximate spatial resolution (meters)	Bands	Bits/pixel
1	1972	MSS RBV	80 80	4 3	6
2	1975	MSS RBV	80 80	4 3	6
3	1978	MSS RBV	80 40	5[a] 1	6
4	1982	TM MSS	30 80	7 4	8
5	1984	TM MSS	30 80	7 4	8
6	1993[b]	ETM[c]	15 30 120	Pan[d] 6 1	8
7	1998	ETM+	15 30 60	Pan[d] 6 1	8

Notes: MSS, multispectral scanner; RBV, return-beam vidicon; TM, thematic mapper; ETM, enhanced TM; ETM+, enhanced ETM; Pan, panchromatic.

[a]Infrared band 5 with 240-meter resolution failed

[b]Launch failure

[c]Enhanced TM

[d]Panchromatic band

Source: Based on NRC (1995, Table 4.2, p. 111).

Table 2. Search Criteria for Peer-Reviewed Publications Describing Use of Landsat and Landsat-Type Data for Policy Innovation

Step1. Search of social science literature published from 1977 to February 2007 on natural resources and the environment (economics, management, policy analysis, geography, and land use) using Social Science Citation Index and EconLit[a] —A universe of 450 articles identified	
	Step 2. Omission of articles that develop algorithms, test or compare algorithms, or focus exclusively on other methodological research —139 articles identified out of the universe of 450
	Step 3. Selection of peer-reviewed articles (omitting proceedings papers, working papers, and so on) —130 articles identified out of the universe of 139
	Step 4. Selection of articles using Landsat or other moderate-resolution imagery —82 articles identified out of the universe of 130[b] — —

[a]Search criteria: ("remote sens*" OR satellite* OR "earth observ*" and data* or statistic*)

[b]May undercount articles using Landsat or Landsat-type imagery; 24 articles did not include source/type of data.

Table 3. Social Science Citation Indices—Timing of Publications

Time period	Number of publications
1977–1986	–
1987–1996	8
1997–2006	68
2005 – February 2007	6
Total 1977 – February 2007	82

Note: Search criteria: ("remote sens*" OR satellite* OR landsat* OR "earth observ*") AND (agricult* OR forest* OR water* OR climat* OR air* OR energy* OR "land use*") AND (data* OR statistic*)

Table 4. Distribution of Articles by Resource Focus (Percentage of Total)

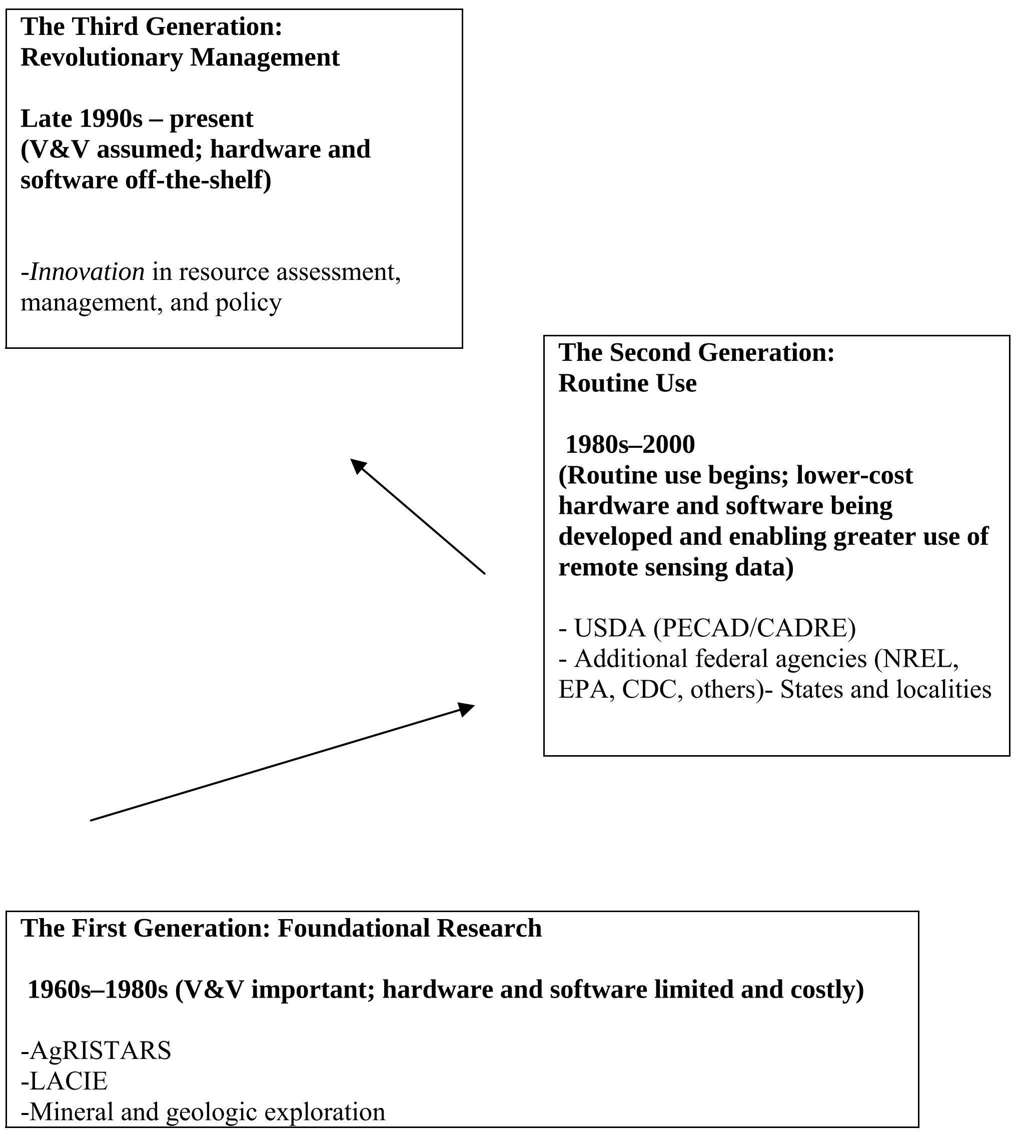
Distribution of Articles by Resources Focus (percent of total)					
	Air	Land/ forests	Habitat	Archaeology	Hydropower
	4%	92%	4%	4%	3%

Note: Total exceeds 100% because some articles focus on more than one resource.

Table 5. Peer-Reviewed Social Science and Policy-Related Research on Natural and Environmental Resources by Date and Type of Resource

1987–1996
Land: Battese et al. (1988), Huber (1993), Oneill et al. (1993), Reynolds (1993), Taylor et al. (1994), Apan (1996), Moran (1996)
Hydropower: Adinarayana et al. (1994)
Habitat: Huber (1993; also listed under "Land")
1997–2006
Land: Nelson and Hellerstein (1997), Apan and Peterson (1998), Peterson and Aunap (1998), Finder et al. (1999), Hunziker and Kienast (1999), Smil (1999), Harwell (2000), Hudak and Wessman (2000), Mertens and Lambin (2000), Mertens et al. (2000), Place and Otsuka (2000), Sierra (2000), Ward et al. (2000), Ochoa-Gaona (2001), Bucini and Lambin (2002), Laris (2002), Lo and Yang (2002), Muller and Zeller (2002), Munroe et al. (2002), Rudel et al. (2002), Vance and Geoghegan (2002), Alvarez and Naughton-Treves (2003), Anderson et al. (2003), Foster and Rosenzweig (2003), Perz and Skole (2003a), Perz and Skole (2003b), Schweik et al. (2003), Yang and Lo (2003), Apan et al. (2004), Jensen et al. (2004), Qi et al. (2004), Zhao et al. (2004), Alix-Garcia et al. (2005), Ayad (2005), Braimoh and Vlek (2005), Dai et al. (2005), Dennis et al. (2005), Emch et al. (2005), Jepson (2005), Jerrett et al. (2005), Liu et al. (2005), Messina and Walsh (2005), Nagendra et al. (2005), Pedlowski et al. (2005), Pfeffer et al. (2005), Reginster and Goffette-Nagot (2005), Seto and Fragkias (2005), Tan et al. (2005a), Tan et al. (2005b), Tian et al. (2005), Wakeel et al. (2005), Aldrich et al. (2006), Brown (2006), Burchfield et al. (2006), Dennis and Colfer (2006), Ellis et al. (2006), Grove et al. (2006), Ji et al. (2006), Kintz et al. (2006), Kirby et al. (2006), Muller and Sikor (2006), Nichol (2006),Tsai et al. (2006), Vagan (2006)
Hydropower: Hipple et al. (2005)
Air quality: Jerrett et al. (2005; also listed under "Land"), Brown (2006; also listed under "Land"), Nichol (2006; also listed under "Land")
Habitat: Peres (2001), Jepson (2005; also listed under "Land")
Archaeology: Nichol (1998), Hudson (2004)
January – February 2007
Land: Kamusoko and Aniya (2007), Martinuzzi et al. (2007), Nautiyal and Kaechele (2007), Olsen et al. (2007), Saroinsong et al. (2007)
Archaeology: Porter and Marlowe (2007)

Figure 1. Evolution of Landsat Applications



Notes: V&V, validation and verification of data quality; LACIE, Large Area Crop Inventory Experiment; AgRISTARS, Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing; USDA, U.S. Department of Agriculture; PECAD/CADRE, Production Estimate and Crop Assessment Division and its Crop Condition Data Retrieval and Evaluation system; EPA, U.S. Environmental Protection Agency; CDC, Centers for Disease Control and Prevention; NREL, National Renewable Energy Laboratory.