Earth Observations in Social Science Research for Management of Natural Resources and the Environment: Identifying the Landsat Contribution

Molly K. Macauley

Resources for the Future, Washington, DC

ABSTRACT

This paper surveys the peer-reviewed social science literature in which Landsat data are used to inform public policy in managing natural resources and the environment. The paper differentiates articles in which methodology is developed (for example, developing and testing algorithms or demonstrating how data could be used) 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. Selection uses social science-oriented bibliographic search indices. Searching the social science literature leads to identification of applications of Landsat by a community of experts unlikely to be identified by surveys or overviews of the Landsat program. Surveys and overview studies have tended to target researchers specializing in remote sensing or photogrammetry rather than researchers drawn from the social sciences. The usefulness of Landsat data as a basis for public investment in the Landsat program is underestimated in the absence of recognizing this body of research.

KEYWORDS

natural resources policy, environmental policy, Landsat, social science, environmental management

ACKNOWLEDGMENTS

The financial support of the United States Geological Survey (USGS), Geography Discipline, and Resources for the Future is gratefully acknowledged. Comments and guidance from Richard Bernknopf, Carolyn Hermans, their colleagues with USGS, two anonymous reviewers, and the editors are also deeply appreciated. Carl Jantzen and Chris Clotwothy provided excellent research assistance. Responsibility for errors and opinions rests exclusively with the author.

INTRODUCTION

From the first hand-held cameras on the Gemini space missions to present day, sophisticated satellite instruments, Earth observations from the vantage point of space have enhanced understanding of humankind's relationship with the environment and natural resources. This paper surveys the peer-reviewed social science literature in which Landsat data are used to inform public policy in managing natural resources and the environment. The paper differentiates articles in which methodology is developed (for example, developing and testing algorithms or demonstrating how data could be used) 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. Selection uses social science-oriented bibliographic search indices. Searching the social science literature leads to identification of applications of Landsat by a community of experts unlikely to be identified by surveys of the Landsat program. [1] The usefulness of Landsat data as a basis for public investment in the Landsat program is underestimated in the absence of recognizing this body of research.

The paper extends and updates previous discussion of social science applications of Landsat data (for example, see National Research Council (NRC), 1998 and Blumberg and Jacobson, 1997). The previous studies cite a wide range of applications from archaeology and land use to public health. However, the citations almost exclusively are research on methodology development and demonstrations of the use of data rather than taking the data as an off-the-shelf research input and using them as a basis for making decisions or implementing policy. Examples of the methodology-oriented literature cited in the NRC report include Green et al., (1997), who demonstrate the use of remote sensing to detect and monitor changes in land cover and use; Cowen et al., (1995), who demonstrate design and integration of GIS for environmental applications, Hutchinson (1991), who show uses of data for famine early warning, and Brondizio et al., (1996), who show the link of thematic mapper data with botanical and historical data. Blumberg and Jacobson describe the promise and likely limits of observations for social science research and cite one 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 more recent uses of the data for several reasons discussed below. The earliest applications of Landsat data were in large-scale government demonstration programs and later, in state and local agencies. Many of these applications served as experiments on how to use the data and to test their limitations—precursors to more recent use by the social sciences. The newest generation of applications, those advancing use of the data to enable innovation in public policy governing management of environmental and natural resources—is represented by a body of literature largely of social science approaches to policy design. 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. Examples of these innovations include the use of 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 are some of the most recent approaches to US and international environmental management. Another example of a new approach is participatory resource management, an approach significantly facilitated by Landsat data.

This article seeks to show that the usefulness of Landsat data is underestimated in the absence of recognizing this body of social science and policy research. In addition, several factors influence the use of these data in this research. For example, the use of data from advanced instruments that may be included on future Landsat missions will progress first from technical validation, verification, and algorithm development, and then to policy-related research. This literature review in this article 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 usability of data for policy.

BACKGROUND AND CONTEXT

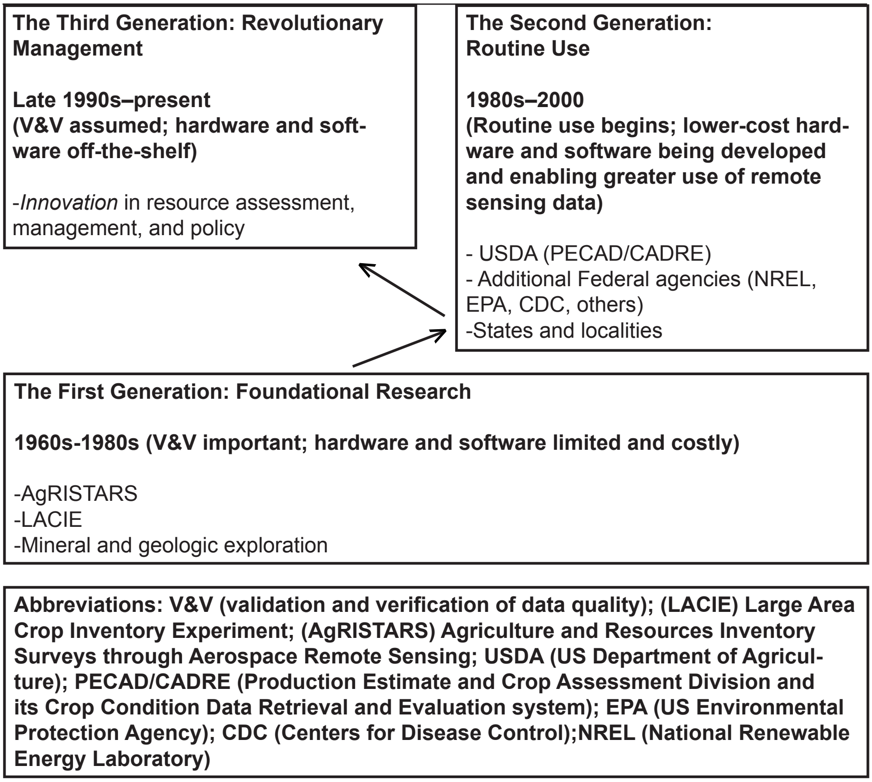
The use of space-derived Earth observations has evolved through several generations of applications. Early research projects—a "first generation"—centered on government demonstration programs. Subsequent research—a "second generation"—built on the experiences and lessons from these efforts and included the beginning of adoption of Landsat data for routine use. The most recent research and the focus of this paper—the "newest generation"—has benefited significantly from the legacy of these earlier generations. This section briefly discusses these early applications 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 use of Landsat sought to introduce and exemplify the potential of this new information. These activities provided a foundation for subsequent uses of data by developing methods, protocols, and other complementary, supporting techniques to manipulate, store, and interpret data. This period began in the 1960s with the successful launch of moderate spatial resolution imaging instruments on the Earth Resources Technology Satellite (ERTS), later called Landsat.

Two major activities during this period were demonstration programs led by federal government agencies and some projects undertaken by private geologic exploration companies. The government programs focused on the agricultural sector. The Large Area Crop Inventory Experiment (LACIE), jointly sponsored by the US National Aeronautics and Space Administration (NASA), the US Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration (NOAA) during 1974 to 1978 demonstrated the potential for satellite observations (from the Landsat series of multi-spectral scanners) to make accurate, extensive, and repeated surveys for global crop forecasts. The Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing program (AgRISTARS) followed LACIE and extended the use of satellite observations. These extensions included early warning of changes in forecasts of seasonal food production due to extreme weather or other events, the inventory and assessment of resources such as water storage

Figure 1. Evolution of Landsat Applications



capacity in river basins (which affects irrigation), and related activities (Congressional Research Service, 1983).

Companies conducting geologic resource exploration also were exploring 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, no date). These companies already had sophisticated experience in using aerial remote sensing capabilities and also had the necessary tools in the form of both facilities (computers, other equipment) and 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 began to routinely incorporate Earth observations in resource assessment and environmental management. Much of this well-established community 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; these systems form part of the basis of how many agencies carry 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 geographic information systems and related software), the growth in the number of personnel trained to use remote sensing data, and the spread of information about Landsat data (enabling 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 US Climate Change Science Program office (US CCSP) describes in detail federal agency use of remote sensing, including Landsat data.[2] The report shows that USDA has continued to use 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) to support activities of the Foreign Agricultural Service (FAS). PECAD/CADRE is used to evaluate worldwide agricultural productivity.[3]

Table 1. Developments in the Landsat Series.

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

Abbreviations and Notes:
MSS – Multispectral Scanner; RBV – Return-beam Vidicon; TM - Thematic Mapper; ETM – Enhanced Thematic Mapper; 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 National Research Council, 1995, Table 4.2, p. 111.

Also documented in the US CCSP report are several other examples of Landsat use. For example, to fulfill regulatory responsibilities in regulating air quality, the US Environmental Protection Agency (EPA) has several large, computer models of industrial location, air emissions, atmospheric conditions, and other information. The EPA's Community Multiscale Air Quality Monitoring System (CMAQ) uses Landsat in modeling and measurement of multiple pollutants at multiple scales for air quality regulations and standards.[4] 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 US Department of Energy's National Renewable Energy Laboratory (NREL) has also incorporated use of Landsat and other Earth observations in its Hybrid Optimization Model for Electric Renewables (HOMER). HOMER is a model for designing small-scale power systems and 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 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 US CCSP documents a model of the US Centers for 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 there are tens of thousands of cases annually in the United States. Landsat data provide information about tree cover, which influences the location and density of tick populations.[5]

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 reports by the National Research Council (NRC) document use of Landsat data by state and local agencies (National Research Council 2002, 2003). The NRC found that use of these data—although now increasing—had been 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 hiring of new personnel trained to use Landsat as well as the purchase of required hardware and software.

By the late 1980s and early 1990s, however, the institutional and technical capabilities changed to better enable use of moderate-resolution data. There are many examples; some noted by the NRC include the following:

- The state of Maryland uses Landsat to create a "greenprint" to identify the state's forested areas. Baltimore City uses data to create land use maps of urban areas. The city also plans to use data for mapping flood plains, planning watersheds, and identifying viewsheds.

- Boulder County, Colorado uses Landsat data in addition to data from the French Systeme pour l'Observation de la Terre (SPOT), the Indian Remote Sensing Satellite (IRS) and aerial photos to maintain and upgrade tax maps. The County also uses these data for identifying wetlands, parks and other open space; maintaining roads, and redrawing precinct boundaries as population distribution changed.

- The Missouri Department of Natural Resources uses Landsat data to monitor state wetlands, map land use for tax purposes, and to assess the health of forests.

- The Washington Department of Natural Resources uses Landsat data to manage federal lands within the state and for mapping changes in land use for the state's fire protection program.

The NRC also cites use of Landsat data by large, multi-jurisdictional regional governments. For instance, Portland Metro, which includes 24 city governments, three counties, and several special-purpose management districts, uses data for planning land use and transportation. The Regional Land Information System for Portland Metro had first 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 uses of Landsat among public agencies and illustrate a "second generation" in which the data have come to have a role in public resource management.

A New Generation—Revolutionizing Management

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

This community is unlikely to be included in surveys typically used to identify Landsat use. The researchers are usually in social science departments and 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. This search uses two widely available citation indices, the Social Science Citation Index 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 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 nine working papers and non-peer reviewed conference proceedings).

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

Step 1. Search of social science literature on natural resources and the environment (economics, management, policy analysis, geography and land use) using *Social Science Citation Index and EconLit**

--Search of all articles during 1977–February 2007; 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 universe of 450

Step 3. Selection of peer-reviewed articles (omit proceedings papers, working papers, etc.)

--130 articles identified out of universe of 139

Step 4. Selection of articles using Landsat or other moderate resolution imagery

--82 articles identified out of universe of 130**
--99% used Landsat
--Article author(s), title, journal, date listed in References

* Search criteria ("remote sens*" OR satellite* OR "earth observ*" and data* or statistic*)
** May undercount articles using Landsat or Landsat- type of imagery; 24 articles did not include source/type of data.

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, non-moderate-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 eighty-two articles.

This search method has several limitations that can lead to an underestimate of Landsat data applications. For example, there were twenty-four additional articles in which 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 use of Landsat data. An example is Gatrell and Jensen (2002), who used 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, while considered to be 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.[6]

The first of the peer-reviewed articles identified in the search was published in 1988; most are much more recent, from about 2000 and beyond. Table 3 shows the distribution of these articles over time. The distribution suggests the time period that has elapsed between data validation, verification, and other methodology development and the use of data as a basis for social science applications in public policy. The period appears to be about twenty years. Of course, as discussed above, these intervening years also include adoption of the data for federal and other governmental agency use. And, the

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*)

intervening years also brought technological and cost-saving improvements in computing and software capability, as well as greater availability of training in use of geographic information systems as a complementary tool. All of these factors influence the capacity of public policy scholars to ask and answer "what policy innovation might these data enable?" [7]

The literature represented by this set of articles are centered on applying Landsat or other moderate resolution imagery to managing 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 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:

- 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, Albania, Cameroon, Puerto Rico, Mali, Peru, Zimbabwe, Belize, and Ghana
- Agricultural production
- Urban growth
- Wildfires
- Hydrological resources
- Air pollution

Table 4. Distribution of Articles by Resource 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 et al., (1993), Oneill et al., (1993), Reynolds (1993), Taylor et al., (1994), Apan (1996), Moran (1996)

Hydro: Adinarayana et al., (1994)

Habitat: Huber et al., (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), Tan et al., (2005), Tian et al., (2005), Wakeel et al., (2005), Seto and Fragkias (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), Vagen (2006)

Hydro: 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)

Jan–Feb 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)

- Soil erosion
- Wildlife habitat
- Aquaculture
- Watersheds

The discussion below highlights twenty of these articles, selected to show the breadth of these applications:

- *Using "Credits" to Manage Natural Resources*

Alvarez and Naughton-Treves (2003) linked national agrarian policy to deforestation in the Peruvian Amazon and illustrated the role of moderate resolution imagery in informing future programs that would provide tax-like credits for environmental management.

- *Responding to Forest Deforestation, Reforestation, Rehabilitation, and Afforestation*

Apan (1996) used Landsat TM data to define the appropriate size of forest rehabilitation plots depending on the steepness of slopes in Mindoro, Philippines. Dennis et al., (2005) compared 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 et al., (2006) linked social science and remote sensing to explore additional causes of Indonesian forest fires. Foster and Rosenzweig (2003) analyzed an increase in demand for forest products as a factor that increased 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) studied 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 et al., (2005) observed greater deforestation in communities that formed coalitions to cooperate in forest clearing; the authors identified a threshold size for these communities. To improve management of deforestation, Aldrich et al., (2006) used imagery to distinguish the relative magnitudes of forested land conversion to agriculture by small and large landholders.

• *Participatory Resource Management*

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

• *Quantifying Neighborhood "Satisfaction" with Commercial and Residential Zoning*

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

• *Wildlife Habitat and Vehicle Collisions*

Finder et al., (1999) used imagery to identify site and landscape conditions at white-tailed deer vehicle collisions in Illinois and recommended policy responses.

• *Monetary Estimates of Environmental Quality as a Neighborhood Amenity*

Jensen et al., (2004) related land cover to monetary estimates of neighborhood characteristics including income and housing values. Reginseter (2005) used imagery to demonstrate the effects of environmental quality on residential location choices and land values.

•*Monetary Estimates of Ecosystem Services*

Zhao et al., (2004) used 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 et al., (2006) applied imagery to show how the practice of aquaculture responded to changes in land use, exports, and other economic, environmental, and demographic factors.

•*Advances in River Basin (Cachement) Management Practices*

Adinarayana et al., (1994) demonstrated new approaches for hydrological management enabled by combining Landsat data with geographic information systems (GIS).

• *Valuing Land*

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

• *Urban Development*

Burchfield et al., (2006) studied the relationship among ground water availability, climate, terrain, employment, and transportation infrastructure as determinants of various measures of "sprawl." Grove et al., (2006) examined urban land use in relation to neighborhood characteristics (such as property ownership and income) and measures of neighborhoods' "affinity" for caring 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 then 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 use of data during the next decades as part of routine decision making. Throughout this period, data validation and verification together with software and algorithm development characterized many of these applications.

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 of 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 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 in the absence of recognizing this body of research. 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 Imagery Working Group, 2007).

The paper also notes in passing the length of the lag between initial use of Landsat in demonstration programs and later use in policy applications. The lag time appears to be as long as two decades, although in the case of growth in use of Landsat, these intervening years also brought technological advances in computing capability as well (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. This observation lends support to concerns expressed by many experts about the desirability of "continuity" and "stability" in any series of data collection efforts.

NOTES

1 For example, the American Society of Photogrammetry and Remote Sensing (ASPRS) recently surveyed "remote sensing professionals," a large community but one which would not necessarily include the social scientists who've authored the papers identified in this study. 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 Systems (see Stoney, Fletcher, and Lowe, 2001) and a customer satisfaction survey by the US Geological Survey (in 2007; available from USGS by contacting Holly S Stinchfield, Policy Analysis and Science Assistance Branch, U.S. Geological Survey at stinchfieldh@usgs.gov)). For an overview of the Landsat program and general discussion of communities using Landsat, see Lauer et al., (1997).

2 See US Climate Change Science Program, forthcoming.

3 In May 2003, the USDA began to substitute remote sensed data from land surfaces from the Indian Remote Sensing Advanced Wide Field sensor instead of Landsat data, due to problems with the scan line corrector on Landsat. See Reynolds (no date) and Mueller (no date).

4 See http://www.epa.gov/asmdnerl/CMAQ/

5 See Climate Change Science Program, chapter 4.

6 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 paper cannot observe these reductions, but their analysis is important to understand reasons why Landsat may be underused.

7 It would be misleading to assume that another twenty years would 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 assimilation of new data than was available twenty years' ago.

REFERENCES

Acevdo, W., T.W. Foresman, and J.T. Buchanan. (1996). Origin and philosophy of building a temporal database to examine human transformation processes. *Netscape* (http://research.umbc.edu/tbenja1/bwhp/main.html), August.

Adinarayana, J., Flach, J.D., and Collins, W.G. (1994). Mapping Land-Use Patterns in a River Catchment Using Geographical Information-Systems. *Journal of Environmental Management*. 42(1): 55-61.

Aldrich, S.P., Walker, R.T., Arima, E.Y., Caldas, M.M., Browder, J.O., and Perz, S. (2006). Land-Cover and Land-Use Change in the Brazilian Amazon: Smallholders, Ranchers, and Frontier Stratification. *Economic Geography*. 82(3): 265-288.

Alix-Garcia, J., de Janvry, A., and Sadoulet, E. (2005). A Tale of Two Communities: Explaining Deforestation in Mexico. *World Development*. 33(2): 219-235.

Alvarez, N.L., and Naughton-Treves, L. (2003). Linking national agrarian policy to deforestation in the Peruvian Amazon: A case study of Tambopata, 1986-1997. *Ambio*. 32(4): 269-274.

Andersen, F.M., Grinderslev, D., and Werner, M. (2003). Environmental satellite models for a macroeconomic model. *Environmental & Resource Economics*. 24(3): 197-212.

Apan, A.A. (1996). Tropical landscape characterization and analysis for forest rehabilitation planning using satellite data and GIS. *Landscape and Urban Planning*. 34(1): 45-54.

Apan, A.A., and Peterson, J.A. (1998). Probing tropical deforestation - The use of GIS and statistical analysis of georeferenced data. *Applied Geography*. 18(2): 137-152.

Apan, A.A., Raine, S.R., Le Brocque, A., and Cockfield, G. (2004). Spatial Prioritization of Revegetation Sites for Dryland Salinity Management: An Analytical Framework Using GIS. *Journal of Environmental Planning and Management*. 47(6): 811-825.

Ayad, Y.A. (2005). Remote sensing and GIS in modeling visual landscape change: a case study of the northwestern and coast of Egypt. *Landscape and Urban Planning.* 73(4): 307-325.

Battese, G.E., Harter, R.M., and Fuller, W.A. (1988). An Error-Components Model for Prediction of County Crop Areas Using Survey and Satellite Data. *Journal of the American Statistical Association*. 83(401): 28-36.

Blumberg, D. and Jacobson, D. (1997). New frontiers: remote sensing in social science research. *The American Sociologist* Fall, 62-68.

Braimoh, A.K., and Vlek, P.L.G. (2005). Land-cover change trajectories in Northern Ghana. *Environmental Management*. 36(3): 356-373.

Brondizio, E., Moran, E., Mausel, P., and Wu, U. (1996). Land cover in the Amazon estuary: linking of the thematic mapper with botanical and historical data. *Photogrammetric Engineering and Remote Sensing* 62(8): 921-929.

Brown, M.E. (2006). Assessing Natural Resource Management Challenges in Senegal Using Data from Participatory Rural Appraisals and Remote Sensing. *World Development*. 34(4): 751-767.

Bucini, G., and Lambin, E.F. (2002). Fire impacts on vegetation in Central Africa: a remote-sensing-based statistical analysis. *Applied Geography*. 22(1): 27-48.

Burchfield, M., Overman, H.G., Puga, D., and Turner, M.A. (2006). Causes of Sprawl: A Portrait from Space. *Quarterly Journal of Economics*. 121(2): 587-633.

Congressional Research Service, Science Policy Research Division. 1983. "United States Civilian Space Programs, Volume II Applications Satellites," prepared for the Subcommittee on Space Science and Applications of the Committee on Science and Technology, U.S. House of Representatives, May.

Cowen, D., Jensen, J., Bresnahan, G., Ehler, D., Traves, D., Huang, X., Weisner, C., and Mackey, H.E. (1995). The design and implementation of an integrated GIS for environmental applications. *Photogrammetric Engineering and Remote Sensing* 61(11): 1393-1404.

Dai, E., Wu, S.H., Shi, W.Z., Cheung, C.K., and Shaker, A. (2005). Modeling change-pattern-value dynamics on land use: An integrated GIS and artificial neural networks approach. *Environmental Management*. 36(4): 576-591.

Dennis, R.A., and Colfer, C.P. (2006). Impacts of land use and fire on the loss and degradation of lowland forest in 1983-2000 in East Kutai District, East Kalimantan, Indonesia. *Singapore Journal of Tropical Geography*. 27(1): 30-48.

Dennis, R.A., Mayer, J., Applegate, G., Chokkalingam, U., Colfer, C.J.P., Kurniawan, I., Lachowski, H., Maus, P., Permana, R.P., Ruchiat, Y., Stolle, F., Suyanto, and Tomich, T.P. (2005). Fire, people and pixels: Linking social science and remote sensing to understand underlying causes and impacts of fires in Indonesia. *Human Ecology*. 33(4): 465-504.

Ellis, C.D., Lee, S.W., and Kweon, B.S. (2006). Retail land use, neighborhood satisfaction and the urban forest: an investigation into the moderating and mediating effects of trees and shrubs. *Landscape and Urban Planning*. 74(1): 70-78.

Emch, M., Quinn, J.W., Peterson, M., and Alexander, M. (2005). Forest cover change in the Toledo District, Belize from 1975 to 1999: A remote sensing approach. *Professional Geographer*. 57(2): 256-267.

Finder, R.A., Roseberry, J.L., and Woolf, A. (1999). Site and landscape conditions at white-tailed deer vehicle collision locations in Illinois. *Landscape and Urban Planning*. 44(2-3): 77-85.

Foster, A.D., and Rosenzweig, M.R. (2003). Economic Growth and the Rise of Forests. *Quarterly Journal of Economics*. 118(2): 601-637.

Future Land Imaging Interagency Working Group. (2007). A plan for a US national land imaging program (Washington, DC: Executive Office of the President), August.

Gatrell, J.D. and Jensen, R.R. (2002). Growth through greening: developing and assessing alternative economic development programmes *Applied Geography* 22: 331-350.

Green, K., Kempka, D., and Lackey, L. (1994). Using remote sensing to detect and monitor land-cover and land-use change. *Photogrammetric Engineering and Remote Sensing* 60(3): 331-337.

Grove, J.M., Cadenasso, M.L., Burch, W.R., Pickett, S.T.A., Schwarz, K., O'Neil-Dunne, J., Wilson, M., Troy, A., and Boone, C. (2006). Data and methods comparing social structure and vegetation structure of urban neighborhoods in Baltimore, Maryland. *Society & Natural Resources*. 19(2): 117-136.

Harwell, E.E. (2000). Remote Sensibilities: Discources of Tenchnology and the Making of Indonesia's Natural Disaster. *Development and Change.* 31(1):

313-323.

Hipple, J.D., Drazkowski, B., and Thorsell, P.M. (2005). Development in the Upper Mississippi Basin: 10 years after the Great Flood of 1993. *Landscape and Urban Planning*. 72(4): 313-323.

Huber, T.P. (1993). Integrated Remote-Sensing and Gis Techniques for Elk Habitat Management. *Journal of Environmental Systems*. 22(4): 325-339.

Hudak, A.T., and Wessman, C.A. (2000). Deforestation in Mwanza District, Malawi, from 1981 to 1992, as determined from Landsat MSS imagery. *Applied Geography*. 20(2): 155-175.

Hudson, P.F. (2004). Geomorphic context of the prehistoric Huastec floodplain environments: lower Panuco basin, Mexico. *Journal of Archaeological Science*. 31(6): 653-668.

Hunziker, M., and Kienast, F. (1999). Potential impacts of changing agricultural activities on scenic beauty - a prototypical technique for automated rapid assessment. *Landscape Ecology*. 14(2): 161-176.

Hutchinson, C.F. (1991). Uses of satellite data for famine early warning in sub-Saharan Africa. *International Journal of Remote Sensing* 12(6): 1405-1421.

Jensen, R., Gatrell, J., Boulton, J., and Harper, B. (2004). Using remote sensing and geographic information systems to study urban quality of life and urban forest amenities. *Ecology and Society*. 9(5):

Jepson, W. (2005). A disappearing biome? Reconsidering land-cover change in the Brazilian savanna. *Geographical Journal*. 171(99-111.

Jerrett, M., Arain, A., Kanaroglou, P., Beckerman, B., Potoglou, D., Sahsuvaroglu, T., Morrison, J., and Giovis, C. (2005). A review and evaluation of intraurban air pollution exposure models. *Journal of Exposure Analysis and Environmental Epidemiology*. 15(2): 185-204.

Ji, W., Ma, J., Twibell, R.W., and Underhill, K. (2006). Characterizing urban sprawl using multi-stage remote sensing images and landscape metrics. *Computers Environment and Urban Systems*. 30(6): 861-879.

Kamusoko, C., and Aniya, M. (2007). Land use/cover change and landscape fragmentation analysis in the Bindura District, Zimbabwe. *Land Degradation & Development*. 18(2): 221-233.

Kintz, D.B., Young, K.R., and Crews-Meyer, K.A. (2006). Implications of land use/land cover change in the buffer zone of a National Park in the Tropical Andes. *Environmental Management*. 38(2): 238-252.

Kirby, K.R., Laurance, W.F., Albernaz, A.K., Schroth, G., Fearnside, P.M., Bergen, S., Venticinque, E.M., and da Costa, C. (2006). The future of deforestation in the Brazilian Amazon. *Futures*. 38(4): 432-453.

Laris, P. (2002). Burning the seasonal mosaic: Preventative burning strategies in the wooded savanna of southern Mali. *Human Ecology*. 30(2): 155-186.

Lauer, D.T., Morain, S.T., and Salomonson, V.V. 1997. The Landsat program: its origins, evolution, and impacts, *Photogrammetric Engineering and Remote Sensing* 63(7), July, 831-838.

Liu, J.Y., Zhan, J.Y., and Deng, X.Z. (2005). Spatio-temporal patterns and driving forces of urban land expansion in china during the economic reform era. *Ambio*. 34(6): 450-455.

Lo, C.P., and Yang, X.J. (2002). Drivers of land-use/land-cover changes and dynamic modeling for the Atlanta, Georgia Metropolitan Area. *Photogrammetric Engineering and Remote Sensing*. 68(10): 1073-1082.

Martinuzzi, S., Gould, W.A., and Gonzalez, O.M.R. (2007). Land development, land use, and urban sprawl in Puerto Rico integrating remote sensing and population census data. *Landscape and Urban Planning*. 79(3-4): 288-297.

Mertens, B., and Lambin, E.F. (2000). Land-cover-change trajectories in southern Cameroon. *Annals of the Association of American Geographers*. 90(3): 467-494.

Mertens, B., Sunderlin, W.D., Ndoye, O., and Lambin, E.F. (2000). Impact of macroeconomic change on deforestation in South Cameroon: Integration of household survey and remotely-sensed data. *World Development*. 28(6): 983-999.

Messina, J.P., and Walsh, S.J. (2005). Dynamic spatial simulation modeling of the population - environment matrix in the Ecuadorian Amazon. *Environment and Planning B-Planning & Design*. 32(6): 835-856.

Moran, E.F. (1996). Restoration of Vegetation Cover in the Eastern Amazon. *Ecological Economics*. 18(1): 41-54.

Mueller, R. No date. "Assessment of TM and AWiFS Imagery for Cropland Classification: Three Case Studies," U.S. Department of Agriculture, National Agricultural Statistics Service, Research and Development Division, at http://www.pecad.fas.usda.gov/pdfs/2006/NASS_AWiFS_TM_CDL_comparison_Final.pdf (accessed 7 July 2008).

Muller, D., and Zeller, M. (2002). Land Use Dynamics in the Central Highlands of Vietnam: A Spatial Model Combining Village Survey Data with Satellite Imagery Interpretation. *Agricultural Economics*. 27(3): 333-354.

Muller, D., and Sikor, T. (2006). Effects of postsocialist reforms on land cover and land use in South-Eastern Albania. *Applied Geography*. 26(3-4): 175-191.

Munroe, D.K., Southworth, J., and Tucker, C.M. (2002). The dynamics of land-cover change in western Honduras: exploring spatial and temporal complexity. *Agricultural Economics*. 27(3): 355-369.

Nagendra, H., Karmacharya, M., and Karna, B. (2005). Evaluating forest management in Nepal: Views across space and time. *Ecology and Society*. 10(1).

National Research Council. 1995. *Earth Observations from Space: History, Promise, and Reality* (Washington, DC: National Academies Press).

National Research Council. (1998). *People and Pixels: Linking Remote Sensing and Social Science* (Washington, DC: National Academies Press).

National Research Council. 2002. *Toward New Partnerships in Remote Sensing: Government, the Private Sector, and Earth Science Research* (Washington, DC: National Academies Press).

National Research Council. 2003. *Using Remote Sensing in State and Local Government: Information for Management and Decision Making* (Washington, DC: National Academies Press).

Nautiyal, S., and Kaechele, H. (2007). Adverse impacts of pasture abandonment in Himalayan protected areas: Testing the efficiency of a Natural Resource Management Plan (NRMP). *Environmental Impact Assessment Review*. 27(2): 109-125.

Nelson, G.C., and Hellerstein, D. (1997). Do Roads Cause Deforestation? Using Satellite Images in Econometric Analysis of Land Use. *American Journal of Agricultural Economics*. 79(1): 80-88.

Nichol, J.E. (2006). Assessment of urban environmental quality in a subtropical city using multispectral satellite images. *Environment and Planning B-Planning & Design.* 33(1): 39-58.

Nichol, J.E. (1998). Quaternary climate and landscape development in West Africa: evidence from satellite images. *Environment and Planning B-Planning & Design.* 23(6): 733-747.

Ochoa-Gaona, S. (2001). Traditional land-use systems and patterns of forest fragmentation in the highlands of Chiapas, Mexico. *Environmental Management*. 27(4): 571-586.

Olsen, L.M., Dale, V.H., and Foster, T. (2007). Landscape patterns as indicators of ecological change at Fort Benning, Georgia, USA. *Landscape and Urban Planning*. 79(2): 137-149.

Oneill, A.L., Head, L.M., and Marthick, J.K. (1993). Integrating Remote-Sensing and Spatial-Analysis Techniques to Compare Aboriginal and Pastoral Fire Patterns in the East Kimberley, Australia. *Applied Geography*. 13(1): 67-85.

Pedlowski, M.A., Matricardi, E.A.T., Skole, D., Cameron, S.R., Chomentowski, W., Fernandes, C., and Lisboa, A. (2005). Conservation units: a new deforestation frontier in the Amazonian state of Rondonia, Brazil. *Environmental Conservation*. 32(2): 149-155.

Peres, C.A. (2001). Synergistic effects of subsistence hunting and habitat fragmentation on Amazonian forest vertebrates. *Conservation Biology*. 15(6): 1490-1505.

Perz, S.G., and Skole, D.L. (2003a). Secondary forest expansion in the Brazilian Amazon and the refinement of forest transition theory. *Society & Natural Resources*. 16(4): 277-294.

Perz, S.G., and Skole, D.L. (2003b). Social determinants of secondary forests in the Brazilian Amazon. *Social Science Research*. 32(1): 25-60.

Peterson, U., and Aunap, R. (1998). Changes in agricultural land use in Estonia in the 1990s detected with multitemporal Landsat MSS imagery. *Landscape and Urban Planning*. 41(3-4): 193-201.

Pfeffer, M.J., Schlelhas, J.W., DeGloria, S.D., and Gomez, J. (2005). Population, conservation, and land use change in Honduras. *Agriculture Ecosystems &*

Environment. 110(1-2): 14-28.

Place, F., and Otsuka, K. (2000). Population Pressure, Land Tenure, and Tree Resource Management in Uganda. *Land Economics*. 76(2): 233-251.

Porter, C.C., and Marlowe, F.W. (2007). How marginal are forager habitats? *Journal of Archaeological Science*. 34(1): 59-68.

Qi, Y., Henderson, M., Xu, M., Chen, J., Shi, P.J., He, C.Y., and Skinner, G.W. (2004). Evolving core-periphery interactions in a rapidly expanding urban landscape: The case of Beijing. *Landscape Ecology*. 19(4): 375-388.

Reginster, I., and Goffette-Nagot, F. (2005). Urban Environmental Quality in Two Belgian Cities, Evaluated on the Basis of Residential Choices and GIS Data. *Environment and Planning A*. 37(6): 1067-1090.

Reynolds, C. No date. "USDA's Foreign Agricultural Service (FAS) Approach for Estimating Crop Area," at http://agrifish.jrc.it/ftp/Public/Javier/GEOSS/summaries/USDA_FASarea_estimates_short.doc (accessed 7 July 2008).

Reynolds, J.E. (1993). Urban Land Conversion in Florida - Will Agriculture Survive. *Soil and Crop Science Society of Florida Proceedings*. 52(6-9).

Richers, D.M. No date. "An Old Friend to Oil and Gas Exploration" at www.mtevans-g.s.info/html/9story4.html (accessed October 2007).

Rudel, T.K., Bates, D., and Machinguiashi, R. (2002). A tropical forest transition? Agricultural change, out-migration, and secondary forests in the Ecuadorian Amazon. *Annals of the Association of American Geographers*. 92(1): 87-102.

Saroinsong, F., Harashina, K., Arifin, H., Gandasasmita, K., and Sakamoto, K. (2007). Practical application of a land resources information system for agricultural landscape planning. *Landscape and Urban Planning*. 79(1): 38-52.

Schweik, C.M., Nagendra, H., and Sinha, D.R. (2003). Using satellite imagery to locate innovative forest management practices in Nepal. *Ambio*. 32(4): 312-319.

Seto, K.C., and Fragkias, M. (2005). Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. *Landscape Ecology*. 20(7): 871-888.

Sierra, R. (2000). Dynamics and patterns of deforestation in the western Amazon: the Nape deforestation front, 1986-1996. *Applied Geography*. 20(1): 1-16.

Smil, V. (1999). China's Agricultural Land. *China Quarterly*. 158): 414-429.

Tan, M.H., Li, X.B., and Lu, C.H. (2005). Urban land expansion and arable land loss of the major cities in China in the 1990s. *Science in China Series D-Earth Sciences*. 48(9): 1492-1500.

Stoney, W., Fletcher, A. and Lowe, A. 2001. Data only report of Landsat user survey (Arlington, VA: Mitretek Systems), Mimeo, available from author.

Tan, M.H., Li, X.B., Xie, H., and Lu, C.H. (2005) .Urban land expansion and arable land loss in China - a case study of Beijing-Tianjin-Hebei region. *Land Use Policy*. 22(3): 187-196.

Taylor, D.M., Hortin, D., Parnwell, M.J.G., and Marsden, T.K. (1994). The Degradation of Rain-Forests in Sarawak, East Malaysia, and Its Implications for Future Management Policies. *Geoforum*. 25(3): 351-369.

Tian, G.J., Liu, J.Y., Xie, Y.C., Yang, Z.F., Zhuang, D.F., and Niu, Z. (2005). Analysis of spatio-temporal dynamic pattern and driving forces of urban land in China in 1990s using TM images and GIS. *Cities*. 22(6): 400-410.

Tsai, B.W., Chang, K.T., Chang, C.Y., and Chu, C.M. (2006). Analyzing spatial and temporal changes of aquaculture in Yunlin County, Taiwan. *Professional Geographer*. 58(2): 161-171.

US Climate Change Science Program. Forthcoming. "Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions," *Synthesis and Assessment Report 5.1* at www.climatescience.gov/Library/sap/sap5-1/public-review-draft (accesssed 25 April 2008).

Vagen, T.G. (2006). Remote sensing of complex land use change trajectories - a case study from the highlands of Madagascar. *Agriculture Ecosystems & Environment*. 115(1-4): 219-228.

Vance, C., and Geoghegan, J. (2002). Temporal and Spatial Modelling of Tropical Deforestation: A Survival Analysis Linking Satellite and Household Survey Data. *Agricultural Economics*. 27(3): 317-332.

Wakeel, A., Rao, K.S., Maikhuri, R.K., and Saxena, K.G. (2005). Forest management and land use/cover changes in a typical micro watershed in the mid elevation zone of Central Himalaya, India. *Forest Ecology and Management*. 213(1-3): 229-242.

Ward, D., Phinn, S.R., and Murray, A.T. (2000). Monitoring growth in rapidly urbanizing areas using remotely sensed data. *Professional Geographer*. 52(3): 371-386.

Yang, X.J., and Lo, C.P. (2003). Modelling urban growth and landscape changes in the Atlanta metropolitan area. *International Journal of Geographical Information Science*. 17(5): 463-488.

Zhao, B., Kreuter, U., Li, B., Ma, Z.J., Chen, J.K., and Nakagoshi, N. (2004). An ecosystem service value assessment of land-use change on Chongming Island, China. *Land Use Policy*. 21(2): 139-148.