

Journal of Terrestrial Observation

Volume 2, Issue 1

Winter 2010

Article 4

From Science to Applications: Determinants of Diffusion in the Use of Earth Observations

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ABSTRACT

We offer a framework and empirical evaluation to demonstrate how the use of Earth observations data has diffused over time in social science research, across many applications topics and geographic regions of focus. Our research is motivated by the continuing debate by policymakers over whether the nation's investment in Earth observations is merited and how our community can improve our ability to help answer this question in a systematic and documented manner. We consider the role of factors including use of GIS as a complementary tool in use of Earth observations and the role of data prices. Our approach in this section of the paper uses statistical regression. In the second part of the paper we draw from standard bibliometric methods used by government agencies to evaluate the extent to which a research field is growing. This approach asks whether authors tend to cross-reference and build on each others' work, providing evidence of Earth observations adopted in a growing community of practice. We realize that these strands of the value of Earth observations are often part of policy debate but we offer insights into how to substantiate and document these claims. We find evidence of increasingly widespread use of Earth observations in an ever widening number of applications and regions. GIS and data prices do matter in influencing the diffusion. However, we see less evidence of a community of practice within the large social science literature represented in our data.

ACKNOWLEDGMENTS

The financial support of the National Aeronautics and Space Administration (NASA), the United States Geological Survey Geography Discipline (USGS) and Resources for the Future is gratefully acknowledged. At USGS, Barron Bradford kindly provided Landsat price data and Richard L. Bernknopf offered additional helpful advice. Danny Morris, Laurie Houston, and Chris Clotworthy provided excellent research assistance. Responsibility for errors and opinions rests exclusively with the authors.

INTRODUCTION

In the annual federal appropriations discussions, the U.S. Congress routinely asks “how much is it worth to continue investment in the nation’s Earth observing satellites?” The answer has, apparently, not been fully satisfactory. Funding for the next in the series of Landsat missions and for many of the missions proposed in the “decadal survey” of the Earth sciences community (National Research Council, 2007) remains uncertain (and the plight at present is worsened in light of the fiscal crisis confronting the nation). In the case of Landsat, Gabrynowicz has aptly described the tumultuous history of the program by likening it to the heroine tied to the railroad tracks in silent films. Landsat is “yanked from doom” at the last minute by “administrative hat-passing” to fund the program (Gabrynowicz, 2005). A recent report by the U.S. Congressional Budget Office (CBO) underscores the concern, noting the delay in funding for the Landsat Data Continuity Mission (Behrens, 2009). In the case of the missions proposed by the decadal survey carried out the National Academy of Sciences, its committee felt compelled to draft an interim report referred to as “the crisis” (National Research Council, 2005) and at present, funding for most missions is still delayed.

The usual answer to “why fund Earth observations” is a set of examples offered by the relevant federal agencies (usually, the National Aeronautics and Space Administration, the U.S. Geological Survey, and the National Oceanic and Atmospheric Administration) of science research and findings and some examples of applications of observations for decision making. These examples demonstrate compelling uses of data to manage the nation’s energy and water resources, inform decisions about agricultural, forestry, and other land uses, and improve use of other natural and environmental resources. A collection of examples will continue to be an important and probably the principal means of showing the value of Earth observations. Even so, the examples represent fragmented anecdotes.

This paper suggests an approach for systematic collection, assembly, and evaluation of applications. We illustrate such an approach by documenting the use of Earth observations within a large peer-reviewed literature drawn from more than 2000 journals. We describe the breadth of applications and thus help to extend previous surveys of the field (including National Research Council, 1998; Blumberg and Jacobson, 1997). We then use bibliometric approaches (counts of peer-reviewed publications) to discern trends in applications. Bibliometrics have long been used as a measure of returns to research funding in other disciplines and are a means of assessing the diffusion of research output (Office of Technology Assessment, 1986, describes bibliometric measures as a noneconomic quantitative measure of the “output” of science; a recent application of this approach is Yokota and Thompson, 2004). We also consider possible determinants of these trends.

Our approach extends a previous literature review (Macauley, 2009) by focusing on the growth in applications over time. We first identify trends in the variety of applications and the geographic regions on which the studies have focused. We then seek to explain the overall growth in applications. In this step we reason by

analogy to conventional patterns of diffusion of a new technology. That pattern is often slow acceptance by a few “early adopters” at first, then faster adoption, and then slower adoption as the technology becomes widely diffused. We see evidence of this pattern in our analysis. We also trace factors that influence the rate of diffusion. Previous assessments of the use of Earth observations suggest that lack of relevant software and direct or indirect costs of data (such as prices, data access, or training) are possible barriers to adoption (National Research Council, 2001, 2003). Our findings substantiate these concerns with evidence that factors influencing diffusion include the spread of the use of geographic information systems (GIS) and the level of data prices. Finally, our data allow us to use citation analysis (a count of references among authors to each other’s work) as an indicator of a strengthening field of applications.

This paper organizes our evidence and discussions into the following Sections: Section 1 provides background on technology diffusion and its application in our study. Section 2 describes our method and data. This section also briefly describes the breadth of topics addressed by the articles comprising our dataset. This breadth itself is an indicator of diffusion. Section 3 reports statistical evaluation of some of the possible determinants of diffusion of uses of observations. Section 4 provides our conclusions.

BACKGROUND: “ADOPTING” NEW TECHNOLOGY IN THE DIFFUSION OF THE USE OF TERRESTRIAL OBSERVATIONS

The theoretical and empirical literature on the diffusion of technology has focused on tangible goods and services (Stoneman, 1995 surveys this literature). Examples are the spread in the use of cell phones and flat panel televisions and computer monitors. The usual approach to identifying determinants of diffusion is modeling and estimation over time of market shares, prices, and other factors influencing people’s willingness adopt a new technology.

In the case of government-provided environmental data, the subject matter (the public good of the environment), the nature of the good (information), and the supplier (government) complicate measurements of why these data become useful, are adopted, and eventually become widely used (diffused) in informing resource management. We lack market shares, prices, and other conventional measures. We often don’t even know who is using the observing data. Yet understanding factors that influence adoption of Earth observations beyond the science research they permit is an element of the public-sector investment decision to fund the collection of these data.

METHODS AND PROCEDURES

We began by identifying and systematically documenting applications of Earth observations. We compiled a dataset of peer-reviewed articles with a bibliographic

search of two widely used indices: the Social Science Citation Index (SSCI) and EconLit. These databases cover about 2000 U.S. and international journals representing a range of social science disciplines and interdisciplinary research. We realize that using peer-reviewed articles may omit applications documented in conference proceedings, workshop papers, and other reports. Despite these limits, our approach provided a sample cohort of a wide range of applications, allowing us to observe how use changes over time and factors influencing use. We also expect that our findings can be generalized to types of publications omitted in our approach (we return to this in our conclusions).¹

The databases contain the bibliographic information and abstracts for all articles in the journals. We experimented with keywords for searching the databases to identify articles that use Earth observations for land-related applications. We found that authors typically referred to Earth observations not with the words “Earth observations” but with the words “remote sensing” and “satellite data” and we included these in our search.

We included articles published between 1994 and February 2008. We thus dovetail with previous literature surveys carried out in the late 1990s; these surveys reviewed articles up to about the mid-1990s (Blumberg and Jacobson, 1997; National Research Council, 1998). We limited our search to articles in which remote sensing data are used for land use studies, rather than, for example, air quality or water management. Applications of Earth observations to land use represent one of the longest time series of applications and thus allowed us a long series with which to estimate diffusion.

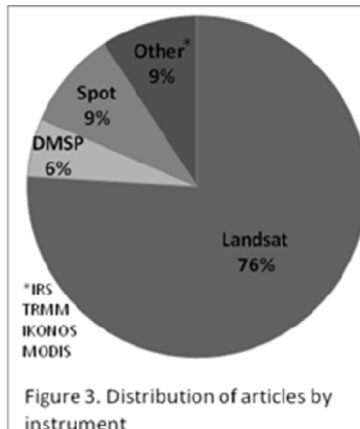
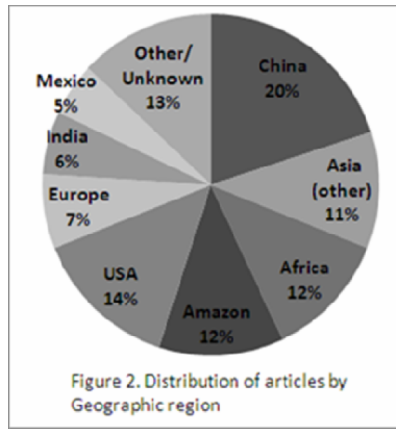
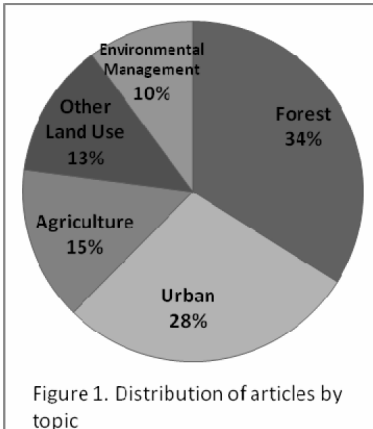
For all articles identified by the keywords, we reviewed the abstracts to sort the articles into four categories: (1) keep; (2) omit as not relevant; (3) omit as a technical article rather than an application of remote sensing data; and (4) omit as not involving an application specifically to land-related applications. An example of category (2) are “satellite accounts,” which is terminology for sub-sections of the national income and product accounts used to produce GDP and other statistics about the economy. Our keyword search identified these articles on the basis of “satellite.” An example of category (3) is a set of articles developing and testing algorithms, comparing ground references and remote sensing data, fusing data from different instruments, and other largely methodological research on validation, verification, and other means of characterizing the data--rather than our focus on applications of data. The preponderance of articles in our search addressed land applications, but a few articles fall into category (4).

This search method has several limitations that can lead to an underestimate of data applications. For example, although we tested our search criteria on randomly selected articles to design the best keywords, the two indices search only the abstracts. Author(s) may not indicate use of remote sensing data in the abstracts of their articles. Additionally, while SSCI and EconLit are considered to be the most comprehensive social science indices, they do not include all journals in which so-

cial science applications appear. As noted earlier, our use of peer-reviewed literature allowed us to systematize our search but we omitted applications documented in conference proceedings, workshop papers, and other reports.

Description of the articles

The search yielded a total of 107 articles published in 59 different journals. Figures 1, 2, and 3 summarize the thematic and geographic focuses of the articles and the instruments serving as sources of the Earth observations data. The articles spanned themes from agriculture, forestry, and urban development to general studies of land policy and management. Three-fourths of the articles address agriculture, forest, and urban land uses. Over a third of the articles centered on four areas, all outside of the United States. These were Africa, the Amazon, China, and other parts of Asia. Less than 15% applied remote sensing data to the United States. This distribution suggests the “window on the world” enabled by remote sensing. About half of the articles identified the source of data by instrument. Of these articles, Landsat is the data source for three-fourths of the articles. Other data sources included SPOT, DMSP, IKONOS, IRS, MODIS ASTER (airborne simulator), and TRMM.



Our purpose was to consider trends in these applications over time. We organized the sample of articles based on publication date within five-year intervals: 1994-1998, 1999-2003, and 2004-2008. We find several patterns over the intervals in the themes, geographic focus, and types of Earth observations data used in the articles. Table 1 illustrates these trends.

	Period		
	1994-1998	1999-2003	2004-2008
Themes (% all articles)			
Agriculture	50	16	10
Forest	50	47	25
Urban	-	18	37
Environmental Management	-	8	13
Other	-	11	15
Regions	Amazon, Mexico, US	Amazon, China, Asia(other), Europe, India, Mexico, Africa, US	Amazon, Asia, China, Europe, India, Mexico, Africa, US, Other
Instrument(s) (% all articles identifying instrument)			
Landsat	100	56	84
Other	-	44	16
Use of Landsat for Time Series of Data			
Of all articles using Landsat (%)	40	40	60
Length of series (years)	4 – 7	4 – 27	11 – 30
Mean length of series(years)	6	16	17
Journals (number)	4	27	45

Among themes, particularly notable was the increase in the diversity of topics from a concentration on agriculture and forestry in the 1990s to a larger number of topics more recently, including urban studies and environmental management. The geographic regions of interest have also broadened over time from the Amazon, Mexico, and the United States to include China and other parts of Asia, Europe, India, and Africa. Among data sources, applications now span a wider variety of instruments. We noticed the most variety among instruments in the middle of our time series (1999-2003) when almost half of the articles were based on SPOT, DMSP, and Ikonos. A trend toward a variety of data sources was not apparent in the most recent period, however, where we saw that most articles use Landsat.

An explanation for the large percentage of articles using Landsat in the most recent time period could rest at least in part with the time series provided by Landsat. The accumulation of Landsat data over the past decades provides the longest time series of land use observations available at present. One of the most frequently cited attributes of the U.S. Landsat program is the continuity of data over time (for example, see discussion in National Science and Technology Council, 2007). Our sample helps to document this perspective. Of all articles in which Landsat data were used, 40 to 60% of the articles used the data as a time series (the other uses *The Journal of Terrestrial Observation* | Volume 2 Number 1 (Winter 2010)

were for cross section rather than time series analyses). The fourth row of the table shows a count of articles for which the author(s) use a time series of Landsat data. The length of the time series ranges from 4 to 7 years in the 1990s to 11 to 30 years in the more recent articles. The mean length of the time series used in the articles has increased from 6 to 17 years.

Associated with greater breadth of subject and region, as well as the trend in time series, was an increase from 4 to 45 in the number of different journals in which applications of Earth observations data appear. The last row of the table reports this increase. The number of journals had increased from 4 during 1994 to 1998 to 45 journals by 2008 based on the journals covered by our databases. Table 2 lists the journal titles.

Our thematic classifications are admittedly broad and understate the diversity of specific topics, whereas we sought to illustrate the increase in diversity of applications of Earth observations. To serve this purpose, we next briefly summarize the articles. We then turn to analysis of possible determinants of this increase in the scope of applications.

Agriculture

A diverse range of studies in our sample uses Earth observations to assess land used or to study land use changes over time. A majority of these studies examined agricultural trends in Africa, Asia, and Eastern Europe--many at large spatial scales as entire countries or regions. At the most general level, studies classified land uses in the absence of national maps or offered improved estimates of agricultural capacities in specific regions of the world (for example, Peterson and Anunap, 1998; Smill, 1999; Xiao et al., 2003). Several of these studies estimated significantly higher agricultural capacities than government-reported figures, especially in China and other low-income nations, and provided insights into food security concerns.

Many of the articles considered the determinants of land use change by examining land imagery across different time periods, often integrated with historical population and political data. Variables included in these studies of land use change include population density, proximity to markets, road access, and the introduction of new agricultural methods, as well as factors that affect rates of cultivation frequency, agricultural expansion, and reforestation (Braumoh and Vlek, 2005; Vogt et al., 2006; Muller and Zeller, 2002; Xu et al., 2005). A theme in several of the articles was abandonment over time of prime agricultural land near population centers, due to over-use and soil degradation, shifting fields farther from village boundaries. Several authors offer policy recommendations such as encouraging location-specific sustainable agriculture or proposing other intervention to influence land use change. Some research also shows the effects of economic- and policy-induced changes in agricultural practices, overall agricultural capacity, and farmland values (Muller and Zeller, 2002; Amissah-Arthur et al., 2000; Sengupta and Osgood, 2003; Nivens et al., 2002).

Table 2. Journals Represented

Journal Title	Journal Title
<i>Agricultural Economics</i>	<i>Journal of Business and Economic Statistics</i>
<i>Agriculture Ecosystems & Environment</i>	<i>Journal of China University of Geosciences</i>
<i>Ambio</i>	<i>Journal of Environmental Economics and Management</i>
<i>American Journal of Agricultural Economics</i>	<i>Journal of Environmental Management</i>
<i>Annals of the Association of American Geographers</i>	<i>Journal of Environmental Planning and Management</i>
<i>Applied Geography</i>	<i>Journal of Urban Planning and Development-Asce</i>
<i>Catena</i>	<i>Land Degradation & Development</i>
<i>China Quarterly</i>	<i>Land Economics</i>
<i>Cities</i>	<i>Land Use Policy</i>
<i>Climate Research</i>	<i>Landscape and Urban Planning</i>
<i>Computers Environment and Urban Systems</i>	<i>Landscape Ecology</i>
<i>Development and Change</i>	<i>Latin American Research Review</i>
<i>Ecological Economics</i>	<i>Natural Resource Modeling</i>
<i>Ecological Indicators</i>	<i>Natureza & Sonservacado</i>
<i>Ecology and Society</i>	<i>Photogrammetric Engineering and Remote Sensing</i>
<i>Economic Geography</i>	<i>Photonirvachak-Journal of the Indian Society of Remote Sensing</i>
<i>Environment and Planning A</i>	<i>Professional Geographer</i>
<i>Environment and Planning B-Planning & Design</i>	<i>Progress in Planning</i>
<i>Environmental Conservation</i>	<i>Quarterly Journal of Economics</i>
<i>Environmental Management</i>	<i>Remote Sensing of Environment</i>
<i>Environmental Monitoring and Assessment</i>	<i>Review of Regional Studies</i>
<i>Forest Ecology and Management</i>	<i>Science in China Series: D-Earth Sciences</i>
<i>Futures</i>	<i>Singapore Journal of Tropical Geography</i>
<i>Geoforum</i>	<i>Social Science Research</i>
<i>Global and Planetary Change</i>	<i>Society & Natural Resources</i>
<i>Human Ecology</i>	<i>Soil Science Society of America Journal</i>
<i>Hydrological Processes</i>	<i>Space Policy</i>
<i>International Journal of Geographical Information Science</i>	<i>Water resources management</i>
<i>International Journal of Remote Sensing</i>	<i>World Development</i>
<i>Journal of Agricultural and Resource Economics</i>	

Note: The newest journal for related research, *The Journal of Terrestrial Observation*, is too new to appear in our sample.

Forestry

Studies of forested areas focused on tropical deforestation, predominately in the Amazon, Mexico, and Southeast Asia. The lion's share of these studies analyzed the biophysical, demographic, and infrastructure influences on deforestation in the Amazon. Linking Earth observations to social science datasets and survey data, these studies identified roads (paved and unpaved), rainfall, seasonal conditions, soil quality, land ownership, parcel size, length of residence, and other population parameters as determinants of deforestation (Messina and Walsh, 2005; Alvarez and Naughton-Treves, 2003; Pfaff, 1999; Place and Otsuka, 2000). Several studies use statistical analysis to determine the relative importance of determinants under various conditions, for example, finding that primitive road infrastructure is a much stronger driver of deforestation than population density (Kirby et al., 2006; Aldrich et al., 2006; Nelson and Hellerstein, 1997).

Deforestation studies outside of the Amazon used diverse approaches to uncover drivers distinct to specific parts of the world. Deforestation in Southeast Asia

and Africa was linked to social and biophysical variables such as political and economic conditions, elevation changes, and forest fires--requiring different types of data and analytic techniques than Amazonian studies (Taylor et al., 1994; Vagen, 2006; Dennis and Colfer, 2006; Mertens et al., 2000). Studies of community-owned forests in Mexico and India revealed a complex interplay of social and ecological dynamics when considering the determinants and effects of common property deforestation (Alix-Garcia et al., 2005; Kohlin and Amacher, 2005).

Beyond the drivers of deforestation, a handful of studies considered reforestation, including economic conditions that encouraged forest regrowth, spatial patterns of reforestation, transitional stages between deforestation and reforestation, and best-practice approaches for reforestation policies in specific ecological settings (Foster and Rosenzweig, 2003; Rudel et al., 2002; Apan, 1996; Moran et al., 1996). Another group of studies focused on the “mechanics” of deforestation, studying fragmentation of contiguous lands and distinct deforestation patterns found between primary and secondary forest types (Ochoa-Gaona, 2001; Perz and Skole, 2003a, 2003b). Some studies sought to quantify the spatial distribution of Amazonian deforestation, using Earth observations as a method of validation and improvement upon traditional survey-based deforestation estimates (Cardille and Foley, 2003; Caviglia-Harris and Harris, 2005). Biodiversity and climate change received less attention in this cohort, with only one study geared toward the carbon cycle (Justice et al., 2001) and no studies referencing species dynamics.

Urban

Topics in this category focused largely on urban development in the United States and China. These studies covered a range of spatial and temporal scales and touched upon a variety of urban issues. All of the studies used time-series analysis to characterize dynamic spatial-temporal patterns associated with urban growth. In general, these studies quantified urbanization patterns with detailed landscape metrics and urban growth models.

Studies of the United States addressed urban growth and peripheral development within individual cities. These analyses considered small spatial scales--at the city or sub-city scale--with some studies utilizing multiple scales by simultaneously analyzing metrics at the county, metropolitan, city, and census tract levels (Ji et al., 2006; Lo and Yang, 2002). Most studies examined land imagery from the 1970s to 2000s, with decadal snapshots to generally characterize what lands are replaced by urbanization and identify the social, geographic, and infrastructure factors that influenced urban growth (Burchfield et al., 2006; Lo and Yang, 2002; Herold et al., 2002; Ji et al., 2006). Beyond characterization, some studies also modeled urban growth and forecast land use changes based upon specific social and policy scenarios (Herold et al., 2003; Yang and Lo, 2003). Several studies also considered “green” issues related to the loss of open space during development, quality of life and health issues tied to urban forests, and socioeconomic-vegetation relationships

in residential settings (Yang and Lo, 2003; Jensen et al., 2004; Grove et al., 2006; Mennis, 2006; Ellis et al., 2006; Nichol et al., 2006).

Urban studies of China used a wide range of spatial scales, including national-, regional-, and city-level analyses. Timescales are generally shorter than U.S. studies; most began in the 1990s with time series ranging from annual to five-year increments. At the broadest level, national studies quantified the annual rate of urban growth across all of China's major cities, while also measuring loss of arable land and identifying general growth characteristics across regions (Tian et al., 2005; Tan et al., 2005a; Liu et al., 2005). Several studies focused on regional analysis of the interactions and dynamics among groups of nearby cities. Regional studies reveal expansion features of different-tier cities within close proximity as well as the development of urban transects, a multistage process of urbanization describing growth patterns between urban industrial centers and satellite cities (Tan et al., 2005b; Schneider et al., 2005; Seto and Kaufmann, 2003; Seto and Fragkias, 2005). Analyses of individual cities describe intricate core-periphery interdependencies within city limits and quantify evidence of fringe "desakota" land use patterns. These patterns were characterized by complex, amorphous categorizations of land use types that intertwine rural and urban processes (Qi et al., 2004; Xie et al., 2006; Yu and Ng, 2007). Econometric studies identified primary drivers of urbanization, including wages, direct foreign investment, and relative productivity gains over agriculture. These studies considered the extent to which urban growth may be controlled by large-scale industrial development rather than local land users (Tan et al., 2005b; Seto and Kaufmann, 2003).

Policy and Environmental Management

Studies focusing on policy and management included several subjects, predominately policy instruments, such as models or monitoring systems, and policy insights that evaluated or guided policy development. Policy instruments include tools used to monitor, model, or forecast events that can inform environmental planning, management, or policy development. Some applications developed a spatially explicit alternative to GDP using nighttime light emissions, and then integrated data on non-market ecological wealth to create a global index of sustainable growth (Sutton and Costanza, 2002; Lo, 2002). Another study developed an index of Canadian forest cover, an annual indicator that is merged with national economic data to measure Canada's "overall" economic-ecological wealth (Chen et al., 2006). Several tools for environmental management were watershed-level models that use multispectral sensor data to simulate runoff, erosion, and sediment processes or to develop an index of catchment scenarios in specific localities (Dwivedi et al., 2006; Pandey et al., 2007; Reddy et al., 2007; Walker et al., 2006; Tang et al., 2007). Similar models integrated imagery with soil, salinity, and geologic maps to model landscape degradation and revegetation strategies for dry-land salinity sites (Apan et al., 2004; Li et al., 2001). Another study developed a spatial system for

monitoring and forecasting locust plagues by integrating GIS and remote sensing platforms with UN data concerning locust breeding, swarm movements, and environmental conditions (Healey et al., 1996).

“Policy insights” included studies that identified, assessed, and guided existing policies or demonstrated new policy concepts. Two studies used Earth observations to identify innovative forest management practices in remote sections of Nepal and to evaluate the effectiveness of different small-scale community forestry approaches (Schweik et al., 2003; Nagendra et al., 2005). Others examined the role of Earth observations to devise conservation units and tax credit policies for tropical forest management. (Pedlowski et al., 2005; Alvarez and Naughton-Treves, 2003). Another group of studies of Africa and Indonesia analyzed fire patterns to discern the relative impacts of early-season burnings, vegetation structure, and social conditions in improving long-term fire management plans to prevent catastrophic forest fires (Dennis et al., 2005; Bucini and Lambin, 2002; Harwell, 2007). Several quality-of-life studies used multi-spectral sensing to examine how urban vegetation metrics impact air quality, microclimates, and location preferences--all relationships useful in guiding city planning (Reginster and Goffette-Nagot, 2005; Nichol et al., 2006, Jenerette et al., 2007; Grove et al., 2006).

INFLUENCES ON THE USE OF EARTH OBSERVATIONS IN OUR SAMPLE

In applications as diverse as those described above, we asked if we can discern determinants of the diffusion of Earth observations as reflected in this cohort of articles. We used two standard methods. One was a statistical estimation of a conventional “diffusion curve.” The other was a bibliometric analysis of citations among authors to each other’s work. We next described these approaches and their relevance to our study.

Diffusion

The conventional characterization of how new technologies are adopted over time is a pattern of a few adopters followed by an increasingly large number, and then a gradual tapering off as the technology becomes widespread (and in turn, possibly supplanted by yet another new technology). Stoneman (1995) and references therein describe this s-shaped pattern (Figure 4) and its use in the extensive literature on technology diffusion. The model is typically used to describe diffusion of new goods and services, manufacturing processes, and other innovations.

Reasoning by analogy, we define the “use of Earth observations” as the new technology--that is, a new type of data--for studies in environmental and resource management. We asked whether the pattern we see in use of these data over time bears resemblance to the standard s-curve. We then considered two possible influences on diffusion. One influence is the availability and deployment of geospatial tools and complementary technologies that facilitate use of remote sensing data.

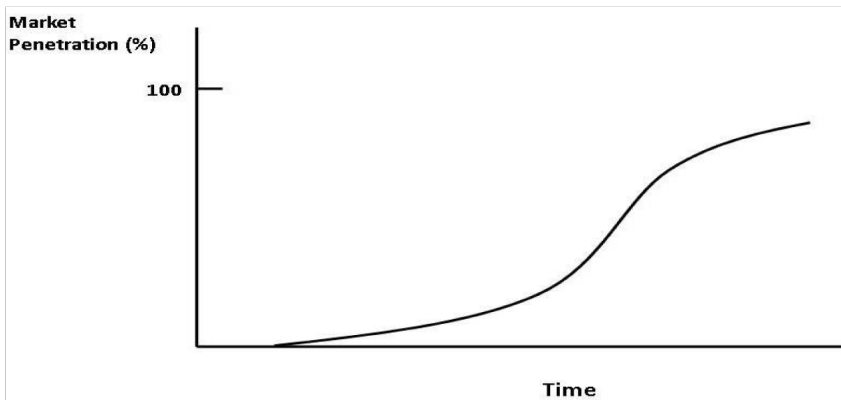


Figure 4. The diffusion curve

Another influence is the cost of data in terms of the direct costs of data fees and indirect costs of other inputs needed to use the data (for instance, training of students and resource managers). We selected these factors because they have been previously identified as likely influences on use of Earth observations, and because they illustrate two types of policy implications. GIS has many purposes beyond facilitating use of remote sensing data and is an industry that functions largely external to government policy and investment decisions about Earth observing missions. In contrast, fees for data are a factor over which policymakers have influence in establishing data policy, and thus representative of an endogenous policy determinant.

For statistical analysis of these factors, we used data on the spread over time of GIS tools and data on Landsat scene prices. Experts at ERDAS, Incorporated recommended a widely recognized survey database to measure the spread of GIS for our purposes. The Geospatial Information and Technology Association surveys adoption of GIS in six business sectors--electric, gas, water, pipeline, telecommunications, and the public sector. We used their results as published in the Association's *Geospatial Technology Report* for the 244 public-sector participants surveyed to ascertain GIS adoption and installation between 1994 and 2007. We used these data as a proxy to indicate the spread of GIS over time in social science (GITA, 2008). For the price of data, we used data provided by the U.S. Geological Survey.² Experts there suggested that we use the price per scene of MSS color paper products, under the assumption that these are the most popular product in social science applications. We know based on data policies that some but not all of the data used in our sample were free (for example, MODIS and DMSP). For Landsat and other data for which fees were in effect, we do not know whether authors had access to free data on the basis of sharing arrangements.³ Even if data are free, some cost is likely incurred to ingest, manipulate, and use the data. In this case, the price variable can proxy for other costs that may be involved in using data. Thus including a price variable allows us to explore the effect of "data cost" on diffusion.

We statistically estimated the effect of these influences on the use of Earth observations data in our sample with equation (1), a conventional expression to characterize a diffusion curve (for example, see Karshenas and Stoneman, 1995). The expression takes the following form:

$$y_t(\mathbf{x}_t) = \frac{L}{1 + e^{-(\beta_0 + \mathbf{a}^T \mathbf{x}_t)}} \quad (1)$$

where y_t is the cumulative number of articles at time t , \mathbf{X}_t is a vector of explanatory variables at time t , and L is the upper limit (where the s-curve finally flattens).

The *time* subscript merits additional discussion. Our articles are referenced by their publication date. But this date typically lags the period during which the research was carried out. Accordingly, we sought to match the correspondence between the year of publication and the explanatory variables. Because the use of or familiarity with GIS is likely to precede the actual publication date of the article, we expected the GIS variable to lag the timing of the article by some period of elapsed time. Similarly, the price of data may be relevant in the years coinciding with the research effort itself and thus prior to the actual publication date, assuming most articles are in press for several months or more. Additionally, researchers may use data purchased at any point prior to the project. We considered several different time lags between publication date and the explanatory variables: no lag, a two-year lag, a five-year lag, and a ten-year lag. Table 3 lists descriptive statistics for the data. The variables GIS and PRICE are the measures for the trend in adoption of GIS technology and the price of Landsat data. We had these data for the period 1994 to 2007.

Table 3. Sample descriptive statistics

Variable*	Mean	Standard Deviation	Min	Max
GIS (number organizations)	145.90	80.35	16	244
PRICE (\$ per scene)	383.18	181.22	170	600

* See text for description.

We used a nonlinear estimation routine to estimate (1). Table 4 displays the results.

Table 4. Estimation results

Variable	Estimated Coefficient
GIS	.029 (.002)
PRICE	-.002 (.001)
β_0	-17.66 (.436)

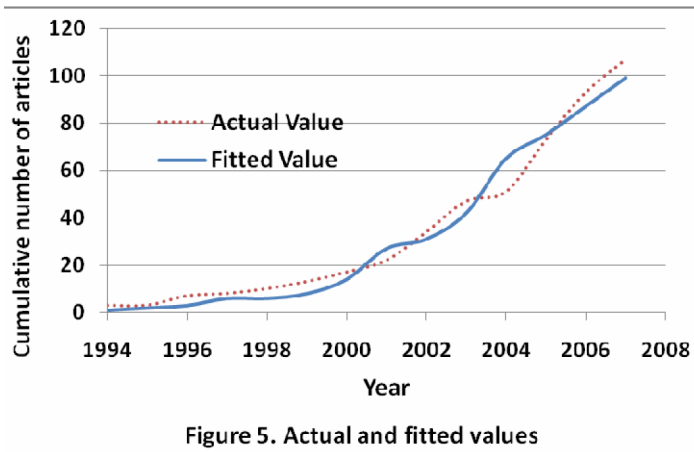
*Adjusted R*² = .99

Notes:

Standard errors in parentheses.

GIS and PRICE are lagged two years (see text).

We find that both the GIS trend and the data price gave the best statistical fit when both are lagged by two years relative to the article publication date. The standard errors of the estimates are noted in parentheses. The constant term and the coefficient on the GIS variable are statistically significant at the 99% level and the coefficient of the price variable is statistically significant at the 10% level. Figure 5 shows the fitted and actual values.



The estimated coefficients confirm our prior expectations. Based on our sample data, increases in the deployment of GIS encourage spread of use of Earth observations data. Increases in data prices reduce the spread of use. We also found that our sample suggests that we are not yet at the point where the “s-shape” begins to flatten. In other words, the spread of applications of Earth observations has not yet reached the limit where diffusion slows markedly (when a technology has fully “penetrated” or “saturated” a market).⁴ Future research that continues to track applications may shed light on determinants of whether, when, and why this point is reached.

We acknowledge the simplicity of these findings, but to our knowledge they provide the first empirical support for several policy-related implications. For example, the results underscore that continued deployment of GIS, including software and training, is likely to be critical to further the continued use of Earth observations data (the link between GIS and remote sensing data is a concern expressed in National Research Council, 2001, 2003). Furthermore, we would anticipate that as using data becomes more complex (for instance, in fusing data or using new types of data from forthcoming new spacecraft missions), the deployment of GIS tools will need to advance to support diffusion of data applications. We found that the cost of using data also matters in social science research. The cost of data was a concern that resulted in a recent policy decision to provide standard Landsat scenes at no charge, but costs remain a policy issue for other data, including those from foreign instruments.

A factor not explicit in our model was the research undertaken to enable applications. This research includes verifying and validating data, algorithm development, and other technical research necessary for applications. We classified 90 articles as technical in our literature survey but, as noted in the Method discussion above, we omitted them from the set of applied research articles.⁵ We now return to these articles and plot the cumulative distribution of both the technical and applications articles in Figure 6.

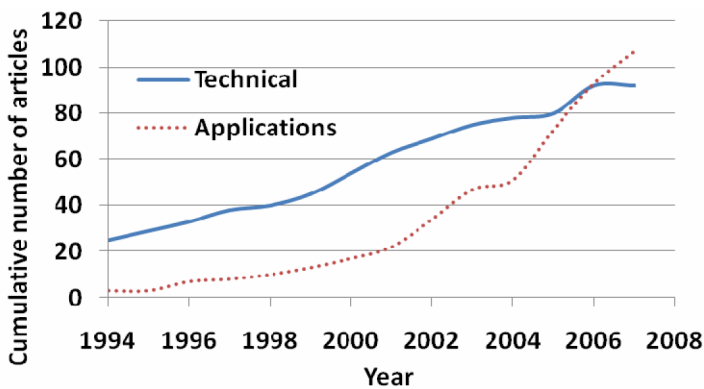


Figure 6. Distribution of technical and applications articles over time

The cumulative number of technical articles has exceeded applications articles until recently. A conventional test suggests that these distributions are statistically different, implying that drivers of the technical literature may be different from those of the applications literature.⁶ We also note that the distribution of technical articles seems to be leveling off. We speculate that this may be indicative of a slowing of research until launch of the next generation of missions. We leave for future study further exploration of the relationship between technical research and the applications it enables.

Citation analysis

Another pathway for diffusion is reference among scholars to each other's work. Citation analysis, by which references to a publication are studied, is often used to indicate the strength of a field of research. This approach has been used to evaluate the performance of research programs in Europe and in the United States (for example, at research institutions such as the National Science Foundation and the National Institutes of Health; see OTA, 1986). Limits include the quality of the search databases, variations in the citation rate over the "life" of a paper, and possible biases introduced by self-citation and in-house citation (since these could tend to overstate the breadth of diffusion among different researchers).

We used citation analysis within our sample to consider whether the published articles appear to provide a foundation for reference by other scholars in building on and extending applications of Earth observations data. We used a standard bibliometric approach of citation counts (see OTA, 1986) to trace which authors refer to previously published work within our sample.

We found 45 articles (about 40% of our sample) containing references to other articles within the sample. These included 9 self-citations (the author or authors are the same in the citing and cited article). We found 12 citations with overlapping authorship (that is, where one or more of the authors of an article cite a previous article to which they were a contributor, but the full list of authors is not the same for each article). The citations were within 12 different journals and across 4 of our themes. The absolute number of citations increased over time; there were 16 citations during 1998-2003 and 29 during 2004 to 2008. As a percent of all articles, however, and with the increase in the number of articles published over time, the relative frequency of citations has not changed since the 1999-2003 period. The relative frequency then and now is about 5%. We speculate that this finding could suggest the absence of a strong network of scholars familiar with each other's work; if so, the result points to the usefulness of conferences, workshops, further survey and synthesis of research, special journals and special issues of journals, and other steps to enhance exchange among scholars.

CONCLUSIONS

We offered a framework to improve understanding of diffusion of applications of Earth observations. We used a combination of standard statistical analysis and citation surveys. We saw this approach and our results as complementary with other efforts to demonstrate the benefit of investment in Earth observing missions and supportive of the need to improve how to document this benefit.

Our study showed an increasing rate of peer-reviewed applications of Earth observations in a broadening range of topics and geographic regions. Earth observations remain a "window on the world" for study of a host of countries and regions, and relevant to a variety of land use issues. We offer empirical evidence of factors previously thought to be influential in the diffusion of Earth observations, including the availability of geographic information tools and reductions in *The Journal of Terrestrial Observation* | **Volume 2 Number 1 (Winter 2010)**

data costs. Within our sample, we find these to be significant determinants of the number of applications over time. We also found a trend toward research enabled by and based on time series of data, lending support to the value of data continuity. This finding is relevant both to continuation of data series provided by Landsat and to the desirability of tools with which to fuse old data with new data from future instruments.

We found limited support for evidence of applications of Earth observations moving beyond a collection of one-time applications toward a body of literature building on and extending previous research. This finding leads us to recommend steps to improve cross-scholar communication in social science applications of Earth observations. The steps could include survey and syntheses of the literature, special journals and journal issues, and conferences and workshops. Enhancing this foundation would bode well for continued diffusion of Earth observations and strengthen the evidence of the benefits to investment in them.

NOTES

1 Social science also represents a community of scholars that may be under-represented in professional trade association surveys and assessments of Landsat or other Earth observing programs based on publications in the physical sciences.

2 Bryon Bradford of the U.S. Geological Survey kindly provided these data.

3 Prices were charged for Landsat data during the time period represented by the sample (our most recent articles were already in press before standard-format Landsat scenes became freely available in 2008).

4 In our statistical procedure, we specify the value of L , the limiting factor when diffusion slows. The results of the regression are robust with respect to a wide range of choices of L .

5 This set of technical articles is a small subset of all such articles since our literature review did not include engineering, science, and other technical journals.

6 We use the two-sample Kolmogorov-Smirnov test for equality of distribution functions.

REFERENCES

- 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. 2007. A spatial analysis of common property deforestation. *Journal of Environmental Economics and Management* 53(2):141-157.
- 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.
- Amissah-Arthur, A., Mougenot, B., and Loireau, M. 2000. Assessing farmland dynamics and land degradation on Sahelian landscapes using remotely sensed

- and socioeconomic data. *International Journal of Geographical Information Science* 14(6):583-599.
- 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., Raine, S.R., and Paterson, M.S. 2002. Mapping and analysis of changes in the riparian landscape structure of the Lockyer Valley catchment, Queensland, Australia. *Landscape and Urban Planning* 59(1):43-57.
- Behrens, C. 2009. Landsat and the data continuity mission *CRS Report for Congress* R40594 22. Washington, DC: Congressional Research Service, May.
- Blumberg, D., and Jacobson, D. 1997. New frontiers: remote sensing in social science research. *The American Sociologist*, 62-68.
- Braimoh, A.K., and Vlek, P.L.G. 2005. Land-cover change trajectories in Northern Ghana. *Environmental Management* 36(3):356-373.
- 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.
- Cardille, J.A., and Foley, J.A. 2003. Agricultural land use change in Brazilian Amazonia between 1980 and 1995: evidence from integrated satellite and census data. *Remote Sensing of Environment* 87(4):551-562.
- Caviglia-Harris, J.L., and Harris, D.W. 2005. Examining the reliability of survey data with remote sensing and Geographic Information Systems to improve deforestation modeling. *Review of Regional Studies* 35(2):187-205.
- Chen, J. 2007. Rapid urbanization in China: a real challenge to soil protection and food security. *Catena* 69(1):1-15.
- Chen, W., et al. 2006. Canada's forest cover indicator: definition, methodology and results. *Natural Resource Modeling* 19(1):91-116.
- 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.
- Dwivedi, R.S., Sreenivas, K., Ramana, K.V., Reddy, P.R., and Sankar, G.R. 2006. Sustainable development of land and water resources using geographic information system and remote sensing. *Environmental Management* 34(4):351-367.
- 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.

- Foster, A.D., and Rosenzweig, M.R. 2003. Economic growth and the rise of forests. *Quarterly Journal of Economics* 118(2):601-637.
- Gabrynowicz, J.I. 2005. The perils of Landsat from grassroots to globalization: a comprehensive review of U.S. remote sensing law with a few thoughts for the future. *Chicago Journal of International Law* 6(1):45-67.
- Geospatial Information and Technology Association (GITA). 2008. *Geospatial Technology Report*. The Geospatial Information & Technology Association. Aurora, CO.
- 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. 2007. Remote sensibilities: discourses of technology and the making of Indonesia's natural disaster. *Development and Change* 31(1):313-323.
- Healey, R.G., Robertson, S.G., Magor, J.I., Pender, J., and Cressman, K. 1996. A GIS for desert locust forecasting and monitoring. *International Journal of Geographical Information Systems* 10(1):117-136.
- Herold, M., Scepan, J., and Clarke, K.C. 2002. The use of remote sensing and landscape metrics to describe structures and changes in urban land uses. *Environment and Planning A* 34(8):1443-1458.
- Herold, M., Goldstein, N.C., and Clarke, K.C. 2003. The spatiotemporal form of urban growth: measurement, analysis and modeling. *Remote Sensing of Environment* 86(3):286-302.
- Jenerette, G.D., Harlan, S.L., Brazel, A., Jones, N., Larsen, L., and Stefanov, W.L. 2007. Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. *Landscape Ecology* 22(3):353-365.
- 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).
- 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.
- Justice, C., Wilkie, D., Zhang, Q., Brunner, J., and Donoghue, C. 2001. Central African forests, carbon and climate change. *Climate Research* 17(2):229-246.
- Karshenas, M., and Stoneman, P. 1995. Technological diffusion. In Stoneman, P. (ed.). *Handbook of the Economics of Innovation and Technological Change*. Cambridge: Blackwell.
- 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.

- Kohlin, G., and Amacher, G.S. 2005. Welfare implications of community forest plantations in developing countries: the Orissa Social Forestry Project. *American Journal of Agricultural Economics* 87(4):855-869.
- Li, X.J., Peterson, J., Liu, G.J., and Qian, L. 2001. Assessing regional sustainability: the case of land use and land cover change in the middle Yiluo catchment of the Yellow River basin, China. *Applied Geography* 21(1):87-106.
- 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. 2002. Urban indicators of China from radiance-calibrated digital DMSP-OLS nighttime images. *Annals of the Association of American Geographers* 92(2):225-240.
- 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.
- Macauley, M.K. 2009. Earth observations in social science research for management of natural resources and the environment: identifying the Landsat contribution. *Journal of Terrestrial Observation* 1(2):31-51.
- 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.
- Mennis, J. 2006. Socioeconomic-vegetation relationships in urban, residential land: the case of Denver, Colorado. *Photogrammetric Engineering and Remote Sensing* 72(8):911-921.
- 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., et al. 1996. Restoration of vegetation cover in the Eastern Amazon. *Ecological Economics* 18(1):41-54.
- 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.
- 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. 1998. *People and Pixels: Linking Remote Sensing and Social Science*. Washington, DC: National Academies Press.
- National Research Council. 2001. *Transforming Remote Sensing Data into Information and Applications*. Washington, DC: National Academies Press.

- National Research Council. 2003. *Using Remote Sensing in State and Local Government*. Washington, DC: National Academies Press.
- National Research Council. 2005. *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*. Washington, DC: National Academies Press.
- National Research Council. 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: National Academies Press.
- National Science and Technology Council (NSTC). 2007. *A Plan for a U.S. National Land Imaging Program*. Washington, DC: Office of the White House.
- Nichol, J.E., Wong, M.S., Fung, C., and Leung, K.K.M. 2006. Assessment of urban environmental quality in a subtropical city using multispectral satellite images. *Environment and Planning B-Planning & Design* 33(1):39-58.
- Nivens, H. D., et al. 2002. Using satellite imagery in predicting Kansas farmland values. *Journal of Agricultural and Resource Economics* 27(2):464-480.
- 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.
- Office of Technology Assessment (OTA). 1986. *Research Funding as an Investment: Can We Measure the Returns? A Technical Memorandum*. Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-TM-SET-36, April.
- Pandey, A., Chowdary, V.M., and Mal, B.C. 2007. Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. *Water Resources Management* 4(21):729-746.
- 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.
- 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.
- Pfaff, A.S.P. 1999. What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data. *Journal of Environmental Economics and Management* 37(1):26-43.
- Place, F., and Otsuka, K. 2000. Population pressure, land tenure, and tree resource management in Uganda. *Land Economics* 76(2):233-251.

- 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.
- Reddy, K.V., Eldho, T.L., Rao, E.P., and Hengade, N. 2007. A kinematic-wave-based distributed watershed model using FEM, GIS and remotely sensed data. *Hydrological Processes* 21(20):2765-2777.
- 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.
- Rudel, T.K., Bates, D., and Machinguishi, 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.
- Schneider, A., Seto, K.C., and Webster, D.R. 2005. Urban growth in Chengdu, Western China: application of remote sensing to assess planning and policy outcomes. *Environment and Planning B-Planning & Design* 32(3):323-345.
- 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.
- Sengupta, S., and Osgood, D.E. 2003. The value of remoteness: a hedonic estimation of ranchette prices. *Ecological Economics* 44(1):91-103.
- 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.
- Seto, K.C., and Kaufmann, R.K. 2003. Modeling the drivers of urban land use change in the Pearl River Delta, China: integrating remote sensing with socioeconomic data. *Land Economics* 79(1):106-121.
- Smil, V. 1999. China's agricultural land. *China Quarterly* 158:414-429.
- Stoneman, P. 1995. *Handbook of the Economics of Innovation and Technological Change*. Cambridge, MA: Blackwell Handbooks in Economics.
- Sutton, P.C., and Costanza, R. 2002. Global estimates of market and non-market values derived from nighttime satellite imagery, land cover, and ecosystem service valuation. *Ecological Economics* 41(3):509-527.
- Tan, M.H., Li, X.B., and Lu, C.H. 2005a. 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.
- Tan, M.H., Li, X.B., Xie, H., and Lu, C.H. 2005b. Urban land expansion and arable land loss in China--a case study of Beijing-Tianjin-Hebei region. *Land Use Policy* 22(3):187-196.
- Tang, F.S., Chen, X., Luo, G.P., Lin, Q., and Liu, H.L. (2007). A contrast of two typical LUCC processes and their driving forces in oases of and areas: a case study of Sangong River Watershed at the northern foot of Tianshan Mountains. *Science in China Series: D-Earth Sciences* 50:65-75.

- 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.
- 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.
- Vogt, N., Bahati, J., Unruh, J., Green, G., Banana, A., Gombya-Ssembajjwe, W., and Sweeney, S. 2006. Integrating remote sensing data and rapid appraisals for land-cover change analyses in Uganda. *Land Degradation & Development* 17(1):31-43.
- Walker, J., Dowling, T., and Veitch, S. 2006. An assessment of catchment condition in Australia. *Ecological Indicators* 6(1):205-214.
- Xiao, X.M., Liu, J.Y., Zhuang, D., Froking, S., Boles, S., Xu, B., Liu, M., Salas, W., Moore, B., and Li, C. 2003. Uncertainties in estimates of cropland area in China: a comparison between an AVHRR-derived dataset and a Landsat TM-derived dataset. *Global and Planetary Change* 37(3):297-306.
- Xie, Y.C., Yu, M., Bai, Y.F., and Xing, X.R. 2006. Ecological analysis of an emerging urban landscape pattern-desakota: a case study in Suzhou, China. *Landscape Ecology* 21(8):1297-1309.
- Xu, J.C., Fox, J., Vogler, J., Peifang, Z., Yongshou, F., Lixin, Y., Jie, Q., and Leisz, S. 2005. Land use and land-cover change and farmer vulnerability in Xishuangbanna prefecture in southwestern China. *Environmental Management* 36(3):404-413.
- 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.
- Yokota, F., and Thompson, K.M. 2004. Value of information literature analysis: a review of applications in health risk management. *Medical Decision Making* 24:287-298.
- Yu, X.J., and Ng, C.N. 2007. Spatial and temporal dynamics of urban sprawl along two urban-rural transects: a case study of Guangzhou, China. *Landscape and Urban Planning* 79(1):96-109.

ADDITIONAL REFERENCES USED FOR INFORMATION PURPOSES

- Al Bassam, B.F. 2007. Dynamics of land use/cover change in Puding city area using remotely sensed data. *Journal of China University of Geosciences* 18:165-167.
- 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.
- Backhaus, R., and Beule, B. 2005. Efficiency evaluation of satellite data products in environmental policy. *Space Policy* 21(3):173-183.
- Beaumont, P. 1996. Agricultural and environmental changes in the upper Euphrates catchment of Turkey and Syria and their political and economic implications. *Applied Geography* 16(2):137-157.
- 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.
- Hung, H.-M., and Fuller, W.A. 1987. Regression estimation of crop acreages with transformed Landsat data as auxiliary variables. *Journal of Business and Economic Statistics* 5(4):475-482.
- 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.
- Jacquin, A., Misakova, L., and Gay, M.A. 2008. A hybrid object-based classification approach for mapping urban sprawl in periurban environment. *Landscape and Urban Planning* 84(2):152-165.
- Jat, M.K., Garg, P.K., and Khare, D. 2008. Modelling of urban growth using spatial analysis techniques: a case study of Ajmer city (India). *International Journal of Remote Sensing* 29(2):543-567.
- 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.
- Leal, F.A., Ramos, M.B., and Machado, R.B. 2007. Evaluation of deforestation after the interruption in the creation process of protected areas in Goisa. *Natureza & Conservacao* 5(1):141-151.
- Li, A.N., Wang, A.S., Liang, S., and Zhou, W. 2006. Eco-environmental vulnerability evaluation in mountainous region using remote sensing and GIS--a case study in the upper reaches of Minjiang River, China. *Ecological Modelling* 192(1-2):175-187.
- Long, H.L., Tang, G.P., Li, X.B., and Heilig, G.K. 2007. Socio-economic driving forces of land use change in Kunshan, the Yangtze River Delta economic area of China. *Journal of Environmental Management* 83(3):351-364.
- Madelene, O.A., and Chen, D.L. 2006. Land use change: impacts of climate variations and policies among small-scale farmers in the Loess Plateau, China. *Land Use Policy* 23(4):361-371.

- 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., Forni, E., and Lambin, E.F. 2001. Prediction of the impact of logging activities on forest cover: a case-study in the East province of Cameroon. *Journal of Environmental Management* 62(1):21-36.
- 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.
- Mundia, C.N., and Aniya, M. 2005. Analysis of land use/cover changes and urban expansion of Nairobi city using remote sensing and GIS. *International Journal of Remote Sensing* 26(13): 2831-2849.
- 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.
- 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.
- Nizeyimana, E.L., Petersen, G.W., Imhoff, M.L., Sinclair, H.R., Waltman, S.W., Reed-Margetan, D.S., Levine, E.R., and Russo, J.M. 2001. Assessing the impact of land conversion to urban use on soils with different productivity levels in the U.S.A. *Soil Science Society of America Journal* 65(2):391-402.
- Pfeffer, M.J., Schelhas, 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.
- Rogan, J., and Chen, D.M. 2004. Remote sensing technology for mapping and monitoring land-cover and land use change. *Progress in Planning* 61:301-325.
- Rudel, T.K., Bates, D., and Machinguiashi, R. 2002. Ecologically noble Amerindians? Cattle, ranching and cash cropping among Shuar and colonists in Ecuador. *Latin American Research Review* 37(1):144-159.
- 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.
- 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.

- Wang, X.L., Song, B., Chen, J., Zheng, D., and Crow, T.R. 2006. Visualizing forest landscapes using public data sources. *Landscape and Urban Planning* 75(1-2):111-124.
- Wang, H., and Trauth, K.M. 2006. Urban origins/destinations from high-resolution remote sensing images. *Journal of Urban Planning and Development-Asce* 132(2):104-111.
- Wang, J.F., Treitz, P.M., and Howarth, P.J. 1992. Road network detection from spot imagery for updating geographical information-systems in the rural urban fringe. *International Journal of Geographical Information Systems* 6(2):141-157.
- Weber, C., and Puissant, A. 2003. Urbanization pressure and modeling of urban growth: example of the Tunis Metropolitan Area. *Remote Sensing of Environment* 86(3):341-352.
- Wilson, E.H., Hurd, J.D., Civco, D.L., Prisloe, S., and Arnold, C. 2003. Development of a geospatial model to quantify, describe and map urban growth. *Remote Sensing of Environment* 86(3):275-285.
- Xiao, X.M., Zhang, Q.Y., Saleska, S., Hutyrá, L., De Camargo, P., Wofsy, S., Frohking, S., Boles, S., Keller, M., and Moore, B. 2005. Satellite-based modeling of gross primary production in a seasonally moist tropical evergreen forest. *Remote Sensing of Environment* 94(1):105-122.