DISCUSSION PAPER

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

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RESOURCES
FOR THE FUTURE

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Abstract

We demonstrate the diffusion in use of Earth observations data in social science research. Our study is motivated by the continuing debate among policymakers over the value of the nation's investment in Earth observations. We also consider the role of related factors including the spread of geographical information systems (GIS; a complementary tool for using Earth observations data) and the role of data prices. We first estimate a diffusion curve and then draw from standard bibliometric methods to evaluate further the extent to which the research field is growing. We realize that these aspects 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 geographic regions. GIS and data prices influence this diffusion. However, we see less evidence of a community of practice within the large social science literature represented in our data. These findings have implications for steps to take to increase the benefits of Earth observations.

Key Words: Earth observations, Landsat, natural resources policy, technical diffusion, knowledge diffusion, remote sensing, environmental management

JEL Classification Numbers: Q28, R10, Q19, Q38

Contents

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Introduction

In its annual federal appropriations discussions, the U.S. Congress routinely asks, "How much is it worth to continue investing in the nation's Earth-observing satellites?" Apparently, the answer has 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, 45). A recent report by the U.S. Congressional Budget Office 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, the National Academy of Sciences committee carrying out the survey felt compelled to draft an interim report titled *Urgent Needs*; at present, funding for some missions is delayed (National Research Council 2005).

The usual answer to the question "why fund Earth observations?" is a set of examples offered by the relevant federal agencies—usually, the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA)—of science research and findings and some examples of the application of observations to decisionmaking. These examples demonstrate compelling uses of data to manage the nation's energy and water resources; inform decisions about agricultural,

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forestry, and other land uses; and improve the 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.

In this paper, we suggest several steps toward a somewhat more systematic approach. We document the use of Earth observations within a large, peer-reviewed literature drawn from more than 2,000 journals. We describe the breadth of applications and thus help to extend previous surveys of the field, including those by the National Research Council (1998) and 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. (The Office of Technology Assessment [OTA; 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 find that Earth observations are truly a "window on the world," in that most of the applications are to resource use and management in countries other than the United States. We also find that one of the types of data, those from the Landsat program, have provided a time series of data to enable a growing number of studies looking overtime at resource practices. The Landsat program is the longest continuously operating Earth observations satellite system in the world, and Landsat data are often cited as an increasingly unique time series. Our findings support this contention.

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 a lack of relevant software and the price of data as well as indirect costs of data, such as data access or training required to use the data, are possible barriers to adoption (National Research Council 2001, 2003). Our findings substantiate these concerns with evidence that factors influencing diffusion include the increasing use of geographical information systems (GIS) and 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.

The rest of our discussion proceeds as follows. First, we provide background on technology diffusion and its application in our study. We next describe our methods and data. We also briefly describe the breadth of topics addressed by the articles composing our data set; this breadth is, itself, an indicator of diffusion. We then report our statistical evaluation of some of the possible determinants of the diffusion of uses of observation and offer conclusions.

Background: Adopting New Technology in the Diffusion of Use of Terrestrial Observations

The theoretical and empirical literature on the diffusion of technology has focused on tangible goods and services such as the spread in the use of cell phones and flat-panel televisions and computer monitors (Stoneman [1995] surveys this literature). The usual approach to identifying determinants of diffusion is the modeling and estimation over time of market shares, prices, and other factors influencing peoples' 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 the measurement of how 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 the factors that influence the adoption of Earth observations beyond the scientific research they permit is an element of the public sector decision to fund the collection of these data.

Method

We begin by identifying and systematically documenting applications of Earth observations. We compile a data set 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 2,000 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 provides a sample cohort of a wide range of applications, allowing us to observe how use changes over time and to explore 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 refer to Earth observations not with the term *Earth observations*, but with *remote sensing* and *satellite data*, and we therefore used these terms in our search.

We include articles published between 1994 and February 2008. We thus dovetail with previous literature surveys carried out in the late 1990s that reviewed articles up to about the mid 1990s (Blumberg and Jacobson 1997; National Research Council 1998). We limit 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 allow us a long series with which to estimate diffusion.

For all articles identified by the keywords, we review the abstracts to sort the articles into four categories: (a) keep, (b) omit as not relevant, (c) omit as a technical article rather than an application of remote-sensing data, and (d) omit as not involving a land-related application. Examples of category (b) include articles addressing *satellite accounts*—subsections of the national income and product accounts used to produce estimates of gross domestic product (GDP) and other statistics about the economy. Our keyword search identifies these articles with the term *satellite*. An example of category (c) is a set of articles developing and testing algorithms, comparing ground-truth and remote-sensing data, and fusing data from different instruments, as well as other, largely methodological, research on validation, verification, and other means of characterizing the data; these articles do not address applications of data. The preponderance of articles in our search address land applications, but a few articles fall into category (d).

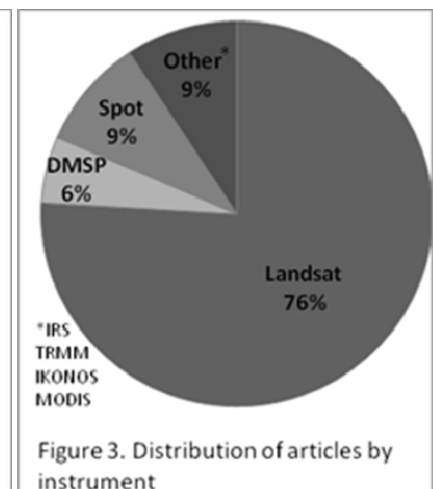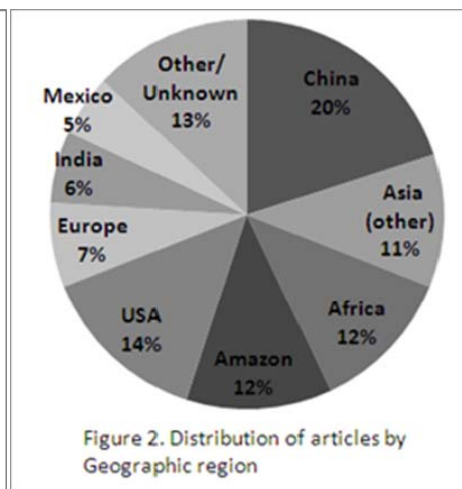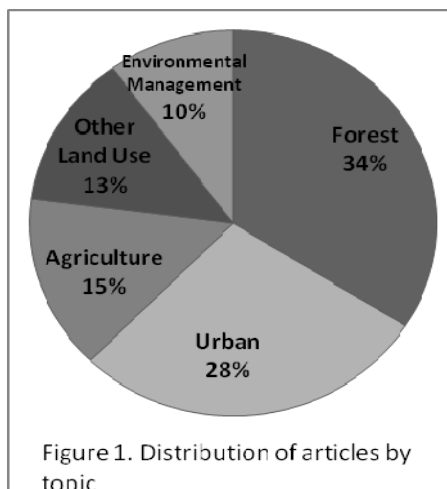This search method has several limitations that could lead to an underestimate of data applications. For example, although we tested our search criteria on randomly selected articles to

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

design the best keywords, the two indices search only the abstracts. Authors may not address the use of remote-sensing data in their abstracts. Additionally, although SSCI and EconLit are considered the most comprehensive social science indices, they do not include all journals in which social science applications appear. And, as noted earlier, our use of peer-reviewed literature allows us to systematize our search, but we omit applications documented in conference proceedings, workshop papers, and other reports.

Description of the Articles

The search yields a total of 107 articles published in 59 journals. Figures 1, 2, and 3 summarize the thematic and geographic focuses of the articles and the instruments serving as sources of Earth observations data. The articles address themes ranging 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. More than a third of the articles center on four geographic areas, all outside of the United States; these are Africa, the Amazon, China, and other parts of Asia. Fewer than 15 percent apply remote-sensing data to the United States. This distribution illustrates the "window on the world" enabled by remote sensing. About half of the articles identify the source of data by instrument. Of these articles, three-fourths use Landsat as the data source. Other data sources include the Satellite Pour l'Observation de la Terre (SPOT), the Defense Meteorological Satellite Program (DMSP), IKONOS, the Indian Remote Sensing (IRS) Satellite, the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer airborne simulator, and the Tropical Rainfall Measuring Mission (TRMM).

Figure 1. Distribution of articles by topic

Figure 2. Distribution of articles by Geographic region

Figure 3. Distribution of articles by instrument

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

Table 1. Trends in Applications

	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, United States	Amazon, China, Asia (other), Europe, India, Mexico, Africa, United States	Amazon, Asia, China, Europe, India, Mexico, Africa, United States, Other
Instrument(s) (% all articles identifying instrument(s))			
Landsat	100	56	84
Other	—	44	16
Use of Landsat for time series of data			
Percentage of all articles using Landsat	40	40	60
Length of series (years)			
Mean length of series (years)	4–7	4–27	11–30
	6	16	17
Journals (number)	4	27	45

Note: (–) indicates no examples found.

Among themes, particularly notable is 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 an initial focus on the Amazon, Mexico, and the United States to a focus that also includes China and other parts of Asia, Europe, India, and Africa. Among data sources, applications now span a wider variety of instruments. We notice the most variety among

instruments in the middle of our time series (1999–2003), when almost half of the articles are based on SPOT, DMSP, and IKONOS A trend toward use of a variety of data sources is not apparent in the most recent period, however, where we see 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 are used, 40 to 60 percent use the data as a time series (the other uses are for cross-sectional analyses). The fourth row of Table 1 shows the number of articles in 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 more recently. The mean length of the time series used in the articles has increased from 6 to 17 years.

Associated with a greater breadth of subject and region, as well as the trend in time series, the number of different journals in which applications of Earth observations data appear increased from 4 in 1994–1998 to 45 by 2008, based on the journals covered by our databases (Table 1). Table 2 lists the journal titles.

Our thematic classifications are admittedly broad and understate the diversity of specific topics. Therefore, because we seek to illustrate the increase in the diversity of applications of Earth observations, we next briefly summarize the articles. We then turn to an analysis of possible determinants of this increase in the scope of applications.

Table 2. Journals Represented

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

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

Agriculture

A diverse range of studies in our sample use Earth observations to assess land use or to study land-use changes over time. A majority of these studies examine agricultural trends in Africa, Asia, and Eastern Europe—many at large spatial scales, such as entire countries or regions. At the most general level, studies classify land uses in the absence of national maps or offer 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 estimate significantly higher agricultural capacities than government-reported figures, especially in China and other low-income nations, and provide insights into food security concerns.

Many of the articles consider 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 (Braimoh and Vlek 2005; Vogt et al. 2006; Muller and Zeller 2002; Xu et al. 2005). A theme in several of the articles is the abandonment over time of prime agricultural land near population centers as a result of overuse and soil degradation, shifting fields farther from village boundaries. Several authors offer policy recommendations, such as encouraging location-specific sustainable agriculture or proposing other interventions 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 and Mougenot 2000; Sengupta and Osgood 2003; Nivens et al. 2002).

Forestry

Studies of forested areas focus on tropical deforestation, predominately in the Amazon, Mexico, and Southeast Asia. The lion's share of these studies analyze the biophysical, demographic, and infrastructure influences on deforestation in the Amazon. Linking Earth observations to social science data sets and survey data, these studies identify 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; these include studies, 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).

Deforestation studies outside of the Amazon use diverse approaches to uncover drivers specific to different parts of the world. Deforestation in Southeast Asia and Africa is linked to social and biophysical variables, such as political and economic conditions, elevation changes, and forest fires; thus, studies of these regions require data and analytical techniques that differ from those that are appropriate for Amazonian studies (Taylor et al 1994; Vagen 2006; Mertens et al. 2000). Studies of community-owned forests in Mexico and India reveal 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 de Janvry 2005).

Beyond the drivers of deforestation, a handful of studies consider reforestation, including economic conditions that encourage 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, Perz and Skole 2003b). Another group of studies focus on the *mechanics* of deforestation, studying the fragmentation of contiguous lands and distinct deforestation patterns found between primary and secondary forest types (Ochoa-Gaona 2001; Perz and Skole 2003a). Some studies seek 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 receive 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

Studies in this category focus largely on urban development in the United States and China. These studies cover a range of spatial and temporal scales and touch on a variety of urban issues. All of these studies use time series analysis to characterize dynamic spatial–temporal patterns associated with urban growth. In general, these studies quantify urbanization patterns with detailed landscape metrics and urban growth models.

Studies of the United States address urban growth and peripheral development within individual cities. These analyses consider small spatial scales—at the city or subcity scale—with some studies using 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

examine land imagery from the 1970s to 2000s, with decadal snapshots to characterize generally the lands replaced by urbanization and to identify the social, geographic, and infrastructure factors that influence urban growth (Burchfield et al 2006; Lo and Yang 2002; Herold et al. 2002; Ji et al. 2006). Beyond characterization, some studies also model urban growth and forecast land-use changes based on specific social and policy scenarios (Herold et al. 2003; Yang and Lo 2003). Several studies also consider "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; Nichol et al 2006).

Studies of urban regions in China use a wide range of spatial scales, including national-, regional-, and city-level analyses. Timescales are generally shorter than those in U.S. studies: most begin in the 1990s with time series ranging from annual to five-year increments. At the broadest level, national studies quantify the annual rate of urban growth across all of China's major cities, while also measuring the loss of arable land and identifying general growth characteristics across regions (Tian et al. 2005; Tan et al. 2005a). Several studies focus on regional analyses 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 Kaufman 2003). Analyses of individual cities describe intricate core–periphery interdependencies within city limits and quantify evidence of fringe *desakota* land-use patterns. These patterns are 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 identify the primary drivers of urbanization, including wages, direct foreign investment, and relative productivity gains over agriculture. These studies consider 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 Kaufman 2003).

Policy and Environmental Management

Studies focusing on policy and management address several subjects—predominately policy instruments, such as models or monitoring systems—and offer policy insights that evaluate or guide policy development. Policy instruments include tools used to monitor, model, or forecast events that can inform environmental planning, management, or policy development. Some applications develop a spatially explicit alternative to GDP using nighttime light

emissions, then integrate data on nonmarket ecological wealth to create a global index of sustainable growth (Sutton and Costanza 2002; Lo 2002). Another study develops 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 are 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; Pandy et al. 2007; Reddy et al. 2007; Walker et al. 2006; Tang et al. 2007). Similar models integrate imagery with soil, salinity, and geologic maps to model landscape degradation and revegetation strategies for dryland salinity sites (Apan et al. 2002 Li et al. 2001. Another study develops a spatial system for monitoring and forecasting locust plagues by integrating GIS and remote-sensing platforms with U.N. data concerning locust breeding, swarm movements, and environmental conditions.

Studies focusing on policy insights include those that identify, assess, and guide existing policies or demonstrate new policy concepts. Two studies use 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 examine the role of Earth observations to devise conservation units and tax credit policies for tropical forest management (Pdelowski et al. 2005; Alvarez and Naughton-Treves 2003). Another group of studies of Africa and Indonesia analyze 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 2000). Several quality-of-life studies use multispectral 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 ask if we can discern determinants of the diffusion of Earth observations as reflected in this cohort of articles. We use two standard methods. One is the statistical estimation of a conventional diffusion curve. The other is the bibliometric analysis of citations among authors to each others' work. We next describe 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 is possibly supplanted, in turn, 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 the diffusion of new goods and services, manufacturing processes, and other innovations.

Figure 4. The Diffusion Curve
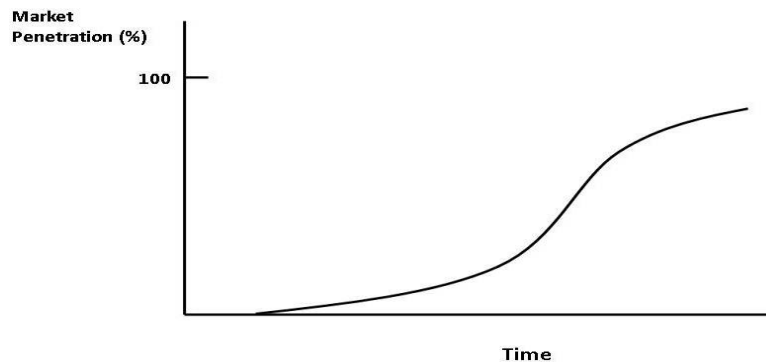
Source: Karshenas and Stoneman (1995, 269)

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 ask whether the pattern we see in the use of these data over time bears resemblance to the standard S-curve. We then consider two possible influences on diffusion. One influence is the availability and deployment of geospatial tools and complementary technologies that facilitate the use of remote-sensing data. Another influence is the cost of data in terms of the direct costs of data fees and the indirect costs of other inputs needed to use the data (for instance, training of students and resource managers). We select these factors because they have been previously identified as likely influences on the use of Earth observations and because they illustrate two types of policy implications. GIS has many purposes beyond facilitating the 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 are representative of an endogenous policy determinant.

For statistical analysis of these factors, we use 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 of the spread of GIS for our purposes. The Geospatial Information and Technology Association (GITA) surveys the adoption of GIS in six business sectors—electric, gas, water, pipeline, telecommunications, and the public sector. We use 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 use these data as a proxy to indicate the spread of GIS over time in social science (GITA 2008). For the price of data, we use data provided by USGS.[2] Experts with USGS suggested that we use the price per scene of multispectral scanner (MSS) color paper products, under the assumption that these are the most popular products 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 serve as a 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 estimate 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 form

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

where y_t is the cumulative number of articles at time t, 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. Although our articles are referenced by their publication date, this date typically lags the period during which the research was carried out. Accordingly, we seek 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

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[2] Bryon Bradford of USGS 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).

publication date of the article, we expect 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 that most articles are in press for several months or more. Additionally, researchers may use data purchased at any point prior to the project. We consider 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 provides 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 have these data for the period 1994 to 2007.

Table 3. Sample Descriptive Statistics

| Variable[a]	Mean	Standard deviation	Min	Max
GIS (number of organizations)	145.90	80.35	16	244
PRICE ($ per scene)	383.18	181.22	170	600

[a]See text for description.

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

Table 4. Estimation Results

Variable	Estimated coefficient (standard error)
GIS	0.029 (0.002)
PRICE	–0.002 (0.001)
β_0	–17.66 (0.436)
Adjusted R^2 = 0.99	

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

We find that both the GIS trend and the data price give the best statistical fit when both are lagged by two years relative to the article publication date. The constant term and the coefficient of the GIS variable are statistically significant at the 99 percent level, and the coefficient of the price variable is statistically significant at the 10 percent level. Figure 5 shows the fitted and actual values.

Figure 5. Actual and fitted values
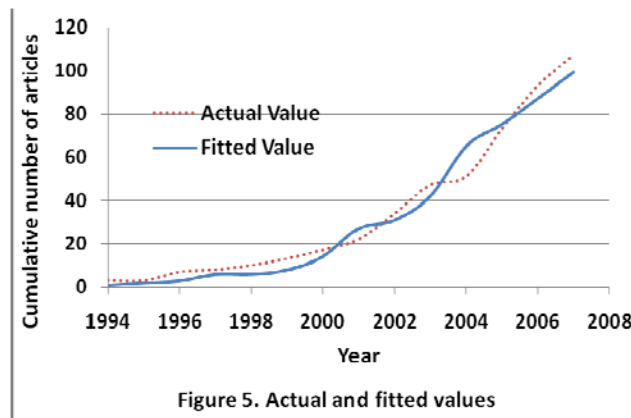
The estimated coefficients confirm our prior expectations. Based on our sample data, increases in the deployment of GIS encourage the spread of Earth observations data use, whereas increases in data prices reduce the spread of use. Our sample also suggests that we are not yet at the point where the S-shape begins to flatten. In other words, the spread of Earth observations applications 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 the 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 the likely importance of continued deployment of GIS, including software and training, in further promoting the use of Earth observations data (the link between GIS and remote-sensing data is a concern expressed by the National Research Council [2001, 2003]). Furthermore, we would anticipate that as data uses become 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 the diffusion of data applications. The cost of data is 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 non-US instruments.

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[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.

A factor not explicit in our model is 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
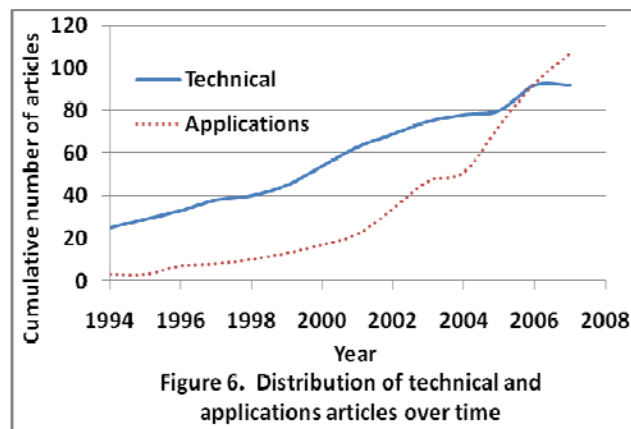
The cumulative number of technical articles has exceeded applications articles until recently. A conventional test suggests that these distributions are statistically different, implying that the drivers for the technical literature may differ from those for the applications literature.[6] We also note that the distribution of technical articles seems to be leveling off. We speculate that this may be indicative of a slowing of research until the launch of the next generation of missions. We leave for future study the 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

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[5] This set of technical articles is a small subset of all such articles because 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.

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 "lifetime" of a paper, and possible biases introduced by self-citation and in-house citation (because these could tend to overstate the breadth of diffusion among different researchers).

We use 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 use a standard bibliometric approach of citation counts (see OTA 1986) to trace which authors refer to previously published work within our sample.

We find 45 articles (about 40 percent of our sample) containing references to other articles within the sample; these include 9 self-citations, in which the author or authors are the same in the citing and cited article. In addition, we find 12 citations with overlapping authorship—that is, cases in which one or more of an article's authors cite a previous article to which they were contributors, but the full list of authors is not the same for each article. The citations are within 12 different journals and across four of our themes. The absolute number of citations increases over time, with 16 citations during 1999-2003 and 29 during 2004–2008. As a percentage 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 percent. 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 offer a framework to improve understanding of the diffusion of applications of Earth observations, using a combination of standard statistical analysis and citation surveys. We see this approach and our results as (a) complementary with other efforts to demonstrate the benefit of investments in Earth-observing missions and (b) supportive of the need to improve the means by which this benefit is documented.

Our study shows 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 the study of a host of countries and regions and are 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 data costs. Within our sample, we find these to be significant determinants of the number of applications over time. We also find 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 the 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 find limited 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, such as surveys and syntheses of the literature, special journals and journal issues, and conferences and workshops. Enhancing this foundation would bode well for the continued diffusion of Earth observations and would strengthen the evidence for the benefits of investing in them.

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