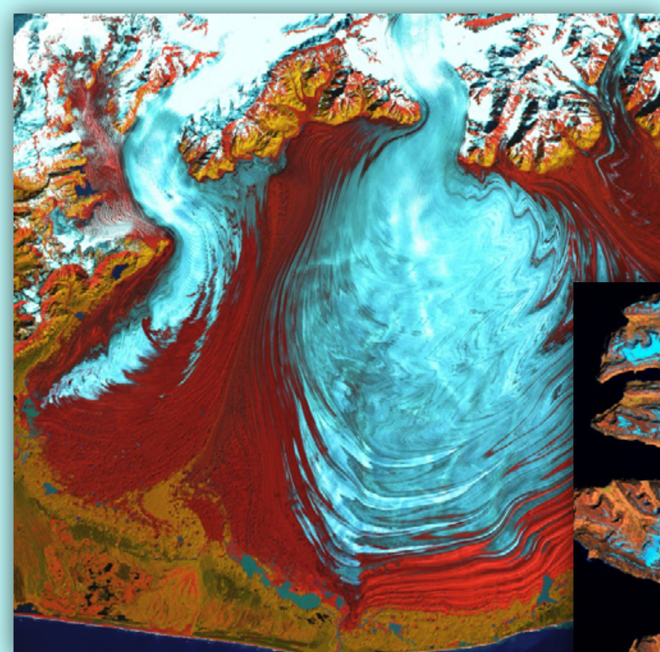
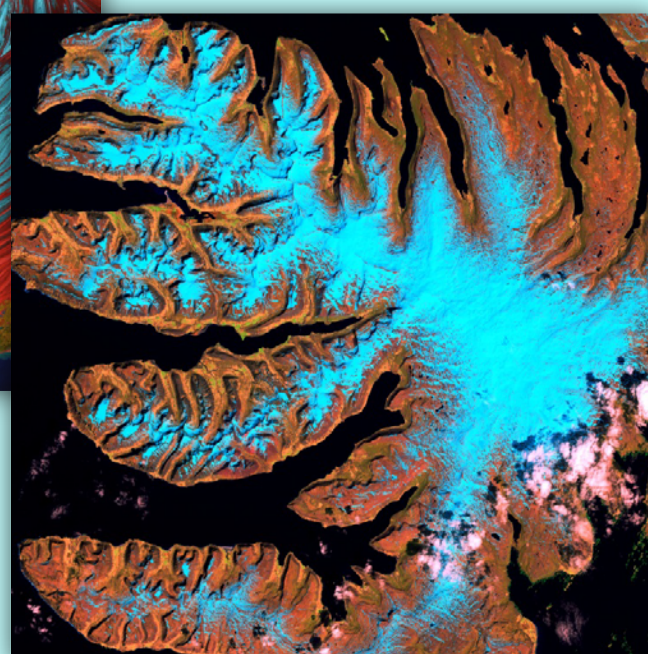
Users, Uses, and Value of Landsat Satellite Imagery—Results from the 2012 Survey of Users

By Holly M. Miller, Leslie Richardson, Stephen R. Koontz, John Loomis, and Lynne Koontz





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Acronyms and Initialisms

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ALOS	Advanced Land Observing Satellite
AVHRR	Advanced Very High Resolution Radiometer
CBERS	China-Brazil Earth Resources Satellite
CI	confidence interval
CVM	contingent valuation method
EO-1	Earth Observing One
EROS	Earth Resources Observation and Science Center
ETM+	Enhanced Thematic Mapper Plus
IKONOS	Derived from *eikōn*, the Greek word for image
LB	lower bound
MSS	Multispectral Scanner
MODIS	Moderate Resolution Imaging Spectroradiometer
SLC	scan-line corrector
SPOT	Satellite Pour l'Observation de la Terre
TM	Thematic Mapper
WTP	willingness-to-pay

Executive Summary

Landsat satellites have been operating since 1972, providing a continuous global record of the Earth's land surface. The imagery is currently available at no cost through the U.S. Geological Survey (USGS). We conducted a survey in early 2012 to explore who uses Landsat imagery, how they use the imagery, and what the value of the imagery is to them. The survey was sent to all users registered with USGS (users who have created a login and password to access imagery through USGS directly) who had accessed Landsat imagery in the year prior to the survey (n = 44,731). All contact with users was via email and the survey was administered online. The response rate was 30% with 13,473 users responding. Of those users, 11,275 were current Landsat users who had used the imagery in their work in the year prior to the survey. The results reported below apply to current Landsat users registered with USGS.

Landsat Users

Slightly less than three-quarters of the users were international (73%) and the rest were from the United States. New users (those who had never used Landsat imagery before it became available at no cost in 2008) constituted a large group of users (43%), as did established users (those who used Landsat regularly both before and after it became available at no cost, 41%). There was also a small group of returning users (those who had used Landsat in the past, but had not used Landsat for at least a year prior to it becoming available at no cost, 16%). The majority of users were end users who apply imagery or products derived from imagery to accomplish work. More than half of the users worked in academia, but users from all sectors were represented.

Landsat Use

Of the satellite imagery used in the year prior to the survey, one-quarter of users indicated that they used only Landsat imagery. The rest of the users used a mix of imagery, with more than half of the imagery, on average, coming from Landsat sensors. Of the Landsat imagery used, on average, 44% was from ETM+ (Enhanced Thematic Mapper plus, Landsat 7) and 44% was from TM (Thematic Mapper, Landsats 4 and 5), with 7% from MSS (Multispectral Scanner, Landsats 1-5) and the remainder from an unspecified Landsat sensor. The majority of users (78%) used scenes acquired by Landsat sensors during two or more 5-year time periods and more than half (57%) used scenes from three or more time periods, indicating most users are working on projects spanning multiple years. In the year prior to the survey, projects that used Landsat imagery ranged from local to global geopolitical scales in locations around the world. Users applied the imagery in 38 different primary application areas, with the most common being environmental sciences and land use/land cover.

Impacts of No-Cost Data Policy

The entire archive of Landsat imagery became available online at no cost at the end of 2008. To determine the impacts of this free and open data policy, we asked established users about their imagery acquisitions before and after the policy went into effect. USGS was the most common source of Landsat imagery both before and after the policy change but the percentage of users obtaining Landsat from USGS increased from 54% before the policy change to 81% after the policy change. Additionally, after the policy change, the average number of scenes obtained from all sources annually per user more than doubled while the average amount spent annually on Landsat imagery per user decreased by 78%. Though it may be expected that users would spend zero dollars on imagery after it became available at no cost from USGS, this is not the case. One reason for this is that users are not obtaining all their Landsat imagery from USGS. Some users are still purchasing imagery from other providers, possibly to obtain imagery which has been processed beyond what is provided by USGS.

Value of Landsat Imagery

Importance and Satisfaction

We used four approaches to estimate the value of Landsat to users. First, we explored the importance of Landsat imagery to users, as well as their satisfaction with the imagery. Users were asked to rate 14 Landsat attributes, ranging from availability and cost to spatial and spectral resolution. On average, all attributes were rated as important and users were satisfied with the provision of those attributes. The highest ratings were for availability, accessibility, and cost, which indicate that these are the most important attributes to users and they are satisfied with how the imagery is being provided.

Benefits of Landsat

Second, we asked about the environmental and societal benefits users observed from their projects that used Landsat. More than 80% of users saw environmental benefits, including improving or enabling long-term planning or monitoring, protecting or improving environmental conditions, and maintaining or improving ecosystem services. Almost 90% saw improvements in decision-making through better communication of concepts using Landsat imagery. More than three-quarters cited supporting enforcement of regulations or policies and reducing human risk or increasing human safety as benefits. Close to 70% of users also saw some resolution of disputes or reduction in conflicts as a result of projects using Landsat.

Dependence on Landsat

Third, we asked about dependence on Landsat imagery. This was measured by level of use, self-described dependence on the imagery, what users would do if Landsat imagery was no longer available, and how the inability of Landsat 5 to collect new imagery from fall 2011 to spring 2012 had affected their work. One-quarter of users were classified as heavy users, applying Landsat in 71% or more of their work and another 28% were medium users, applying Landsat in 31-70% of their work. Regardless of level of use, the majority of users indicated they were very (39%) or moderately (36%) dependent on Landsat imagery to do their job.

When asked what actions they would take if new and archived Landsat imagery was no longer available, 62% of users said they would discontinue at least some of their work. Of users who would discontinue work, they would discontinue, on average, half of their work. Two-thirds of users would substitute other information in some of their work. The most common substitute information would be other imagery, followed by non-imagery data sets and on-the-ground fieldwork. Of those users who would use substitute imagery, more than half would be likely to replace Landsat with imagery that is also available at no cost, such as ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer), and CBERS (China-Brazil Earth Resources Satellite). Still, if Landsat was no longer available, the majority of users (70%) believed it was somewhat or very likely that their overall costs would increase, indicating there are other costs related to switching to different imagery, beyond any cost of the imagery itself.

While the survey was underway in early 2012, new Landsat 5 data were not available. Although the loss of newly acquired Landsat 5 imagery was obviously undesirable, the situation provided an opportunity to ask users about their actual responses to the loss of imagery. More than three-quarters of current Landsat users (79%) had used Landsat 5 imagery in the year prior to the survey. More than 40% of those users decreased or ceased their use of Landsat imagery after Landsat 5 stopped acquiring imagery. More than two-thirds of Landsat 5 users indicated that the loss of the imagery negatively impacted their work through decreased quality or scope of work, increased time spent on work, and (or) increased costs of work.

Economic Benefits from Landsat

Lastly, we utilized the contingent valuation method (CVM) to estimate the economic benefits to users from Landsat imagery. CVM is a survey-based nonmarket valuation approach, widely used to estimate the economic benefits of goods or services that are not bought and sold in markets. Two CVM questions were asked in which survey participants were asked to decide whether a Landsat scene is worth the amount specified in the questions. An estimate of the average economic benefits of Landsat is inferred from the responses to these questions. The average benefits per scene varied across user groups. Established users reported higher benefits than new/returning users. International users also reported greater benefits than U.S. users. Using the average economic benefit per scene for each of four user groups (established and new/returning U.S. and international users) and the estimated number of Landsat scenes directly distributed to these groups from EROS in 2011, an aggregated value of the imagery was calculated. In 2011, the economic benefit from Landsat imagery obtained from EROS was estimated to be just over $1.79 billion (lower bound (LB) = $1.64 billion) for U.S. users and almost $400 million (LB = $363 million) for international users, resulting in a total annual economic benefit of $2.19 billion (LB = $2 billion). This estimate does not include benefits from reuse of the imagery after it has been obtained from EROS or from the use of value-added products based on Landsat imagery.

Conclusion

The results of the survey revealed that users around the globe from multiple sectors use Landsat imagery in many different ways, as demonstrated by the breadth of project locations and scales, as well as application areas. Changes in acquisition patterns, including the increase in the number of scenes acquired and the decreasing amount of money spent after the imagery became available at no cost, point toward increases in future use. The value of Landsat imagery to these users was demonstrated by the high importance placed on the imagery, the numerous benefits observed from projects using Landsat imagery, the impacts if Landsat imagery was no longer available, and the substantial aggregated annual economic benefit from the imagery.

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By Holly M. Miller[1], Leslie Richardson[1], Stephen R. Koontz[2], John Loomis[2], and Lynne Koontz[1]

Introduction

Remotely sensed data, such as satellite imagery, are an increasingly important component in understanding and monitoring the Earth. There are a wide variety of satellites now flying; the United States alone had more than 80 civil Earth observation instruments operating in 2012 (National Research Council, 2012). Landsat satellites provide multispectral, moderate-resolution land imagery that offers a unique combination of three important characteristics. First, the archive of imagery extends back to 1972, allowing for broad-area analyses over several decades. Second, the imagery is and has been collected globally on a regular basis, providing consistent repeat coverage. Third, the imagery is currently available at no cost and with no user restrictions to those downloading images from the U.S. Geological Survey (USGS). Landsat satellites are operated by USGS which receives, processes, distributes, and archives the imagery at the Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota.

The successful launch of the Landsat Data Continuity Mission (LDCM) on February 11, 2013, continues the decades-long Landsat program with Landsat 8. Landsat 8 is now the lead satellite along with Landsat 7 which will also continue to provide imagery. Landsat 7 was launched in 1999 and provided 4 years of high-quality data before it sustained a critical technical malfunction in May 2003. The imaging instrument's scan-line corrector (SLC) failed and this limitation (commonly referred to as SLC-off) has since reduced the usability of Landsat 7 imagery. Until December of 2012, Landsat 5 operated concurrently with Landsat 7 which helped to mitigate the issues caused by the SLC-off. However, after more than 28 years of service, the decision was made to decommission Landsat 5 due to a gyroscope issue. As the satellites have changed over the last decade, so has the provision of the imagery. The entire archive of Landsat imagery, including all new acquisitions, became available online at no cost at the end of 2008 under a new free and open data policy. From late 2008 to September 2012, 9 million scenes were downloaded from EROS, with more than 3 million scenes distributed in 2012 alone. Prior to the availability of no cost imagery, the most scenes sold in one year totaled 25,000.

Landsat imagery provides unique spatial information for use by many people both within and outside of the United States. However, the population of these users is unknown, so determining exactly who these users are, how they use the imagery, and the value and benefits derived from the imagery is a challenge. There have been a few surveys and studies that have addressed this issue. As part of a larger study including multiple surveys and case studies, we conducted a survey of users in 2009 (Miller and others, 2011) to provide baseline information on

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the users, uses, and value of the imagery, but the results were not generalizable to a larger population of users. Other recent studies have surveyed specific groups of users of Landsat and other imagery (for example, EROS, 2007; Green and others, 2007; National States Geographic Information Council, 2006; Stoney, Fletcher, and Lowe, 2001). These surveys tended to be more technical in nature and have added to the body of knowledge regarding opinions on the attributes of various sensors. The last comprehensive evaluation was completed almost 40 years ago and attempted to project the conceivable economic benefits of a continued Landsat program (ECON, Inc., 1974). Much has changed since that time—not only with the characteristics of remotely sensed data but the applications of the imagery. One of the most impactful changes is the free and open data policy, which has resulted in a dramatic increase in both scenes distributed from EROS and users registered with EROS. The number of registered EROS users has increased tenfold since 2008 providing an opportunity to sample a greater variety of Landsat users while still being able to generalize to a population. To obtain information regarding these users and their uses of the imagery, we conducted a second survey in 2012.

Sampling

The population of interest for this study comprised all people who had accessed Landsat images through EROS within the year prior to the survey; it did not include downstream and secondary users who do not obtain imagery from EROS. A list of 46,146 email addresses was provided by EROS. After duplicate and nonworking email addresses were removed, 44,730 addresses remained. Because of the low time and cost barriers associated with contacting users via email and providing the survey exclusively online, we chose to conduct a census of this population, rather than take a sample. One of the main reasons for a census approach was because just over half of the users (52%) on the list resided in countries where English is not an official language. Because the survey was only available in English, we anticipated that there would be language barriers with some users. Every user must have at least some knowledge of the English language to navigate the web sites that provide access to Landsat imagery. However, because of the complexity of some of the questions on the survey, not all users may have been able to fully understand every question. A random sample would have limited the number of users contacted and thus potentially increased the impact of any existing language barriers on the response rate. A census ensured that everyone who had sufficient knowledge of English was afforded an opportunity to take the survey. The language barrier may have introduced some bias into the results, but it is very difficult to determine if this is the case for this survey effort. Although there were some open-ended questions where users had the opportunity to write in responses, the small amount of writing hindered any kind of fluency analysis.

Survey

We launched the survey in April 2012 to all the users with valid email addresses on the EROS list. For continuity, the survey was very similar to the 2009 survey. The survey was developed in conjunction with experts at EROS to ensure that the technical details were accurate and that the instrument would gather information that would inform the USGS Land Remote Sensing Program's distribution of imagery and future program requirements. The 2009 survey was conducted entirely online and we followed the same model for the 2012 survey, using a modified Dillman method for contacting users via email (Dillman, 2007). Users received up to six emails asking for their participation in the survey. The sender and subject line were varied with each email to decrease the chances of being caught in spam filters and to increase the chances of recipients opening an email. Each email contained a link unique to that recipient to the online survey, which allowed individual users to enter and exit the survey as they wished while saving their answers. As soon as users clicked on the Submit button at the end of the survey, the survey was considered complete and they were sent no further emails.

An online survey is not appropriate for all populations, because often members cannot be assumed to have access to a computer, access to the Internet, an email account, or the technological skills necessary to complete a survey online. In this case, the population consists of imagery users who must have access to a computer and the Internet to have accessed the imagery through EROS, who have an email account, and who must be at least somewhat technologically adept to use the imagery. Providing the survey online allowed an opportunity to ask only the questions relevant to each respondent through the use of automated logic patterns in the survey. Because there was no guarantee that all the users had used Landsat imagery in their work in the year previous to the survey, we constructed a survey with questions tailored to both current (used Landsat in the year prior to the survey) and past (used the imagery at some point but not in the year prior to the survey) users of the imagery. The set of questions for each of these users was considered a survey "path." The answers to certain questions directed users to the appropriate survey path, reducing the burden on users and collecting the most relevant information from each respondent.

Results

Analyses

We analyzed the data in several different ways, including examining frequency data, chi-square analyses, and t-tests (as described in Ott and Longnecker, 2001). A contingent valuation analysis was used to estimate economic benefits (Champ and others, 2003). Because Landsat satellites are built and operated by the U.S. Government, the views of U.S. users were of particular interest, so most of the results are presented for all users and for U.S. users and international users separately. Significant differences between U.S. and international users are reported when they occur (refer to the following section on statistical significance and interpretation for what constitutes significance for these analyses). Where there are differences, chi-squares are reported for categorical variables and t-tests are reported to compare means computed from scale variables. The contingent valuation analysis is described in detail in the Economic Benefits from Landsat Imagery section and in appendix 2.

Statistical Significance and Interpretation

Because of the large sample size, the statistical power of all tests is very high (close to or at 100%), which may lead to differences that are statistically significant but not meaningfully different (in other words, practically significant). Because of this, we consider differences to be statistically significant at $p \leq 0.001$, rather than the more typical $p \leq 0.05$ found in most social science research. Although this significance level may seem conservative, in these analyses, p-values are mainly used as guides to identify tests that may yield significant effect sizes; p-values greater than 0.001 are unlikely to yield significant effect sizes. Effect sizes are measurements of the amount of impact an independent variable has on a dependent variable (Murphy and Myors, 1998, p. 12) and are better indicators of meaningful differences than p-values. The effect sizes calculated for these analyses are phi (Φ) and Cramer's V for chi-square analyses and Cohen's d for t-tests (table 1).

Cohen (1988, p. 25–27, 79–80) provides the following examples to assist in interpreting these effect sizes:

- A small effect = difference in mean height between 15- and 16-year-old girls,
- A medium effect = difference in mean height between 14- and 18-year-old girls, and
- A large effect = difference in mean height between 13- and 18-year-old girls.

Following Cohen's recommendations on the interpretation of effect size for behavioral and psychological studies (1988, p. 25), we consider a statistically significant measure with an effect size of 0.1 (for phi and Cramer's V) or 0.2 (for Cohen's d) or greater to indicate a meaningful difference for this study. All statistical results are located in the footnotes or tables.

Table 1. Guidelines for interpretation of effect sizes (from Cohen, 1988).

Effect size	Small effect	Medium effect	Large effect
phi (Φ) and Cramer's V	0.1	0.3	0.5
Cohen's d	0.2	0.5	0.8

Response Rate

Almost 13,500 people responded to the survey for a response rate of 30% (n = 13,473). This response rate is equivalent to the average response rates for online surveys reported in several meta-analyses (for example, Lozar Manfreda and others, 2008; Sheehan, 2001; Shih and Fan, 2008). This number includes both completed surveys (n = 11,749) and partially completed surveys (n = 1,724). Partially completed surveys were only included if the respondent had answered a key question about their status as a Landsat user (new, established, or returning) located about halfway through the survey.

Because the response rate was not 100%, there was the possibility of non-response bias in the results. Non-response bias can occur when those people who did not respond to the survey are different in some way than those who did. A non-response survey was conducted to help to determine if non-response bias might exist. This short survey contained four questions: current or past Landsat user; new, established, or returning user; work sector (government, private business, academia, and so forth); and citizenship. A total of 1,622 individuals responded to the non-response survey. These results were compared to those of the respondent sample to determine differences. There were no statistically significant differences in the distribution of the four variables between respondents and non-respondents.

Response rates to individual questions are also of concern when conducting statistical analyses. The percentage of missing data per question ranged from 0 to 34%. The percentage of missing data generally increased as respondents progressed through the survey, most likely due to attrition as well as the increasing difficulty of the questions. Although more than 10% missing data on any given question may be problematic (Lynch, 2003), given the large sample sizes for this survey, the power remains very high for all results reported here. However, there is a chance that respondents who did not respond to certain questions would have responded differently than those who did respond, so where the percentage of missing data is more than 10% for a given question, that information is given in the text or in a footnote.

User Types

Current Landsat users (users who had used Landsat in their work in the year prior to the survey) composed 84% of the sample and past Landsat users composed 16% (fig. 1). Past Landsat users were asked only a handful of questions to determine why they were not currently using Landsat (see appendix 1 for a summary of results for these users). The results reported here apply to current Landsat users registered with USGS EROS. Of the current Landsat users, 27% were citizens or permanent residents of the United States and 73% were from other countries. Not all users answered the citizenship question on the survey; for those who did not (18%), the citizenship information from the original list provided by EROS was used instead. The distribution of users is very similar to the distribution in the original EROS list, which contained 31% U.S. users and 69% international users. Users from 167 countries responded to the survey. More than half (54%) were from countries where English is not an official language, slightly more than the percentage on the original EROS list (52%). This indicates language barriers may not have played a large role in whether users chose to respond.

The large increase in the number of registered users at EROS after the free and open data policy went into effect led us to hypothesize that at least some of these users would be new (they had never used Landsat imagery before it became available at no cost). In fact, new users were the largest group of users (43%), followed by established users (those who used Landsat regularly both before and after it became available at no cost, 41%, fig. 2). There was also a small group of returning users (those who had used Landsat in the past, but had not used Landsat for at least a year prior to it becoming available at no cost, 16%).

How the imagery is used can also delineate types of users. More than 60% of users identified themselves as end users who apply imagery or products derived from imagery to accomplish work, one-quarter of users classified themselves as product developers who create products derived from imagery, and 6% of users identified themselves as technical users who work on issues related to imagery such as calibration and validation. Less than 4% of users classified themselves as data providers who provide imagery for someone else to use and less than 3% as managers who supervise imagery users.

Figure 1. Respondents by Landsat imagery use and current Landsat users by citizenship (n = 13,473).

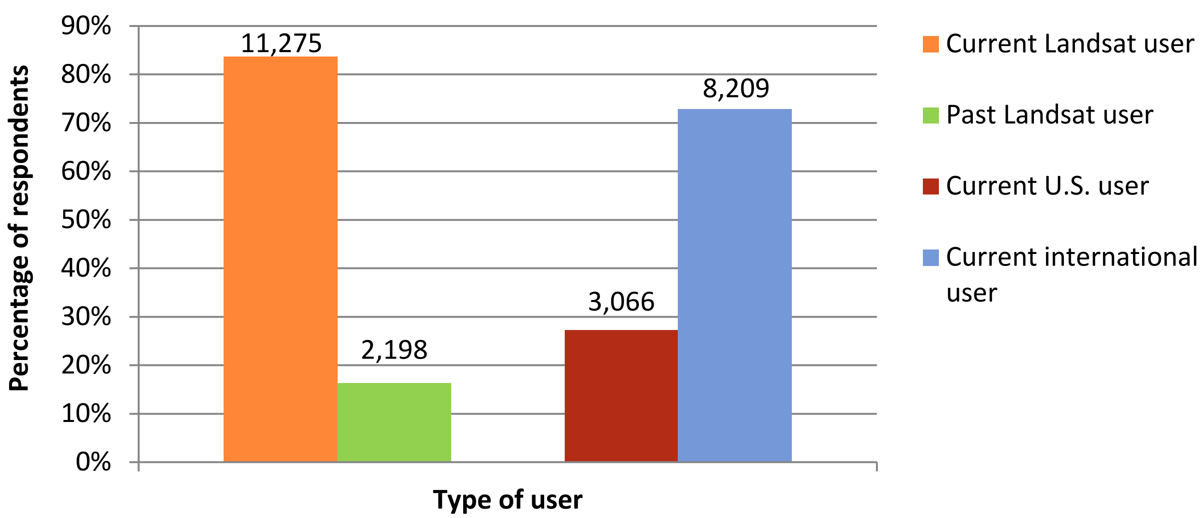
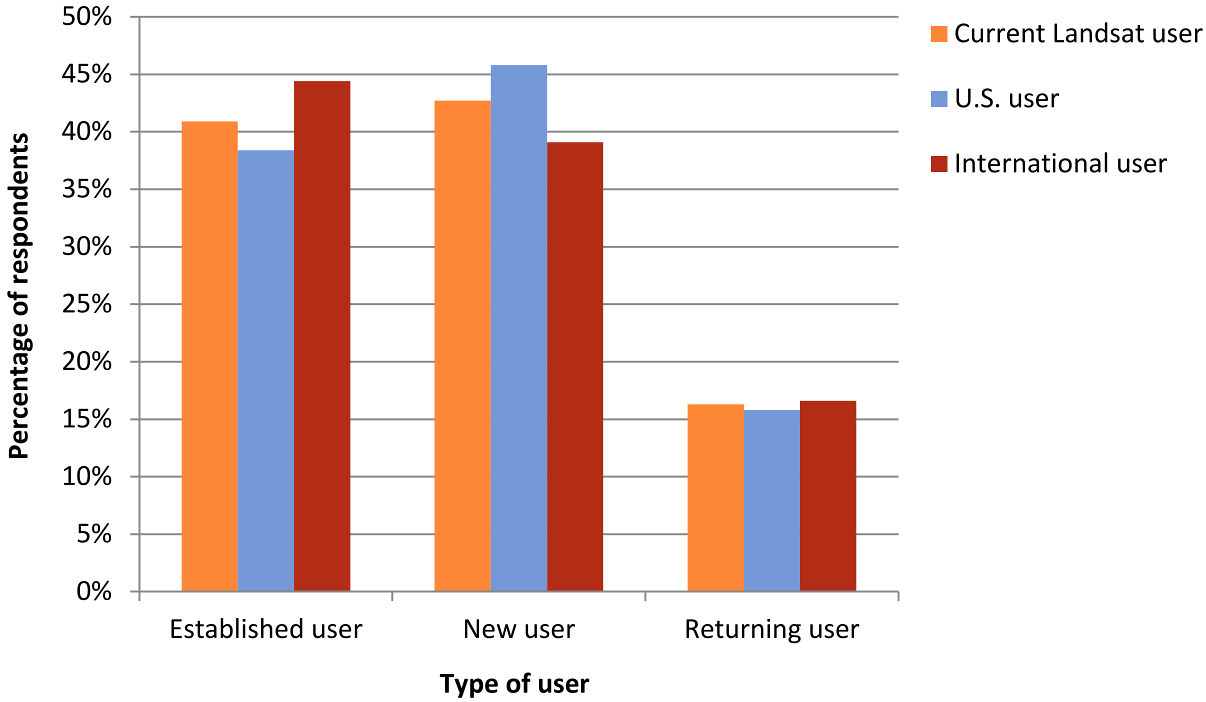


Figure 2. Status of Landsat imagery use among current Landsat users (n = 11,227).

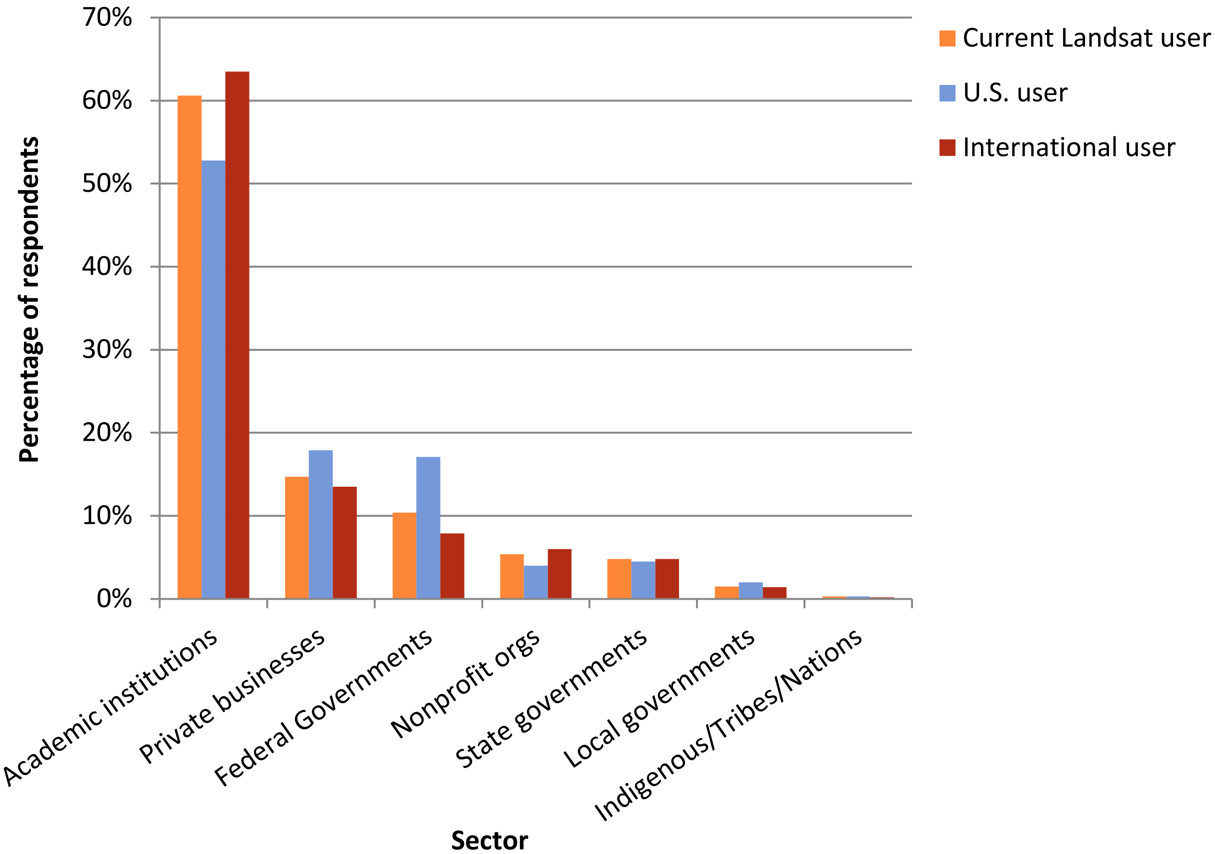


Demographics

The average current Landsat user was male, 38 years old,[3] and highly educated. More than three-quarters of the users were male[4] and 57% had at least 18 years of education.[5] Users had, on average, 10 years of experience using satellite imagery and (or) GIS software,[6] and a third were members of remote sensing and (or) GIS professional organizations.[7] U.S. users were more likely to be a member of such an organization (48%) compared to international users (26%).[8] The predominant sector was academic institutions (58%), followed by private businesses (15%), Federal Governments (11%), nonprofit organizations (6%), and State[9] governments (5%) (fig. 3). Only 2% of the users worked for local governments, and less than 0.3% worked for indigenous groups, tribes, or nations. Slightly more than 2% of users chose “other” because they worked for more than one sector or had recently retired (they are not shown in fig. 3).

[3] 20% of eligible respondents did not answer this question.
[4] 17% of eligible respondents did not answer this question.
[5] 15% of eligible respondents did not answer this question.
[6] 34% of eligible respondents did not answer this question.
[7] 19% of eligible respondents did not answer this question.
[8] $\chi^2 = 391.73$, $\Phi = -0.207$
[9] State governments include Provinces, Departments, and other similar geopolitical designations.

Figure 3. Sectors of current Landsat users (n = 10,789).



Use of Landsat Imagery

The first section of the survey established how the imagery is used, including types of imagery used, the temporal and geopolitical characteristics of projects, and application areas. Each question asked users to consider their use of Landsat in their work over the year prior to the survey. Users were also asked how their use of Landsat had changed over time.

Types of Imagery Used

About 26% of users indicated that the only satellite imagery they used in the year prior to the survey came from Landsat sensors. The remaining 74% of Landsat users indicated they used a mix of satellite imagery, with the majority on average coming from Landsat, followed by MODIS (Moderate Resolution Imaging Spectroradiometer), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), SPOT (Satellite Pour l'Observation de la Terre), and Quickbird (table 2). Of the Landsat imagery obtained in the past year, on average an equivalent amount came from the ETM+ (Enhanced Thematic Mapper plus) sensor on Landsat 7 and TM (Thematic Mapper) sensors on Landsats 4 and 5, while much less came from the MSS (Multispectral Scanner) sensors (Landsats 1 through 5; table 3). The remainder came from an unspecified Landsat sensor.

Table 2. Mean percentage of imagery used in the year prior to the survey among current Landsat users who used a mix of satellite imagery (n = 8,330). See p. vi for definitions of acronyms.

Imagery	Current Landsat users (n = 8,330)	U.S. users (n = 2,088)	International users (n = 6,242)
Landsat	51%	54%	50%
MODIS	11%	12%	11%
ASTER	8%	7%	9%
SPOT	6%	4%	7%
Quickbird	4%	5%	4%
IKONOS	3%	3%	3%
GeoEye-1	3%	3%	2%
WorldView-2	3%	3%	3%
ALOS	2%	1%	2%
AVHRR	2%	2%	1%
Other[1]	7%	6%	8%
Total	100%	100%	100%

[1]Contains 1% or less from each of the following: CBERS, Envisat, EO-1, Formosat 2, RapidEye, Resourcesat-1/IRS, and other imagery.

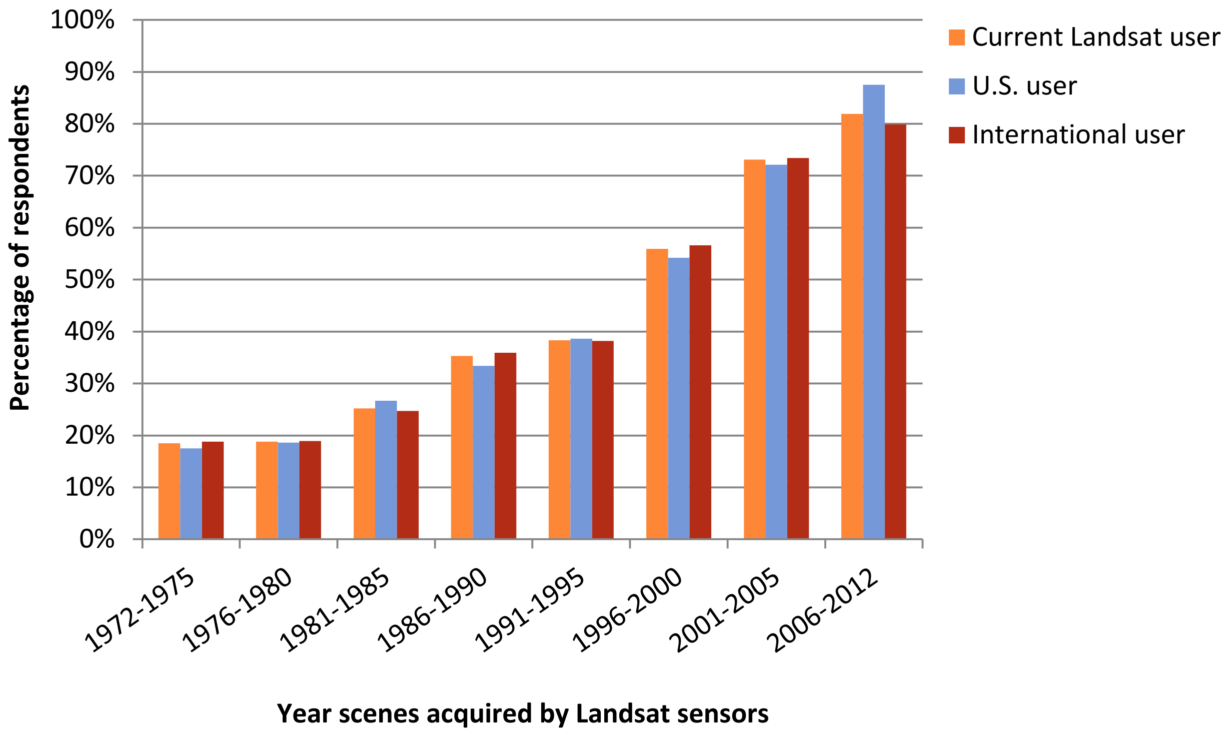
Table 3. Mean percentage of imagery from Landsat sensors used in the year prior to the survey among current Landsat users (n = 11,275). See p. vi for definitions of acronyms.

Imagery	Current Landsat users (n = 11,275)	U.S. users (n = 3,066)	International users (n = 8,209)
ETM+ (Landsat 7)	44%	40%	46%
TM (Landsats 4 and 5)	44%	45%	43%
MSS (Landsats 1-5)	7%	7%	7%
Unspecified Landsat sensor	5%	8%	4%
Total	100%	100%	100%

Temporal and Geopolitical Characteristics of Projects Using Landsat Imagery

Users were working on projects spanning the entire 40 years of the Landsat archive, though they were more likely to obtain more recently acquired scenes than older scenes from the Landsat archive. The majority of users obtained scenes acquired in 1996 or later, as compared to less than one-fifth of users obtaining scenes acquired in 1980 or before (fig. 4). This trend mirrors the number of scenes downloaded from EROS; more recent scenes are downloaded more often than older scenes. This trend also may reflect the fact that there were fewer scenes acquired in the earlier years and users may simply not be able to find scenes that correspond to their area of study during those time periods. The majority of users (78%) obtained scenes from two or more 5-year time periods and more than half (57%) obtained scenes from three or more time periods, indicating most users are working on projects spanning multiple years.

Figure 4. Acquisition years of scenes obtained by current Landsat users (n = 11,170).



Projects that used Landsat imagery ranged from local to global geopolitical scales in locations around the world. Almost three-quarters of users (73%) worked only on projects located outside of the United States, 14% worked on projects only within the United States, and 13% worked on projects in both the United States and internationally (fig. 5). Very few international users (7%) worked on projects located in the United States, whereas 52% of U.S. users worked on international projects. More than 80% of all users, except Europeans, worked on projects located within the geographic region of which they were a citizen (fig. 6). A third of Europeans had not worked on projects located in Europe in the year prior to the survey. More than half of users (58%) worked only within the geographic region of which they are a citizen.

Respondents predominantly worked at the regional (for example, multi-state or province) geopolitical scale or smaller (fig. 7). U.S. users were more likely to have worked at the multiple local[10] and global[11] scales than international users.

[10] $\chi^2 = 146.37$, $\Phi = -0.114$
[11] $\chi^2 = 299.31$, $\Phi = -0.164$

Figure 5. Locations of projects using Landsat imagery in the year prior to the survey among current Landsat users (n = 11,183).

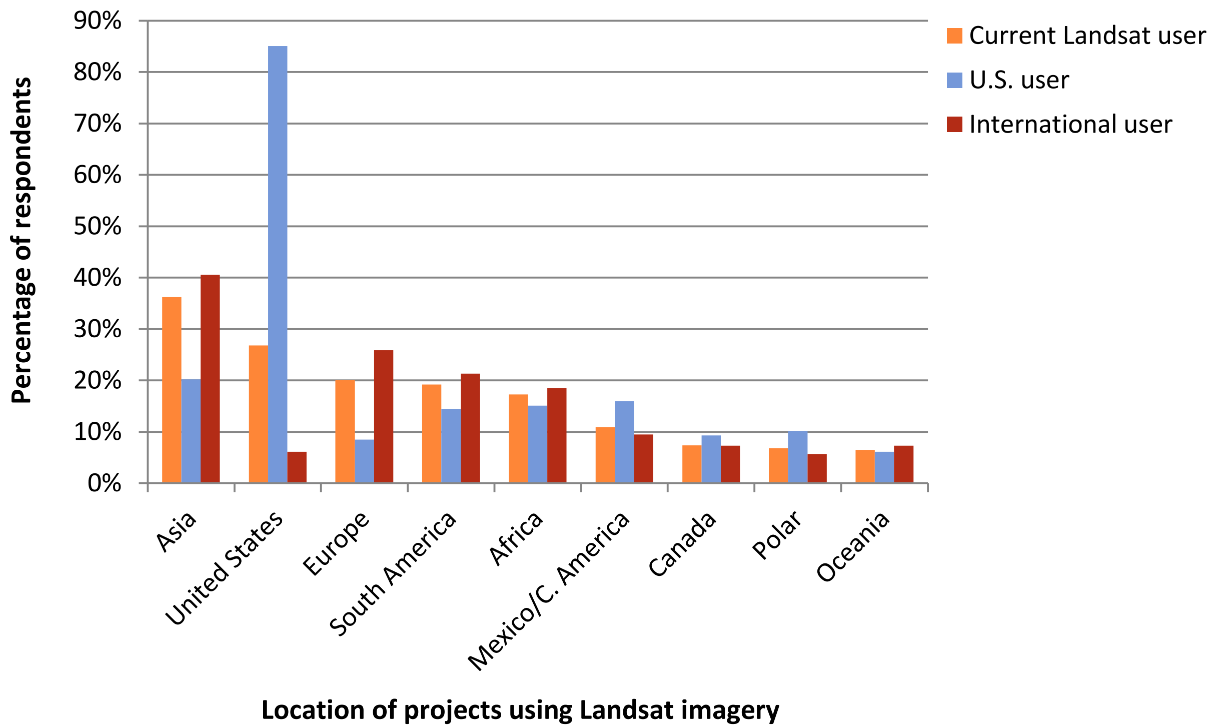


Figure 6. Locations of projects using Landsat imagery among citizens of each geographic region who conducted projects within that region in the year prior to the survey (n = 11,183).

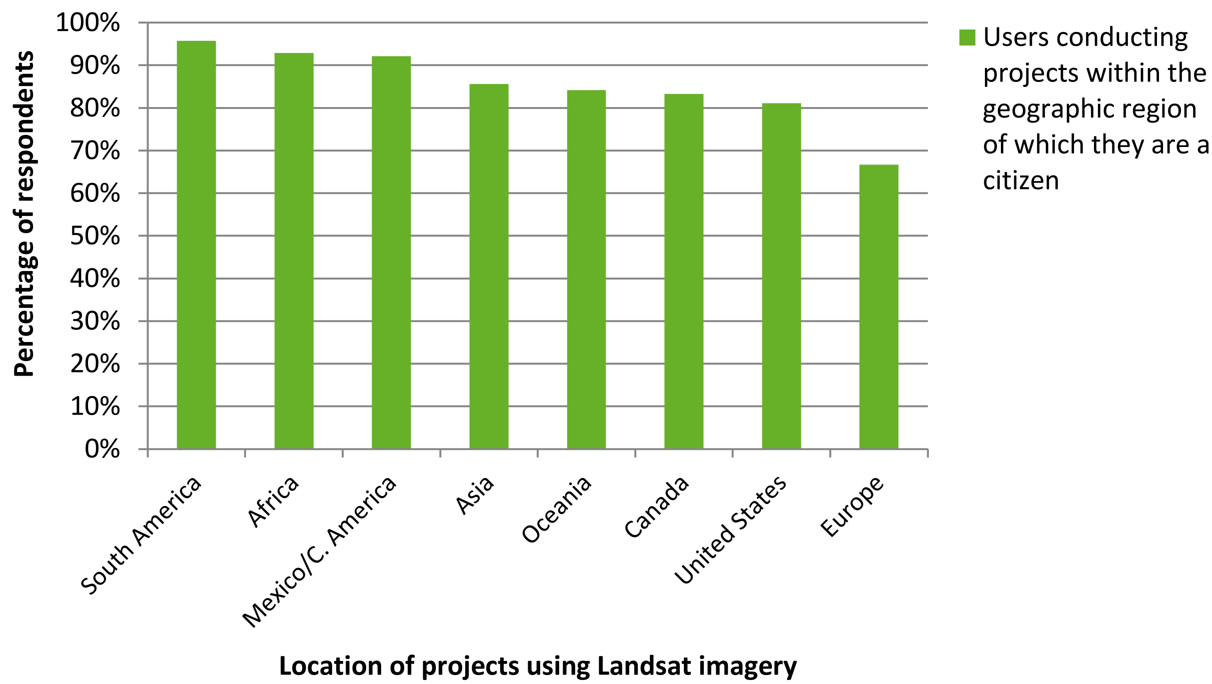
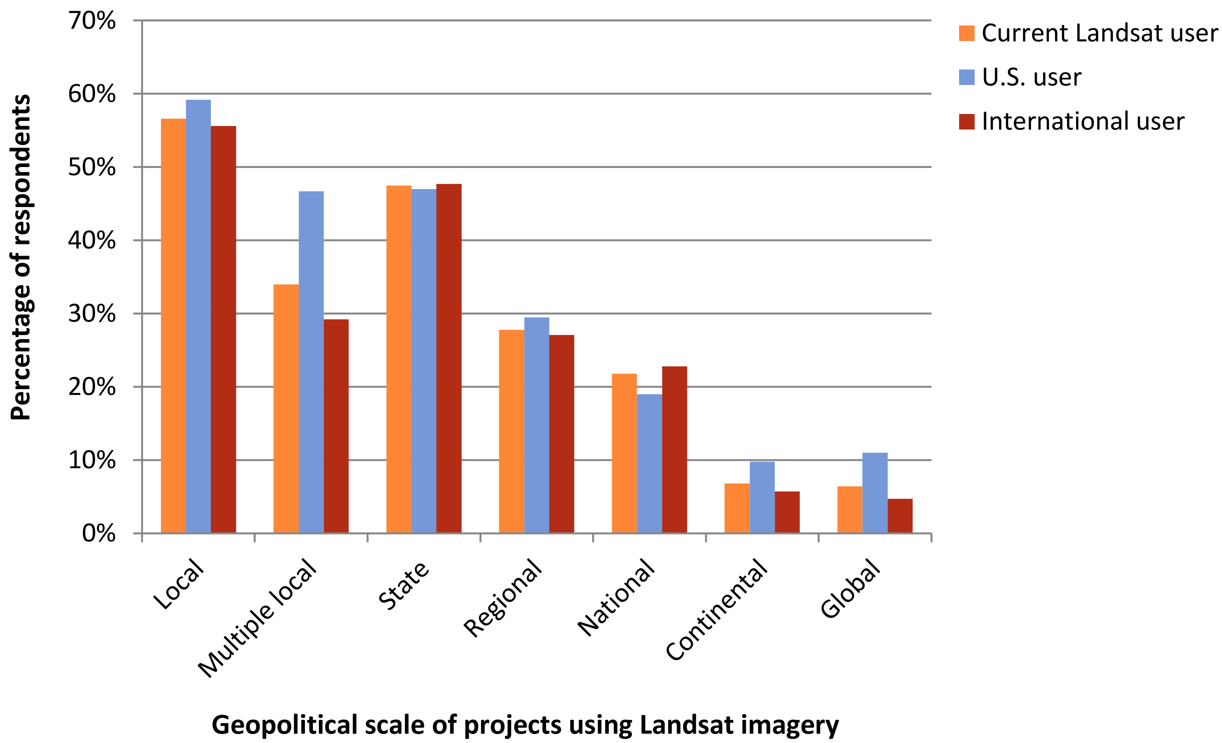


Figure 7. Geopolitical scales of projects using Landsat imagery in the year prior to the survey among current Landsat users (n = 11,184).



Application Areas

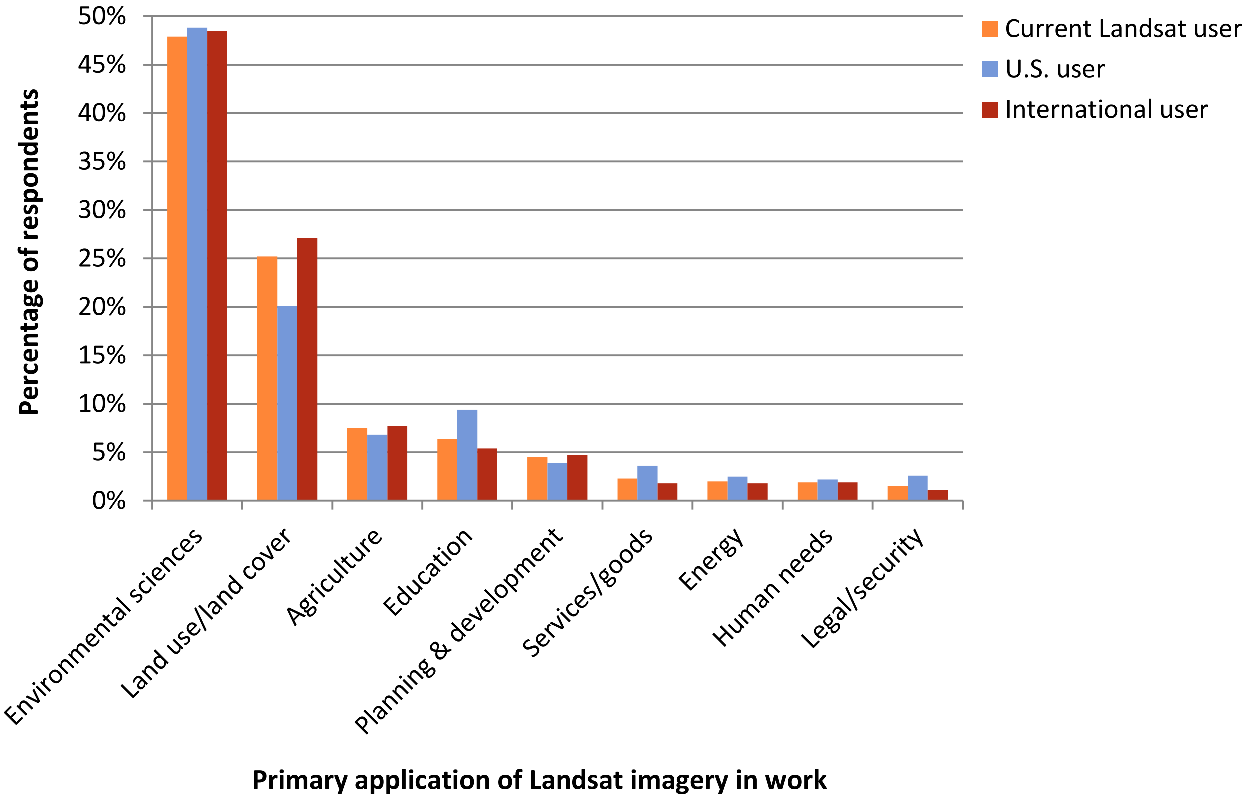
The list of application areas originally developed for the 2009 survey (Miller and others, 2011) was modified slightly based on responses to that survey. Respondents were first asked to select their primary application of Landsat imagery from the list (table 4). They were then asked to select as many secondary applications as they wished from the same list. The 38 applications were collapsed into nine larger categories for the purposes of analysis (table 4). Environmental science and management applications were the most commonly selected with almost half (48%) of users choosing one of these applications (fig. 8). Land use/land cover (25%) was the second most common application, followed by agriculture (8%), education (6%), and planning and development (5%). Land use/land cover is different than the rest of the applications because users can be working in environmental science, planning and development, or any number of other application areas where land use/land cover analyses could be conducted. Of those who chose land use/land cover as their primary application, the most common secondary applications were environmental sciences (77%), followed by planning and development (38%), and education (29%) applications.

Table 4. Applications of Landsat imagery among current Landsat users.

Collapsed applications	Individual applications
Agriculture	Agricultural forecasting
	Agricultural management/production/conservation
Education	Education: K–12
	Education: university/college
	Technical training (for example, workshops, short courses)
Energy	Energy (for example, oil, natural gas, coal)/metals/minerals development
	Alternative energy development (for example, wind, solar, geothermal)
Environmental sciences and management	Biodiversity conservation
	Climate science/change
	Coastal science/monitoring/management
	Cryospheric science (for example, sea ice, ice caps, glaciers)
	Ecological/ecosystem science/management
	Fish and wildlife science/management
	Fire science/management
	Forest science/management
	Geology/volcanology
	Range/grassland science/management
	Recreation science/management
	Water resources (for example, watershed management, water rights, hydrology)
Human needs	Emergency/disaster management
	Hazard insurance (for example, crop, flood, fire)
	Humanitarian aid
	Public health
Land use/land cover[1]	Land use/land cover
Legal/security	Defense/national security
	Environmental regulation
	Law enforcement
Planning and development	Assessments and taxation
	Engineering/construction/surveying
	Rural planning and development
	Urban planning and development
	Urbanization
Services/goods	Cultural resource management (for example, archaeology, anthropology)
	Real estate/property management
	Software development
	Telecommunications
	Transportation
	Utilities

[1]Land use/land cover encompasses a wide variety of other application areas, such as environmental sciences and planning and development. It was included in the applications list after pretesting indicated a substantial number of users would write it in the "other" category.

Figure 8. Primary applications of Landsat imagery in projects conducted in year prior to survey among current Landsat users (n = 11,190).



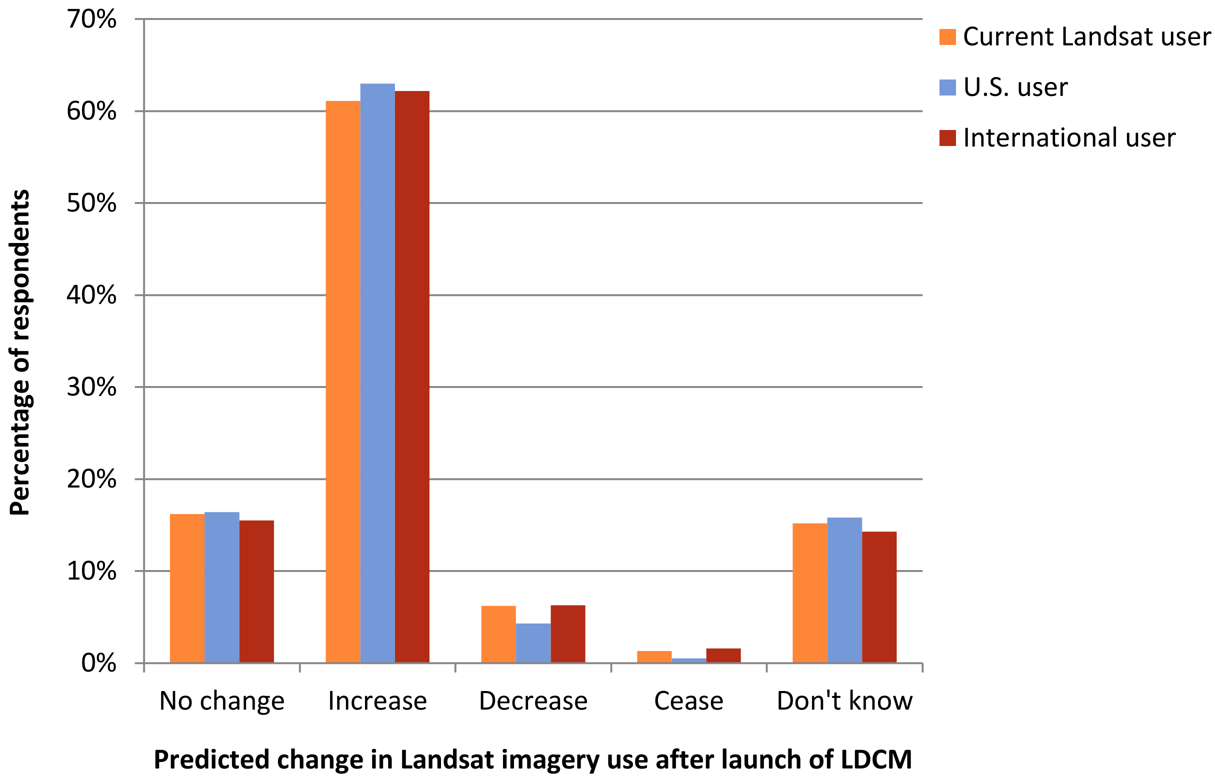
Change in Use of Landsat Over Time

Many events over the recent history of the Landsat mission may have impacted people's use of the imagery. To track how these events may impact use, users were asked how their use of Landsat changed over the past 10 years and how they envisioned it would change over the next 5 years. More than three-quarters of users said their use increased or stayed the same in the past 10 years and will increase or stay the same in the next 5 years. Less than 7% of users said their use of Landsat imagery had decreased or would decrease. When asked specifically how the launch of Landsat 8 in early 2013 would impact their use, more than 60% believed it will increase their use of Landsat (fig. 9).

Discussion: Use of Landsat Imagery

Overall, Landsat imagery was the primary satellite imagery used by EROS users, but the uses of the imagery varied greatly. Users obtained imagery from the entire 40-year catalog of Landsat imagery and worked on projects at all different geopolitical scales in locations around the world. Additionally, users identified 38 application areas as primary applications. For almost all users, the amount of Landsat imagery they have used and anticipate using over time had increased or stayed the same. The majority of users believed the launch of Landsat 8 will increase their use of Landsat imagery.

Figure 9. Predicted changes in use of Landsat imagery after the launch of the Landsat Data Continuity Mission (LDCM) among current Landsat users (n = 9,860).

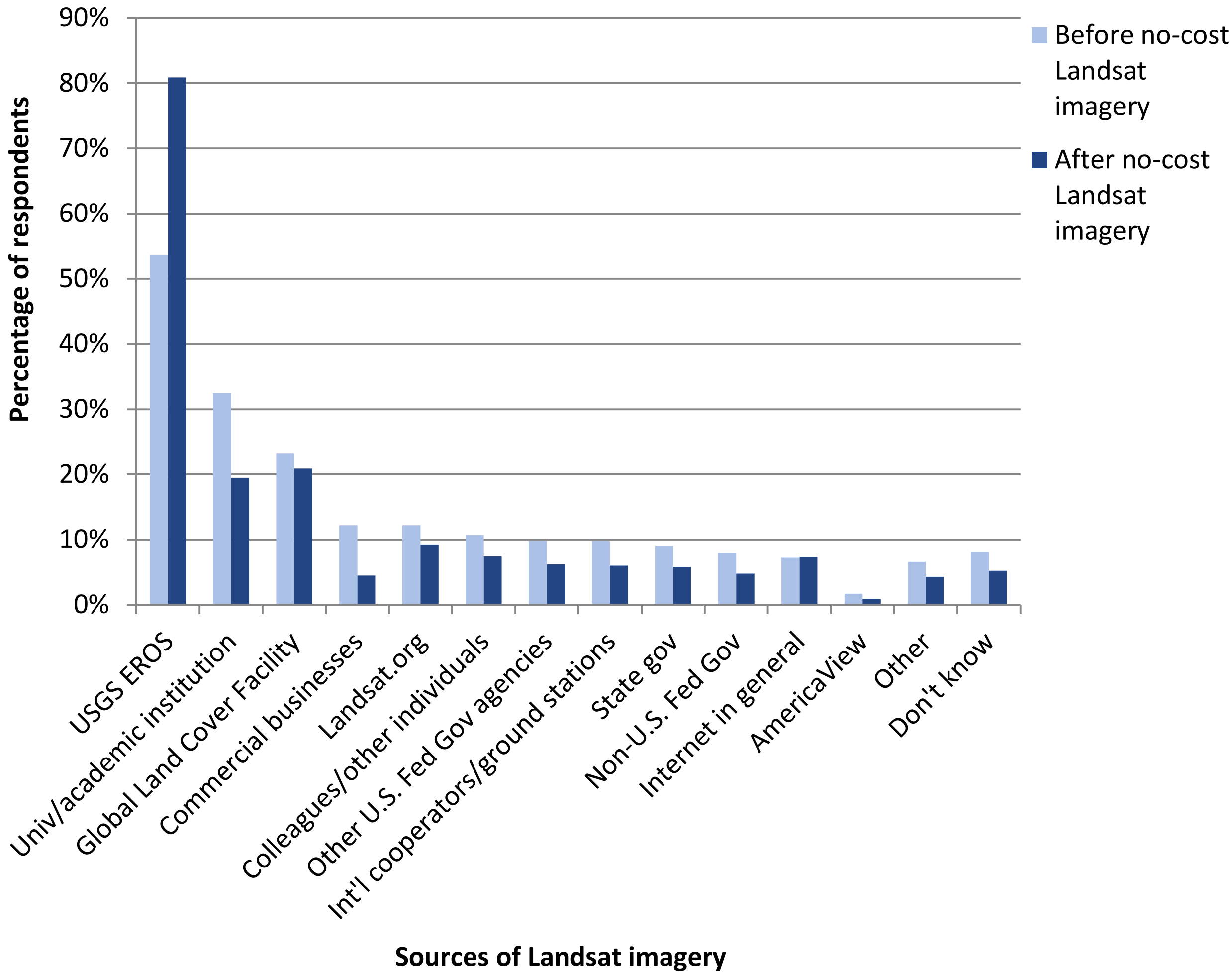


Impacts of No-Cost Data Policy

The entire archive of Landsat imagery became available online at no cost at the end of 2008. To determine the impacts of this free and open data policy, we asked established users about their imagery acquisitions before and after the policy went into effect. Because new and returning users were not obtaining imagery in the year prior to the policy change, they were asked only about their imagery acquisitions after the policy change. For established users who responded for both before and after the policy change (n = 4,494), USGS EROS was the most common source of the imagery both before and after the policy change (fig. 10). However, there was a significant increase in the percentage of users obtaining Landsat from EROS after the policy change.[12] There was also a significant increase in the percentage of users obtaining Landsat only from EROS before (17%) compared to after (40%) the policy change.[13] There were significant decreases in the percentages of users obtaining Landsat from universities or other academic institutions[14] and from commercial businesses[15] after the policy change. There were no significant differences between established and new/returning users regarding sources of Landsat imagery used after the policy change.

[12] $t = -34.27$, Cohen's $d = -0.515$
[13] $t = -31.61$, Cohen's $d = -0.480$
[14] $t = 19.95$, Cohen's $d = 0.293$
[15] $t = 16.79$, Cohen's $d = 0.262$

Figure 10. Sources used by established Landsat users to obtain Landsat imagery before and after the imagery became available at no cost from the U.S. Geological Survey Earth Resources Observation and Science (EROS) Center (n = 4,494).

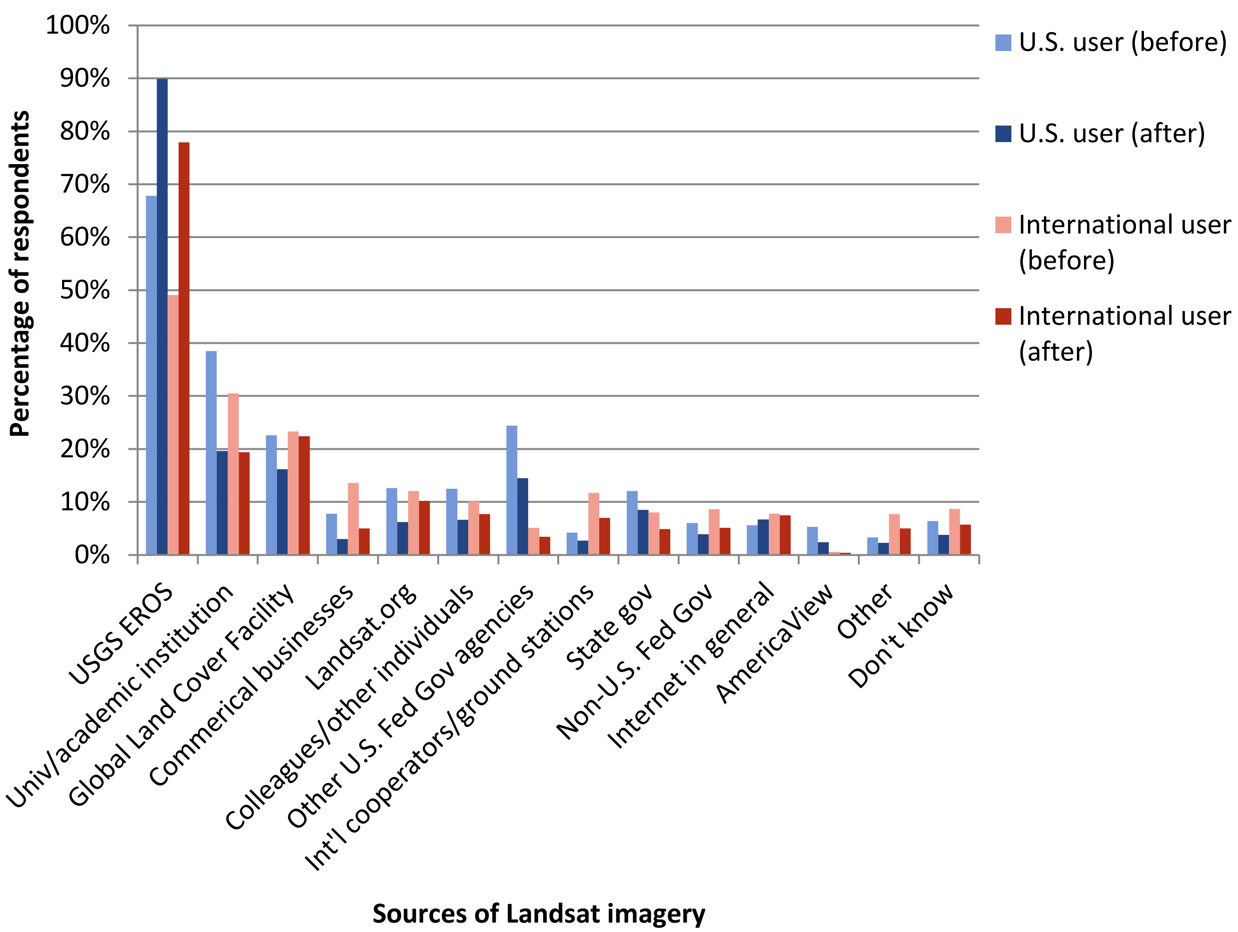


There were significant differences between U.S. and international established users regarding where they obtained Landsat imagery both before and after the policy change. U.S. users were more likely than international users to obtain imagery from USGS EROS,[16] other U.S. Federal Government agencies,[17] and AmericaView[18] before the policy change (fig. 11). U.S. users were also more likely to obtain imagery from other U.S. Federal Government agencies[19] after the policy change. U.S. users would not only likely be more familiar with these U.S.-based sources, but also more likely to have easy access to these sources. International users were more likely to obtain imagery from international cooperators and ground stations[20] before the policy change. International users would most likely have easier access to the ground stations

[16] $\chi^2 = 124.43$, $\Phi = -0.162$
[17] $\chi^2 = 371.36$, $\Phi = -0.279$
[18] $\chi^2 = 114.54$, $\Phi = -0.155$
[19] $\chi^2 = 304.26$, $\Phi = -0.168$
[20] $\chi^2 = 55.98$, $\Phi = 0.108$

in their areas than U.S. users. However, since the policy went into effect, EROS has obtained a large amount of imagery previously stored only in ground stations in other countries, thus decreasing the amount of imagery that can only be obtained through cooperators.

Figure 11. Sources used by established U.S. and international Landsat users to obtain Landsat imagery before and after the imagery became available at no cost from the U.S. Geological Survey Earth Resources Observation and Science (EROS) Center (n = 4,494).



In addition to the differences in where users obtained imagery before and after the free and open data policy, there were significant changes in the annual number of scenes obtained, U.S. dollar amount spent on scenes, and percentage of scenes obtained from EROS. Paired samples t-tests were conducted on these three variables for which data from both before and after the policy change were available for established users. The majority of established users (between 73% and 87%) provided information for both time periods for each of the three variables.[21] To mitigate the influence of outliers, 1% trimmed means were calculated for the number of scenes obtained and the amount spent for both time periods. Statistically significant results were found overall for the number of scenes obtained, the amount spent, and the percentage of scenes acquired from EROS. After the policy change, the average number of scenes obtained annually more than doubled (table 5), while the average amount spent annually on Landsat imagery decreased by more than 75% (table 6). Based on the average decrease in the amount spent per established user and the estimated number of established users registered at EROS, we estimate the one-time cost savings for established users registered with EROS resulting from the free and open data policy change to be $52.8 million. The average percentage of Landsat scenes acquired from EROS rose 20% after the policy change (table 7).

Significant changes were found for both U.S. and international users on these variables as well, though the changes were greater among U.S. users. On average, U.S. users almost tripled the average number of scenes obtained annually, whereas international users more than doubled the number of scenes obtained annually (table 5). Also, U.S. users reported, on average, a greater than 90% decrease in the amount spent annually on Landsat imagery after the policy change, whereas international users saw a 71% decrease in the amount spent (table 6).

Though it may be expected that these users would spend zero dollars on imagery after it became available at no cost from USGS, this is not the case. One reason for this is that users are not obtaining all their Landsat imagery from EROS. Some users are still purchasing imagery from other providers, possibly to obtain imagery that has been processed beyond what is provided by USGS. However, the percentage of established users spending zero dollars for Landsat imagery rose from 41% to 73% after the imagery became available at no cost. More than 88% of U.S. established users spent zero dollars on Landsat imagery after the imagery became available at no cost compared to 68% of international established users. This may explain why international established users spent more than U.S. established users, on average, after the policy change.

Discussion: Impacts of No Cost Data Policy

Before and after the free and open data policy, EROS was the most common source for obtaining Landsat imagery among established users. However, the percentage of established users obtaining imagery from EROS increased significantly after the policy went into effect, while the percentage of established users obtaining imagery from all other sources decreased. There were also significant changes in how many scenes were obtained annually and how much was spent on those scenes. On average, the number of scenes obtained annually by established users more than doubled, while the amount spent annually fell by 78%.

[21] To ensure that the high percentage of missing data for these pairs of variables was not influencing the results of the t-tests, the missing data points were replaced with estimated data and the t-tests were run again to see if the significance of the tests changed. The missing data points were replaced using the following criteria: (1) If both before and after data points were missing (5-14% of eligible respondents), these were replaced with the mean from the “before” variable. (2) If one data point was available, the missing data point was replaced with the same amount. These criteria created pairs of data points that were exactly the same while maintaining the variance and thus should have reduced the significance of the test. When the t-tests were run again on this data, all p-values were still less than 0.001 and all Cohen’s d values were above 0.200, indicating that even if all of the respondents who did not answer the question had experienced no change in their acquisitions as a result of no-cost data, there would still be a significant difference in the means of these variables before and after the policy change.

Table 5. Average number of Landsat imagery scenes obtained annually by current established Landsat users before and after it became available at no cost (n = 3,997).

Landsat user	Number of scenes before	Number of scenes after	t[1]	p[2]	Cohen's d[3]
Current Landsat users	30	68	–16.37	<0.001	–0.306
U.S. users (n = 986)	31	89	–10.13	<0.001	–0.407
International users (n = 3,011)	30	62	–12.92	<0.001	–0.271

[1]Test statistic for t-test.
[2]Statistical significance of the test statistic (values ≤0.001 are considered significant).
[3]Effect size (see table 1 for interpretation).

Table 6. Average amount in U.S. dollars spent annually on Landsat imagery scenes obtained by current established Landsat users before and after it became available at no cost (n = 3,367).

Landsat user	Amount spent before	Amount spent after	t[1]	p[2]	Cohen's d[3]
Current Landsat users	$4,213	$932	15.54	<0.001	0.317
U.S. users (n = 848)	$5,242	$426	10.21	<0.001	0.430
International users (n = 2,519)	$3,867	$1,103	11.88	<0.001	0.278

[1]Test statistic for t-test.
[2]Statistical significance of the test statistic (values ≤0.001 are considered significant).
[3]Effect size (see table 1 for interpretation).

Table 7. Average percentages of Landsat imagery scenes obtained by current established Landsat users from the U.S. Geological Survey Earth Resources Observation and Science (EROS) Center before and after it became available at no cost (n = 3,971).

Landsat user	Percentage of scenes from EROS before	Percentage of scenes from EROS after	t[1]	p[2]	Cohen's d[3]
Current Landsat users	51%	71%	–28.51	<0.001	–0.454
U.S. users (n = 1,009)	61%	82%	–16.55	<0.001	–0.530
International users (n = 2,962)	48%	68%	–23.55	<0.001	–0.433

[1]Test statistic for t-test.
[2]Statistical significance of the test statistic (values ≤0.001 are considered significant).
[3]Effect size (see table 1 for interpretation).

Value of Landsat Imagery

Value can be understood as the benefits received from a good or service. Though value can be measured monetarily, it can also be measured with less tangible metrics, such as quality of life. Macauley (2005, 2006) notes that there are several ways the economic value of information, such as that provided by Landsat, has been examined, including output or productivity measures, hedonic price studies, contingent valuation studies, and measurement of societal benefits. There have been recent workshops focused on how to measure the benefits from geospatial information (for example, Borzacchiello and Craglia, 2011; Pearlman and Bernknopf, 2012), and some research that specifically values Landsat imagery (for example, Forney and others, 2012). However, societal benefits can be difficult to measure economically, especially when the realized value is in relation to a nebulous, but important, concept like quality of life. Additionally, the comprehensive value of Landsat may always be elusive, given the widespread use of the imagery in applications like Google Earth™ and the difficulty in finding all direct and indirect users of the imagery. All of these factors emphasize the importance of measuring the value of information provided by Landsat imagery in multiple ways.

We used four approaches to estimate the value of Landsat to this population of Landsat users. First, we explored the importance of Landsat imagery to users, as well as their satisfaction with the imagery. Second, we asked about the environmental and societal benefits users observed from projects that used Landsat. Third, we asked what users would do if Landsat imagery was no longer available and how it would impact their work. Lastly, we utilized a method called contingent valuation to determine the economic benefits to users from Landsat.

Importance and Satisfaction

Determining the importance of Landsat imagery to users is one way to approach value. More than 75% of the users said the imagery is somewhat or very important to their work.[22] We also asked users to rate how important certain attributes are in determining whether to use Landsat imagery in their work and how satisfied they are with those same attributes as they exist today in Landsat imagery. This is a common approach in marketing research to assess how well a product is meeting the needs of customers (Martilla and James, 1977). From this data, we created an importance-performance framework that maps satisfaction on the X-axis by importance on the Y-axis (fig. 12). It allows us to look at where things are going well and where room for improvement exists.

All of the Landsat attributes we asked about fall in the "Keep Up the Good Work" quadrant; in other words, on average, users think all of the attributes measured are important and they are satisfied with the provision of those attributes. The highest ratings were for availability, accessibility, and cost, which indicate that users are satisfied with how the imagery is being provided. USGS has directly impacted these three attributes by consolidating Landsat imagery into a central repository, creating automated processing and online distribution systems, and enacting the free and open data policy.

There were few significant differences in attribute ratings between U.S. and international users. U.S. users were more satisfied, on average, with the availability[23] and cost[24] of Landsat

[22] 14% of eligible respondents did not answer the question.
[23] $t = 9.12$, Cohen's $d = 0.200$
[24] $t = 12.29$, Cohen's $d = 0.255$

imagery. However, the means for both groups of users were well above four for both attributes, indicating both U.S. and international users were satisfied with availability and cost.

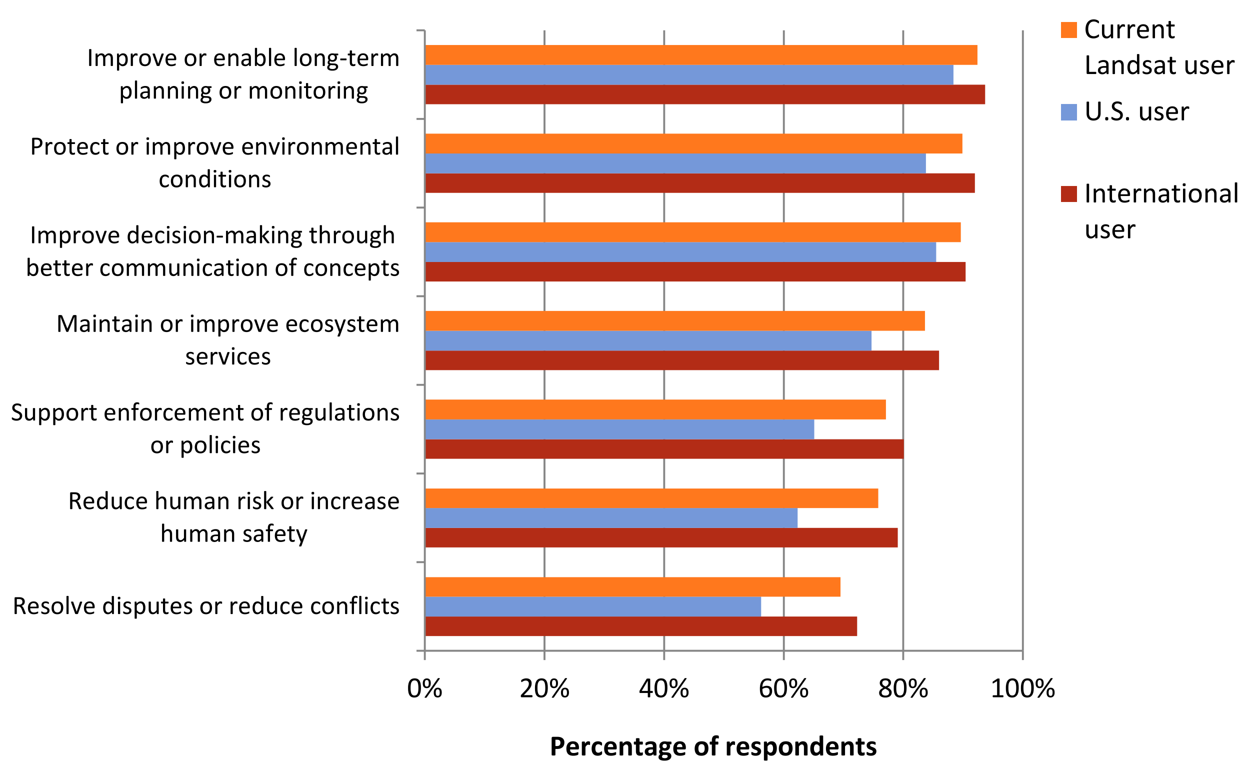
Figure 12. Mean importance of and mean satisfaction with specific attributes of Landsat imagery among current Landsat users (n ≥ 10,225).

Benefits of Landsat

In the 2009 survey, we asked a series of open-ended questions regarding the social and environmental benefits of projects that used Landsat imagery. Open-ended questions were chosen because a comprehensive list of benefits had not been developed, and we wanted to give users the opportunity to provide their own ideas about benefits. The responses were examined for repeating themes, which were used to create closed-ended questions for this survey.

A majority of users observed each of the benefits listed on the survey from their projects that used Landsat imagery (fig. 13). More than 80% of users saw environmental benefits, including improving or enabling long-term environmental planning or monitoring, protecting or improving environmental conditions, and maintaining or improving ecosystem services. Almost 90% saw improvements in decision-making through better communication of concepts using Landsat imagery. More than three-quarters cited supporting enforcement of regulations or policies and reducing human risk or increasing human safety as benefits. Close to 70% of users also saw resolution of disputes or reduction in conflicts as a result of projects using Landsat imagery. U.S. users were significantly less likely to report these benefits than international users,[25] with the exception of improving or enabling long-term monitoring and improving decision-making through better communication of concepts. However, a majority of U.S. users still saw all of these benefits from their projects that used Landsat.

Figure 13. Benefits observed by current Landsat users from their projects that used Landsat imagery (n ≥ 10,196).



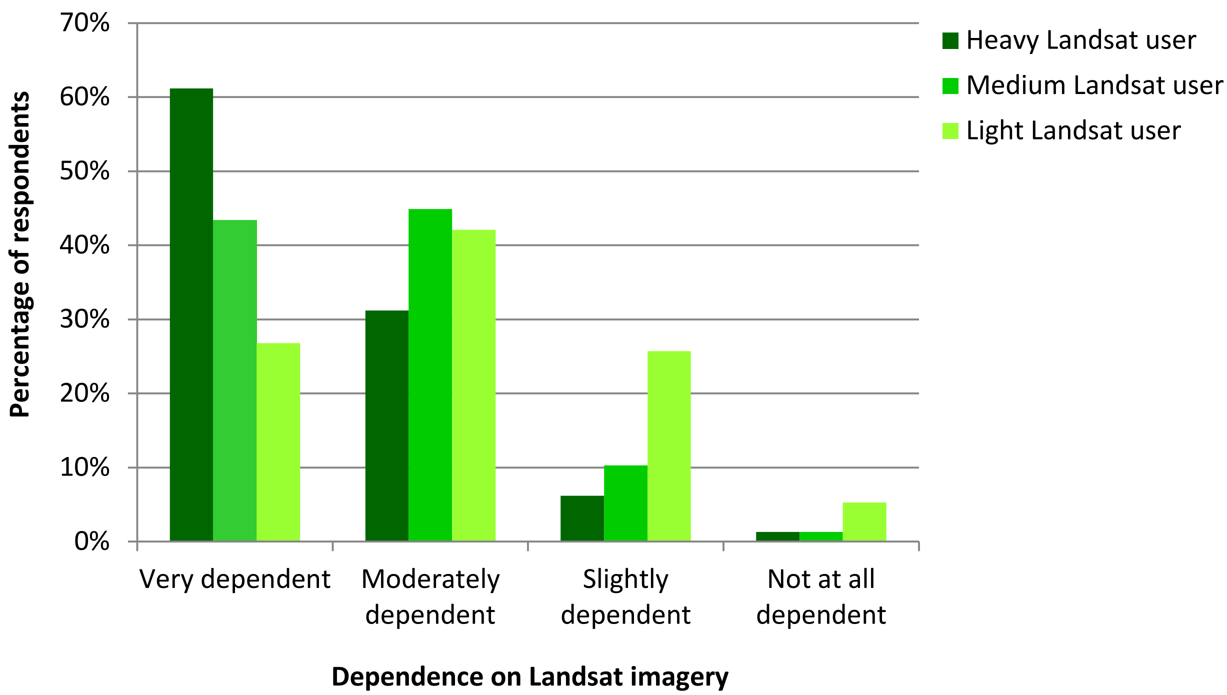
[25] Protect or improve environmental conditions - χ^2 = 147.57, Φ = 0.118; maintain or improve ecosystem services - χ^2 = 181.88, Φ = 0.133; support enforcement of regulations or policies - χ^2 = 243.36, Φ = 0.154; reduce human risk or increase human safety - χ^2 = 282.10, Φ = 0.166; resolve disputes or reduce conflicts - χ^2 = 234.48, Φ = 0.152.

Level of Use and Dependence on Landsat in Work

The percentage of users' work that used Landsat in the year prior to the survey ranged from 1% to 100%. We categorized users as heavy, medium, or light users. Light users relied on Landsat for 30% or less of their work, medium users relied on it for 31–70% of their work, and heavy users relied on it for 71% or more of their work. Overall, 44% of users were classified as light users, 28% as medium users, and 26% as heavy users. The majority of users indicated they were very (39%) or moderately (36%) dependent on Landsat imagery to do their job. Almost half of U.S. users (48%) indicated they were very dependent on the imagery compared to 35% of international users.[26]

The level of use in work does not necessarily indicate dependence, though there were significant differences between the levels of dependence among users with different levels of use[27] (fig. 14). Heavy and medium users were more likely to be very or moderately dependent on the imagery to complete their work in the year prior to the survey, whereas light users were more likely to be slightly or not at all dependent. However, more than one-quarter of the light users stated they were very dependent on Landsat imagery. This may be due to their work that was operational (continuous or ongoing work that either relies on the consistent availability of Landsat imagery or is mandated or required). We found that the percentage of operational work was related to dependence. Very dependent users, on average, estimated 40% of their work to be operational, whereas users who were not at all dependent estimated only 24% of their work to be operational. Dependence may also be expected to be related to the sector and application area of the users; however, neither was found to be related to dependence.

Figure 14. Dependence on Landsat imagery among users with varying levels of use of Landsat imagery (n = 8,398).



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[26] χ^2 = 148.47, Cramer's V = 0.116
[27] χ^2 = 331.55, Cramer's V = 0.239

If Landsat Imagery Was No Longer Available

Another way to examine the value of a good is to explore the impacts that would occur if it ceased to exist. To better understand the potential impacts of the loss of Landsat imagery, we asked users the following question:

> "To better understand the value of Landsat imagery, the following questions explore the potential impact to your work **if new and archived Landsat imagery was no longer available**.
>
> If new and archived Landsat imagery was no longer available, you could choose to:
>
> - discontinue some or all of your work;
> - continue your work without substituting other imagery or information; or
> - use other imagery or information as a substitute in your work.
>
> Of your work that uses Landsat imagery, what percentage would you **discontinue, continue without substituting other imagery or information,** and/or **use other imagery or information as a substitute** if the imagery was no longer available?"

Of those who would use substitute information, we asked, "Of your work that would **use other imagery or information as a substitute**, what percentage would use each of the following types of imagery or information?" The response options were (1) different type of imagery, (2) other data sets (not imagery), and (3) on-the-ground fieldwork. For both questions, users were also offered a "Don't know" checkbox if they could not estimate the percentages. For the first question, the percentage of users who checked "Don't know" ranged from 34% (n = 3,198) to 37% (n = 3,485). For the second question, the percentage of users who checked "Don't know" ranged from 10% (n = 587) to 16% (n = 879). These responses were treated as missing data when calculating the percentages in tables 8 and 9. In addition, 16% of eligible respondents did not answer these questions at all. As a result, the sample sizes (n) in these tables are lower than might be expected.

More than 65% of the users would discontinue at least some of their work (table 8). On average, those users would discontinue half of their work, indicating a strong dependence on the imagery (table 9). Slightly less than 60% would continue at least some of their work without substitute information. Two-thirds of the users would substitute other information in, on average, more than half of their work. The large majority of these users would substitute different imagery (82%), but 57% would substitute other data sets and 58% would substitute fieldwork for Landsat imagery. Specifically, they would use different imagery in 71% of their work, other data sets in 30% of their work, and fieldwork in 26% of their work. Given that fieldwork is often expensive and time consuming, this seems to indicate that fieldwork might be the only viable substitute to provide certain types of data. This may be because appropriate imagery or other data do not exist or is not affordable or accessible. In both cases where the work is continued with or without substitute data, the inputs into that work would have changed. This change would likely have an effect on the work process and outcome.

Table 8. Percentages of current Landsat users who would take certain actions if Landsat imagery was no longer available.

Action taken if Landsat was no longer available	Current Landsat users	U.S. users	International users
For work that uses Landsat, percentage of users who would…	*n ≥ 5,903*	*n ≥ 1,703*	*n ≥ 4,200*
…discontinue some of work	66%	66%	66%
…use substitute information in some of work	86%	83%	87%
...continue some of work without substitute information	57%	46%	61%
For those who would use substitute information, percentage of users who would use…	*n ≥ 4,779*	*n ≥ 1,301*	*n ≥ 3,478*
…different imagery	98%	97%	98%
…other data sets	59%	49%	63%
…on-the-ground fieldwork	57%	46%	61%

Table 9. Average percentages of work affected by predicted actions taken by current Landsat users if Landsat imagery was no longer available.

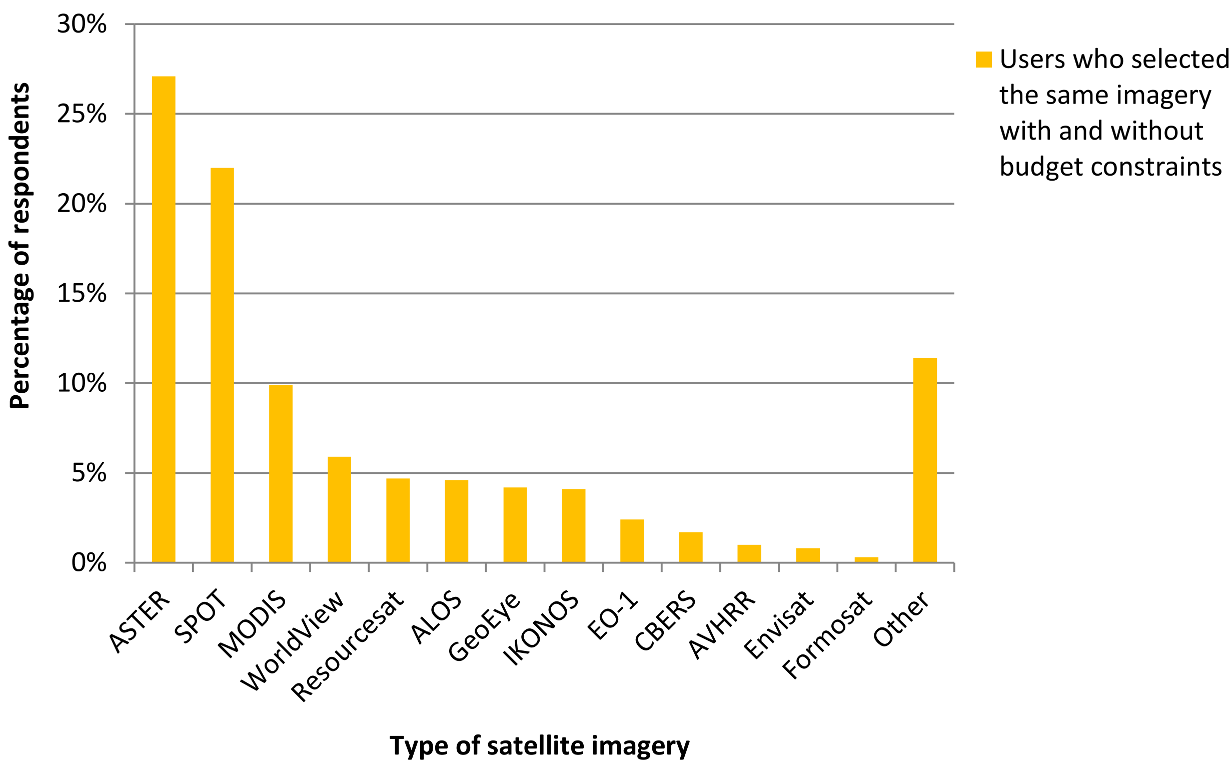
Action taken if Landsat was no longer available	Current Landsat users	U.S. users	International users
Average percentage of work that uses Landsat that would…	*n ≥ 3,352*	*n ≥ 782*	*n ≥ 2,570*
…be discontinued	49%	55%	48%
…use substitute information	57%	59%	56%
...be continued without substitute information	40%	41%	40%
Average percentage of work using substitute information that would use…	*n ≥ 2,757*	*n ≥ 612*	*n ≥ 2,145*
…different imagery	71%	77%	69%
…other data sets	32%	33%	32%
…on-the-ground fieldwork	29%	28%	29%

If users indicated they would use substitute imagery, they were asked what imagery they would prefer regardless of budget constraints, as well as what imagery they would most likely obtain given their current budget constraints. Slightly less than 40% would choose the same imagery in both situations — the most common choices were ASTER, followed by SPOT, and then MODIS (fig. 15). However, more than 60% would choose different imagery based on whether they were constrained by budget. For those users, SPOT, Worldview, and IKONOS (from *eikōn*, the Greek word for image) were most preferred without budget constraints, but the majority would be most likely to obtain ASTER, MODIS, and SPOT with budget constraints (fig. 16).

The results show that more than half of these users would be likely to obtain imagery to replace Landsat that is also available at no cost, such as ASTER, MODIS, and CBERS. Given that current SPOT imagery is not free to all users, it is somewhat unexpected that as many users would likely obtain it with budget constraints. However, current SPOT imagery was available at no cost through USGS to U.S. Government users and may be available to some international users at a discount or no cost as well, making it a viable option for those users. It also may be that the higher spatial resolution of SPOT imagery (10 meters or less for SPOT 5 and 6) or acquisition plan makes it worth the additional cost, if users are indeed paying for it.

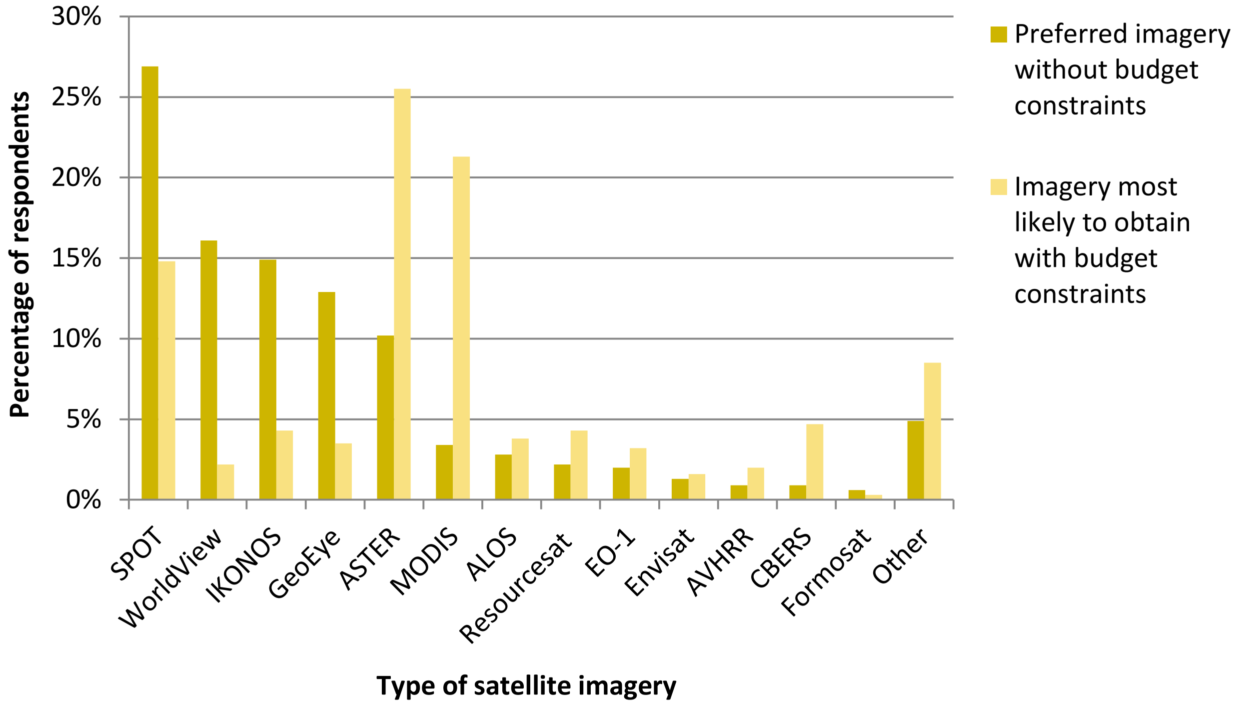
Though there were no significant differences between U.S. and international users for their preferred imagery, there were some significant differences for the imagery they would select when faced with budget constraints. International users were more likely than U.S. users to select ALOS (Advanced Land Observing Satellite)[28] and CBERS,[29] whereas U.S. users were more likely to choose MODIS.[30] These differences may be driven by the acquisitions plans of each satellite, as well as the cost and availability of the imagery.

Figure 15. Imagery preferences among current Landsat users who selected the same imagery both with and without budget constraints to substitute for Landsat imagery if it was no longer available (n = 1,804). See p. vi for definitions of acronyms.



[28] $\chi^2 = 61.34$, $\Phi = 0.113$
[29] $\chi^2 = 49.71$, $\Phi = 0.102$
[30] $\chi^2 = 67.17$, $\Phi = -0.118$

Figure 16. Imagery most likely to be obtained within budget constraints to substitute for Landsat imagery if it was no longer available among current Landsat users who selected different imagery with and without budget constraints (n = 2,966). See p. vi for definitions of acronyms.



Another way to explore value is to examine what would happen to the costs and revenues (or funding) of users if Landsat were no longer available. Increases in costs could occur, for instance, if users have to pay for other imagery, data, or field work to replace the information provided by Landsat imagery. Revenues could possibly decrease because a product based on Landsat can no longer be produced or the product must be created from a more expensive type of data. Typically, these sorts of budgetary questions can only be answered by certain individuals in an organization who have access to that information. We knew that not everyone surveyed would be able to respond to these questions; therefore, we only asked for information regarding the projects in which the users were involved. Respondents also had the option to indicate they did not know.

When asked about the potential impact on the costs[31] of their Landsat-related projects if Landsat was no longer available, 31% of the users felt their costs would increase, 64% did not know if their costs would increase, and 5% felt their costs would not increase. Of those who believed their costs would increase, the average total percentage increase in costs[32] was 82%, which equated to $14,028 on average among those who were able to provide the current costs of all their projects that use Landsat imagery[33] (table 10). The average total percentage increase in

[31] 15% of eligible respondents did not answer this question.
[32] 21% of eligible respondents did not answer this question.
[33] Of users who believed their costs would increase without Landsat imagery, 31% did not provide the current costs for their projects. For these users, the average total percentage increase in costs was 81%. The average dollar amount increase was calculated only for users who provided both the average total percentage increase in costs and the average current total costs (n = 2,058).

costs was 104% for U.S. users, compared to 75% for international users. However, this difference had an insignificant effect size.[34] The average increase in costs for U.S. users was significantly higher compared to international users.[35] This was due to U.S. users reporting significantly higher current costs for projects that use Landsat imagery than international users[36] and to the higher average percentage increase in costs for U.S. users.

Table 10. Impacts on costs and revenues (or funding) of current Landsat users if Landsat imagery was no longer available.

Impacts on costs and revenues (or funding) if Landsat was no longer available	Current Landsat users	U.S. users	International users
Impacts on costs of projects using Landsat imagery	*n ≥ 2,058*	*n ≥ 430*	*n ≥ 1,628*
Average total percentage increase in costs	82%	104%	75%
Average current total costs	$19,695	$38,025	$14,828
Average dollar amount increase in costs	$14,028	$33,200	$8,964
Impacts on revenues or funding of projects using Landsat imagery	*n ≥ 891*	*n ≥ 184*	*n ≥ 707*
Average total percentage decrease in revenues or funding	47%	51%	46%
Average current total revenues or funding	$51,582	$134,575	$29,712
Average dollar amount decrease in revenues or funding	$21,745	$54,816	$13,138

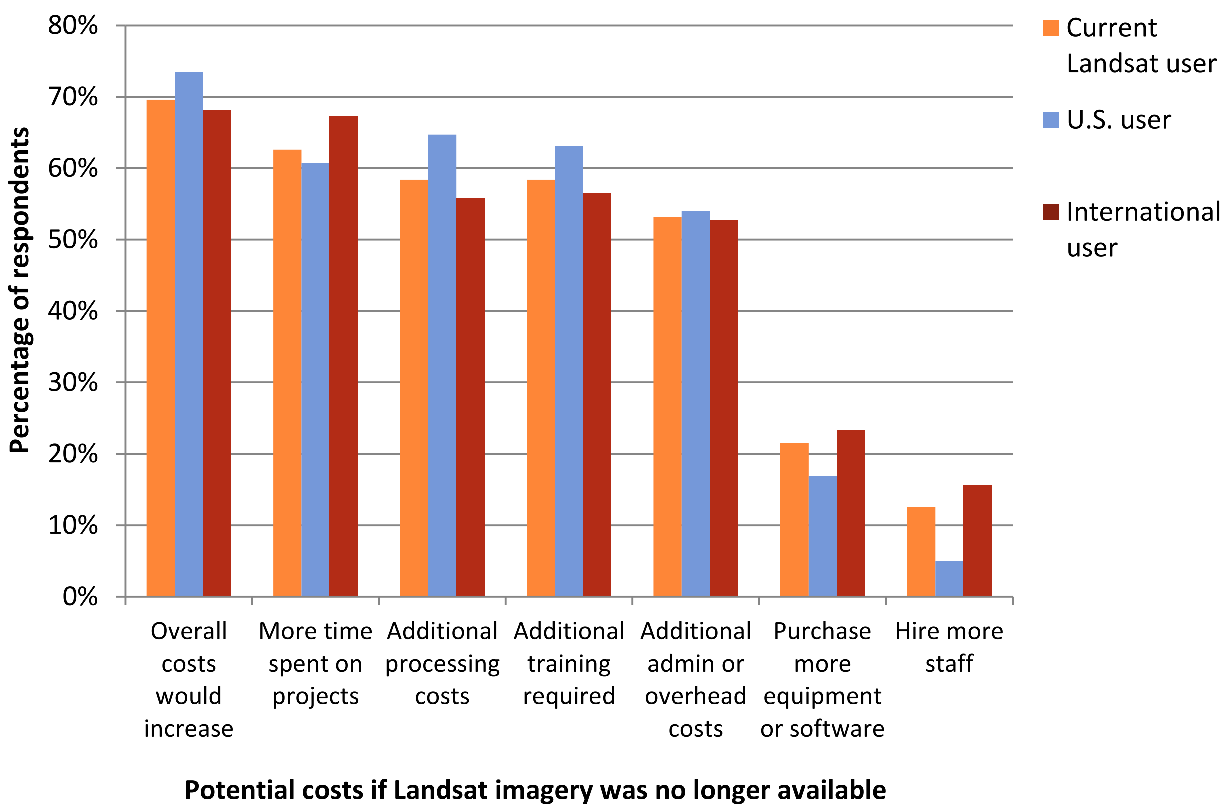
When asked about certain types of cost increases,[37] more than half of the users said it is somewhat or very likely that total, processing, and administration or overhead costs would increase (fig. 17). More than half also thought it was likely that more time would be spent on projects and additional training would be required if Landsat imagery was no longer available. However, most did not believe it is likely they would purchase additional equipment or software or hire more staff.

Regarding changes in revenues or funding, 79% of users did not know what impact the loss of Landsat would have. Slightly less than 8% felt there would be no impact, and 13% thought their revenues or funding would decrease.[38] Of those who believed their revenues or funding would decrease, the average total percentage decrease[39] was 47%, which equated to $21,745 on average among those who were able to provide the current revenues or funding of all their projects that use Landsat imagery[40] (table 10). The average total percentage decrease in revenues or funding was not significantly different between U.S. and international users. The

[34] $t = 3.91$, Cohen's $d = 0.194$
[35] $t = 3.43$, Cohen's $d = 0.260$
[36] $t = 5.85$, Cohen's $d = 0.371$
[37] 17-20% of eligible respondents did not answer these seven cost questions.
[38] 17% of eligible respondents did not answer this question.
[39] 18% of eligible respondents did not answer this question.
[40] Of users who believed their revenues or funding would decrease without Landsat imagery, 26% did not provide the current revenues or funding for their projects. For these users, the average total percentage decrease in revenues or funding was 54%. The average dollar amount decrease was calculated using only users who provided both the average total percentage decrease in revenues or funding and the average current total revenues or funding (n = 891).

average decrease in revenues or funding for U.S. users was significantly higher compared to international users.[41] This was due to U.S. users reporting significantly higher current revenues or funding for projects that use Landsat imagery than international users.[42]

Figure 17. Likelihood that current Landsat users' costs would increase if Landsat imagery was no longer available (n ≥ 9,051).



Loss of Landsat 5 Imagery

Beginning in October 2011, Landsat 5 was taken offline for a few months due to technical problems. Limited imagery acquisition resumed in 2012, but while the survey was underway, new Landsat 5 data were not available. Although the loss of newly acquired Landsat 5 imagery was obviously undesirable, the situation provided an opportunity to ask users about their actual responses to the loss of imagery and gain a better understanding of the value of one segment of Landsat imagery. More than three-quarters of current Landsat users (79%) had used Landsat 5 imagery in the year prior to the survey. More than 40% of those users decreased or ceased their use of Landsat imagery after Landsat 5 stopped acquiring imagery[43] (fig. 18). Though 31% of Landsat 5 users saw no impact on their work from the loss, 69% felt their work had been impacted in some way, identifying decreased quality of work, decreased scope of work, and increased time spent on work as the most common impacts[44] (fig. 19).

[41] $t = 5.33$, Cohen's $d = 0.524$
[42] $t = 6.12$, Cohen's $d = 0.635$
[43] 13% of eligible respondents did not answer this question.
[44] 14% of eligible respondents did not answer this question.

Figure 18. Change in use of Landsat imagery in response to the loss of Landsat 5 imagery among Landsat 5 users (n = 7,711).

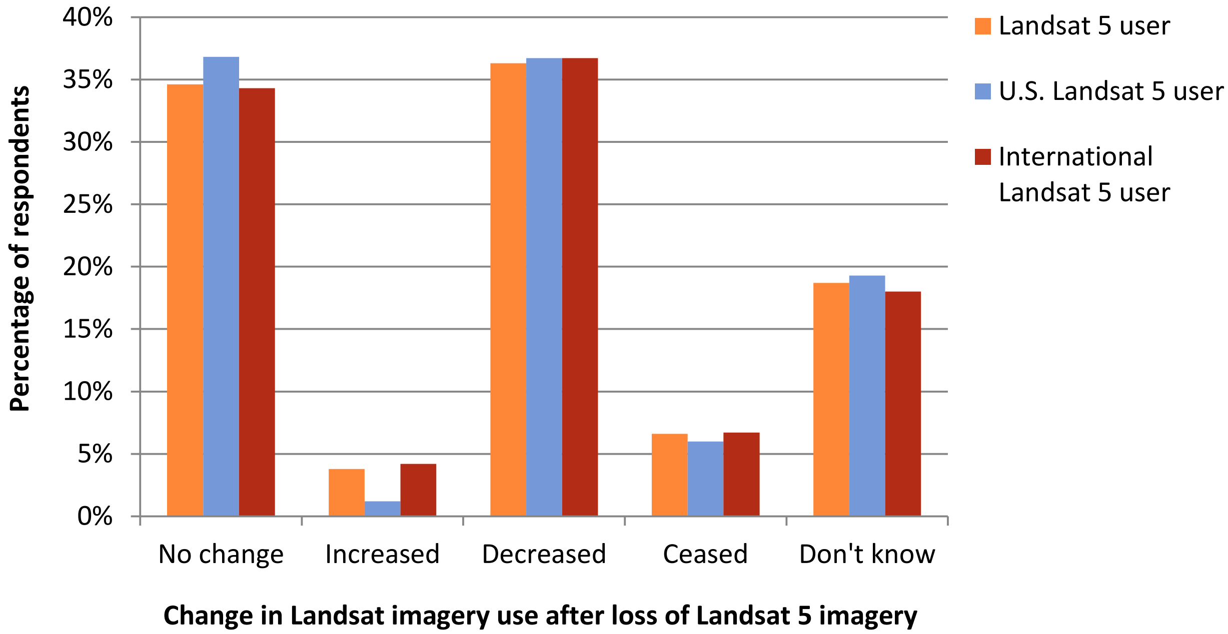
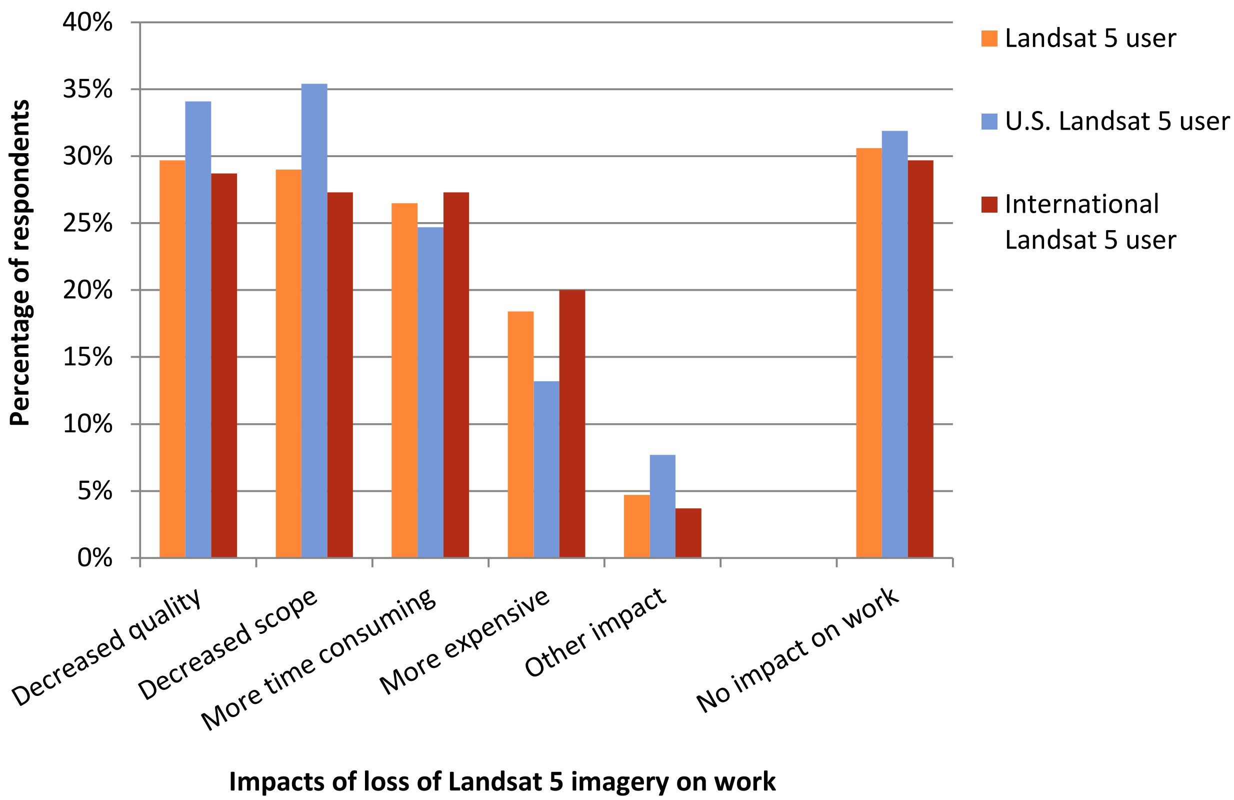
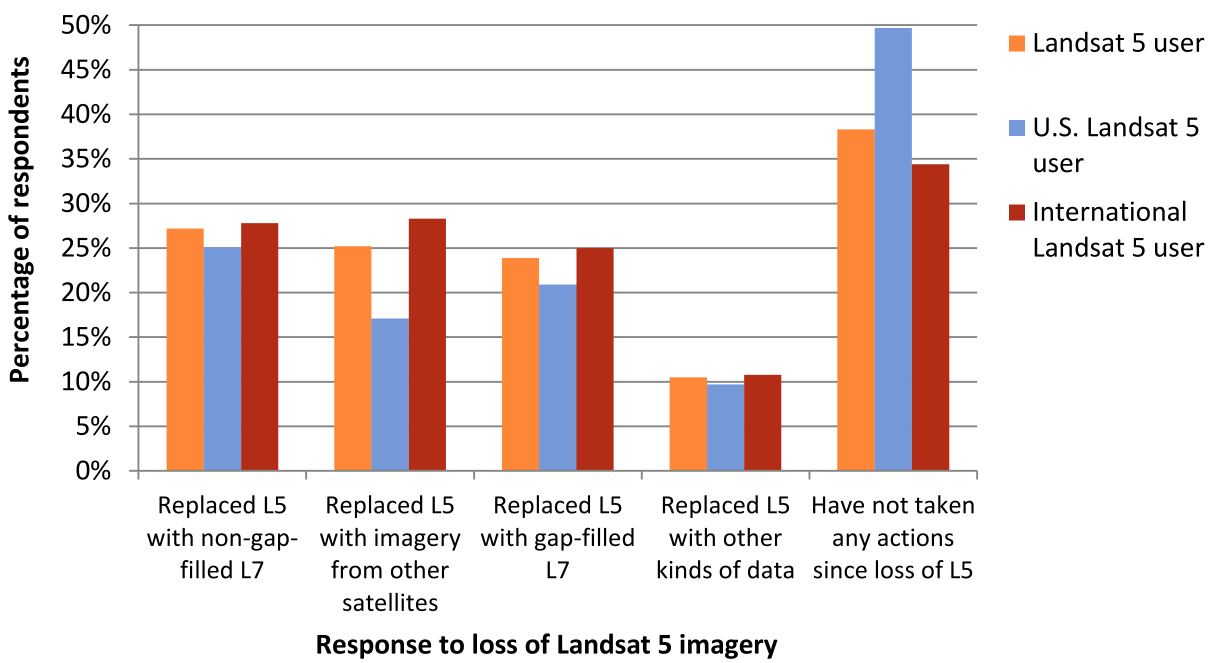


Figure 19. Impacts of loss of Landsat 5 imagery on projects among Landsat 5 users (n = 7,686).



More than 60% of Landsat 5 users had taken some action in response to the loss of the imagery (fig. 20). About one-quarter of users had replaced Landsat 5 imagery with imagery from Landsat 7 or another sensor. Slightly more than 10% had replaced the imagery with other kinds of data. International users were more likely than U.S. users to have replaced Landsat 5 imagery with imagery from a non-Landsat sensor.[45] U.S. users were more likely to have taken no actions since the loss of Landsat 5 imagery.[46] Of those who replaced Landsat 5 imagery with imagery from non-Landsat sensors, the most common replacement was SPOT, followed by ASTER and MODIS (fig. 21). The users of SPOT imagery were primarily international users from all sectors and U.S. users from the Federal and State government and private sectors. This is most likely due to the fact that U.S. Government users could obtain SPOT imagery at no cost through USGS at the time and private sector users may be able to account for imagery costs in the prices of their products and services. Less than one-quarter of U.S. users from academia and nonprofit organizations obtained SPOT imagery to replace Landsat 5, and no local government users reported obtaining SPOT imagery, even though local government users could have obtained the imagery at no cost. There were other differences between U.S. and international users. U.S. users were more likely to obtain GeoEye-1[47] and WorldView-2[48] imagery than international users. International users were more likely to obtain ALOS[49] and CBERS[50] imagery. As mentioned before, these differences are most likely driven by the acquisition plans of the sensors, as well as the cost and availability of the imagery.

Figure 20. Responses to the loss of Landsat 5 (L5) imagery among Landsat 5 users (n = 7,878; L7, Landsat 7).



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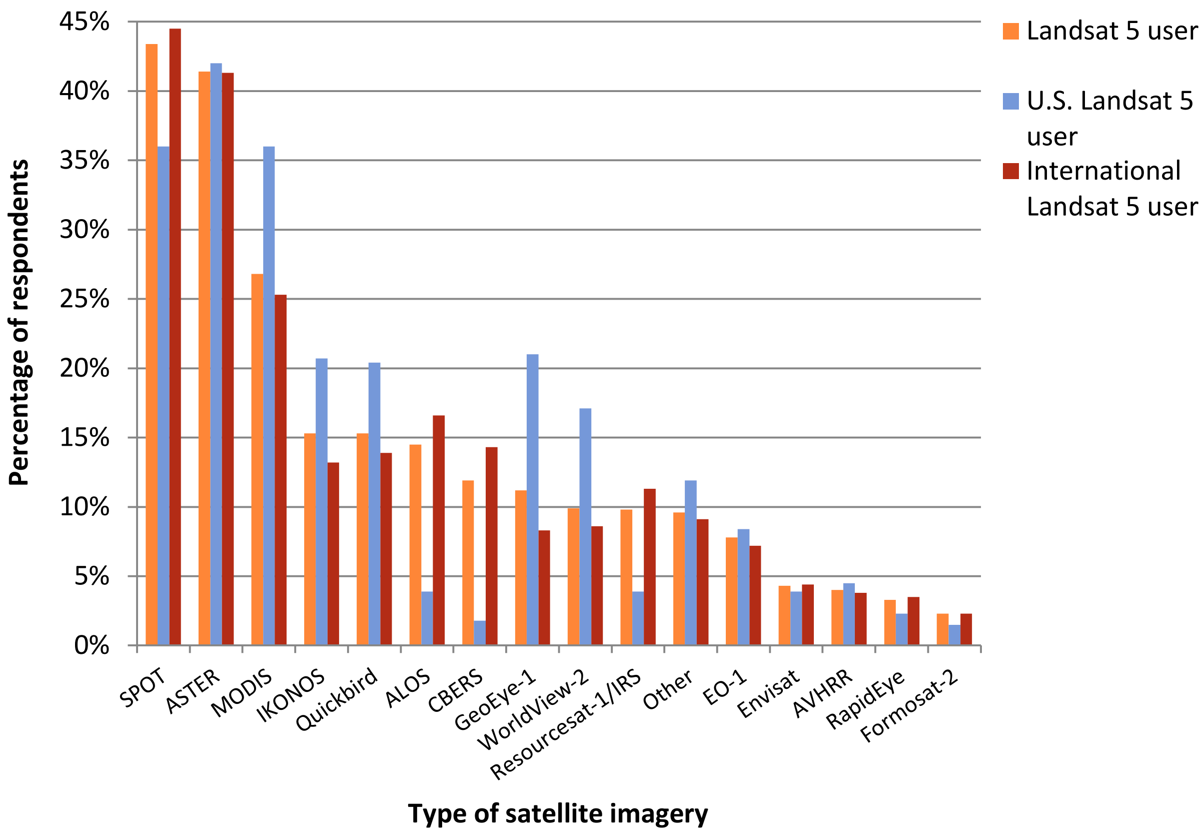
45 $\chi^2 = 98.94$, $\Phi = 0.112$
46 $\chi^2 = 154.49$, $\Phi = -0.140$
47 $\chi^2 = 47.23$, $\Phi = -0.155$
48 $\chi^2 = 20.63$, $\Phi = -0.103$
49 $\chi^2 = 36.44$, $\Phi = 0.137$
50 $\chi^2 = 40.05$, $\Phi = 0.143$

Figure 21. Satellite imagery obtained from non-Landsat sources in response to the loss of Landsat 5 imagery among Landsat 5 users who obtained imagery from other sources (n = 1,955). See p. vi for definitions of acronyms.



These acquisitions can be compared to the imagery users selected when given the hypothetical situation of no Landsat imagery being available. For Landsat 5 users who also responded to the question regarding which imagery they would obtain within budget constraints if Landsat was no longer available, 56% actually obtained the same imagery to replace Landsat 5 imagery. There are many factors that may have entered into the decision of which imagery to obtain. First, the hypothetical question posited that both new and archived Landsat imagery was no longer available, whereas in reality, only new Landsat 5 imagery was not available. Users may well have made a different decision of which imagery to obtain when the Landsat archive and new Landsat 7 imagery were still available. Second, depending on the immediate needs of the users, their preferred imagery in the hypothetical situation might not actually have been the best choice for the specific project in which the imagery was being used.

Of those who replaced Landsat 5 imagery with other imagery or data, 28% spent money on that imagery or other data in the 30 days prior to the survey. On average, these users spent $4,284 on other imagery[51] and $2,519 on other types of data.[52] There were no significant differences between U.S. and international users for the amount spent; however, international users did spend more, on average, on both imagery and other types of data to replace Landsat 5 imagery.

[51] 14% of eligible respondents did not answer this question.
[52] 17% of eligible respondents did not answer this question.

Economic Benefits from Landsat Imagery

Given the wide range of users of Landsat imagery and various uses the imagery is put towards, significant economic benefits are likely to be generated from its use. However, determining these benefits can be a difficult task, partly because there is no market price to reflect the value of the imagery to society. Landsat imagery has characteristics of a public good, meaning the socially optimal level of provision through private markets is not likely. Even the previous price did not accurately reflect economic benefits because it was administratively set. To measure these economic benefits accurately, consumer surplus is the appropriate measure. This is the standard measure of benefits in benefit-cost analysis (Sassone and Schaffer, 1978), and the Office of Management and Budget (1992) also recommends using it, stating, “When it can be determined, consumer surplus provides the best measure of the total benefit to society from a government program or project.” Although other types of value may be derived from the use of Landsat imagery, in this section, value refers only to the monetary value of the benefits received by direct users of the imagery.

Economists use a range of methods to monetize the economic benefits provided by goods and services that are not traded in markets. When there is no price, or there is little or no market data available on the benefits to users, a stated preference or intended behavior technique known as the contingent valuation method (CVM) is commonly used. CVM is a survey-based approach used to estimate the economic benefits individuals receive from a nonmarket good or service. This method is recommended for use by Federal agencies (U.S. Environmental Protection Agency, 2000; U.S. Water Resources Council, 1983).

In this study, CVM was used to quantify the economic benefits associated with the use of Landsat imagery. Regarding the question response format, a dichotomous choice question was asked in which the user was asked to decide only whether a Landsat scene is worth the cost specified in the question. The specific question asked was

> “At the moment, current Landsat 5 imagery is not available (expected to be available again in spring of 2012) and you may have already obtained imagery elsewhere to replace Landsat 5. If both Landsat 5 and 7 became permanently inoperable before the next Landsat satellite is operational (scheduled to launch in early 2013), you may have to obtain imagery elsewhere again. Assume that you are restricted to your current project or agency budget level and that the money to pay this cost would have to come out of your existing budget. If such a break in continuity did occur and you had to pay for imagery that was equivalent to the Landsat standard product typically available (which assumes both Landsat 5 and 7 imagery are available), would you pay $X for one scene covering the area equivalent to a Landsat scene?”

The “$X” was randomly filled in with one of 20 different dollar, or bid, amounts, ranging from a low of $10 to a high of $10,000. Respondents were instructed to answer *Yes* or *No*. The range of bid amounts was determined from the 2009 survey of Landsat users (Miller and others, 2011). This question includes an explicit budget constraint (“Assume that you are restricted to your current project or agency budget level…”) and a reminder that the funds used to pay the higher cost would have to come out of this fixed budget. This follows the recommendation of the National Oceanic and Atmospheric Administration panel on CVM (Arrow and others, 1993) that budget reminders are to be included in CVM survey questions. Recognition of budget constraints is important to be consistent with consumer behavior and demand theory, simulating a realistic market setting.

Using a follow-up CVM question allows for improved inference of economic benefits. If the respondent answered *Ye*s to the first question, then a second question asked if they would pay a higher amount. If the respondent answered *No* to the first question, then a second question asked if they would pay a lower amount. The response to these two questions leads to a series of *Yes/Yes*, *Yes/No*, *No/Yes*, and *No/No* answers, providing the data necessary to calculate a "double-bounded" estimate of economic benefits. The responses are regressed on the bid amount, demographic characteristics of the respondent, and other relevant variables. The results of this regression model can then be used to monetize the average and median economic benefits provided by one Landsat scene. In the previous survey conducted in 2009, a follow-up CVM question was also included; however, due to difficulty in interpreting the results, only the results from the original question were used, resulting in a "single-bounded" estimate (Miller and others, 2011). For the 2012 survey, we used a new bid design for the follow-up question that was informed by the 2009 survey.

The main set of results that we report here are from the double-bounded CVM question using the new bid design, because these are the most precise results. We report results for four groups of users: (1) U.S. established users, (2) U.S. new/returning users, (3) international established users, and (4) international new/returning users. Currently, U.S. users download the overwhelming majority of scenes from EROS, so it was important to understand any differences between the benefits provided to U.S. versus international users. We also hypothesized that established users would report greater benefits from using Landsat imagery than new/returning users, based on their consistent use of the imagery over time. For completeness, in appendix 2, we report results from the single-bounded CVM question based on all respondents, including a control group given the same bid design used in the 2009 survey, as well as the new bid design, in the follow-up question.

Results from this analysis show that the median value of the economic benefits, or consumer surplus, obtained from Landsat imagery was $182 per scene (90% confidence interval (CI) = $157-$207) for U.S. established users and $49 per scene (90% CI = $42-$55) for U.S. new/returning users (table 11). This is not the value of the scene to the typical user but the value where half (50 percent) of the sampled users would purchase a scene equivalent to a Landsat scene. The median can also be thought of as the amount where half the Landsat users registered with EROS would not purchase a scene and thus would cease to receive economic benefits from the imagery. The mean consumer surplus or average value of the economic benefits was $912 per scene (lower bound (LB)[53] = $829) for U.S. established users and $367 per scene (LB = $341) for U.S. new/returning users (table 11; averages were weighted and truncated, see appendix 2 for more information). The purpose of the confidence interval and the lower bound is to communicate some of the variation associated with the median and average point estimates. The main conclusion from both, however, is that point estimates are relatively precise. Both the median and average were substantially less for new/returning U.S. and international users than for established users. This would be expected, as the new and returning group of users was motivated to begin using, or return to using, Landsat imagery as a result of the free and open data policy. The average was much higher than the median for all groups of users because there is a small, but significant,

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[53] A confidence interval cannot be calculated for the mean benefit because the estimate was truncated at the highest bid amount ($10,000). However, a lower bound was calculated by truncating the estimate at the second-highest bid amount ($7,500). See appendix 2 for a complete explanation of why truncation was necessary.

group of users that values Landsat imagery very highly. This may be due to the nature of the respondents who are generally technically oriented, professional, and knowledgeable about the good they were asked to value.

Table 11. Median and mean values of economic benefits from Landsat imagery for established and new/returning U.S. and international Landsat users registered with the U.S. Geological Survey (n = 6,619).

Value per Landsat scene	U.S. users				International users			
	Establish	90% CI[1] and LB[2]	New/ return	90% CI and LB	Establish	90% CI and LB	New/ return	90% CI and LB
Median	$182	$157–207[1]	$49	$42–55	$171	$146–205	$59	$54–64
Mean (average)	$912	$829[2]	$367	$341	$930	$842	$463	$425

[1]Confidence interval.
[2]Lower bound.

Economic benefits vary significantly across user sectors. U.S. academic users reported the lowest values for the imagery among established users and second lowest values among new/returning users (table 12). U.S. nonprofit organization users reported the highest values among established users and second highest among new/returning users. This may be due to the type of projects to which the imagery is applied. Nonprofit organizations typically are working on projects that are meant to directly impact society and (or) the environment, so these users may be considering the benefits to society at large when valuing the imagery. In contrast, academic users are often using the imagery in research projects; though there may be great benefits to society and (or) the environment, they may not be considering those benefits when valuing the imagery. There is a greater range in reported benefits among U.S. established users than among new/returning users. For example, the average value for established users from nonprofit organizations was more than double that of academic users. However, the highest average value for new/returning users (private businesses) was only 58% more than the lowest average (state and local governments). The sector of the user did not seem to play as large a role in determining economic benefits among new/returning users as it did among established users. This may indicate that longer-term use of the imagery has created an increased dependency among established users in certain sectors that translates into greater benefits.

Among international users, a similar pattern exists, though with some differences in valuation by sector (table 12). Users from private businesses reported the highest average values among both established and new/returning users. As with U.S. users, academic international users reported the lowest average values. The difference in the range of values between established and new/returning users was not as great among international users as among U.S. users. Private business users reported an 80% higher average value than academic users among established users and a 71% higher value among new/returning users.

Table 12. Median and mean values by sector of economic benefits from Landsat imagery to established and new/returning U.S. and international Landsat users registered with the U.S. Geological Survey (n = 6,619).

	Established users		New/returning users	
	Mean (average)	Median	Mean (average)	Median
Sector	***U.S. users***			
Nonprofit organizations	$1,490	$379	$380	$52
Federal Governments	$1,181	$264	$354	$47
Private businesses	$1,057	$223	$484	$72
State and local governments	$940	$187	$307	$39
Academic	$704	$123	$331	$43
	International users			
Private businesses	$1,374	$312	$696	$106
Federal Governments	$1,150	$236	$526	$71
State and local governments	$1,131	$290	$574	$80
Nonprofit organizations	$859	$151	$548	$75
Academic	$762	$126	$406	$49

To calculate the annual aggregate value of Landsat imagery, two pieces of information are necessary: (1) the number of scenes obtained by each of the four groups of users (U.S. and international established and new/returning users) and (2) the average economic benefit per scene for each group. The latter was calculated using the contingent valuation method outlined earlier. The former uses data provided by EROS and from the survey. EROS keeps records of the number of scenes downloaded each year to U.S. and international users but does not have information on which users are established and which are new or returning users. Using information from the survey on the average number of scenes that each of these groups obtains annually from EROS, the proportion of scenes obtained by each group was calculated. For U.S. users, established users were estimated to have obtained 71% of the scenes annually and new/returning users obtained 29%. For international users, established users were estimated to have obtained 60% of the scenes annually and new/returning users obtained 40%. By applying these proportions to the total number of scenes distributed by EROS to U.S. and international users in 2011 (the last full calendar year before the survey was administered), an estimate of the number of scenes each group obtained in 2011 was attained. The annual value of Landsat is the average value per scene for each group multiplied by the total number of scenes each group obtained in 2011 (table 13). The annual economic benefit from Landsat imagery obtained from EROS in 2011 was just over $1.79 billion (LB = $1.64 billion) for U.S. users and almost $400 million (LB = $363 million) for international users, resulting in a total annual economic benefit of $2.19 billion (LB = $2 billion).

Table 13. Annual aggregate economic benefits to Landsat users registered with the U.S. Geological Survey from Landsat imagery distributed by the Earth Resource Observation and Science (EROS) Center in 2011.

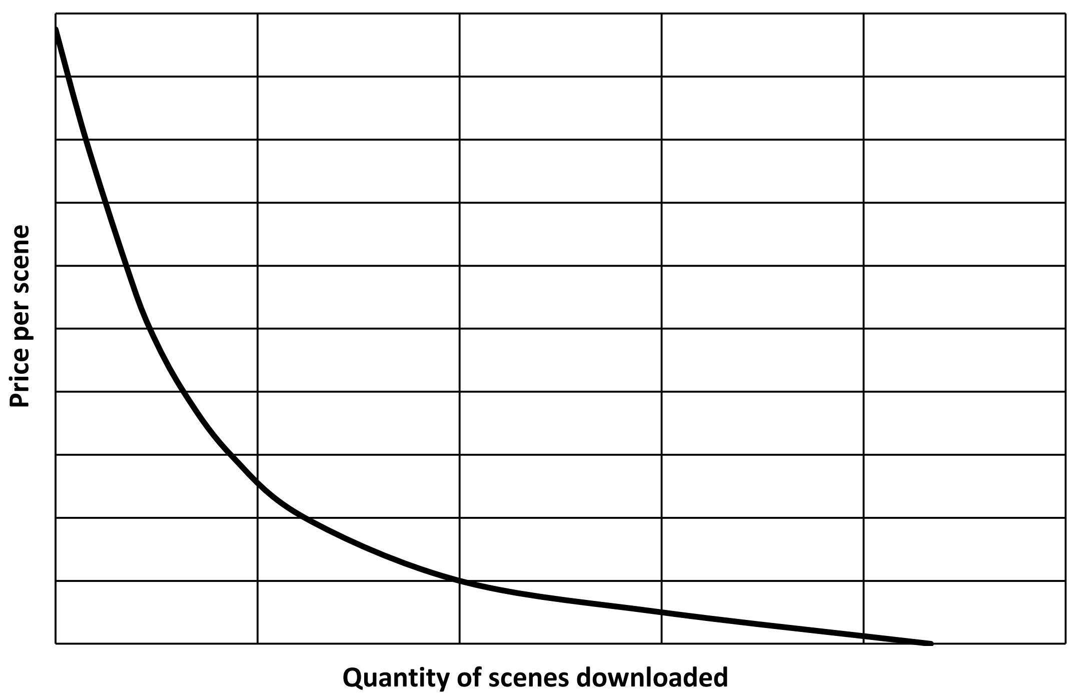
Landsat user group	Number of scenes obtained in 2011 from EROS	Average economic benefit per scene	Annual economic benefit (millions)	Lower bound (millions)
U.S. users				
Established	1,687,600	$912	$1,539	$1,399
New/returning	692,508	$367	$254	$236
U.S. total	***2,380,108***		***$1,793***	***$1,635***
International users				
Established	320,522	$930	$298	$270
New/returning	218,196	$463	$101	$93
International total	***538,718***		***$399***	***$363***
TOTAL	**2,918,826**		**$2,192**	**$1,998**

This estimate does not represent the entire societal benefit from Landsat imagery because it accounts only for the benefits received by direct users (that is, those that download scenes directly from EROS). There are no restrictions on distributing the imagery, and once a scene is downloaded from EROS, it can be used by multiple people for a variety of projects. This figure also does not account for any benefits that users of derived or value-added products that include Landsat imagery receive, because users of those products are not included in this population.

Another consideration when interpreting this estimate is the wording of the CVM question. Though the question did not ask the user to specifically think about newly acquired imagery when responding, it is possible that some users may have been considering only new imagery in their response. If this is the case, aggregating the economic benefit to the entire archive of Landsat imagery may not be appropriate. However, in the year prior to the survey, the majority of users (78%) obtained imagery acquired during at least two different 5-year time periods. For these users, the value of new imagery is most likely linked to the value of the archive and vice versa. In other words, any benefit assigned to new Landsat imagery would also take into account the value of archived imagery. Given that there was a mix of users in the sample and that all of their economic benefits were taken into account when estimating the average value of a scene, we believe it is appropriate to calculate the aggregated benefits for all Landsat imagery downloaded from EROS in 2011.

The information presented in this analysis may raise the question of whether users should be charged to obtain Landsat imagery. As mentioned previously, similar to other data and information sources, Landsat imagery has characteristics of a public good. Specifically, the imagery is nonrival in consumption, meaning more than one person can use the same imagery at the same time, and once the imagery is made publically available, the additional, or marginal, cost of allowing one more person to use it is zero. The inability of the private sector to supply public goods efficiently is a type of market failure, and the Federal Government plays an important role in the provision of data and information sources that are not efficiently provided by the private sector. Assuming Landsat imagery continues to be provided by the public sector, economic analysis can be used to determine the efficient price to charge users for the imagery. The relation between the economic benefits society receives from the use of Landsat imagery at different price points can be shown graphically. An illustrative demand curve for Landsat imagery is shown in figure 22, with the quantity of scenes downloaded on the horizontal axis and the price per scene on the vertical axis.

Figure 22. Illustrative demand curve for Landsat imagery.



The demand curve for Landsat imagery slopes downward, following the law of demand. As the price per scene increases, the quantity of scenes demanded decreases and vice versa. There is considerable evidence to support this downward sloping demand curve for Landsat imagery. First, when prices reached $4,400 a scene during the era of privatization, many users were priced out of the market and switched to other imagery (NASA, 2013). Second, since the imagery has been available at no cost, the number of users and number of scenes downloaded has increased substantially. Finally, the CVM analysis presented here confirms what is expected: at higher bid amounts, there is a lower probability that survey respondents would pay for the imagery. At different price points, both the number of imagery users and the number of scenes downloaded would be expected to change.

Economic benefits, or consumer surplus, can be illustrated graphically as the area under the demand curve and above the price paid for a particular good. At a price of $0 per scene, the entire area under the demand curve reflects the economic benefits received from the use of Landsat imagery, as shown in figure 23.

Figure 23. Illustrative demand curve for Landsat imagery with economic benefits provided at a price of $0.

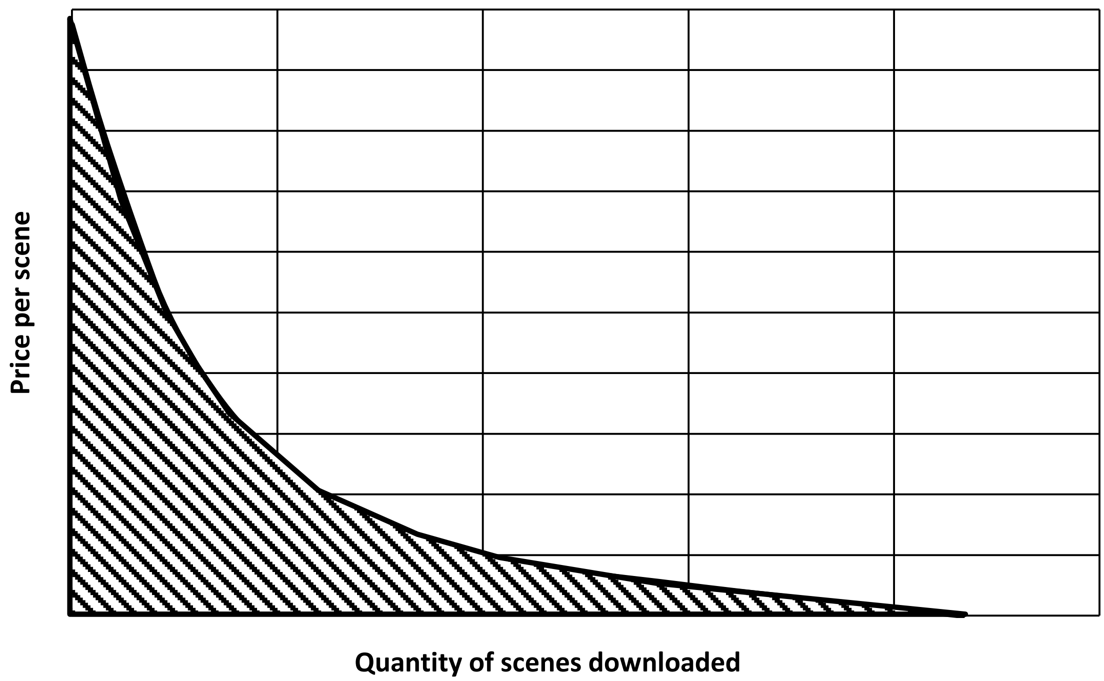
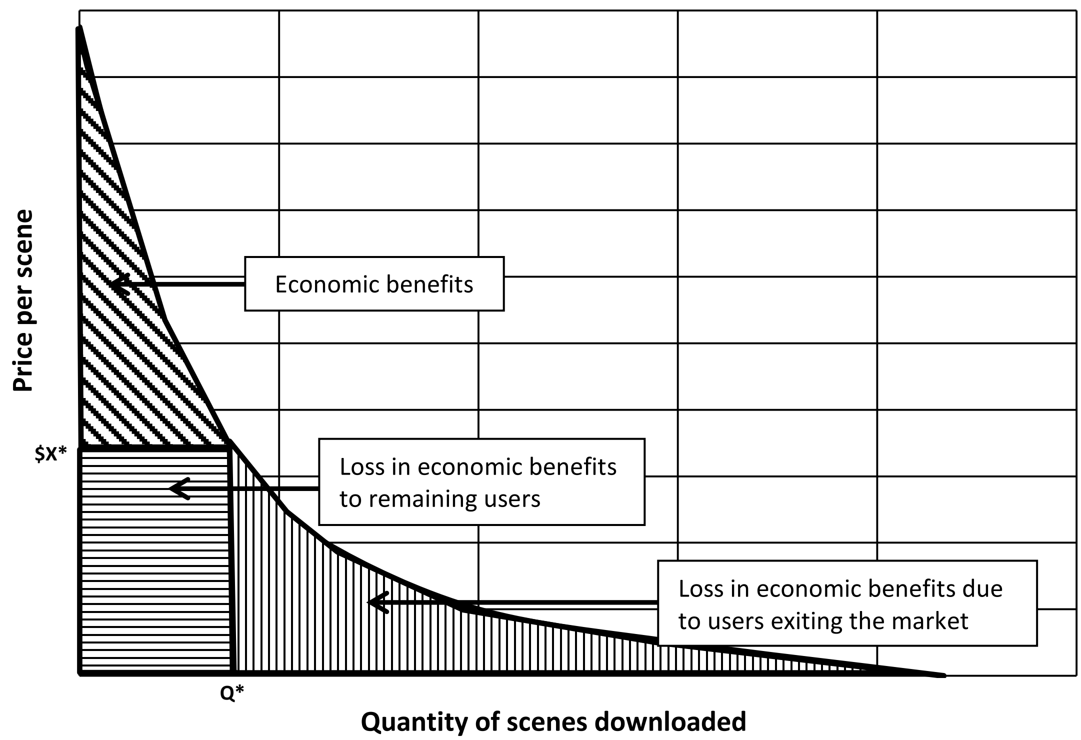


Figure 24 shows the effects of charging a positive price, $X, for the use of Landsat imagery. At this price, a quantity of Q* scenes would be downloaded. The economic benefits that users would receive are illustrated by the shaded area with diagonal stripes. The loss in economic benefits to users who continue to use Landsat imagery but now pay $X per scene is illustrated by the shaded area with horizontal stripes. This same amount would be transferred to the government as revenue. Finally, the shaded area with vertical stripes represents a loss in economic benefits due to users who are not willing to pay $X per scene exiting the market for Landsat imagery. This area is a combination of remaining users downloading fewer scenes and other users completely exiting the market because they value the image at less than $X per scene. Because this loss in surplus accrues to no one as a gain, it is referred to in economics as deadweight loss (Krugman and Wells, 2009, p. 121). Charging any positive price for a nonrival good is economically inefficient; it results in under consumption of the good and a net loss of economic benefits to society.

Figure 24. Illustrative demand curve for Landsat imagery with economic benefits provided at a price greater than $0.



The CVM analysis presented in this section shows that, though there is a small group of users who would pay a lot for Landsat imagery, most users are not willing, or able, to pay very much. More than two-thirds (68%) of users responded *No* to both CVM questions (and thus both bid amounts) they received. Charging a positive price for the use of imagery would restrict access with no associated net gain to society. It would prevent some individuals from receiving benefits from the use of the imagery either by causing them to exit the market or by causing them to obtain fewer scenes than they would otherwise, while the Federal Government would incur no additional cost in letting these users have access to the imagery. As shown in figure 24, charging a positive price for a nonrival good such as Landsat imagery results in a deadweight loss to society; even charging a minimal price would result in considerable economic losses. The economically efficient price to charge users is zero.

Further, there is good reason to believe that charging a positive price for the use of imagery would result in even greater economic losses than those shown in figure 24. Charging for the imagery would hinder innovation resulting from its use. When users paid a price per scene, they downloaded fewer scenes than they do currently, and as a result, were constrained in the uses they could put the imagery towards. Once it became available at no cost, users could download as many scenes as they wanted and use the imagery in new applications, some of which never would have existed if the imagery had not become available at no cost. These uses generate societal benefits that would be reduced in the absence of a free and open data policy. In addition, the discussion thus far has focused on direct users of Landsat imagery. There are many downstream users of Landsat imagery and imagery-derived products. Charging a positive price would also reduce the benefits obtained from these downstream uses.

Discussion: Value of Landsat Imagery

The value of Landsat imagery was high overall for these users, particularly for established users. In general, Landsat imagery was important to users for their work, and they were very satisfied with the attributes provided by Landsat. They found it beneficial for improving decision-making and preventing harm to the environment and humans, among many other benefits. These benefits may increase as the no-cost policy change becomes even more widely known, Landsat 8 imagery is extensively used, and emerging issues facing the nation, such as climate change, become more pronounced and require increasing amounts of global, reliable data. The value of Landsat imagery to these users is also demonstrated by the substantial amount of work that would be discontinued or require a substitute source of data. Finally, the value is demonstrated by economic benefits generated by the imagery. We estimate the aggregate economic benefit for the Landsat scenes directly distributed by EROS in 2011 to be greater than $2 billion. This estimate does not include benefits from reuse of the imagery after it has been obtained from EROS or from the use of value-added products.

Conclusion

The results of the survey revealed that users around the globe from multiple sectors use Landsat imagery in many different ways, as demonstrated by the breadth of project locations and scales, as well as application areas. The current level of use will likely increase among these users, particularly as it becomes better known that the imagery is available at no cost and as new uses are identified. The changes in acquisition patterns, including the increase in the number of scenes acquired and the decreasing amount of money spent after the imagery became available at no cost also point toward increases in future use.

The value of Landsat imagery to these users was demonstrated by the high importance placed on the imagery, the numerous benefits observed from projects using Landsat imagery, the impacts if Landsat imagery was no longer available, and the substantial aggregated annual economic benefit from the imagery. The results of the CVM analysis reveal not only the value of the imagery to these users, but also the potential consequences of charging for the imagery. Some users would cease to use Landsat imagery and thus receive no benefits from that use, which would lead to a decrease in the overall economic benefit. Other users may obtain less imagery and receive less benefit, again reducing the overall economic benefit. There are other potential impacts that were not captured in this analysis, such as loss of innovation due to price-restricted access to the imagery. Also, these results represent only the value of Landsat to users registered with EROS; further research would help to determine what the value of the imagery is to a greater segment of the population, such as downstream users of the imagery and imagery-derived products.

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Appendixes

Appendix 1

Past Landsat Users

In addition to current Landsat users, past Landsat users were also surveyed to discover why they were not currently using Landsat. This group consisted of users who had used Landsat at some point in the past but had not used it in the year prior to the survey (n = 1,769). Of those users, 39% were currently using other types of imagery and 56% were not (5% did not know). When asked why they were not using Landsat, 57% of users stated that their work did not require the imagery. Some users also cited spatial resolution not meeting needs (26%), the SLC-off issue (18%), and insufficient data quality (11%) as main reasons. For respondents who were using other imagery in their work, the most common reasons cited were their work did not require the imagery (45%), spatial resolution (36%), the SLC-off issue (27%), and temporal resolution (17%). For respondents who were not using other imagery in their work, the most common reasons cited were their work did not require imagery (66%), spatial resolution (18%), and the SLC-off issue (11%). These results indicate that work projects are driving the use of Landsat for many respondents, but that characteristics of the imagery itself such as spatial resolution and data quality also play a role. Characteristics of imagery provision, such as cost, availability, and accessibility, were cited infrequently as reasons for not using Landsat imagery.

For the most part, the past Landsat users in the sample were very similar demographically to the current Landsat users. About 72% of the users were male, the average age was 37, and 48% had 18 or more years of education. However, though both groups were highly educated, only 26% of past Landsat users had 20 or more years of education, compared to 37% of current Landsat users. Past users had an average of 7 years of experience using satellite imagery and (or) GIS software, compared to 10 years for current users. One-fifth of past users were members of remote sensing or GIS professional organizations compared to one-third of current users. The predominant sector for past users was academic institutions (49%), followed by private business (23%), Federal Governments (12%), nonprofit organizations (5%), and State governments (4%) (fig. 3). Only 3% of the users worked for local governments and less than 1% worked for indigenous groups, tribes or nations. These percentages are very similar to the sector breakdown for current users, with slightly fewer past users than current users in academia and slightly more past users in the private sector.

Discussion

The results from past Landsat users in this sample indicate that the use of Landsat depended greatly on the work users were doing. However, the spatial resolution of Landsat was also an impediment, as was insufficient data quality, including the SLC-off issue. Because users' work is out of the control of data providers and the spatial resolution of Landsat is unlikely to change in the near future, these barriers to using Landsat are not likely to be removed. However, some data-quality issues, including SLC-off, have been addressed by the successful launch of Landsat 8. Past Landsat users were demographically similar to current Landsat users in regards to gender, age, and education. Past users were, however, less likely to report the highest levels of education or to have as much experience with remote sensing and (or) GIS as current users.

Appendix 2

This appendix provides technical details regarding monetization of the economic benefits of Landsat imagery presented in this report. As mentioned previously, the contingent valuation method (CVM) was used to quantify the economic value of Landsat imagery to direct users. This method allows individuals to state their preferences for a nonmarket good or service, typically through a survey instrument. These responses are then incorporated into an appropriate statistical model to elicit a monetary measure of economic value. When applying this method, great care needs to go into developing the survey questions to ensure that values are accurately estimated. Boyle (2003) provides a summary of the steps that are involved in conducting a CVM study.

The contingent valuation method has been used to quantify the economic benefits associated with a broad range of nonmarket goods and services, including data and information sources such as improved weather forecasts (Lazo and Chestnut, 2002). The method is especially useful because it can be used to quantify the economic value of a specific source of data without confounding that estimate with the value of other inputs used in combination with that data for some beneficial end use. In addition, CVM allows for estimation of the economic value of data across a wide range of users and uses, making it extremely applicable to quantifying the value of Landsat imagery.

By allowing individuals to state their preferences for Landsat imagery, a measure of economic benefits received by direct users of the imagery is elicited, based on respondent's willingness-to-pay (WTP) for the equivalent of a Landsat scene. Willingness-to-pay above and beyond any costs actually paid captures consumer surplus, the measure of economic benefits focused on for this analysis. Regarding the question response format, a dichotomous choice question was asked due to its desirable incentive compatibility properties (Haab and McConnell, 2002; Boyle, 2003). Responses to the first CVM dichotomous choice question presented in the survey provided the data necessary to estimate what is referred to as a single-bounded willingness-to-pay. The underlying distribution of willingness-to-pay, which is unknown, can be specified as:

$$WTP_i^* = x_i'\beta + \varepsilon_i \qquad (1)$$

where x_i' represents a vector of independent variables that could influence individual i's willingness-to-pay for the imagery, and ε_i is the error term. One of those independent variables is the dollar amount the individual is asked to pay. This dollar amount varies within the sample of respondents to provide insight about how the population, as represented by the sample, values Landsat imagery. Whether or not an individual is willing to pay a specified bid amount is observed, so the probability that individual i responds *Yes* to bid amount bid_i is equal to the probability that the random willingness-to-pay function is greater than or equal to that offered bid amount:

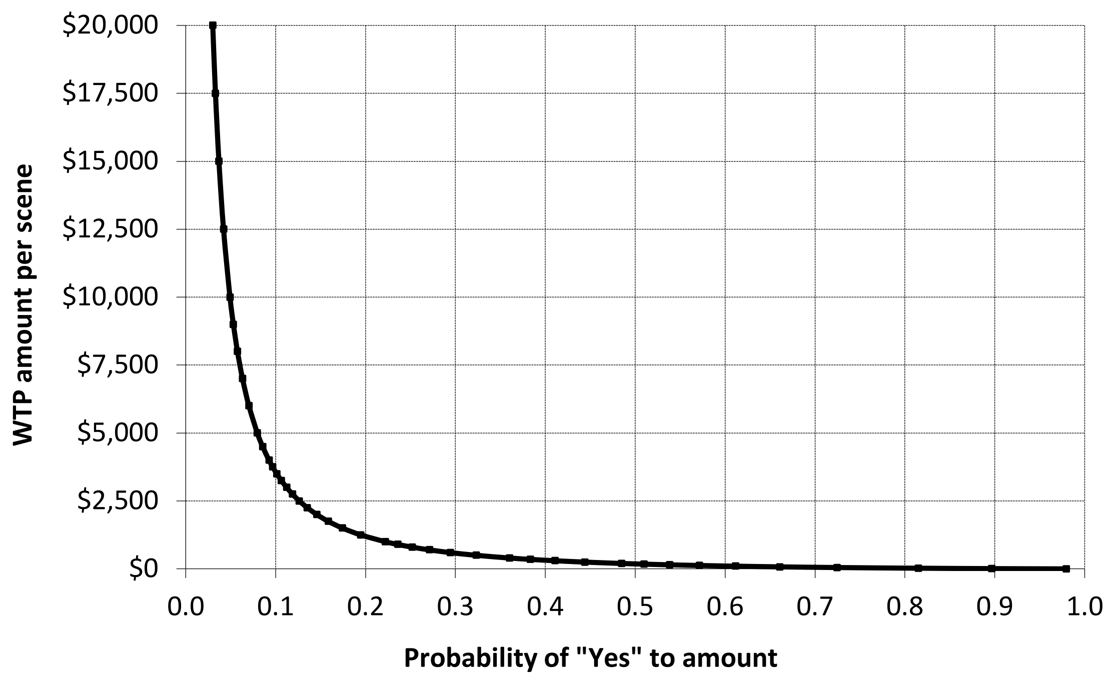
$$Pr\,(WTP_i^* \geq bid_i;\, x_i') = 1 - F(bid_i;\, x_i') \qquad (2)$$

where F is the cumulative distribution function of WTP_i^*. This model is estimated here by the method of maximum likelihood, where the likelihood function can be specified as:

$$ln\, L\,(x_i') = \sum_{i=1}^{N} \{d_i^y\, ln[1 - F(bid_i; x_i')] + d_i^n\, ln\, F(\, bid_i; x_i')\} \qquad (3)$$

where N represents the sample of respondents, d_i^y takes a value of 1 if the i_{th} respondent responds *Yes* to bid_i and 0 otherwise, d_i^n takes a value of 1 if the i_{th} respondent responds *No* to bid_i and 0 otherwise, and we assume a logistic for the underlying distribution of willingness-to-pay. The distributional assumption is necessary but does not determine any of the results. The results of this model can be used to estimate a complete demand function for the imagery, shown in figure 2.1 for all respondents, new and established, U.S. and international.

Figure 2.1. Demand curve for single-bounded willingness-to-pay (WTP) for all respondents.



The demand function, or curve, is one of the outputs of a CVM study and is the combination of quantities consumed at different price amounts. Consistent with economic theory, responses to the bid amount clearly produced a downward sloping demand curve. Respondents were more likely to say *Yes* to low bid amounts and *No* to high bid amounts. This demand curve can be used to determine the median and the average WTP for the sample of users. The median value, which is where half (50 percent) of the sampled users would purchase a scene equivalent to a Landsat scene, was $185 per scene (90% confidence interval (CI) = $157-215) for U.S. established users and $46 per scene (90% CI = $38-54) for U.S. new/returning users (table 2.1).

A further result should be observed in the demand curve. At very high bid amounts—or WTP amounts—there remains a positive probability that the user was willing to pay this amount for a Landsat scene. This means that there was a relatively small group of users that find Landsat imagery very valuable. It should also be noted that small increases in the bid amount from zero results in a rapid decline in the probability that the user was willing to pay. This means that there was a relatively large group that attaches a small economic value to Landsat imagery. This near-dichotomy of users is important in that there is not a typical user of Landsat imagery, and the value of Landsat should not be thought of in terms of the typical user. Rather, the typical user should be thought of as a weighted average of the distribution of users. Using separate models for established users and new/returning users recognizes that there are different demand curves for each. And further, within each one of these groups, there is variation in the value for Landsat imagery.

Estimating the average value of a scene involves integrating the area under the demand curve. However, the parameters associated with the demand curves result in unbounded averages, meaning they do not have a limit. The value of Landsat imagery to some users was substantial, and this pulls the average well above the median. Even with bid amounts of $10,000 per scene, there remain a significant number of users that were still willing to pay. We did not succeed at asking a bid amount high enough that all users would say *No*. The standard practice when faced with an unbounded average is to use the highest bid amount from the sample as the upper bound. Using the highest bid amount from the first CVM question ($10,000) and weighting the average based on the percentage of users within each sector results in an average WTP of $1,175 per scene (lower bound (LB)[54] = $1,040) for U.S. established users and $569 per scene (LB = $513) for U.S. new/returning users (table 2.1).

Table 2.1: Single-bounded median and mean values of economic benefits from Landsat imagery by user group.

Value per Landsat scene	U.S. users				International users			
	Establish	90% CI[1] and LB[2]	New/ return	90% CI and LB	Establish	90% CI and LB	New/ return	90% CI and LB
Median	$185	$157-215[1]	$46	$38-54	$131	$116-146	$33	$28-38
Mean (average)	$1,175	$1,040[2]	$569	$513	$1,629	$1,387	$679	$592

[1]Confidence interval.
[2]Lower bound.

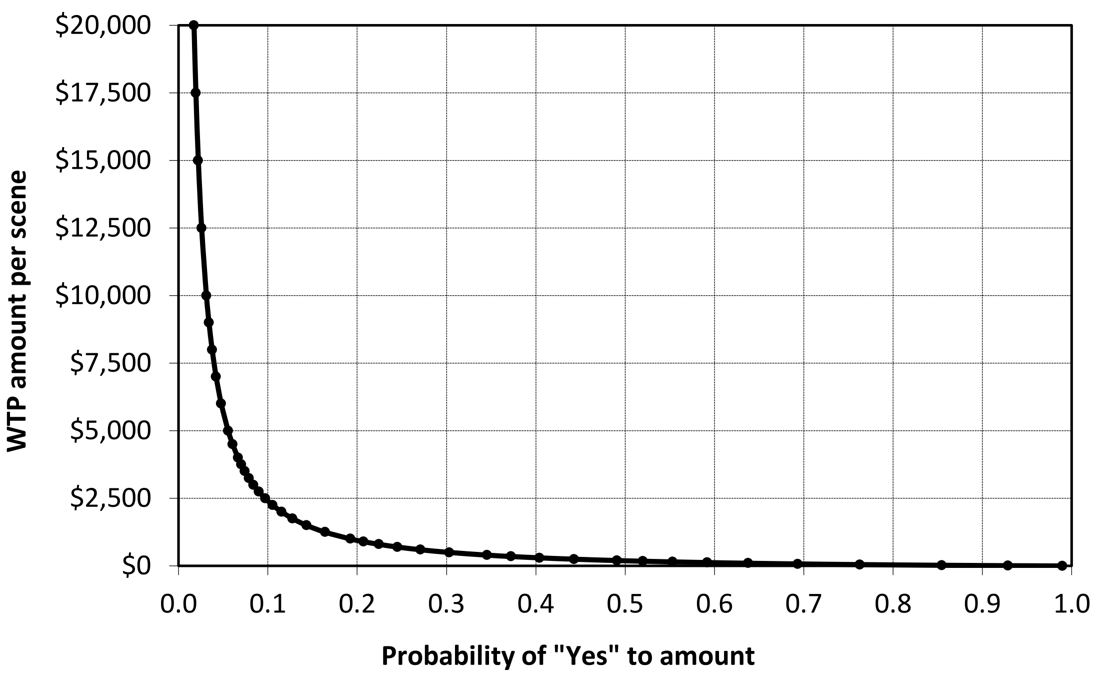
As mentioned in the report, a follow-up CVM question was used to increase the statistical efficiency of the WTP estimate. Combining responses to the first CVM question with responses to the second CVM question leads to a series of *Yes/Yes*, *No/No*, *Yes/No*, and *No/Yes* answers that can be used to estimate a double-bounded estimate of WTP. This has been shown to be statistically more efficient than a single-bounded estimate of WTP (Hanemann and others, 1991). In the case of a *Yes/No* or *No/Yes* series of responses, we know that the respondent's maximum WTP lies between the two bid amounts presented to them in the first and second questions. In the case of a *Yes/Yes* response, we know that the respondent's WTP is higher than the bid amount presented in the second question. In the case of a *No/No* response, we know that the respondent's WTP is lower than the bid amount presented in the second question. The follow-up CVM question is giving the researcher more information regarding the respondent's true maximum WTP for Landsat imagery. Again using the method of maximum likelihood to estimate this model, the likelihood function can be specified as

[54] A confidence interval cannot be calculated for the mean benefit because the estimate was truncated at the highest bid amount ($10,000). However, a lower bound was calculated by truncating the estimate at the second-highest bid amount ($7,500).

$$ln\ L\ (x_i') = \sum_{i=1}^{N}\{d_i^{yy} \ln P(Yes/Yes)\ (bid_i,\ bid_i^u) + d_i^{nn} \ln P(No/No)\ (bid_i,\ bid_i^l) + d_i^{yn} \ln P(Yes/No)\ (bid_i,\ bid_i^u) + d_i^{ny} \ln P(No/Yes)\ (bid_i,\ bid_i^l)\} \quad (4)$$

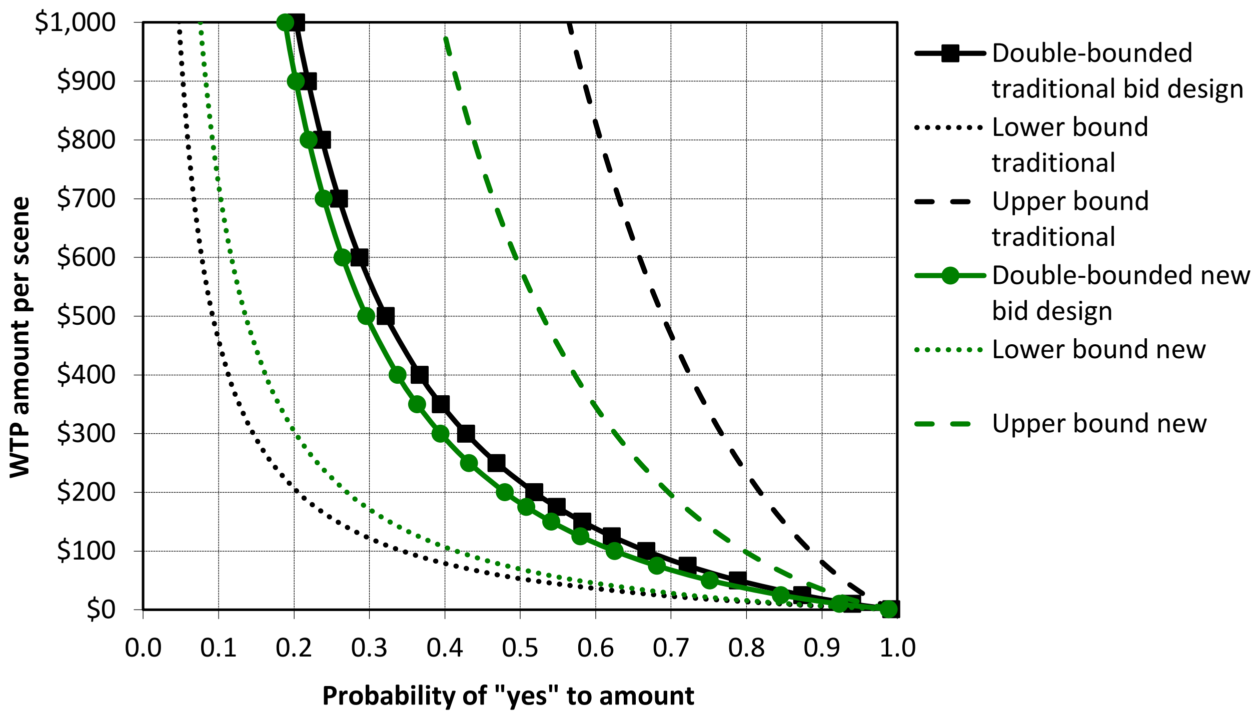
where $d_i^{yy}, d_i^{nn}, d_i^{yn}, d_i^{ny}$ are binary variables indicating the observation of that particular response combination, that is, d_i^{yy} takes a value of 1 if the i_{th} respondent responded *Yes/Yes* and 0 otherwise. Each of these response combinations has an associated probability of occurrence *P(Yes/Yes)*, *P(No/No), P(Yes/No),* and *P(No/Yes)*. The formula for each of these likelihoods is shown in Hanemann and others (1991). Bid^u is the higher bid presented in the second CVM question in the case of a *Yes* response to the first question, and bid^l is the lower bid amounted presented in the second CVM question in the case of a *No* response to the first question. The demand curve derived from this model is shown in figure 2.2, which includes all respondents, new and established, U.S. and international. The demand curve is unbounded, so the double-bounded average values are again truncated using the highest bid amount from the first CVM question ($10,000) to be conservative. This was also the highest bid with a large sample size.

Figure 2.2. Demand curve for double-bounded willingness-to-pay (WTP) for all respondents.



In the previous survey conducted in 2009, a follow-up CVM question was also included; however, due to difficulty in interpreting the double-bounded results, only the results from the original question were used, resulting in a single-bounded estimate of WTP (Miller and others, 2011). In the 2012 survey, we were able to address the problems in the 2009 survey design that made it difficult to interpret the double-bounded WTP results. Previous research suggests that the bid amount for the follow-up CVM question should be twice or half the original bid amount, and this was the approach used in the 2009 survey. For the 2012 survey, a randomly selected subset of respondents received a survey with the same format in order to replicate the first survey; this control group is referred to as the traditional bid design. All other respondents received a different survey design in which we reduced the amount the second bid amount went up or down and also did not round the numbers to the same extent, referred to as the new bid design. We find that the slight randomization of the second question results in substantially improved statistical quality of the results as measured by reduced variance in the WTP estimate. As shown in figure 2.3, compared to the traditional bid design, the new bid design results in tighter confidence intervals around the demand curve. Survey respondents clearly did not like receiving the second bid amount that was very obviously \$2(X) or \$½(X). Therefore, using the double-bounded approach with the new bid design results in the most interpretively reliable estimate of the economic benefits received by direct users of Landsat imagery. These results are reported in the body of the report.

Figure 2.3. Demand curve and confidence intervals for double-bounded willingness-to-pay (WTP) using the traditional and new bid designs.



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