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The Users, Uses, and Value of Landsat and Other Moderate-Resolution Satellite Imagery in the United States: Executive Report

By Holly M. Miller, Natalie R. Sexton, Lynne Koontz, John Loomis, Stephen R. Koontz, Catherine M. Lundy, and Caroline Hermans

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The Users, Uses, and Value of Landsat and Other Moderate-Resolution Satellite Imagery in the United States: Executive Report

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Introduction

A variety of satellites provide remotely sensed images of the earth at different resolutions, generally categorized as high, moderate, or low resolution. According to the 2007 Future of Land Imaging Interagency Working Group report (FLIIWG, 2007), moderate-resolution imagery (MRI) is defined as imagery which:

- covers relatively large geographic areas per scene (>60 km^2),
- has a spatial resolution between 5 and 120 meters,
- is characterized by repetitive coverage, and
- includes measurements from several portions of the electromagnetic spectrum.

MRI is provided by an assortment of satellites operated by governments and private businesses around the world. One main source of MRI is the Landsat satellites operated by the U.S. Geological Survey (USGS) who receives, processes, distributes, and archives Landsat data at the Earth Resources Observation and Science (EROS) Center. Currently, there are two Landsat satellites orbiting earth: Landsat 5 and Landsat 7. They provide imagery that is unique among the variety of MRI available today for three main reasons. First, the archive of imagery extends back over 35 years, allowing for longitudinal analyses over a long time span. Second, the imagery is and has been collected over the entire globe on a regular basis, providing repeat coverage of remote areas that other satellites do not offer. Third, the imagery is available at no cost.

In the past decade, many changes have occurred both with the Landsat satellites themselves and with the provision of the imagery. In 1999, Landsat 7 was launched. It provided three years of high quality data which was complemented by the imagery from Landsat 5, and then sustained a critical technical problem. The scan-line corrector anomaly (commonly referred to as SLC-off) reduced the quality and usability of the Landsat 7 data significantly, such that Landsat 5 now provides the bulk of the imagery. In the next 5 years, the Landsat Data Continuity Mission (LDCM) is scheduled to be launched, which will replace Landsat 5 in providing primary imagery, supplemented by Landsat 7 imagery. However, before LDCM is launched, both Landsat 5 and 7 could cease to operate, creating a gap in the provision of imagery. Additionally, the entire catalog of imagery, including all new acquisitions, became available at no cost at the beginning of 2009, causing a 50-fold increase in the number of scenes downloaded annually from EROS.

Moderate-resolution imagery, such as Landsat, provides unique spatial information for many people both within and outside of the United States (U.S.). However, exactly who these users are, how they use the imagery, and the value and benefits derived from the information are, to a large extent, unknown. The last comprehensive evaluations were completed over 30 years ago and

[1] Policy Analysis and Science Assistance Branch, U.S. Geological Survey, Fort Collins, Colo.

attempted to project the conceivable economic benefits of a continued Landsat program (ECON Inc., 1974; Earthsat, 1974). Much has changed since that time—not only with the capabilities of remotely sensed data but the applications of the imagery in decisionmaking. More recently, there have been a small number of studies that have surveyed limited groups of users of MRI (for example, ASPRS, 2006; EROS, 2007; NSGIC, 2006; Stoney, Fletcher, & Lowe, 2001). While these surveys have added to the body of knowledge regarding opinions on the attributes of various sensors, they have not been comprehensive in nature. Our objectives for this study were to 1) identify and classify the U.S.-based professional users of this imagery; 2) better understand how and why MRI, and specifically Landsat, is being used; and 3) qualitatively and quantitatively measure the value and societal benefits of MRI (focusing on Landsat specifically). To reach these objectives, we conducted a study of U.S.-based professional MRI users from 2008 through 2010 in two parts: 1) a user identification and 2) a user survey.

User Identification

We defined professional users as those who use MRI in their work. Studying these professional users is challenging because the extent of the population is unknown and thus, a representative sample cannot be obtained from the entire population. The membership lists of various remote sensing and GIS professional organizations could be used, but not every user can be assumed to be a member of such organizations. The lists of users from imagery providers, such as EROS (which distributes Landsat), also would not include all the users in the United States. One reason for this is that data procured by one user is often re-distributed to other users, particularly when licensing or distribution restrictions do not exist, as is the case with Landsat. Taking a random sample of the entire population of U.S. residents would not produce usable results, given that the percentage of people in the U.S. who may be classified as professional users of MRI is most likely quite low, making this a rare population as well. Because these traditional random sample selection methods were not adequate or appropriate for this unknown population, we used a more purposive sampling procedure, explained below.

For this survey, the sample was identified in a two-step process. First, an extensive web search was performed in the summer of 2008 to identify potential users of MRI in the U.S. The search was conducted by state and was based on tens of keywords, including remote sensing, moderate-resolution satellite imagery, and Landsat, along with a variety of application areas and sectors where use may occur. This search yielded the email addresses of over 20,000 potential users from across the U.S. Subsequently, snowball sampling was used to confirm the use of MRI and find additional users. Snowball sampling is a purposive (non-probability) sampling method based on the existence of social networks. In any population, it can be assumed there are connections between the members, particularly when that population is specialized in any way, as is the population of MRI users. Using satellite imagery requires a certain level of technical knowledge and there are numerous organizations and communities that exist to facilitate the use of satellite imagery. To take advantage of these social networks, each potential user we identified was contacted via email, asked to participate in the study, to confirm their use of MRI and to provide the contact information for up to three other users. These newly identified potential users were contacted and asked to provide the same information. This process repeated until less than 100 new users were identified in a "wave." Snowball sampling is intended to increase the size of a sample with each wave of new participants, though well-known people within a population tend to be recommended multiple times.

By the conclusion of the snowball sampling, over 4,000 more email addresses had been added to the original list of potential users, totaling approximately 25,400 unique email addresses, of which more than 3,500 were undeliverable. Of the almost 22,000 individuals remaining, 5,229 responded to our request and 4,753 agreed to participate in the survey. It is unknown as to whether the people on the original list were actually users of MRI, so it is not possible to know how many did not respond to the request. Of those who responded, around 80% were MRI users, 16% were not users, and 4% were not sure if they were users. The definition of MRI was included in the snowball sampling email, so the parameters of the imagery were clear. Examples of missions which collect MRI and products based on MRI were given to further illustrate the definition.

User Survey

We launched the survey in September of 2009 to all the people who agreed to participate. We developed the survey 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 (LRS) Program's distribution of imagery and future program requirements. One of the first decisions we made in this study was to conduct the survey online. An online survey is not always appropriate for most populations because 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 consisted of imagery users who must have access to a computer and the internet to use the imagery, who almost certainly have an email account for work purposes, 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. Because the sample included both MRI users and non-users, we constructed a survey with questions tailored to four different types of users:

1) current Landsat users (who had used Landsat in the year previous to the survey),
2) current users of other types of MRI (who had used the imagery in the year previous to the survey),
3) past users of MRI (who had used the imagery at some point but not in the year previous to the survey), and
4) users of high- or low-resolution satellite imagery (who had used the imagery at any time).

The set of questions for each of these users was considered a "survey path." The last two groups were included because we were interested in understanding why users were using imagery other than MRI. The answers to certain questions directed respondents to the appropriate survey paths, reducing the burden on respondents and collecting the most relevant information from each respondent.

Results

Analysis

We analyzed the data in several different ways, including examining frequency data, chi-square analyses, t-tests, and contingent valuation analyses. Frequencies are reported for many results and chi-squares are reported for nominal and ordinal data. While many comparisons were made between various groups in the sample, differences between sectors (e.g., academic institution, government, private business) were the most prevalent and significant; many of those differences are reported below. Individual chi squares are reported for each sector where dichotomous dependent variables exist. Overall chi squares are reported when dependent variables are not dichotomous. T-tests are reported to compare means computed from scale variables. The contingent valuation analyses are described in detail in the Willingness to Pay for Landsat Imagery section.

Statistical Significance and Interpretation

The sample of professional MRI users in this study is not associated with a known population of MRI users. Therefore, it is not possible to generalize the results for this sample to the population as a whole (as is typical when a random sample from a known population is drawn). For example, the majority of the sample was composed of users of Landsat imagery; however, that does not mean that the majority of all moderate-resolution imagery professional users based in the U.S. use Landsat. However, the sample we obtained for this study is robust in terms of its size and the diversity, such that comparisons among groups within the sample are appropriate. These comparisons are helpful to illustrate the diversity of users within the sample.

Because of the large sample size, the statistical power of this sample is very high, which may lead to results that are statistically significant but not meaningfully different (e.g., practically significant). Because of this, we report statistically significant results at the $p < 0.001$ level, rather than the more typical $p < 0.05$ level found in most behavioral and psychological research. Additionally, meaningful differences are estimated through measures of association, commonly called effect sizes. Effect size is a measurement of the amount of impact an independent variable has on a dependent variable (Murphy & Myors, 1998, p. 12). The effect sizes reported most frequently in this report are phi ( ) and Cramer's v for chi-square (^{2}) analyses. Cohen (1988, p. 25-27, 79-80) provides the following guidelines for interpreting these effect sizes:

- a small effect = 0.1 (i.e., difference in mean height between 15- and 16-year old girls)
- a medium effect = 0.3 (i.e., difference in mean height between 14- and 18-year old girls), and
- a large effect = 0.5 (i.e., 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 or greater to indicate a meaningful difference for this study. Occasionally, we report statistically significant results with effect sizes less than 0.1 if they are notable for some other reason. All statistical results are located in the footnotes.

Diversity of the Sample

Determining the diversity of users within the sample is important in order to begin to understand what the larger user community might look like. These data cannot be generalized to the population at large, but the *minimum* amount of variety in the users and uses within the population can be gathered from these results. For example, users in the sample applied MRI in over 35 application areas, but users in the population could be applying the imagery in even more application areas. In other words, while recognizing that this sample may not be representative of the population as a whole, we believe that the diversity of our sample provides a much needed baseline of types of users, uses, and valuations which can be expanded with further research.

One of the goals of the study was to reach users outside of the known community and the results indicate that goal was met. Almost half of the current Landsat users are not members of any type of remote sensing or GIS organization and, during the snowball sampling, almost 35% indicated they do not know any other users of MRI. Additionally, 45% of the current Landsat users did not obtain Landsat imagery from EROS in 2008 or 2009. These results indicate that many of the users in the sample are not part of the known groups within the population, such as professional organizations or users who procure imagery from EROS. Aside from reaching beyond the known user community, the sample was diverse in other ways. Users work in seven different sectors and use the imagery in over 35 different application areas. They conduct projects at scales from local to global in locations around the world. All of these data indicate that the sample is composed of a very diverse group of U.S.-based professional users.

User Types

Over 2,500 professionals responded to the survey for a response rate of 53% (n = 2,523). This response rate is double those typically cited in the literature for online surveys.. The high response rate may have been due to the initial contact during the snowball sampling, as well as the high levels of interest and engagement respondents had regarding the topic. Current Landsat users comprised over half of the sample (fig. 1). Past MRI users comprised 15% of the sample, users of high- or low-resolution imagery comprised 9% , and current other MRI users represented the smallest portion of the group with just under 7%. Around 14% had never used any type of satellite imagery or did not know if they use MRI in their work. The latter two groups were not asked further questions in this survey because their lack of familiarity with the imagery would have made it difficult for them to answer the majority of the questions. Around 24% of the respondents had used Landsat in the past; this group was made up of both current and past MRI users. The survey was structured to enable comparisons between current Landsat users and current users of other MRI. However, many other MRI users were unaware of the type of imagery (i.e., Landsat, Terra, SPOT) they used and other information from the survey (for instance, from open-ended questions) indicate that many of these "other" MRI users may actually be using Landsat. Because of this and because the sample was predominantly made up of current Landsat users, the results in the remainder of the report refer to that group only, except where noted.

Demographics

The average current Landsat user in the sample is male, white, 47 years old, and highly educated. Three-quarters of the users are male, over 90% are white, over 80% are between 30 and 59 years old, and two-thirds have a masters degree or above. The predominant sector is academic institutions (33%), followed by private institutions (18%), and then federal (17%), state (16%), and local government (10%) (fig. 2). Only 4% of the users work for non-profit organizations and less than 1% work for tribes or nations. Anecdotally, we are aware of many tribes who are using the imagery and there were many tribal members identified in the initial web search, but very few responded to the survey. The small number prevented us from comparing respondents in the tribal sector with those in other sectors.

Use of Landsat Imagery

The first section of the survey established how the current Landsat users in the sample use the imagery, including types of imagery used, the scales and locations of projects, application areas, generally how the imagery is used, and the level of use in their work. Each question asked respondents to consider their use of Landsat in their work over the year previous to the survey.

Types of Imagery

About 40% of respondents indicated they had used only Landsat imagery in the past year. The remaining 60% of Landsat users indicated they used a mix of imagery, with about half coming from Landsat, followed by 11% from Terra (ASTER), 8% from SPOT (HRVIR, HRG, HRS), and 3% from Resourcesat (IRS, LISS, AWiFS) (table 1). One percent or less came from ALOS (AVNIR-2) or CBERS (CCD) on average. Around 6% of the imagery came from other satellites and about 16% of the imagery was from unknown satellite sources.

There are interesting differences among sectors in the imagery used for those using a mix of MRI (table 1). Respondents in the local government sector used the least amount of Landsat imagery on average (31%) and used the most imagery from unknown satellite sources (43%). Academic users using a mix of MRI, on the other hand, obtained 65% of their imagery from Landsat satellites and only 5% from unknown satellite sources.

Scales and Locations of Projects

Respondents' projects that relied on Landsat ranged from local to global scales in locations around the world. Two-thirds of respondents (66%) worked only on projects located in the U.S., while 28% have worked on projects in both the U.S. and internationally (fig. 3). Far fewer users (6%) worked only on projects located internationally. Respondents in the state and local government sectors were more likely to have worked only in the U.S. than users in other sectors[2], while academic respondents were more likely to have worked in both the U.S. and internationally[3].

Respondents predominantly worked at the regional scale or lower (fig. 4). Respondents in local government were more likely to have worked at a local scale than other users[4] and those in state government were more likely to have worked at the state scale[5].

Application Areas

A list of 37 application areas was developed by examining previous surveys of satellite imagery users, as well as through consultations with experts at EROS. Respondents were asked to select their primary application of Landsat from the list, which included an "other" category where they could write in an application area (table 2). They were then asked to select as many secondary applications as they wished from the same list. The 37 applications were collapsed into nine larger categories for the purposes of analysis (table 2). Environmental science and management applications were the most commonly selected with over 40% of respondents choosing one (fig. 5). Land use/land cover (17%) was the second most common application, followed by planning and development (11%), education (8%), and agriculture (8%). Land use/land cover is different than the rest of the applications since 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, followed by planning and development applications, such as urbanization and rural and urban planning and development.

There are clear differences among sectors in these primary applications (fig. 5). Respondents in the academic sector were more likely to apply Landsat imagery in the area of education[6], whereas those in the Federal government were more likely to have applied Landsat in agriculture[7] and environmental sciences[8]. Those in local government were more likely to have used Landsat for planning and development[9]. Those in the private sector were also more likely to apply

[2] Local - ^{2} = 55.11, Cramer's v = 0.200; State - ^{2} = 74.98, Cramer's v = 0.233
[3] ^{2} = 127.88, Cramer's v = 0.304
[4] ^{2} = 30.18, = 0.148
[5] ^{2} = 42.26, = 0.175
[6] ^{2} = 162.70, = 0.343
[7] ^{2} = 28.70, = 0.144
[8] ^{2} = 19.98, = 0.120
[9] ^{2} = 98.69, = 0.267

Landsat in planning and development[10], as well as in commercial applications[11] and oil/gas/minerals exploration and extraction[12].

In addition to these current application areas, there may be new and unique uses in the future. We asked respondents to write in uses they foresee in the next five years. Common responses included change detection using time series analyses, integration with other imagery or products, and climate change monitoring and awareness. For example, one respondent believed that new uses will "mostly come from the power of comparing the long catalog with new observations, especially associated with urbanization and global warming induced changes."

How Imagery is Used

To get a sense of how respondents are using MRI in general, we asked them to describe their overall work with the imagery (fig. 6). The majority of respondents (91%) use the imagery to answer questions and/or solve problems, process imagery for themselves or others (62%), and make decisions based on the imagery (57%). Only 19% develop algorithms, 12% provide or sell imagery or value-added products, and 2% develop commercial software. By sector, those in academia are more likely to process imagery[13] and develop algorithms[14] whereas those in local[15] and state[16] government are less likely to use the imagery in these ways. Those respondents in the private sector are more likely to provide or sell imagery[17] and develop commercial software[18].

Level of Landsat Use in Work

While all the current Landsat users in the sample used Landsat, whether exclusively or in conjunction with other imagery, the percentage of their work that relied on Landsat over the past year varied. In order to effectively describe level of use, we categorized respondents 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, almost two-thirds (63%) of respondents were classified as light users, 18% as medium users and 15% as heavy users (fig. 7). There are some differences between these use levels among sectors[19], namely in local government. Only 1% of respondents in local government were classified as heavy users, compared to 10-21% of users in other sectors. In contrast, 81% of local government users were classified as light users, which is 7-30% higher than in any other sector.

While this categorization is helpful in understanding level of use, it does not indicate dependence on Landsat. A light user could rely on Landsat for a critical operational use that accounts for less than 30% of their work, but which would be compromised if Landsat was not available. We did not explicitly ask about dependence in this survey, though there are some proxies for dependence that will be discussed later on in the Value of Landsat Imagery section.

[10] ^{2} = 14.89, = 0.104
[11] ^{2} = 17.43, = 0.112
[12] ^{2} = 96.47, = 0.264
[13] ^{2} = 17.78, = 0.113
[14] ^{2} = 62.33, = 0.212
[15] Process imagery - ^{2} = 22.13, = -0.127; Develop algorithms - ^{2} = 19.50, = -0.119
[16] Process imagery - ^{2} = 17.00, = -0.111; Develop algorithms - ^{2} = 32.19, = -0.153
[17] ^{2} = 47.80, = 0.186
[18] ^{2} = 40.47, = 0.171
[19] ^{2} = 104.93, = 0.275

"Local Users"

After examining the results outlined above, it became clear there was a group of users who were different from the others. We found a group of users characterized by sector, project scale, and project location, dubbed "local users," who represent about 25% of the current Landsat users in the sample. They work for local or state governments applying imagery in local-scale projects located in the U.S. There are several indications that this group may be a less technical user group than other users in the sample. They are less likely to process imagery or develop algorithms, more likely to be a light Landsat user, and less likely to know the satellite source of the imagery they use. They also appear to be less involved in the professional user community, as they are less likely to be a member of a remote sensing or GIS-related organization.

Discussion: Use of Landsat Imagery

Overall, Landsat imagery was the primary MRI used by these respondents, but the uses of the imagery varied greatly among these respondents. In the year previous to the survey, respondents worked on projects at all different scales in locations around the world. Every one of the 37 application areas on the list was selected by a minimum of two respondents as their primary application. The general uses of MRI indicate that there was a mix of technical abilities among the respondents in the sample, with some respondents processing the imagery or developing algorithms or software, and others using it in less technical ways to answer questions or make decisions. There were also respondents using Landsat at all levels in their work, with some using Landsat in all their work and some using it in very little of their work. Taken together, these results reveal a diverse sample of users whose responses provide a baseline for exploring the uses in the population as a whole.

Comparing the results by sector demonstrated that there are significant differences among the sectors in this sample when it comes to the uses of Landsat imagery. For instance, the existence of the group of "local users" demonstrates that many respondents in state and local governments are dissimilar from respondents in other sectors. The results indicate that the different roles and goals of each sector guide the uses of Landsat imagery by respondents in those sectors.

Changes in Use of Landsat Over Time

There have been many events over the recent history of the Landsat mission that may have impacted people's use of the imagery. To track how these events may impact use, respondents 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.

Around 80% of respondents 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 (fig. 8). Of the users who stated their use increased or would increase, the majority (66-80%) chose both changes in work and cost as reasons. Respondents cited many other reasons as well, some under the control of data providers (i.e., availability, accessibility), but most outside of the control of data providers (i.e., fixed attributes of the sensor like spatial resolution, new applications/uses, more demand for imagery from clients, improvements in hardware, more training or more knowledgeable staff). Some respondents based their future increase in use entirely on the successful launch of LDCM and provision of new usable imagery. By sector, respondents in academia were more likely to cite more affordable imagery as a reason for increasing use in both the past[20] and the future[21], whereas those

[20] $^2 = 40.44$, $= 0.216$

[21] $^2 = 24.06$, $= 0.198$

in local government were less likely to cite more affordable imagery in both the past[22] and the future[23].

Given the recent implementation of the no cost data policy for Landsat imagery and the anticipated launch of LDCM, increases in the use of the imagery may also occur among respondents who used Landsat in the past but are not currently using it. Two-thirds of those who had used Landsat in the past said they foresee using it in the future (fig. 9). When asked what would make them more likely to use Landsat in the future, the most common reasons were changes in work and improved spatial resolution. Only 5% said that nothing would make them more likely to use Landsat.

Less than 13% of respondents said their use had decreased or would decrease (fig. 8). Of the respondents who said their use decreased over the past 10 years, most cited spatial resolution and changes in work most often as reasons. However, those who indicated their future use will decrease cited data quality, temporal resolution, and the attractiveness of other imagery more often. Almost all respondents who said they will decrease use in the future cite reasons outside of the control of USGS (96%), including other imagery being more attractive, attributes of the sensor, changes in work and new Landsat data not being available. Less than 20% cite reasons within the control of USGS, including availability, accessibility, and licensing/distribution restrictions. Interestingly, SLC-off on Landsat 7 appears to have had a minimal impact on respondents who said they had decreased use in the past 10 years – only 69 users cited it as a reason. In response, about two-thirds of these respondents replaced Landsat 7 imagery with Landsat 5 imagery (fig. 10). Over half replaced Landsat 7 imagery with other MRI, just under a third used gap-filled or SLC-off Landsat 7, and less than a fifth used some other kind of data as a replacement.

Discussion: Change in Use of Landsat Over Time

Regardless of whether respondents' use increased or decreased in the past or the future, the majority of reasons given are outside of the control of USGS, except for more affordable imagery which was cited only for increasing use. This indicates that most of the current Landsat users in this sample are satisfied with the provision of imagery by USGS, even if they may want to see changes to the imagery itself or to the sensors that capture the images. More affordable imagery was cited by the majority of respondents as a reason for increasing use, except among respondents in the local government sector. Given that local governments are often faced with restricted budgets, this is a surprising result. However, it is possible that they have not traditionally paid for any of the data they use, thus making cost a non-issue. There is also the possibility that they are not aware that Landsat is available at no cost now (there were several comments in the survey to that effect) and so do not know that Landsat has become more affordable. Among respondents who decreased use in the past 10 years, the SLC-off on Landsat 7 was not a major factor. Given that the majority of these users replaced Landsat 7 with Landsat 5, this indicates that the loss of Landsat 5 before the launch of LDCM may impact some users.

Impacts of No Cost Data Policy

The entire archive of Landsat imagery became available at no cost at the beginning of 2009. To determine the impacts of this policy change, we asked respondents about their imagery acquisitions before and after the policy change (calendar year 2008 and calendar year 2009, respectively). Respondents did not have to personally download the data, but did have to use it in

[22] $^2 = 12.35$, $= -0.119$
[23] $^2 = 13.08$, $= -0.146$

their projects. First we asked where respondents had acquired imagery in 2008 and 2009 and provided a list of possible sources. EROS was the most common source of the data in both years for over 45% of respondents, followed by the internet in general (over 20% of users) (fig. 11). A quarter of the respondents did not know where their imagery came from in both years, indicating that perhaps they were not personally acquiring the imagery. We were particularly interested in whether respondents who did not acquire imagery from EROS in 2008 had done so in 2009 in response to the change in policy. However, less than 10% of the respondents behaved in that manner and an almost equal amount acquired imagery from EROS in 2008 but not in 2009 (fig. 12).

Though there were few differences in *where* respondents acquired imagery in 2008 and 2009, there were significant changes in the number of scenes acquired, the percentage of those scenes acquired from EROS, and the dollar amount spent on scenes between the two years (table 3). A paired samples t-test was conducted on those three variables for which data from both 2008 and 2009 were available for any given respondent. Between 900 and 1,000 respondents had provided information for both years for each of the three variables. Statistically significant results were found for each variable. In 2009, the average number of scenes acquired increased by 45% and the percent of those scenes acquired from EROS increased by 6%. The average amount spent on Landsat in 2009 was a fifth of what was spent in 2008.

Discussion: Impacts of No Cost Data Policy

Even though there were few changes overall in where respondents acquired their Landsat imagery before and after the no cost policy went into effect, there were significant changes in how many scenes were acquired and how much was spent on those scenes in 2008 versus 2009. Interestingly, the effect sizes (eta-squared in this case) were small for each comparison (^{2} • 0.025). This means that, for instance, the number of scenes acquired in 2008 accounts for very little of the variation in the number of scenes acquired in 2009. In this case, the lack of connection between the variables over the two years indicates that other factors, including the availability of the imagery at no cost, had a substantial impact on the acquisitions of the respondents in 2009.

Value of Landsat Imagery

In economic terms, the value of information is equal to what individuals would pay for that information (Macauley, 2006). The value depends on the uncertainty of the situation in which the information will be used, the importance of the outcome of the situation, the cost of using the information, and the cost of an appropriate substitute. Macauley (2005, 2006) notes that there are several ways the economic value of information has been examined, including output or productivity measures, hedonic price studies, contingent valuation studies, and measurement of societal benefits. 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 sample of professional Landsat users. First, we explored the importance of Landsat imagery to respondents, as well as their satisfaction with the imagery. Second, we asked about the environmental and societal benefits, including impacts on decision-making, from projects that used Landsat. Third, we asked what respondents 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 respondents' willingness to pay for imagery equivalent to Landsat in the event that there is a gap in imagery provision.

Importance and Satisfaction

Exploring the importance of Landsat imagery to users is one way to approach value. More than 80% of the respondents said the imagery is somewhat or very important to their work (fig. 13). Once again, there are differences by sector. Respondents in academia are more likely to think the imagery is very important to their work[24] while those in the state[25] and local[26] government sectors are less likely to say Landsat is very important.

We also asked respondents to rate how important certain attributes of MRI are in determining which type of MRI to use and how satisfied they are with those same attributes as they occur in Landsat. This is a common approach in marketing research to assess how well a product is meeting the needs of customers (Martilla & 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. 14). 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 are for availability, accessibility and cost, which indicate that users are satisfied with how the imagery is being provided. There were no significant differences in these ratings by sector, application area, or any other variables, except for global coverage. Global coverage is different from the rest of the attributes because it was rated as having only average or neutral importance. We believe this is driven by the large portion of the sample that is doing work only in the U.S. and do not need international coverage. This is supported by the fact that global coverage is more important for people working internationally: only 23% of people working in just the U.S. think it is important, whereas 63% of people working internationally think it is important[27].

Benefits of Landsat

When discussed in most venues, the benefits of Landsat are typically assumed or only anecdotally documented. In an effort to gather more systematic information about the benefits of Landsat, we asked a series of open-ended questions where respondents could write in their responses. Open-ended questions were chosen because no comprehensive list of benefits has been developed and we wanted to give respondents the opportunity to provide their own ideas about benefits. The responses were examined for repeating themes and then categorized into those themes. When asked how projects using Landsat had affected decisionmaking, the most common responses were through more informed decisionmaking, impacts on policies or regulations, and better planning and management. One respondent noted, "We have been able to come up with evidence to change small town policy and challenge politics. Good science is hard to beat."

A second question inquired about the environmental and/or societal benefits that have come about as a result of projects which used Landsat. Assessing impacts and change over time, habitat/land conservation, improving the environment/reducing impacts, increasing human safety/reducing risk to humans, and better decision-making were among the most frequently cited

[24] ^{2} = 55.71, Cramer's v = 0.207
[25] ^{2} = 27.06, Cramer's v = 0.144
[26] ^{2} = 42.35, Cramer's v = 0.181
[27] ^{2} = 276.58, Cramer's v = 0.427

benefits. One respondent said "Perhaps Landsat['s] greatest utility is the long time frame that can be accessed." Another stated, "The greatest benefit I have perceived is that providing stakeholders with spatial data gives them a sense of empowerment to make decisions. The unexpected benefit is that map data act[s] to build consensus among groups with competing interests. Seeing actual data tends to dissolve apparent symbolic differences and helps different groups work together on issues of environmental management."

If Landsat Was No Longer Available…

One of the ways to examine the value of a good is to explore the impacts that would occur if it ceased to exist. We asked users what would happen to their work if both new and archived Landsat was no longer available. We assumed users could:

- discontinue some or all of their work;
- continue their work without substituting other imagery or information; or
- use other imagery or information as a substitute in their work.

Around half of the users would discontinue at least some of their work and would continue at least some of their work without substituting other imagery or information (table 4). Just over 75% of the users would substitute either other imagery, other data sets, or field work for at least some of their work.

Of those who would discontinue some of their work (n = 693), 45% would discontinue a small percentage of their work (30% or less), 32% would discontinue a medium percentage (31-70%), and 23% would discontinue a high percentage (71% or more). In fact, 11% would discontinue over 90% of their work if Landsat was no longer available, which indicates a strong dependence on the imagery. There were some differences by sector on this variable. Academic users were more likely to discontinue a medium to high percentage of their work[28] than users in other sectors.

Of those who would substitute, almost 90% would use other imagery as a substitute, about two-thirds would use other data sets and slightly fewer would use fieldwork (table 5). Given that fieldwork tends to be more expensive and time consuming than using imagery or other data, this seems to indicate that fieldwork might be the only viable substitute to provide certain types of data. This may be because other similar appropriate imagery does not exist or is not affordable. If users indicated they *would* use substitute imagery, they were asked what imagery they would prefer regardless of budget constraints. Then they were asked what imagery they would most likely acquire given budget constraints. More than half would choose the same imagery regardless of budget constraints – the most common choice was Terra (ASTER), followed by SPOT, and Resourcesat (fig. 15). However, 40% would choose different imagery. SPOT was the preferred imagery for over half of these users, but Terra was the imagery that over half of them would be most likely to acquire (fig. 16).

Another way to explore value is to examine what would happen to costs and revenues/funding 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 is 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 in this sample would be able to respond to these questions and therefore, we only asked for information regarding the projects in

[28] ^{2} = 49.98, Cramer's v = 0.216

which the respondents were involved. Respondents also had the option to indicate they did not know.

When asked to estimate the percentage increase in costs for their Landsat-related projects, almost half of the respondents felt their costs would increase by at least 1%, 41% didn't know if their costs would increase, and 11% felt their costs would not increase. Of those who believed their costs would increase (n = 668), the average total percent increase in costs was 30%, which translated to about $27,000 on average among those who were able to provide the current costs of all their projects which rely on Landsat imagery (n = 519). When asked about certain types of cost increases, over half of the respondents said it is somewhat or very likely that total, processing, and administration/overhead costs would increase and that more time would be spent on projects. However, most believed it is unlikely that they would purchase additional equipment/software or hire more staff.

Regarding changes in revenues/funding, 43% of users did not know what impact the loss of Landsat would have. A third felt there would be no impact and a fifth thought their revenues/funding would increase.

Willingness to Pay for Landsat Imagery

Economic benefits, whether of a market or non-market good, are measured by the maximum amount the users would pay for another unit of it. For market goods, price measures the willingness to pay (WTP) for one more unit (e.g., a pound of apples, a gallon of gas). Estimating the user benefits for non-market and publicly provided goods can be challenging since there is either no price (Landsat imagery is currently available at no cost) or only an administrative price (as was the case when Landsat imagery was provided for a fee). The administrative price often does not reflect market forces or an equilibrium price and quantity, and sometimes will substantially under or overstate what a user would pay. A single administrative price will only reveal a single point on the user's demand for the good. Using WTP for both market and non-market goods ensures commensurability between dollar benefit estimates of these two types of goods.

WTP is the standard measure of benefits in benefit cost analysis (Sassone and Shaefer, 1978) and economists use a variety of techniques to estimate the WTP for non-market goods. Champ and others (2003) provide an accessible review of each of the commonly used methods. When there is no price, or there is little data available on what users will pay, a stated preference or intended behavior technique known as the Contingent Valuation Method (CVM) is commonly used. This method uses a simulated or hypothetical market to determine the maximum amount a user would pay for another unit of the good rather than use a more expensive substitute or do completely without. The method is recommended for use by federal agencies performing benefit cost analysis (Office of Management and Budget, 1992; U.S. Environmental Protection Agency, 2000; U.S. Water Resources Council, 1983). As suggested by the National Oceanic and Atmospheric Administration panel on contingent valuation (Arrow and others, 1993), we asked a dichotomous choice format question. In this case, the user must only decide whether the Landsat scene is worth more than the cost specified in the question. The specific question asked was:

> "If Landsat 5 and 7 became inoperable before the next Landsat satellite is operational (scheduled to launch in 2012), you may have to obtain imagery elsewhere during the interim. 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 now available, would you pay $XXX for one scene covering the area equivalent to a Landsat scene?"

The “$XXX” was filled in with one of 21 different dollar amounts. The dollar amounts ranged from a low of $5 to a high of $5000. To measure an individual’s maximum WTP based on Yes/No responses to a single dollar amount the goal was to have a dollar amount low enough that nearly all Landsat users would answer Yes, and a dollar amount high enough that nearly all Landsat users would answer No. The remaining dollar amounts were $10, 20, 30, 40, 50, 60, 70, 80, 100, 150, 200, 250, 300, 400, 500, 700, 1200, 1500, and 2500. The response to this question provides the data necessary to calculate a single-bounded WTP. The response to this question also allows the estimation and development of a demand function for the nonmarket good – as opposed to the single point on the demand function from administrative pricing. This WTP question and approach includes an explicit budget constraint and a reminder that the funds to pay the higher cost would have to come out of this fixed budget. This follows the recommendation of the NOAA panel (Arrow and others, 1993) that budget reminders are to be included in WTP questions. Recognition of budget constraints is important to be consistent with consumer behavior and demand theory.

The precision of the estimate of WTP can be increased by asking respondents a second dichotomous choice question, thus collecting the data necessary for a double-bounded estimate of WTP. With the first WTP response, we know that the respondent’s WTP is higher or lower than the dollar amount asked to pay. If those who answer Yes to the first question are asked if they would pay a higher amount, we can obtain additional information about their WTP: (a) if they state “Yes” to the second, higher dollar amount, we know their WTP is higher than the first bid amount and in fact is even higher than the increased bid amount (the second dollar amount is twice the first in this case); (b) if they state they would not pay this second higher dollar amount we know their WTP is bounded between the first and second dollar amount, thus bracketing their maximum WTP between the first and second dollar amount. The same pattern holds for those answering “No” to the first dollar amount. If a respondent answers “Yes” to the second dollar amount (half the first dollar amount in this case), we can potentially bracket their WTP between the first and second dollar amount. This second question can substantially improve the efficiency of estimating the WTP but risks offending the respondent with a moving price target.

Finally, after the first and second WTP questions, respondents were asked how certain they are that they would (or would not) pay that price on a scale of 0% to 100%. This provides further information about the actual WTP of each respondent and allows for examination of the quality of each respondent’s answers. For example, if a respondent says “Yes” to the first WTP amount and “Yes” to the second higher amount, economic logic suggests they should be less certain (or the same) about paying the higher amount.

Single-Bounded WTP Analysis

The demand curve derived from the responses to the initial question is shown in figure 17. This demand curve can be used to determine the median and mean WTP for this sample of users. The median is the amount where a typical user crosses over between purchasing and not purchasing – in this case, it is approximately $218 per scene. It is not the value of the scene to the user but the value where a majority (>50%) of the sampled users would purchase a scene equivalent to a Landsat scene. The mean value of a scene involves integrating the area under the demand curve, which is a cumulative distribution function in this case. For the curve shown in figure 17, the average is unbounded. The value of Landsat to some users is substantial and this pulls the average well above the median. The standard practice when faced with an unbounded average is to choose one of the high bids in the sample to use for the upper bound in the integration. We chose the second highest bid ($2,500) and calculated a mean WTP of $760 per scene. Choosing the highest bid would increase the mean and choosing the third highest bid would decrease it. A practical implication of the unbounded mean WTP is that we need to increase the number of bid amounts at the middle to higher end of the range and decrease the number of bids at the lower end in future questions. More information about respondent's WTP at these high bids would allow better estimation of the complete demand function.

When WTP is broken out among sectors, significant differences can be seen between the means of the groups (fig. 18). Federal government users are willing to pay the most at over $1,000, followed by academic users at over $800, and private users at around $700. Again, because the sample is not random, neither the median nor the mean WTP for this sample or any of the groups within the sample should be generalized to the population as a whole or any segments of the population.

Double-Bounded WTP Analysis

In concept, the double-bounded analysis is intuitively appealing as statistical theory and past studies have shown that asking the second WTP question does reduce the variance of WTP estimates and gives more precision. However, we found that the respondents' behavioral response to the second bid amount is somewhat different than the response to the first bid amount. For example, one respondent said "No" to $150 with a certainty of 40%, but then said "No" to $75 with a certainty of 60%. In practice, it appears that respondents do not like the follow-up question with the different bid amount. The information gathered from the second question is not as good as the information from the first question. For both the first and second questions, the probability of saying "Yes" goes down as the bid amount increases, but at somewhat different rates in response to each question. There are several reasons this may be the case, including strategic behavior on the part of respondents, uncooperative behavior, or changed preferences. At this time, we hypothesize that the behavioral shift between first and second responses may be due to the large magnitude of the increase between the first and second bids. Especially at high first dollar amounts ($1500, $2500, and $5000), the very large absolute magnitude of the increase in the second dollar amount ($3000, $5000 and $10,000) may have reduced the credibility of the second WTP question to the respondent. It is possible that the response to this second question was more of a signal about the question itself rather than a second "snapshot" of their WTP.

As shown in figure 19, the demand curve of the double-bounded analysis does behave as expected when compared to the curve of the single-bounded analysis. The double-bounded curve shifts to the left and has much tighter confidence intervals than the single-bounded curve.

There are no significant differences found between sectors in the double-bounded analysis. The reasonable differences in WTP across groups of respondents disappear with the information from the second question. The standard errors on the sector variables were larger than the parameter estimates so the variables can reasonably be removed from the double-bounded model.

Discussion: Single-Bounded Vs. Double-Bounded WTP Analyses

The double-bounded analysis improves efficiency but the second question does not have as much value as the first question due to the behavioral shift between questions. This behavior was not expected among Landsat users, since they have experience with the imagery and know the good being valued quite well in most cases. Given the results, we chose to report the standard single-bounded dichotomous choice CVM results because they are the best in terms of the statistical significance of independent variables, goodness of fit (the percent of correct predictions is about 70%), and the method is a well-accepted industry standard.

Several things might be tried for a future WTP for Landsat imagery question to reduce the behavioral difference between the first and second questions. The magnitude of the change between the first and second bid could be reduced from twice and half to 1.25 and 0.75. The number of initial high bid amounts could be increased since these higher amounts are essential to accurate and precise estimates of mean WTP which involves integration across the entire demand function. Other statistical modeling techniques such as ordered logit models which allow for one category for each of the four combinations of responses (Yes-Yes, Yes-No, No-Yes, and No-No) could also be tried.

Conclusion

The results of the survey revealed that respondents from multiple sectors use Landsat in many different ways, as demonstrated by breadth of project locations and scales, as well as application areas. The current level of use will likely continue and more likely to increase among these respondents, 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 spent after the imagery became available at no cost, also point toward increases in future use.

The value of Landsat imagery is high overall for these respondents, and those in certain sectors, such as academia, find it even more valuable than respondents in other sectors. In general, Landsat imagery is important to respondents for their work and they are very satisfied with the attributes provided by Landsat. They find it beneficial for improving decision making and preventing harm to the environment and humans, among many other benefits. These benefits will likely increase as the no cost policy change becomes widely known, LDCM is launched, and emerging issues facing the nation, such as climate change, become more pronounced and require increasing amounts of longitudinal, reliable data. The value of Landsat imagery to these respondents is also demonstrated by the amount of work that would be discontinued or require a substitute source of data. Finally, the value is demonstrated by respondents' willingness to pay for the good. On average, respondents are willing to pay $760 per scene, which is greater than the previous administratively set price.

Throughout the analyses, differences between sectors occurred on almost all variables. The identification of the "local users" group help to explain some of these differences, but respondents in the academic and federal government sectors also tend to differ from the rest of the respondents. They tend to be more technical users, use the imagery more heavily, and are willing to pay more for replacement imagery. These differences between sectors merit further exploration in future studies to see whether they exist within the other segments of the population as well.

The survey collected information from users who are both part of and apart from the known user community. The diversity of the sample delivered results that provide a baseline of knowledge about the users, uses, and value of Landsat imagery. While the results supply a wealth of information on their own, they can also be built upon through further research to generate a more complete picture of the population of Landsat users as a whole. Surveying other segments of the Landsat user population, such as those who procure imagery from EROS and international users, and conducting case studies on the value of Landsat imagery in specific applications would provide additional useful information.

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Figure 1. Types of imagery users.

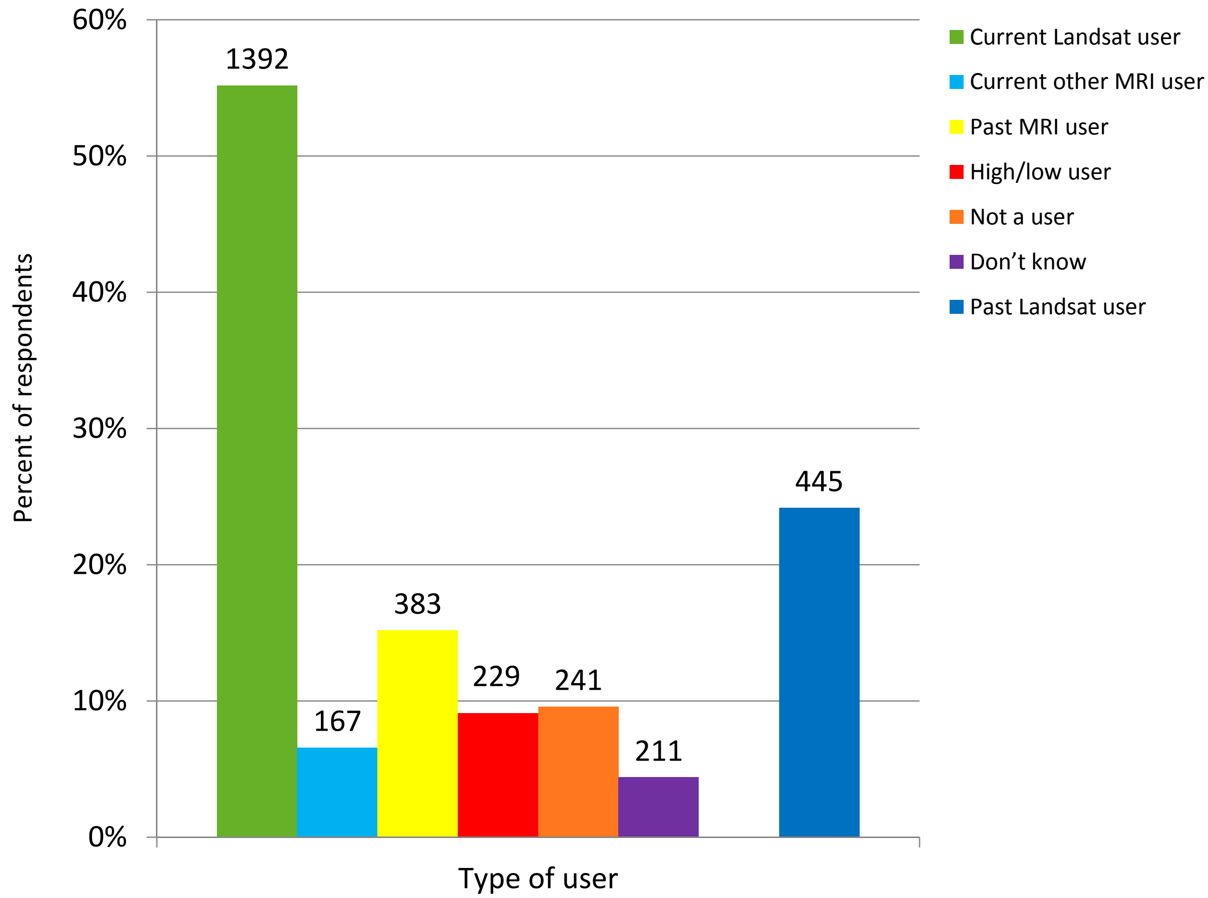

Figure 2. Sectors of respondents who are currently using Landsat.

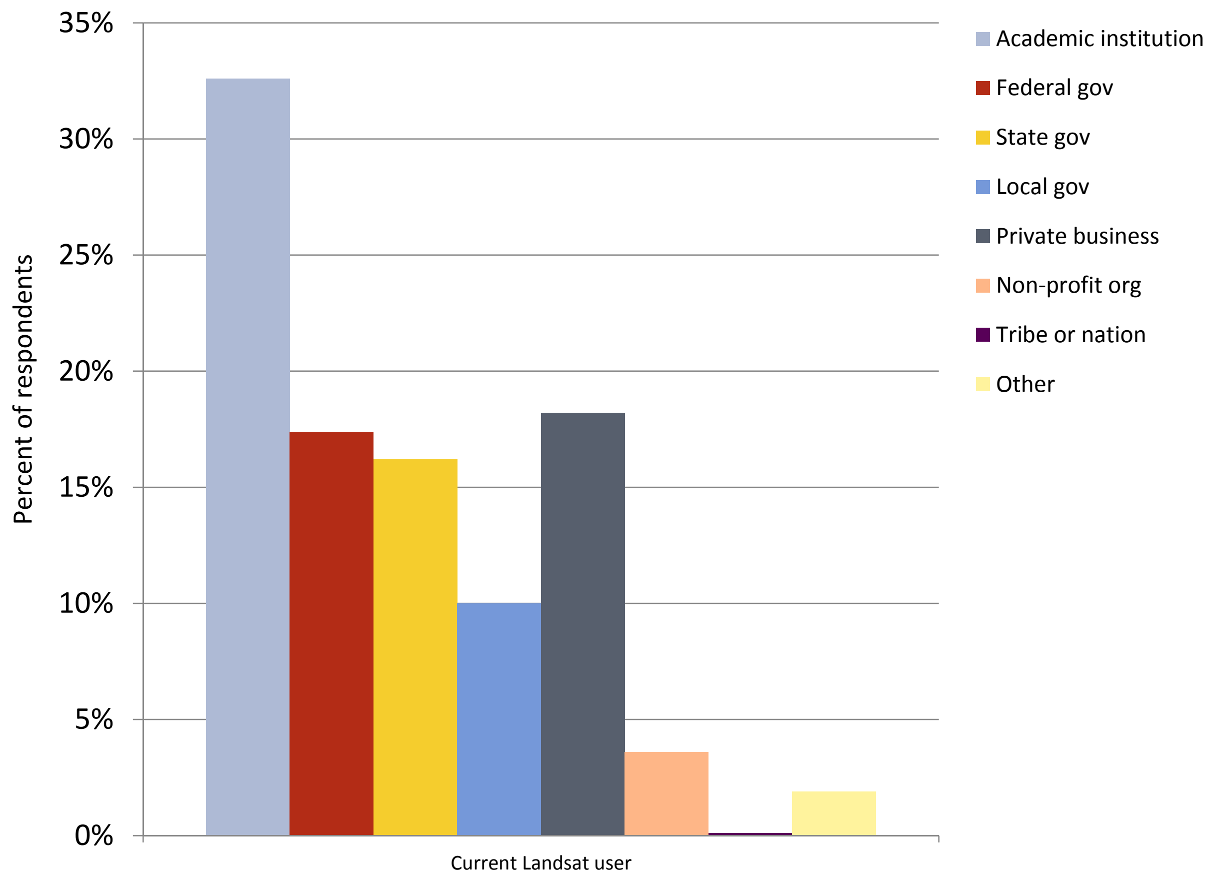

Figure 3. Locations of projects using Landsat imagery in year previous to survey.

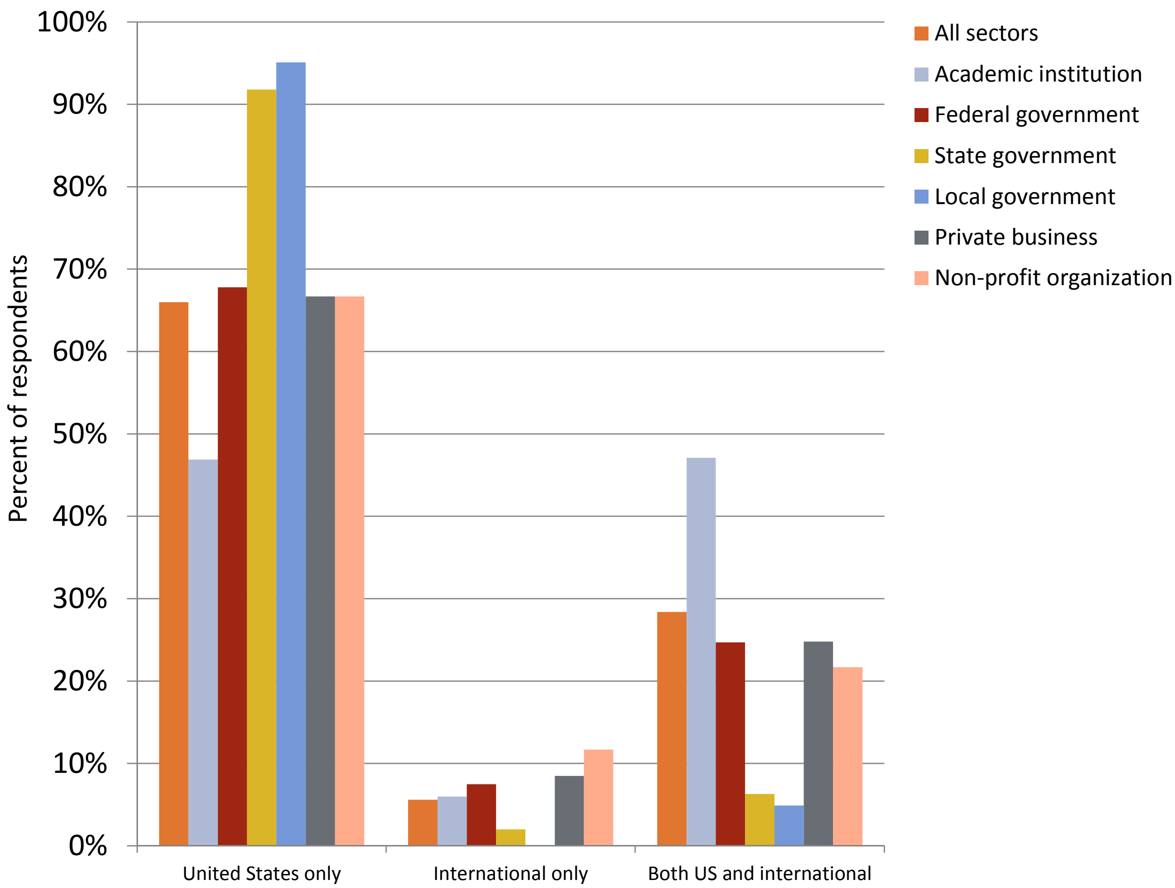

Figure 4. Scales of projects using Landsat imagery in year previous to survey.

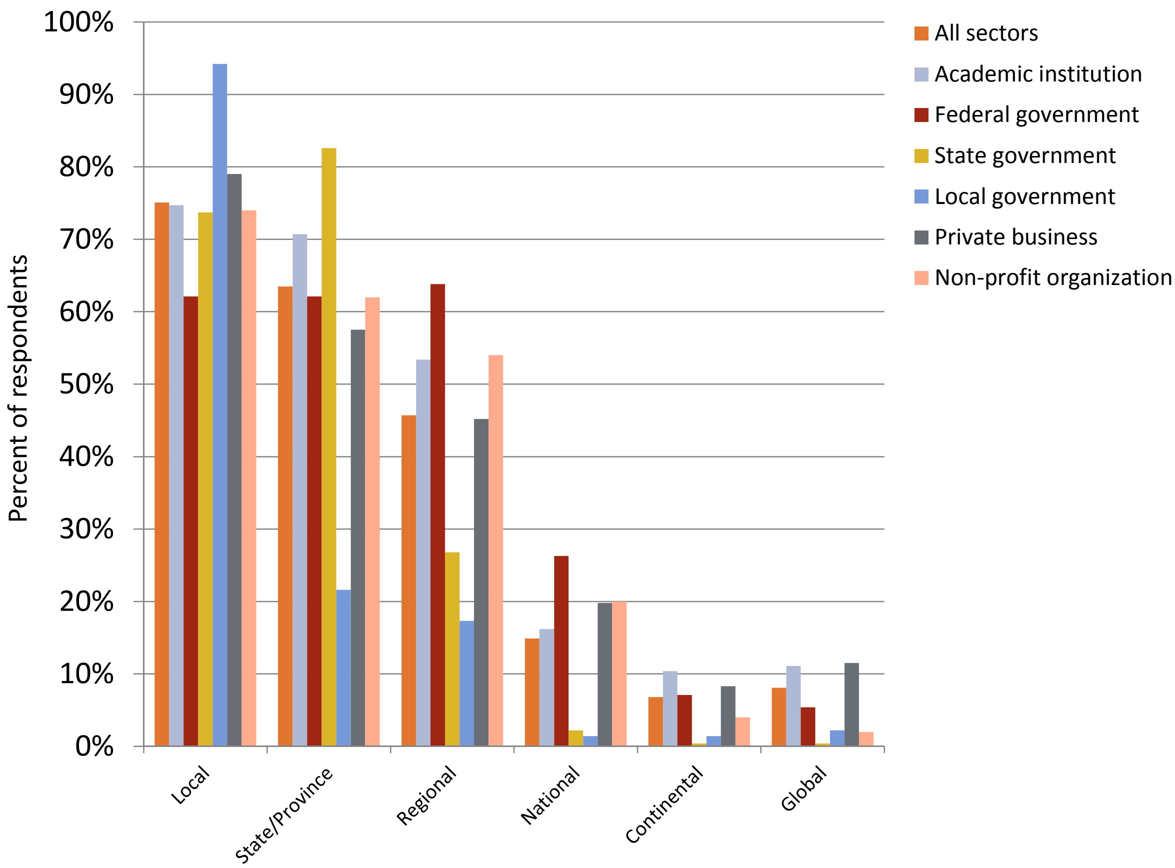

Figure 5. Applications of Landsat imagery in year previous to survey.

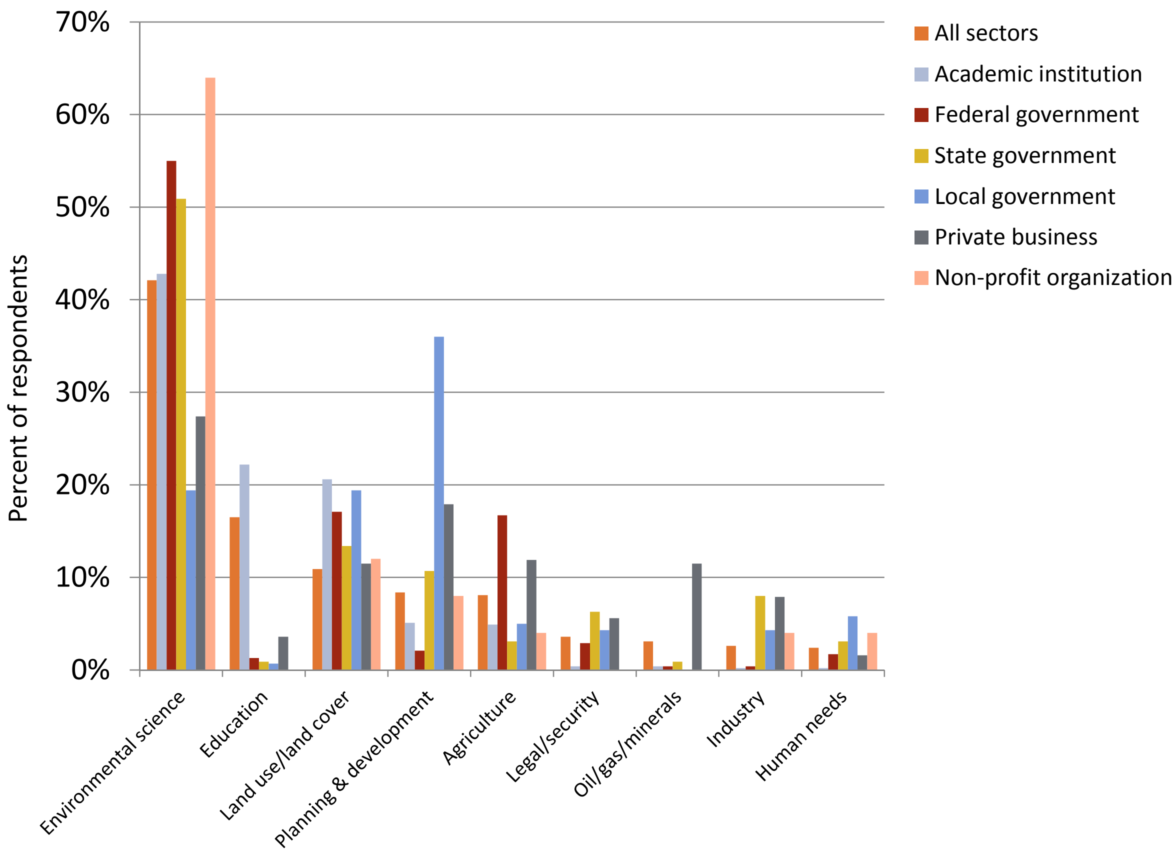

Figure 6. General use of moderate-resolution imagery among respondents who are currently using Landsat.

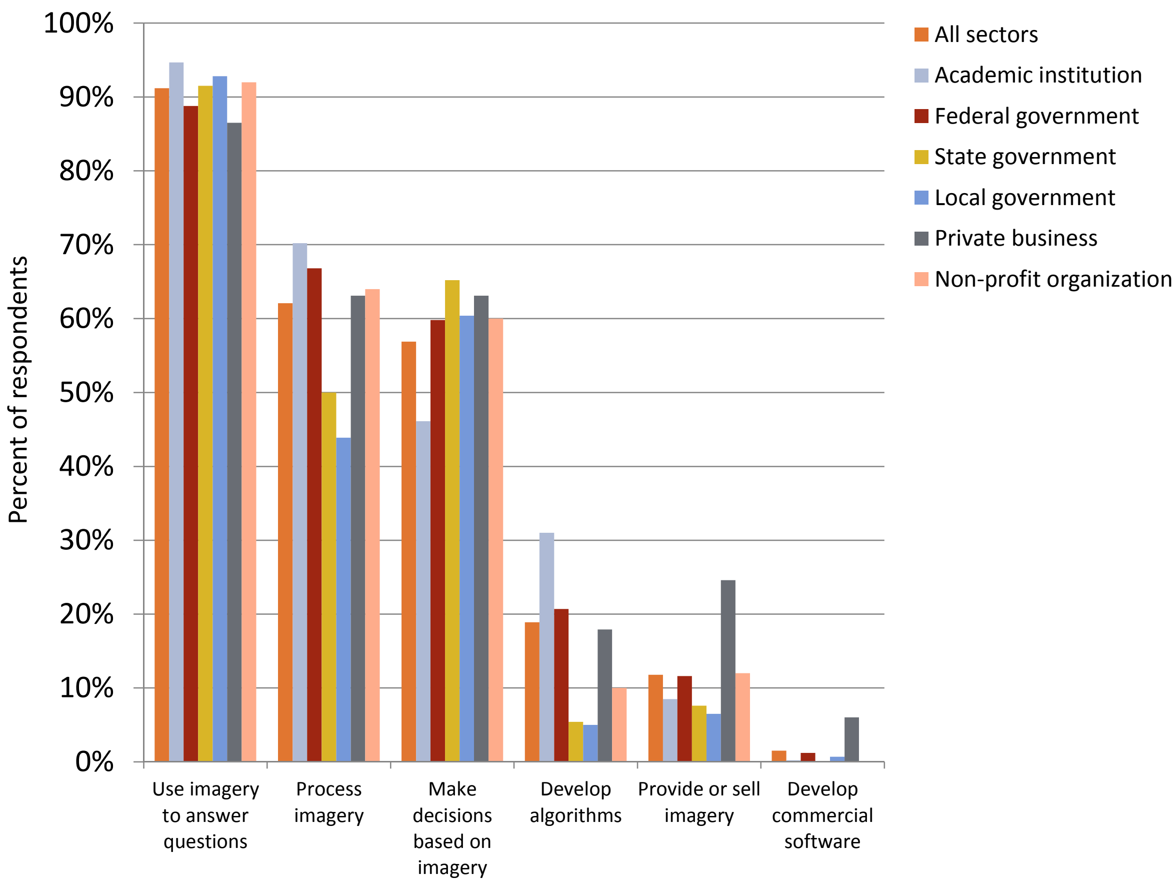

Figure 7. Level of use of Landsat imagery in work in year previous to survey.

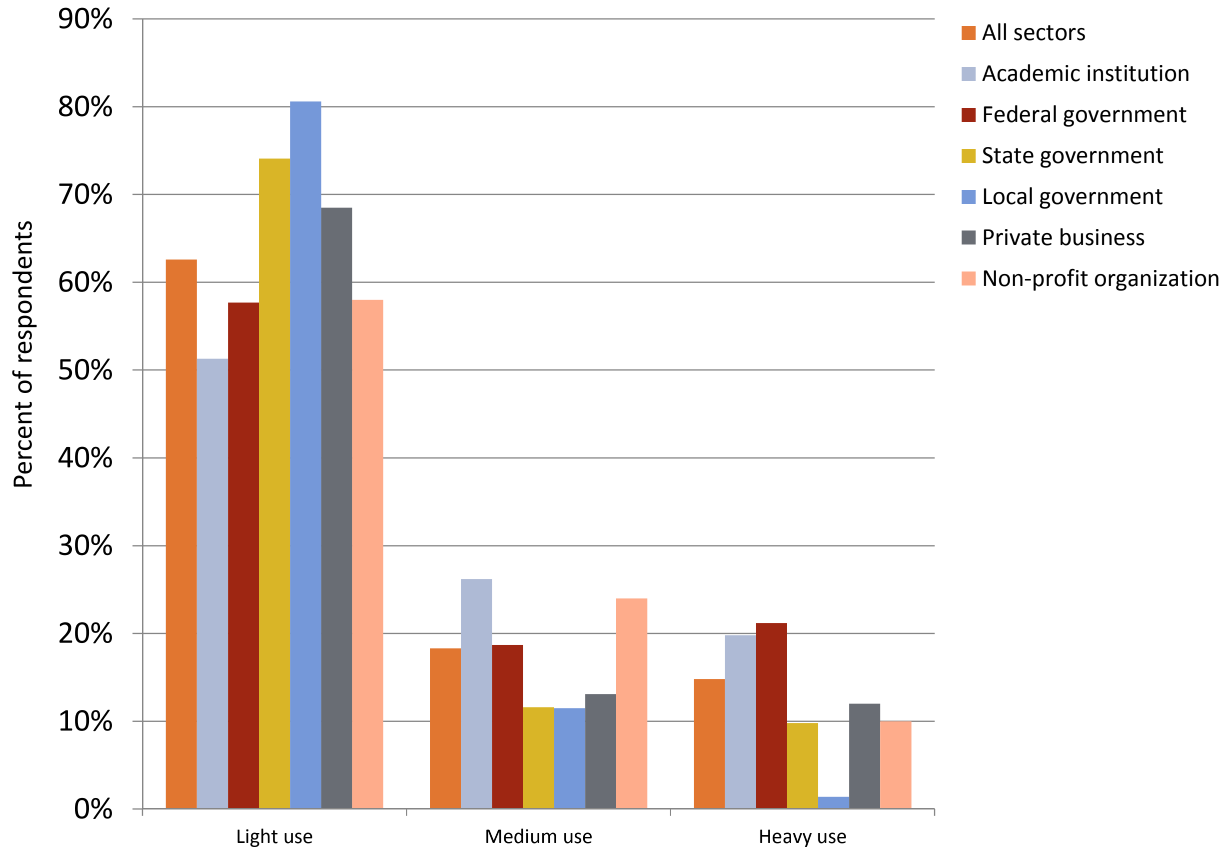

Figure 8. Change in use of Landsat imagery in past 10 years and next 5 years.

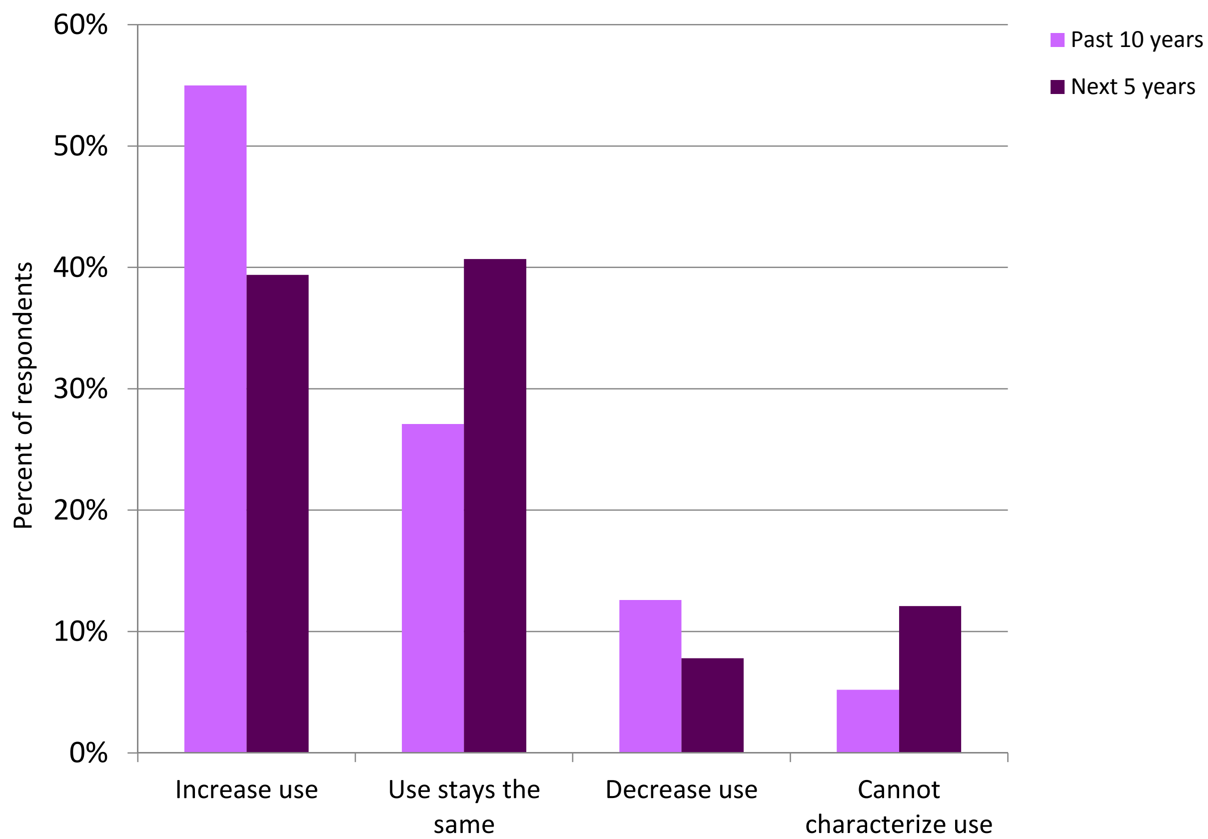

Figure 9. Potential use of Landsat imagery among past Landsat users.

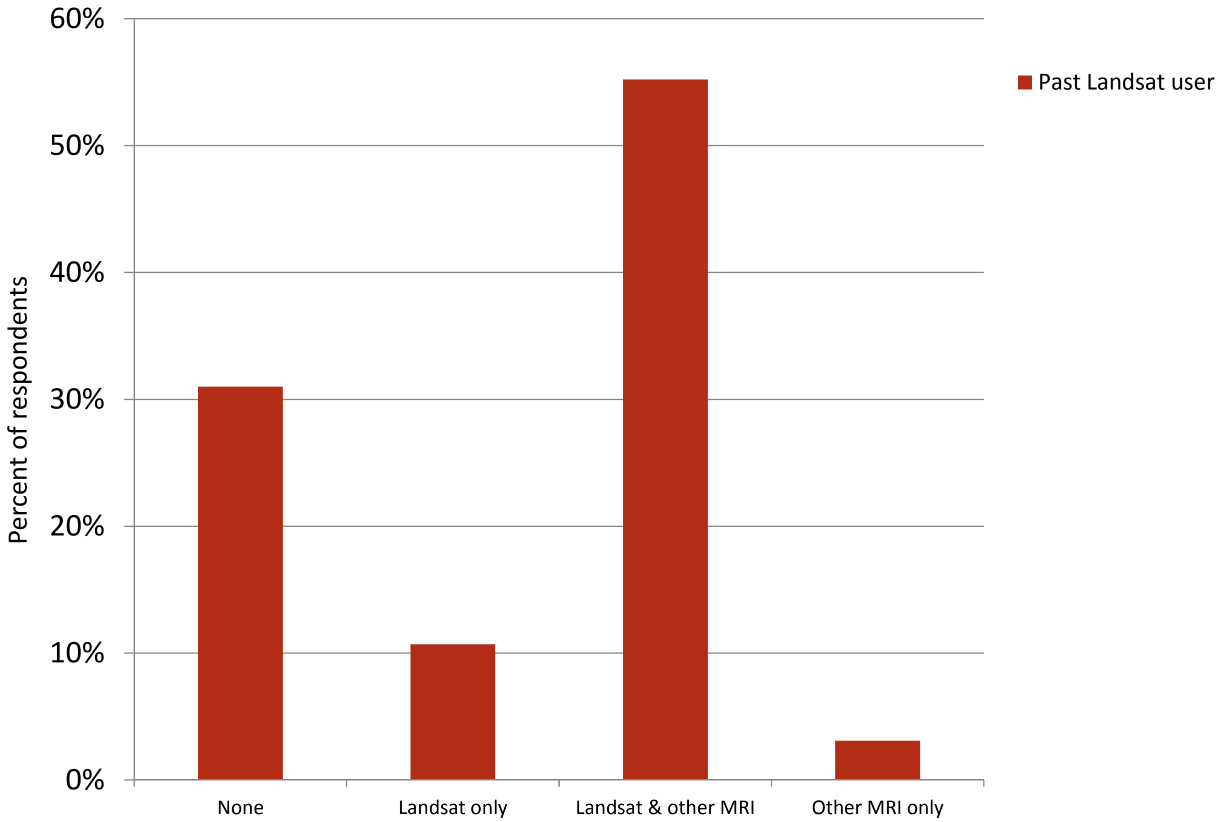

Figure 10. Reactions to SLC-off on Landsat 7.

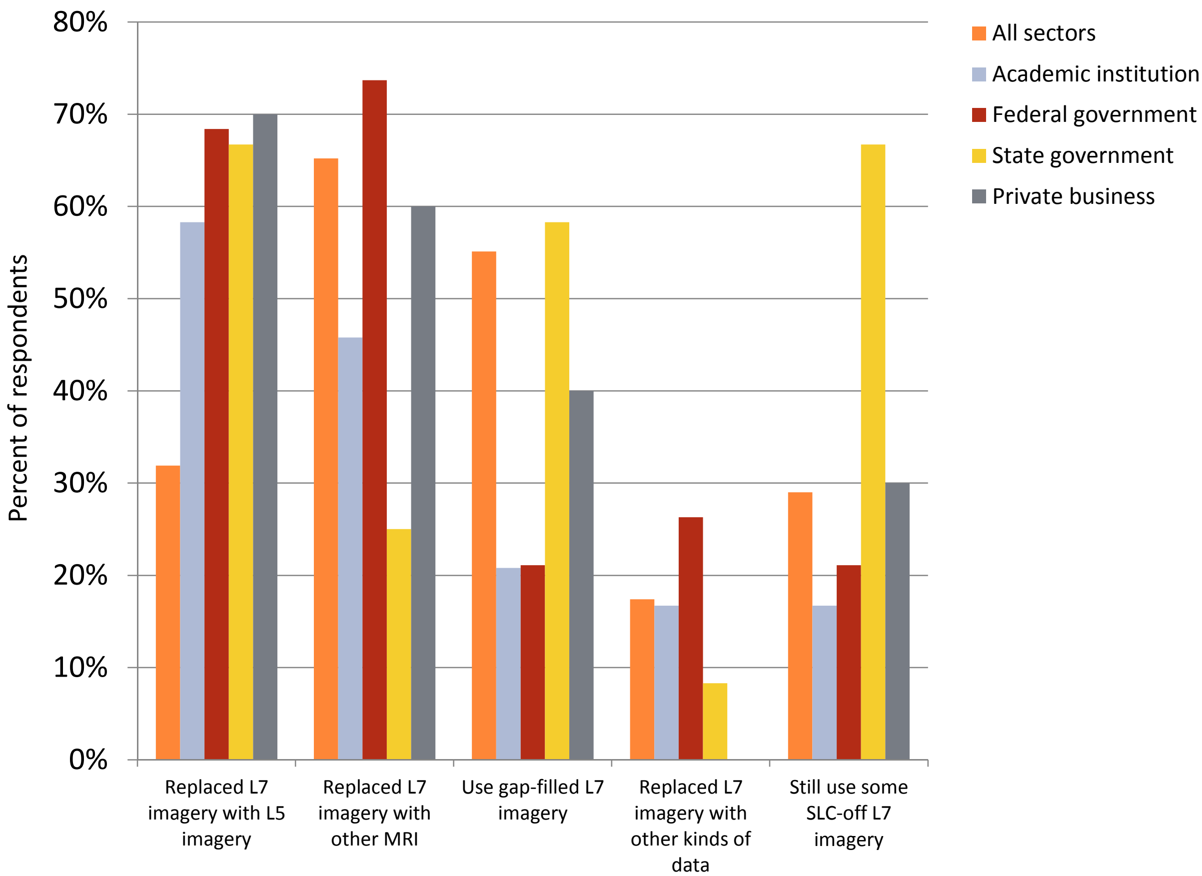

Figure 11. Sources of Landsat imagery acquisitions before and after the imagery became available at no cost (2008 versus 2009).

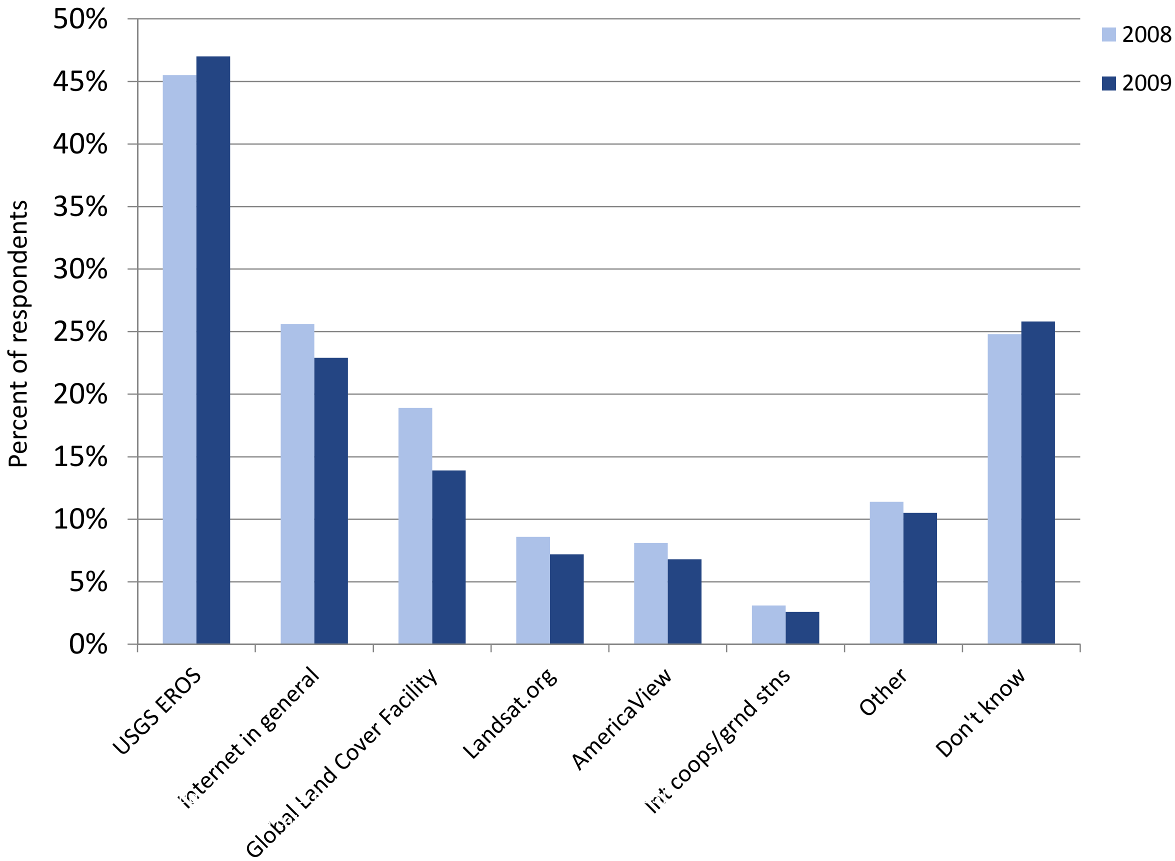

Figure 12. Patterns of acquisitions of Landsat imagery from EROS before and after it became available at no cost (2008 versus 2009).

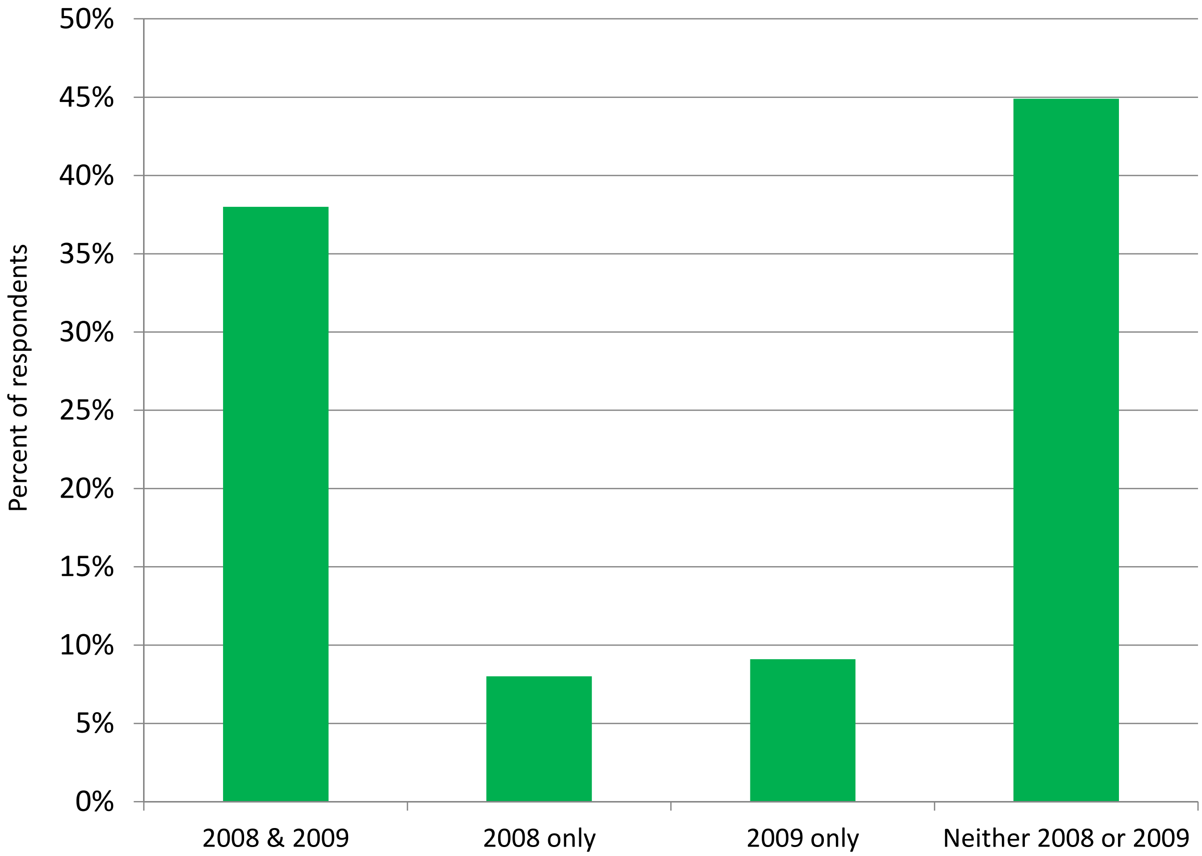

Figure 13. Importance of Landsat imagery to the work of respondents.

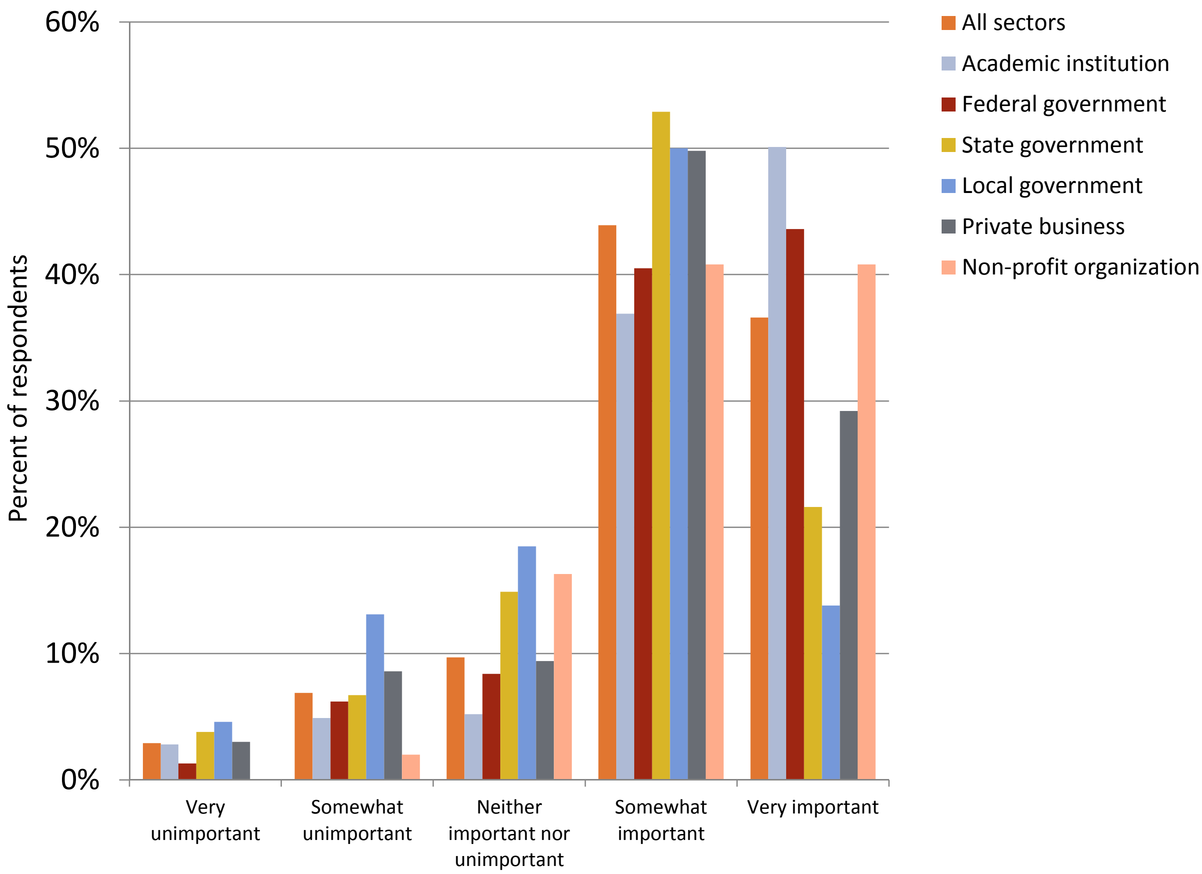

Figure 14. Importance of and satisfaction with certain attributes of Landsat.

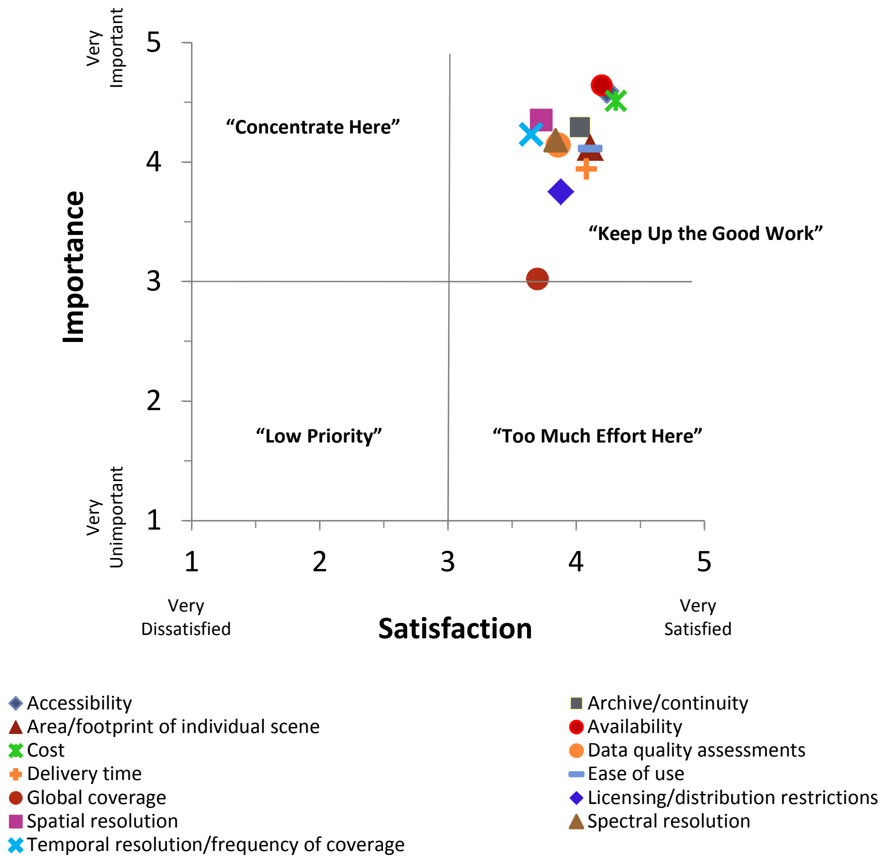

Figure 15. Preferred imagery versus imagery most likely to acquire within budget constraints among respondents who would substitute other imagery for Landsat if it was no longer available.

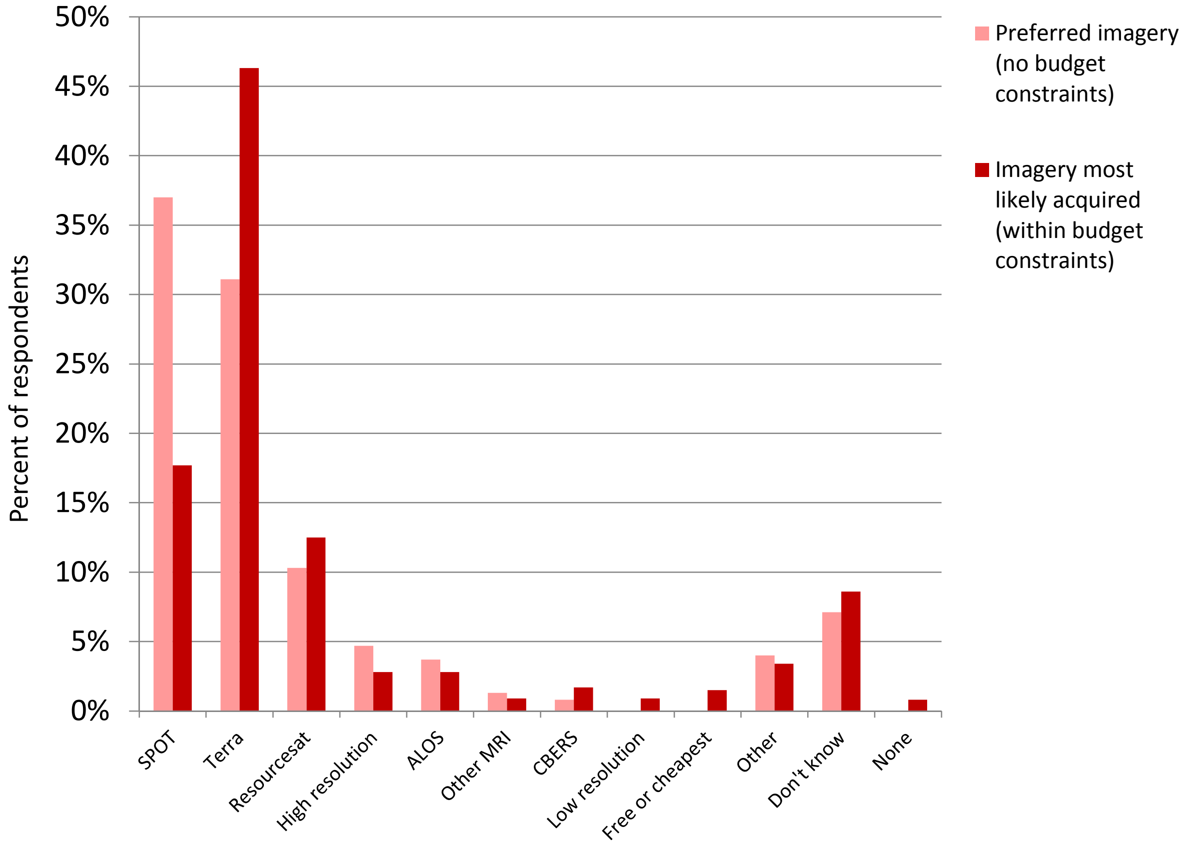

Figure 16. Preferred imagery versus imagery most likely to acquire within budget constraints among respondents who would choose a different imagery based on budget constraints.

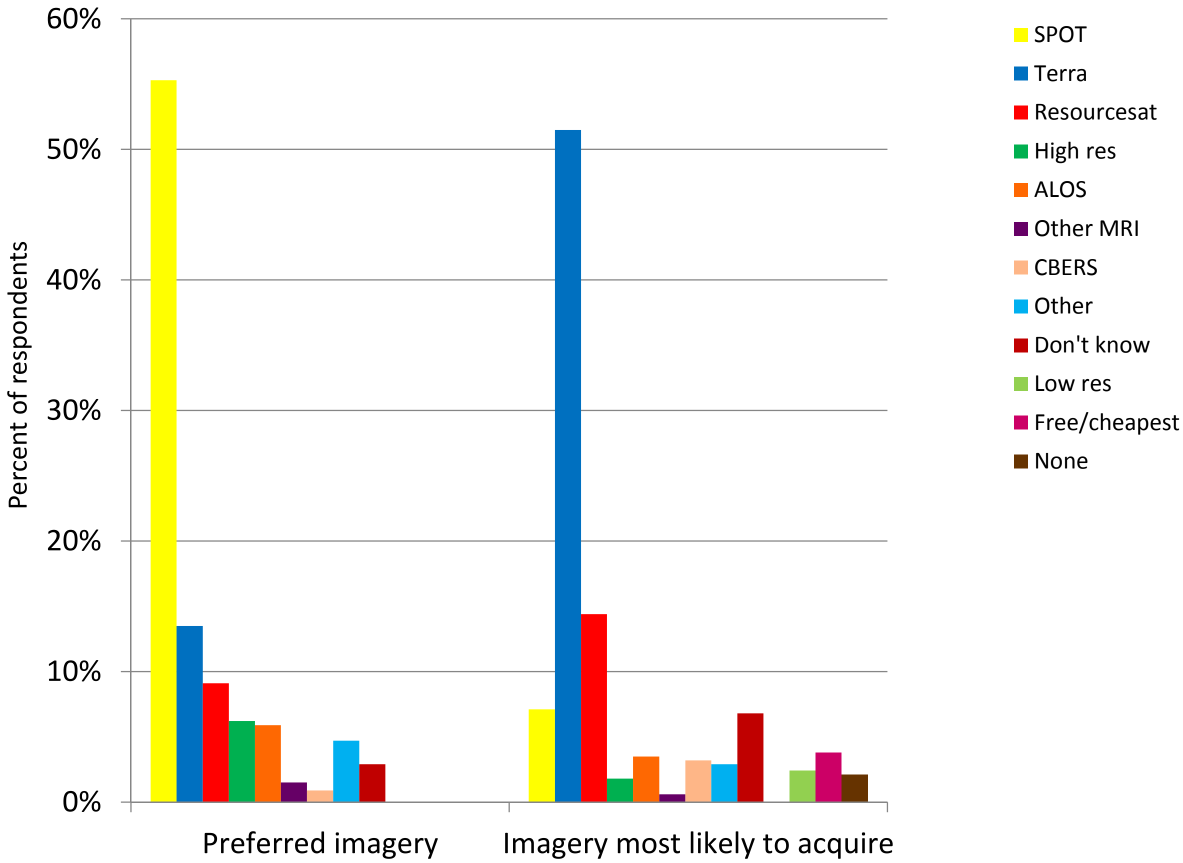

Figure 17. Single-bounded demand curve of willingness to pay for imagery to replace Landsat.

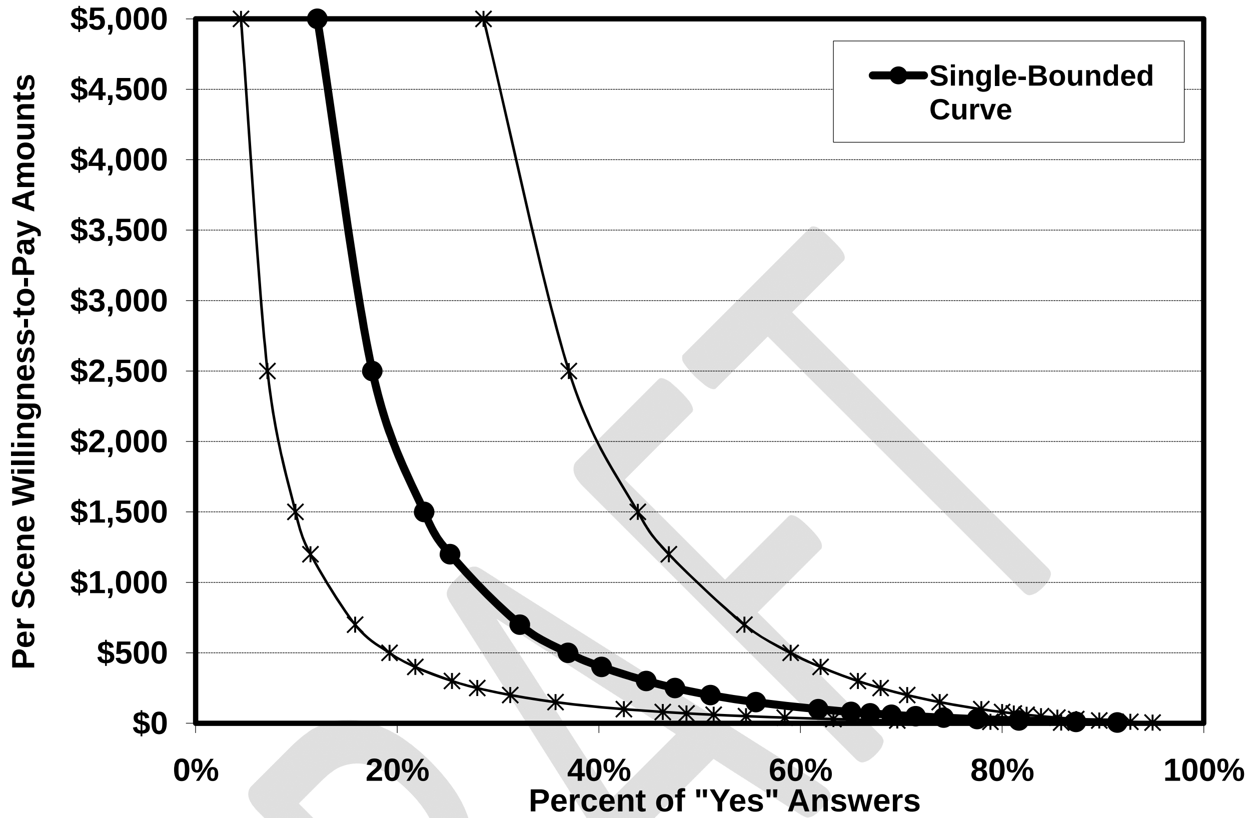

Figure 18. Single-bounded logit model results for willingness to pay for imagery to replace Landsat.

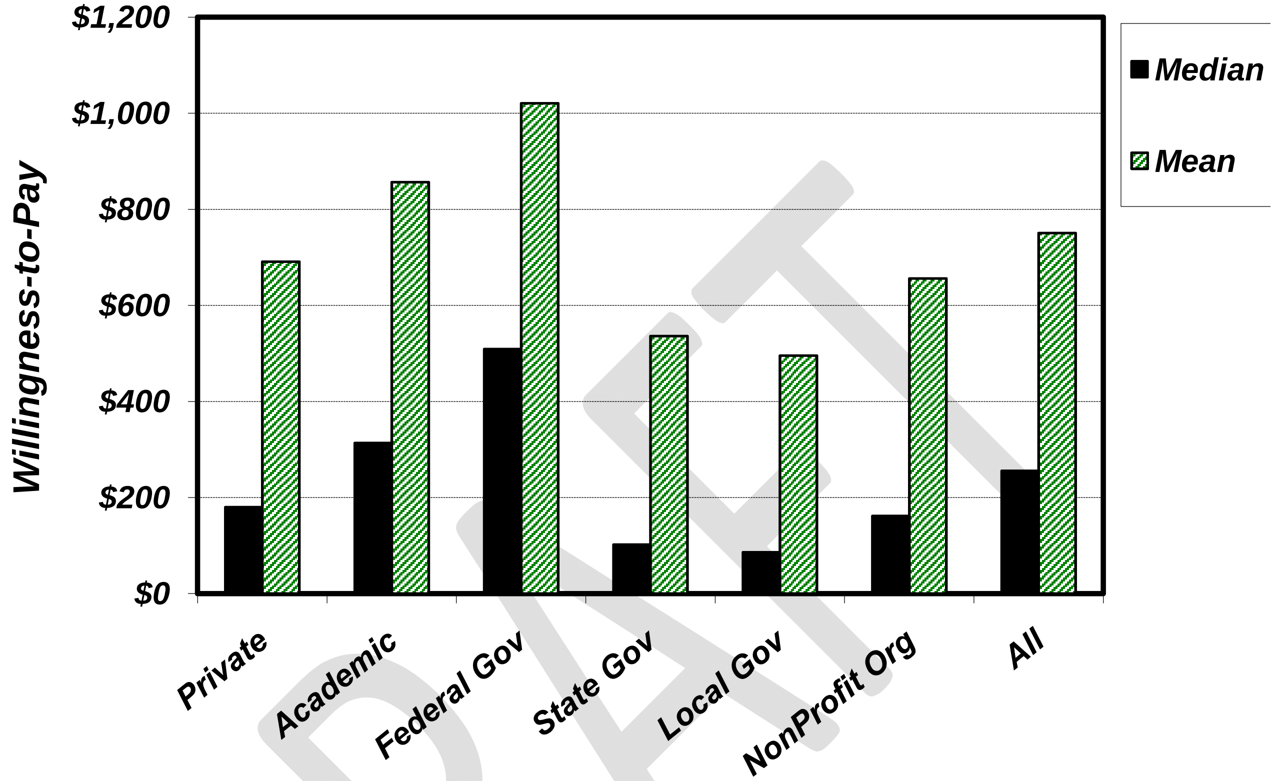

Figure 19. Single- and double-bounded demand curves of willingness to pay for imagery to replace Landsat.

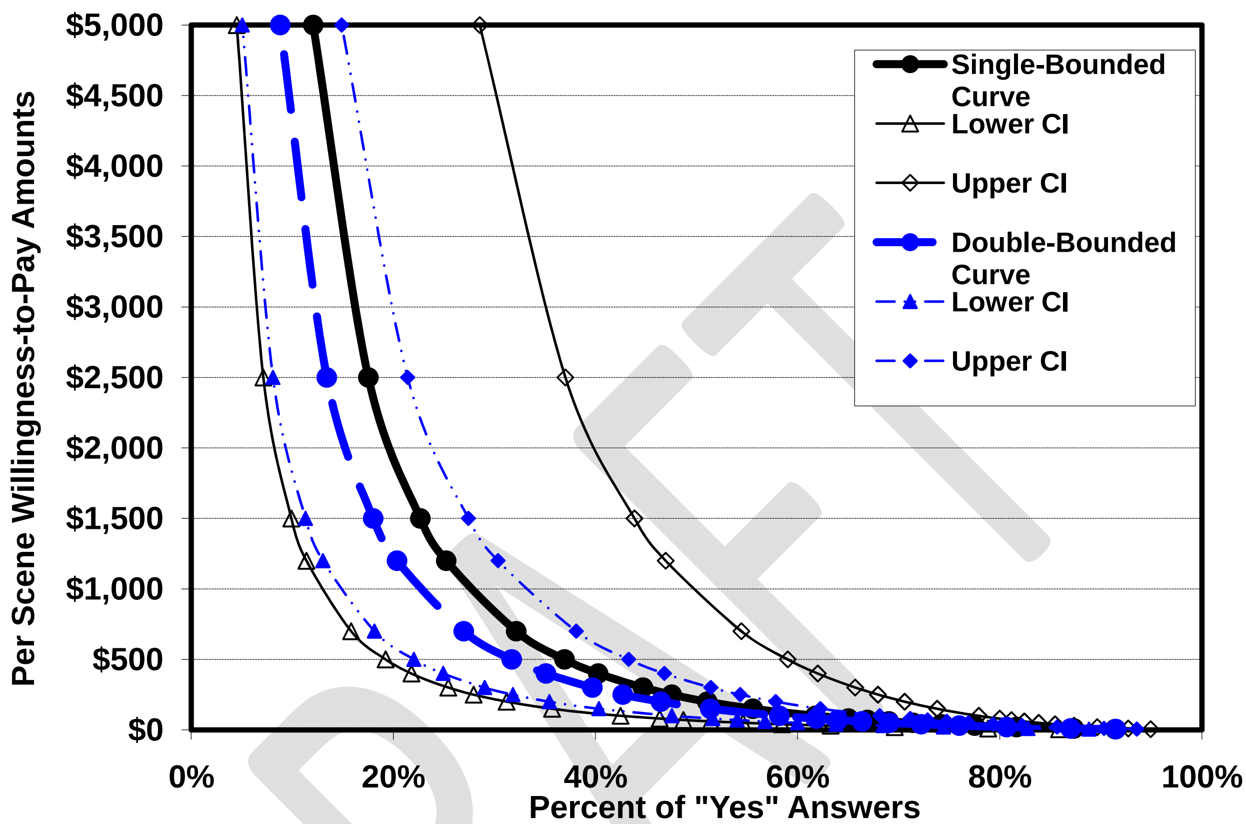

Table 1. Mean percent of different types of imagery used in the year previous to the survey among respondents who used a mix of moderate-resolution imagery.

Imagery	All sectors	Academic institution	Federal gov	State gov	Local gov	Private	Non-profit org
Landsat	54%	65%	57%	49%	31%	48%	57%
Terra	11%	15%	12%	7%	5%	10%	11%
SPOT	8%	7%	8%	9%	8%	7%	9%
Resourcesat	3%	2%	7%	2%	2%	3%	4%
ALOS	1%	<1%	1%	1%	<1%	2%	2%
CBERS	<1%	<1%	1%	<1%	<1%	1%	1%
Other	6%	5%	6%	5%	10%	8%	3%
Unknown	16%	5%	8%	26%	43%	21%	13%
Total	100%	100%	100%	100%	100%	100%	100%

Table 2. Applications of Landsat imagery.

Collapsed applications for analysis	Individual applications
Agriculture	Agricultural forecasting
	Agricultural management/production/conservation
Environmental sciences and management	Biodiversity conservation
	Climate science/change
	Coastal science/monitoring/management
	Ecological/ecosystem science/management
	Fish and wildlife science/management
	Fire science/management
	Forest science/management
	Geology/glaciology
	Range/grassland science/management
	Recreation science/management
	Water resources (e.g., watershed management, water rights, hydrology)
Land use/land cover	Land use/land cover
Planning and development	Assessments and taxation
	Engineering/construction/surveying
	Rural planning and development
	Urban planning and development
	Urbanization
Commercial	Cultural resource management (e.g., archaeology, anthropology)
	Real estate/property management
	Software development
	Telecommunications
	Transportation
	Utilities
Education	Education: K-12
	Education: university/college
	Technical training (e.g., workshops, short courses)
Human needs	Emergency/disaster management
	Hazard insurance (e.g., crop, flood, fire)
	Humanitarian aid
	Public health
Legal/security	Defense/national security
	Environmental regulation
	Law enforcement
Oil/gas/minerals	Oil and gas/mineral exploration/extraction

Table 3. Acquisitions of Landsat imagery before and after imagery became available at no costs (2008 versus 2009).

Acquisition variable	**2008 mean**	**2009 mean**	***t***	***p***
Number of scenes acquired	95	138	-3.95	<0.001
Percent of scenes acquired from EROS	41%	47%	-4.93	<0.001
Dollars spent on imagery	$5,117	$1,163	5.28	<0.001

Table 4. Percentages of respondents who would take each of three actions if Landsat imagery was no longer available.

Action taken if Landsat was no longer available	**Would take action**	**Would not take action**	**Don't know**
Substitute other imagery or information in work	76%	4%	20%
Discontinue work	51%	28%	21%
Continue work without substituting other imagery or information	46%	30%	24%

Table 5. Percentages of respondents who would use each of three types of information as substitutes for Landsat imagery if it was no longer available.

Type of substitute information	**Would use**	**Would not use**	**Don't know**
Other imagery	89%	1%	10%
Other data sets	69%	15%	16%
Fieldwork	63%	25%	12%