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Opening the archive: How free data has enabled the science and monitoring promise of Landsat

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ABSTRACT

Landsat occupies a unique position in the constellation of civilian earth observation satellites, with a long and rich scientific and applications heritage. With nearly 40 years of continuous observation – since launch of the first satellite in 1972 – the Landsat program has benefited from insightful technical specification, robust engineering, and the necessary infrastructure for data archive and dissemination. Chiefly, the spatial and spectral resolutions have proven of broad utility and have remained largely stable over the life of the program. The foresighted acquisition and maintenance of a global image archive has proven to be of unmatched value, providing a window into the past and fueling the monitoring and modeling of global land cover and ecological change. In this paper we discuss the evolution of the Landsat program as a global monitoring mission, highlighting in particular the recent change to an open (free) data policy. The new data policy is revolutionizing the use of Landsat data, spurring the creation of robust standard products and new science and applications approaches. Open data access also promotes increased international collaboration to meet the Earth observing needs of the 21st century.

1. Introduction

The Landsat series of satellite missions has collected imagery of the Earth's surface since 1972, providing an unparalleled record of the status and dynamics of Earth (Cohen & Goward, 2004). The Landsat archive provides a history of how the planet's land cover and land ecosystems have changed over the last 40 years in the face of increasing human population, resource demand, and climate change. In many cases Landsat provides our only detailed and consistent source of information on these changes (Wulder et al., 2008). The continued population of this archive serves current research and applications needs, has resulted in new application opportunities (Wulder et al., 2011), and will undoubtedly lead to unimagined future insights on the Earth system.

Based upon a change in data policy in 2008, all new and archived Landsat data held by the United States Geological Survey (USGS) have been made freely available over the internet to any user (Woodcock et al., 2008). The impact of this decision cannot be overstated, and has spurred a rapid increase in scientific investigations and applications using Landsat, and has set an example for data accessibility to be emulated by all space agencies. The new policy has dramatically increased the distribution of images by the USGS through the Earth Resources Observation and Science (EROS) Center. EROS provided approximately 25,000 Landsat images in 2001, the prior record for annual distribution, at a price of $600 per scene. By comparison, EROS distributed approximately 2.5 million images for free in 2010. As a result of the free data policy, combined with notable advancements in technical capacity to analyze large data sets for long-term and large-area investigations and applications (e.g., Kennedy et al., 2009; Masek et al., 2006; Roy et al., 2010; Wulder et al., 2008), Landsat data are experiencing more widespread use by an ever increasing range of end users in a variety of disciplines.

The ability to utilize a multitude of images acquired over a single region has shifted the perception of Landsat's value. While the radiometric and spectral properties of the Landsat instruments remain critical, exploiting the temporal domain has opened new avenues for understanding ecological and land cover dynamics (Kennedy et al., 2009). These advances have led to "MODIS-like" analysis approaches, relying on mass-processing, physically-based radiometric corrections, and fusion of Landsat with other satellite data and time series information. Mass processing requires consistent and predictable characteristics of data inputs, including the precise geometric characteristics and well calibrated cross-sensor radiometry (e.g., Markham & Helder, this issue-2012). The mass processing of Landsat data is increasingly undertaken

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with an aim to obtain the best available pixel from multiple images, rather than to focus on analysis of a single cloud-free image. Rule-based interrogation of imagery (including screening for clouds and shadows), followed by compositing and normalization procedures enables the creation of seamless imagery suitable for analysis (e.g., Hansen & Loveland, this issue-2012).

Currently there are two operational Landsat satellites in orbit, although both are functioning beyond their design life and have experienced technical problems. Further satellite or sensor anomalies could end the operational life of either satellite at any time (Wulder et al., 2011). Indeed, imaging from the Landsat-5 Thematic Mapper (TM) instrument was suspended in November 2011 due to degradation of the X-band transmitter, with operational and engineering solutions currently on-going leaving the status of the mission under decision prior to the 2012 growing season. The USGS has operational responsibilities for Landsat and the National Aeronautics and Space Administration (NASA) and the USGS are collectively developing the Landsat Data Continuity Mission (LDCM), with a January 2013 launch scheduled. Successive Landsat sensors have evolved to exploit advances in technology, while at the same time retaining the capacity for measurement continuity (Mika, 1997).

This paper presents an overview of the past, present, and future of the Landsat program, highlighting the impact of the recent change in data distribution policy for the program's 40-year data archive. Historic considerations are included to place the opening of the archive in an appropriate context, by illustrating the origin and impact of previous Landsat distribution models. An applications summary underscores the impact of the open archive on land science and applications. Fundamentally, Landsat occupies a unique spatial–temporal niche: the spatial resolution is fine enough to detect and monitor anthropogenic changes in land cover, while at the same time having an imaging footprint that is sufficiently large to enable wide-area applications. As human activities pervasively alter Earth's landscape, the ability to monitor these changes will only become more critical in the future.

2. Evolution of the Landsat program and objectives (1970–2008)

The origins of Landsat stretch back to the 1960s, when the USGS and NASA recognized the opportunity provided by space-based platforms for resource mapping (Mack, 1990). Early experiments aboard Apollo 9 as well as field and airborne multispectral campaigns underscored the value of multispectral imaging including coverage in the near-infrared (and later shortwave-infrared and thermal infrared) parts of the spectrum. The ability of Landsat to track vegetation dynamics was also recognized through experiments and wide-area programs in agricultural remote sensing (e.g., MacDonald et al., 1975), and the creation of multispectral vegetation indices that could provide rapid summaries of vegetation condition (see Goward & Williams, 1997). While much of the early Landsat literature focuses on basic geological and cartographic mapping, it is important to recognize that USGS Director William Pecora correctly foresaw a time when satellites would be used to routinely monitor both physical and biological conditions across the Earth to secure adequate supplies of food, fiber, water, and energy for growing populations (Pecora, 1967).

In many respects the Landsat program was ahead of its time, and arguably suffered for that achievement. Programmatically, it was difficult in the US Government to determine which agency should lead the program, how an operational mission could be sustained, or what the nature of the commercial market was for the data. As a result, authority for Landsat program management was passed successively from NASA to NOAA, from NOAA to the private sector (EOSAT and Space Imaging corporations), from the private sector to the US Air Force, and then back to NASA and USGS by 1999. Current plans call for at least one more transition, with the Landsat-9 mission being fully led by USGS (see OSTP, 2007). Further, as presented by Mack (1990), there were also impediments and concerns expressed by the Department of Defense about the civilian collection of possibly sensitive information. In Fig. 1 we present a summary of the Landsat program since 1965. Each satellite in the series is shown with launch (or projected launch) date, design life, and where applicable the end date (as either a launch failure or decommissioning). Besides a single launch failure (Landsat 6, in 1993) each active mission has exceeded design life. The situations for mission acquisitions and operations are also shown.

While the concept for the Landsat Program was global from the start, technical inexperience and analytical limitations meant that most early investigations were local or regional in nature. Based upon the computing capabilities present at the time, initial applications often relied on visual interpretations of imagery, with mining, geological, geomorphological, and forestry activities prominent (Beaubien, 1986). With each Landsat mission building upon a prescient core, the objectives become more detailed, with a flow from experimental to operational intentions and interests (Table 1). Consistent across all Landsat missions has been the interest (and ability) to gather all data at a central analysis facility to enable modeling of Earth system processes. Inherent to this intention is the establishment and continuation of infrastructure for capture (receiving stations), distribution to a central facility, and appropriate computing infrastructure. A key element of the program was the establishment of International Cooperators (ICs), a network of ground receiving stations that could directly downlink Landsat data and support regional applications. Including both regular and campaign stations, there are approximately 18 possible stations for receiving Landsat-5 data, with an additional 4 receiving Landsat-7 data.[1] Significantly, the IC's currently hold 3–4 million unique Landsat images not available from the US archive. The prospects for consolidating these data into the US archive are discussed below.

The 1984 transition to commercial operations through EOSAT was particularly disruptive to the global monitoring capability of the mission (Mack, 1990; Goward et al., 2001). Commercial operations resulted in a dramatic increase in the cost of data products (up to $4400 per scene) that was only partly remedied with the launch of Landsat-7 in 1999 when USGS assumed operations and the cost per scene dropped to $600. During the EOSAT era there was a slowing of the use of Landsat data related to costs, less data available due to an altered acquisition plan, restrictive copyright rules, and less attention paid to sensor performance — all combining to hinder Landsat's use for science and operational applications.

Despite the challenges posed by the commercial operations model, the scientific use of Landsat steadily advanced. As concern over deforestation mounted during the late-1980s the Landsat Pathfinder project provided a systematic analysis of tropical rainforest deforestation. The paper by Skole and Tucker (1993) resulting from their work to assess the Amazon rainforest remains one of the most widely cited articles in the global change literature. Further, bolstered by the monitoring demonstration and outcomes Landsat data were adopted by Brazil for operational deforestation monitoring (see summary in Hansen et al., 2008). The need for accurate land cover information also spurred the USGS to begin operational land cover monitoring within the United States, culminating in the first National Land Cover Dataset (NLCD) in 1992 (Vogelmann et al., 2001). With Landsat-7 came a marked decrease in the cost of data, as well as a change in licensing policy, whereby images could be shared freely once purchased. As a result, other nations (including China, Canada, and Australia; e.g., Wulder et al., 2008) began using Landsat data for national mapping of land cover and forests. Moreover, consortiums emerged to enable data purchase and sharing (e.g., Wulder et al., 2002). The Global Land Cover Facility hosted by the University of Maryland (www.landcover.org) is an example where archiving and sharing of imagery among the remote sensing community has been promoted and enabled. Non-governmental organizations

[1] http://landsat7.usgs.gov/project_facts/ground_assets/igs_network/index.php

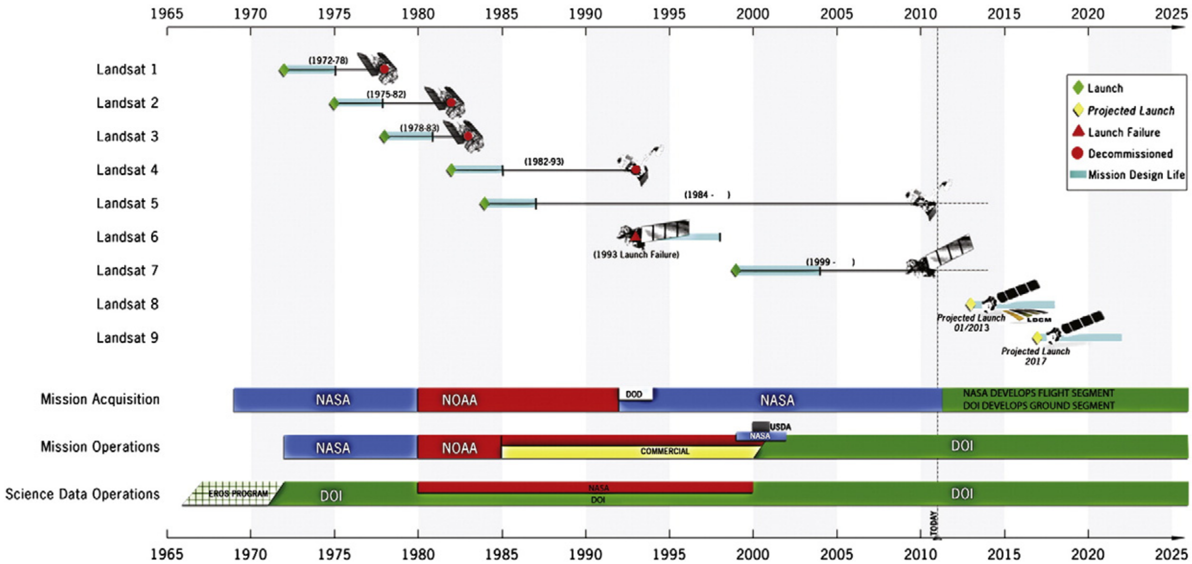

Fig. 1. Graphical illustration of Landsat program from EROS program inception in 1965 through present situation to anticipated launch of LDCM and beyond. Shown are launch dates, engineering design life objectives, and actual mission life spans. Also presented are science data, mission acquisition, and operations responsibilities.

have continued to play an important role in the dissemination and applications use of Landsat imagery.

Beginning in the late-1980s the NASA EOS (Earth Observing System) Program ushered in a new vision of global remote sensing centered on coordinated, multi-instrument observations, standard data products, and integration of these products with Earth System models (Sellers & Schimel, 1993). The EOS model of distributing validated information products at no cost differed substantially from the Landsat approach, which still remained focused on the distribution of raw radiometric products (images). The ability to create consistent, satellite-based records of physical parameters provided a new representation of Earth's environment, focused on temporal dynamics (from daily to decadal scales) and understanding the connections between driver and response variables.

Since 1999, there has been a concerted effort to achieve the original global monitoring goal of the Landsat program. The Landsat-7 Long Term Acquisition Plan has provided roughly seasonal coverage for the globe over the last 12 years, and the number of Landsat-5 international ground stations has expanded (Arvidson et al., 2006). The calibration of the Landsat-5 and Landsat-7 instruments has improved dramatically, and there is now a fully calibrated data record extending back to Landsat-1 MSS (Markham & Helder, this issue-2012). Beginning in the

Table 1
Incremental mission objectives.

Series, sensor(s), launch	Initial mission statement and key increments[a]
Landsat-1, RBV[b], MSS, July 23, 1972	"The primary objective of the Land Satellites 1&2 (Landsat 1&2) missions is to use two imaging systems to achieve periodic and complete coverage of the United States via multispectral, high spatial resolution images of solar radiation reflected from the Earth's surface. Secondary objectives include acquisition of multispectral images over important major land masses other than the United States at least once per season and the relay of data acquired by ground based platforms via the Landsat to a central analysis facility to support the modeling of earth resource oriented processes." http://www.eoportal.org/directory/pres_Landsat1to3.html
Landsat-2, RBV, MSS, January 22, 1975	– Same as Landsat-1
Landsat-3, RBV, MSS, March 5, 1978	– Indicate an interest in experimentation with improved sensors; – Provide continuity of experimentation and verification testing to more fully develop applications
Landsat-4, MSS, TM, July 16, 1982	– Sensor development, TM added – First NASA satellite with GPS – Improvements to spacecraft, including refined engineering to solar array – Multi-band transmission of data to ground stations – Precision altitude control, using inertial reference and star trackers – Propulsion module for orbital adjustments (ensure repeat ground swath coverage) and enable Shuttle rendezvous
Landsat-5, MSS, TM March 1, 1984	– Automation of ground component – Describes data as "satellite-acquired multispectral earth resources data for management of environment and natural resources" – Assess applications capabilities of the TM sensor – Determine and define feasibility of operational system (with user agency focus) – Encourage foreign participation in research studies – Transition users from MSS to TM (e.g., improved transmission rates and higher spatial resolution)
Landsat-6. Launched October 5, 1993, did not achieve orbit.	– NA
Landsat-7, ETM+, April 15, 1999	– Maintain data continuity, expand commercial and research uses (e.g., global change research) – Provide overlap with other Landsat missions to enable inter-comparisons – Make data widely available for the cost of fulfilling a user request (COFUR).
Landsat-8, OLI, Planned launch, January 2013.	– "The LDCM, consistent with U.S. law and government policy, will continue the acquisition, archiving, and distribution of moderate-resolution multispectral imagery affording global, synoptic, and repetitive coverage of the earth's land surface at a scale where natural and human-induced changes can be detected, differentiated, characterized, and monitored over time." (Markham, 2011)

[a] Information culled from: http://landsat.gsfc.nasa.gov/about/technical.html.
[b] Acronyms: RBV, Return Beam Vidicon; MSS, Multispectral Scanner; TM, Thematic Mapper; ETM+, Enhanced Thematic Mapper Plus; OLI, Operational Land Imager.

late 1990s USGS and NASA partnered to sponsor the GeoCover datasets (now Global Land Survey), which provide global, cloud-free orthorectified data on 5-year epochs (e.g., Gutman et al., 2008; Masek et al., 2008). These datasets were supplied in an analysis ready format, known as Level 1T (L1T), which incorporated precision georegistration and orthorectification using digital topography. This format was an improvement over the standard Landsat data product distributed by EROS at the time that did not correct for terrain displacement (EROS has since incorporated terrain correction into Landsat processing and now distributes L1T Landsat images as their standard product). The uptake of the L1T data demonstrated the utility of analysis-ready products and formed the basis for development of more advanced products by the USGS. By providing free access to global datasets, the Global Land Survey played an important role in elevating the scientific awareness of the potential of Landsat, and initiated the recent explosion of large-area applications. In 2008, the USGS adopted an open access policy for the free distribution of all data in the US Landsat archive via the Internet (Woodcock et al., 2008).

3. Opening the archive: Landsat since 2008

3.1. A new data policy

Data policy has had a profound effect on the Landsat Program throughout its existence. Until the adoption of the open access data policy in 2008, there was always a cost associated with ordering Landsat imagery, and this situation became even more onerous during the commercialization era of the Landsat Program, when copyright restrictions (which were later lifted in 1999) were layered on top of high prices. Costs for an individual photographic image varied from $20 (1972–1978) to $200 (1979–1982) for MSS digital data; digital data ranged from approximately $3000 to $4000 for TM data (1983–1998), and $600 for ETM+ data (1999–2008). Prior to October 2008, no calendar month ever recorded more than 3000 scenes sold in a given month. The Landsat Data Policy (http://landsat.usgs.gov/documents/Landsat_Data_Policy.pdf) released in 2008 must be considered among the most important developments in the history of the Landsat Program. The dramatic rise in the use of Landsat data following that decision has verified its wisdom. In our opinion, only now, through the open data policy, can governments and society can gain full value from the Landsat Program. After investing billions of dollars in the Landsat missions, ground systems, and data processing and archiving, the remote sensing community had been limited in its ability to use Landsat data by restrictive data policies and unsuccessful cost recovery efforts. The large discrepancy between the overall cost of the Landsat Program and the amount of money that was recovered by selling data ultimately served to limit the return from the initial investment in the Program.

The Landsat Data Policy has important implications for global remote sensing. Now that there are a number of remote sensing satellites that have been launched by several nations, there is unprecedented choice for sources of imagery (Stoney, 2008). Given the increasing data choices available to end users, cost, coverage, and accessibility are often the most important selection criteria. For example, MODIS data that are free and readily available online are used much more frequently than data from similar sensors with more restricted access (i.e., MERIS). More importantly, with free data policies and open access, it will become increasingly practical to combine data from multiple sensors. If free and open data policies were the norm, then data of similar types from different sources could be used together (e.g., Landsat and similarly configured, soon to be launched, Sentinel-2). Sentinel-2 will have similar spectral characteristics to the Landsat series of satellites, augmented with a higher spatial resolution (variable by spectral band pass, 10–20 m), a wider swath, and shorter temporal revisit (based upon a multi-satellite mission plan) (details in Martimor et al., 2007). Similar orbital characteristics to Landsat are planned, further reducing temporal revisit rates for fusion of differing sources of medium spatial resolution data.

Data assimilation approaches for information generation, akin to those applied by the meteorological community, are under-represented in terrestrial remote sensing applications and would certainly be aided by open data policies. There are two primary advantages in this regard. First, an individual sensor is limited in terms of frequency of observations and free and open access to similar sensors would help to minimize that limitation. Second, free and open access to data aids in mitigating the risk of data gaps. Satellite remote sensing is expensive, yet failures of systems on launch or in orbit are known to occur. Access to data from similar sensors could serve to limit the exposure of individual countries, and the global community, to risk of data gaps. In this regard the international organizations, GEO (Group on Earth Observations) and CEOS (Committee on Earth Observing Systems), have critical roles to play with respect to encouraging free and open access to data. The decision to make Landsat data freely available directly supports the efforts of those organizations and places the Landsat Program in a role of leadership with respect to data policy.

Another important implication of the free data policy concerns international agreements. A key element of international initiatives to limit greenhouse gas emissions focuses on reducing deforestation and forest degradation. To support these kinds of agreements, it will be essential to be able to verify national reports on rates of deforestation and forest degradation, and satellite data will have a critical role. Free and open access to satellite data from sensors like Landsat may therefore facilitate the willingness of countries to agree to a treaty, with the knowledge that appropriate data sources are available for independent monitoring and verification of treaty outcomes. Continuity of measurements, from one or more satellites, also provides the reliability of data streams necessary for national governments and international agencies to build the use of satellite data into their operational programs.

3.2. Access statistics

Open access has resulted in the distribution of over 5.7 million images (through June 2011), representing the full range of Landsat instruments (Table 2). More than 250,000 images are distributed each month — an incredible statistic when considering that for the entire year of 2001 (when the previous record was set for data distribution) approximately 25,000 images were purchased. To date, over 2.8 million images are contained in the USGS archive, with about 440 new

Table 2
Number of downloads per period since Landsat data were made available at no cost. Note that monthly downloads have increased from 108,214 in 2009 to 233,241 in 2010, and thus far in 2011, an average of over 258,000 images are being distributed per month.

Instrument	December 2008–December 2009 (13 months)	January–December 2010 (12 months)	January–June 2011 (6 months)	Total (December 2008–June 2011; 31 months)	Monthly
ETM+	827,138	1,533,082	736,500	3,096,720	99,894
TM	480,240	1,220,198	789,800	2,490,238	80,330
MSS	99,405	45,611	23,300	168,316	5430
Total	1,406,783	2,798,891	1,549,600	5,755,274	185,654
Monthly	108,214	233,241	258,267	185,654	

Landsat-5 TM and -7 ETM+ images added per day (Loveland & Dwyer, this issue-2012). Users from over 181 different nations have downloaded images. Currently, approximately 7500 images per day are processed, with higher volumes occurring occasionally. For instance, 10,250 images were recently processed in a single day, and over 29,500 images were downloaded in a single day. A user preference for ETM+ imagery is evident, likely related to the global coverage afforded. Based on download destinations, it is evident that the use of Landsat imagery in education has doubled since early 2009. The values presented in Table 2 are elaborated upon in Fig. 2, with monthly values presented. The blue bar in the lower left of the Figure represents the best month of sales prior to October 2008 (at 3000 scenes). The increasing trend in scenes distributed per month is evident (shown with the red bars and dashed line), leading to the over 6 million scenes distributed to date (up to September 2011). In Fig. 2 it is evident that interest in acquiring images is high and can be satisfied with the distribution system utilized, with over 1 million scenes per year distributed since inception of the free and open access era.

3.3. Archive consolidation activities

The USGS has undertaken an activity to obtain (as possible) and consolidate global Landsat data holdings from all International Cooperators. The goal of the Landsat Global Archive Consolidation (LGAC) is to obtain and add all possible unique images to the USGS EROS archive. Landsat images from each IC, on behalf of the respective receiving station, may be added to the EROS archive. As noted above, there are approximately 5 million images held by ICs, of which from 3 to 4 million are expected to be unique to those already residing in the EROS archive. These data, representing a highly valuable, otherwise unavailable and irreplaceable source of historic information, are especially important as they are often from data poor locations and regions. Obtaining these images from the ICs could effectively double the size of the USGS archive (currently holding approximately 2.8 million images). The catchment of each receiving station varies, as does the capacity to obtain the archival data. Some locations are problematic for programmatic reasons, while others have physical storage issues. Encouragingly, four key ICs represent about 75% of the outstanding archive. The European Union, Australia, Canada, and China each have systematic storage practices and are poised to cooperate with the LGAC initiative. Since 2009 approximately 300,000 images have been added to the EROS archive, of which over half are from Canada. A simple approach has been implemented where historical data on hard drives are shipped from the Canada Centre for Remote Sensing to the USGS. Additionally, a "bent-pipe" approach for providing new collects directly to the USGS has been established by Canada, which will preclude future needs for separate data collections, archives, and subsequent transfers. A bent-pipe process has also been initiated by Brazil, Argentina, and China (KaShi station), with South Africa and Australia poised for inclusion following further developments. Historical archive transfer is also planned and forthcoming with other nations. While the main thrust of LGAC is to make the full complement of Landsat acquisitions available, one important component of its success concerns upgrading global holdings to the Landsat L1T format, facilitating the use of the data being added to the global archive at EROS.

3.4. Science and applications impact of the open archive

A key value of the Landsat program is its long-term record of observations. Consequently, an increasingly important theme among data users has been the mapping of Earth surface change. Prior to liberation of the archive, when end users had to pay for data access, change mapping was limited to large areas over coarse time steps (Masek et al., 2008) or short time steps over small areas (Sonnenschein et al., 2011). Now, pioneering efforts to develop automated algorithms that leverage the high temporal dimensionality of Landsat data are preparing the user community for applications demanding high temporal resolution over large areas (Hilker et al., 2009; Huang et al., 2010; Kennedy et al., 2010; Zhu et al., this issue-2012). One of the remarkable characteristics of the Landsat user community has been its interdisciplinary breadth, and these new algorithm developments are occurring across a broad set of users. In this section, we highlight that breadth, giving examples of Landsat's use for describing change across an array of processes within a number of Earth system components. Our goal is to illustrate advanced

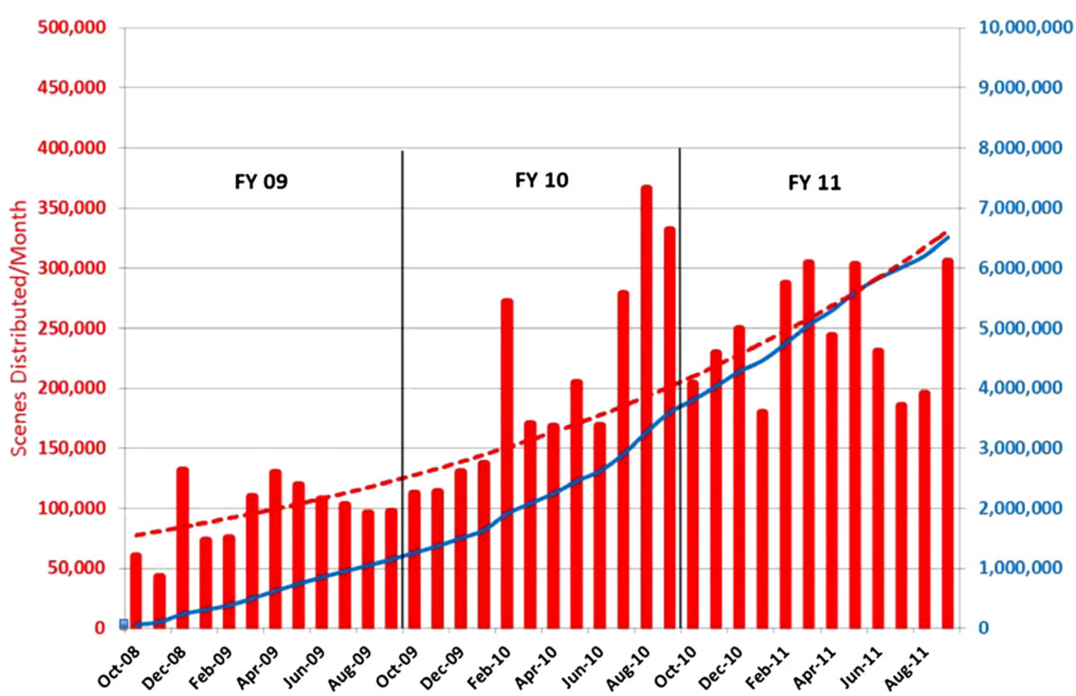

Fig. 2. Monthly summary of scene downloads from the EROS Data Center, covering the period from October 2008 to September 2011, further delineated by US Government fiscal year.

uses of greater temporal dimensionality, which are now accelerating in response to free availability of high quality data.

Perhaps the greatest use of Landsat for change detection is in forested environments (Table 3). Until recently, the dominant approach involved a simplified, discrete classification of change (e.g., Cohen et al., 2002). Now, we see an explosion of uses characterizing trends (i.e., increase or decrease of quantities) in forest cover and other stand-level attributes, associated with disturbance and regrowth (Healey et al., 2006; Beck & Gessler, 2008; Vogelmann et al., 2009; Morton et al., 2011), several of which highlight an increased level of detectability with greater temporal density (e.g., Jin & Sader, 2005). Related time series approaches have also been developed to track forest habitat fragmentation (Lung & Schaab, 2006; Coops et al., 2010), the causal agent of forest disturbance (Schroeder et al., 2011), regeneration (Olsson, 2009), current forest structure (Helmer et al., 2010; Pflugmacher et al., this issue-2012), and burned area (Röder et al., 2008; Schroeder et al., 2011). Also, recent advances are developing applications that monitor forest change as it is detected (with each pixel compared to historic trends as new images are collected), which holds the potential of providing information to forest managers in near real-time (Zhu et al., this issue-2012). Following additional developments, the interrogation of imagery and comparison to previous expectation at the pixel level upon collection also allows for identifying of cloud and shadow and the subsequent development of refined data masks and quality flags.

For other earth system components and processes, there is similar progress using time series approaches. In rangelands, this includes monitoring of trends in productivity (Brinkmann et al., 2011) and cover modification (Stellmes et al., 2010). In urban environments, the focus is on characterizing increases in impervious surface (Powell et al., 2008) and growth patterns (Seto & Fragkias, 2005). Coastal environments are studied for changes in shoreline characteristics (Dewidar & Frihy, 2010), and coral reef health (Palandro et al., 2008) and composition (Dustan et al., 2001). There are an assortment of approaches using time series across a number of other earth system components and processes including water quality assessment (Bustamante et al., 2009), invasive species (Evangelista et al., 2009), volcanic activity (Kaneko and Wooster, 1999), fluctuation of glacial extent (Li et al., 1998), public health (Maxwell et al., 2010), mining effects (Almeida-

Table 3
Thematic summary and bibliography listing the use of Landsat to inform on Earth system components and processes.

Earth system component or process	Reference	Application
Forestland		
– Increase or decrease of quantities	Beck and Gessler (2008)	Tools for operational forest status assessment
	Goodwin et al. (2008)	Detecting the presence and timing of insect attack
	Healey et al. (2006)	Effects of partial harvest on owl habitat
	Helmer et al. (2009), Powell et al. (2010)	Quantification of biomass change
	Huang et al. (2010), Kennedy et al. (2010)	Disturbance detection based on tunable threshold of change magnitude
	Jin & Sader (2005)	Accuracy of disturbance detection as a function of disturbance magnitude and temporal density
	Li et al. (2011)	Height modeled as a function of time since disturbance
	Morton et al. (2011)	Detecting canopy damage from understory fires
	Schroeder et al. (2007)	Early forest succession
	Vicente-Serrano et al. (2011)	Forest regeneration after wildfire
	Vogelmann et al. (2009)	Canopy damage from combined drought and insect disturbance
– Fragmentation	Coops et al. (2010)	Effects of insect infestations on landscape structure
	Lung and Schaab (2006)	Land use effects on landscape structure
– Disturbance agent	Schroeder et al. (2011)	Distinguishing between fire and harvest in boreal forest
– Current condition	Helmer et al. (2010)	Mapping height, cover, and related variables using Landsat time series and other data
	Pflugmacher et al. (this issue-2012)	Predicting current live and dead aboveground biomass and basal area using disturbance history
– burned area	Eidenshenk et al. (2007)	Operational monitoring of burned area
	Röder et al. (2008)	Monitoring fire event and post fire dynamics
Rangeland		
– Trends in productivity	Brinkmann et al. (2011), Sonnenschein et al. (2011)	Monitoring trends in productivity associated natural and anthropogenic factors
– Cover modification	Stellmes et al. (2010)	Monitoring land cover change
Urban		
– Impervious surface	Powell et al. (2008)	Quantification of impervious surface change from 1972 to 2006
– Landscape patterns	Seto and Fragkias (2005)	Spatiotemporal patterns of urban expansion
Coastal		
– Shoreline	Dewidar and Frihy (2010)	Rates of changes in shoreline erosion and accretion
– Coral reef	Palandro et al. (2008)	Habitat decline
	Dustan et al. (2001)	Shifts in community composition
Miscellaneous		
– Water quality	Bustamante et al. (2009)	Turbidity and water depth
– Invasive species	Evangelista et al. (2009)	Mapping invasive tamarisk
– Fumarole activity	Kaneko and Wooster (1999)	Characterizing gas and magma fluxes
– Glaciers	Li et al. (1998)	Measurement of glacial fluctuation
– Public health	Maxwell et al. (2010)	Pesticide exposure assessment
– Mining	Almeida-Filho and Shimabukuro (2002)	Land degradation associated with gold mining
– Phenology	Fisher et al. (2006)	Average green leaf phenology across 18-year period
– Land use and cover change	Kaufmann and Seto (2001)	Econometric modeling
– Wetlands	Elvidge et al. (1998)	Intra- and inter-annual wetlands vegetation monitoring
– Riparian catchments	Wang et al. (2011)	Modeling seasonal N uptake
– Crop cycles	Oetter et al. (2000)	Distinguishing among crop types based on seasonal spectral profiles

Filho & Shimabukuro, 2002), phenology (Fisher et al., 2006), land use and cover change (Kaufmann & Seto, 2001), wetlands (Elvidge et al., 1998), riparian catchments (Wang et al., 2011), and seasonal crop cycles (Oetter et al., 2000).

The ability to harness dense time series to address ecosystem questions has led to the "MODIS-izing" of Landsat — the application of processing approaches originally developed for MODIS and AVHRR to support Landsat-based science. Examples include the image compositing approach used in the WELD system (Roy et al., 2010), and methods that blend information from MODIS and Landsat either thematically (Hansen et al., 2008) or directly (Gao et al., 2006), with these approaches and options summarized in Wulder et al. (2011). Indeed, the merging of data from multiple satellite sources greatly expands the potential of dense time series analysis. At the current time, Landsat data from the US archive and CBERS data from Brazil are freely available, but the potential for combining data from multiple sources could be far greater in the future. In particular the European Union Global Monitoring and Environmental Security (GMES) Sentinel-2 mission is expected to launch in 2013, providing Landsat-like data across 13 spectral bands from two satellite platforms. The European Commission has announced tentative plans for a free and open data policy for Sentinel missions with details remaining to be finalized (deSelding, 2010). This paves the way for synergistic use of both Landsat and Sentinel-2 to capture near-daily changes in global vegetation at 30 m resolution. Additional Landsat-like systems are being operated by India, China, Brazil, and other nations, but data policy restrictions continue to hinder access to these archives, and thus limit the utility of these missions for global monitoring.

Prospects are now enhanced for the use of Landsat time series by a variety of government and non-government agencies for resource monitoring and to inform policies related to global change. With increased confidence that these groups can depend on Landsat for the foreseeable future, many are now developing monitoring plans that depend on frequent earth observations by Landsat (and similar class) data (e.g., Wulder et al., 2008).

4. The road to the future

Slated for launch in January 2013, the Landsat Data Continuity Mission (LDCM) will continue the Landsat legacy of global, multispectral observations (Irons et al., this issue-2012). Developments include push-broom scanning and new bands centered on 443 nm ("ultra blue" for coastal/aerosol work) and 1380 nm (for cirrus cloud detection) with improved radiometric resolution to 12 bits/pixel (see Irons & Masek, 2006). The Thermal Infrared Scanner (TIRS) will provide two bands of infrared imagery at 100 m resolution. LDCM will be launched into the traditional Landsat sun synchronous orbit, 8 days out of phase with Landsat-7 (i.e., it will basically replace Landsat 5 in the current orbital configuration). Although the nominal design life of the mission is 5 years, the observatory will include 10 years of consumables. During this time LDCM will acquire 400 scenes per day, up from the ~250 to 300 acquired per day by Landsat 7, which will improve the odds of acquiring clear observations in cloudy regions. While NASA is responsible for building and launching the LDCM satellite and instruments, USGS EROS is implementing the LDCM ground system overall mission operations, including satellite command and control, data acquisition, processing, archive, and distribution. Data products will be scaled to top-of-atmosphere reflectance (rather than radiance) and feature additional per-pixel metadata through a QA field. USGS will continue the existing "no cost" Landsat data policy. Additionally, the USGS has plans to prototype and evaluate surface reflectance products based upon the LEDAPS methodology (Masek et al., 2006); plus, surface temperature and other climatically or policy relevant attributes (e.g., essential climatic variables; Sessa and Dolman (2008)) are poised for generation or are under consideration (Loveland & Dwyer, this issue-2012).

Despite the evident success of the open USGS archive, at the time of writing (September 2011), the future of the Landsat program remains unclear. Current plans call for program leadership to shift to the Department of Interior, with NASA implementing the space segment on a reimbursable basis. The first mission under this new operational program is to be Landsat-9. A similar arrangement between NOAA and NASA has been used for many years to build and launch the operational Geostationary Operational Environmental Satellite (GOES) and Polar Orbiting Environmental Satellite (POES) weather satellites. However, it is unclear when funding will be appropriated that allows work to begin on the Landsat-9 system. While the scientific and technical success of the Landsat program has been unparalleled, finding consistent programmatic support remains a challenge.

To minimize the risk of a gap in Landsat operations, the Landsat-9 system could likely be a near-copy of LDCM system, with significant technical enhancements deferred until Landsat-10. The USGS-NASA Landsat Science Team recently prioritized a list of technical enhancements for future missions. The highest priorities include improving the spatial resolution of the thermal bands to 60 m (from the 120 m on LDCM and thus comparable to the resolution of the Landsat-7 ETM+ thermal band), providing separate red and near-infrared bands at 15 m resolution in place of the current panchromatic band, and operating Landsat-9 in an "always on" configuration to acquire every possible scene over land. The team also expressed strong support for increasing the frequency of repeat observations, possibly by incorporating a wider swath for future imagers. This again highlights the importance placed on the temporal domain for land monitoring. As the Landsat program transitions to being a fully operational system, there is interest in procuring multiple copies of future satellite observatories (spacecraft plus instruments). Procurement and construction of multiple satellites (including related instruments) will have additional benefits including lower per unit costs, and continued craftsmanship from experienced staff. From an operational and redundancy perspective, the launch of multiple similar sensors would also reduce risk to continuity and increase the frequency of observations.

5. Conclusion

When describing the need for satellite missions to support the meteorological community, the messaging is clear: timely data is needed over wide areas as input to models providing operational weather forecasting. For the terrestrial monitoring community, the needs and uses are more diverse, with various user communities touting the importance of a range of sensor types and data needs. The disparate range of requests can confound policy makers, with research missions of a more limited scope competing with programs with an established user base and community. The reality is that differing systems are needed, depending on the desired information. The capacity to capitalize upon sensors with differing data outputs, say MODIS and Landsat, has shown the direction for how synergy between satellite programs demonstrates the compatibility, rather than competition, between satellite missions. The utility of increased data density, temporally to inform on land dynamics, and spatially to enable the creation of seamless wide-area products, points to where terrestrial remote sensing is heading. Furthermore, an increased use of supplemental spatial data sets when developing models using remotely sensed imagery enables incorporation of information not accessible through the satellite source alone, but also allows applications approaches to build upon what is already known; that is, applications do not need to be entirely driven by remotely sensed data, but can and should incorporate complementary or informative spatial data sets.

Since the launch of Landsat-1 a great deal has been learned. The Landsat program developed from solid principles (e.g., the importance of image geometry and radiometry) and created a base upon which continued development and improvements have been possible.

The importance of the current satellite and archive operations to the on-going utility of Landsat data cannot be overstated. The routine collection of imagery following a comprehensive coverage strategy, rather than only acquiring images of interest or poised for purchase, has resulted in a true global archive that has been continuously refreshed during the Landsat 7 era. The provision of standard products, following transparent methods, has permitted research and value-added communities to thrive. The generation of increasingly refined products, such as reflectance, and attributed data, such as land cover or leaf area, will further support management and scientific activities.

Landsat has been proven as a global asset with nations and international agencies increasingly embedding medium spatial resolution imagery in operational programs to support management objectives, enable reporting, and to inform policy makers. The free and open access status of Landsat is an informative example of how to maximize the return on the large investments in satellite missions. Uniquely, the access to Landsat data provides for consistent methods to be applied across nations and enables a uniformity of outcomes to promote synergies. Further, the ability of all nations to utilize Landsat data to domestically produce data products provides for trusted information that can be used and respected internationally for science, policy, and reporting needs. Such products enable a comparison with other data products providing for strengthened findings on agreement or enabling an open, data supported dialog when disagreements emerge. To this end, Landsat enables national level information independence. As we move to the future, the ability to combine information from similar satellite systems promises to reduce risk of data gaps and improve the frequency of observation, further enhancing the reliability of medium resolution remote sensing, thereby enabling the support of new and exciting applications that benefit society in innovative and insightful ways.

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