Landsat@50

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With the liftoff of the Landsat 1 satellite on July 23, 1972, the Landsat Program started a so far uninterrupted exploration of the Earth, which has – over the past 50 years – enabled ecologists to better understand rapid changes across terrestrial ecosystems on a global scale. According to Sam Goward, an early contributor to Landsat science, "it was the early vision in the late 1960s of William Pecora, then-director of USGS [US Geological Survey], and Stuart Udall, then-Secretary of the Interior, that led to the conceptual development of Landsat, which was launched by NASA [National Aeronautics and Space Administration]" (Goward *et al*. 2017). Little did they and the early developers at the time foresee the tremendous future success of the mission, its influence on subsequent ecological studies and resource decision making, and its operational lifetime of 50+ years, with the launch of Landsat 9 in 2021 and plans near approval for Landsat 10, both of which will extend the mission into the coming decades (Figure 1).

"The Landsat mission almost never got started with its instrument of choice: when the preferred Return Beam Vidicon [RBV] sensor failed, and the more experimental Multispectral Scanner [MSS] proved to be a useful workhorse", added Goward. The initial 79-m pixel resolution of the MSS observations by Landsats 1, 2, and 3 was upgraded with Thematic Mapper (TM) sensors coming online with Landsat 4 in 1982, thereby commencing the era of 30-m pixel observations, which continues to this day.

At spatial scales useful to researchers and natural resource managers, those early observations provided the first opportunities to remotely detect widespread changes in land cover and to document global patterns of ecological features. Over the years, Landsat data products have been used to examine forest phenology, wetland spatial dynamics, land-cover conversions, disturbance patterns related to wildfires and storm effects, and efficacy of conservation efforts (Pasquarella *et al*. 2016). Resource managers and policy makers have relied on Landsat-derived analyses to highlight the rate of land-cover changes occurring in desired regions and to identify areas for further study and protection.

Landsat-based observations have been an effective tool in monitoring deforestation rates in the Amazon Basin (Figure 2) and other tropical regions. Conservation groups and government agencies routinely depend on these datasets to evaluate policies related to biodiversity loss and global environmental change. For instance, concerns over uncertainties in rates of tropical deforestation in the Amazon Basin reported during the late 1980s led to one of the initial investigations of the Landsat Pathfinder Program (namely, the Humid Tropical Forest Inventory Project) in the early 1990s. Headed by David Skole and Compton Tucker, this early study (Skole and Tucker 1993) was able to pull together massive sets of Landsat data spanning the Brazilian Amazon between 1978 and 1988 to objectively quantify the decadal rate of deforestation across the region. Critical in characterizing the scope of Amazon deforestation rates during the 1980s and subsequent decades, these observations and analyses led to the Brazilian government recognizing the extent of deforestation taking place and pledging to reduce the rate of deforestation across the region.

Matt Hansen (University of Maryland), current Landsat science team member, highlighted the importance of the Landsat Pathfinder Program, which changed how satellite images were selected. Before this time, documenting tropical forest coverage at sites in Central Africa and Southeast Asia required the acquisition of cloud-free observations, which was challenging. With the program's implementation of a pixel selection process that rendered cloud-free composite images, the utility of the Landsat image archive in detecting deforestation in remote regions of the tropics was greatly enhanced, allowing for decadal land-cover change analyses (over the 1970–1980 and 1980–1990 periods).

The 1990s also represented the era when Landsat data were increasingly utilized for conservation purposes, especially to investigate the encroachment of land conversion on protected areas. Early adopters of the 30-m Landsat TM data included researchers such as Andy Hansen (Montana State University) and Ruth DeFries (then with the University of Maryland). In collaboration with Warren Cohen (Oregon State University), Andy Hansen remarked that access to 30-m datasets was critical to address changes in the Greater Yellowstone Ecosystem and Yellowstone National Park (YNP). By quantifying changes in evergreen forest cover within the YNP and thereby having the ability to evaluate potential changes in the fragmentation of and carbon storage in the YNP's forested areas, this research helped to advance our understanding of human pressures on a key ecosystem.

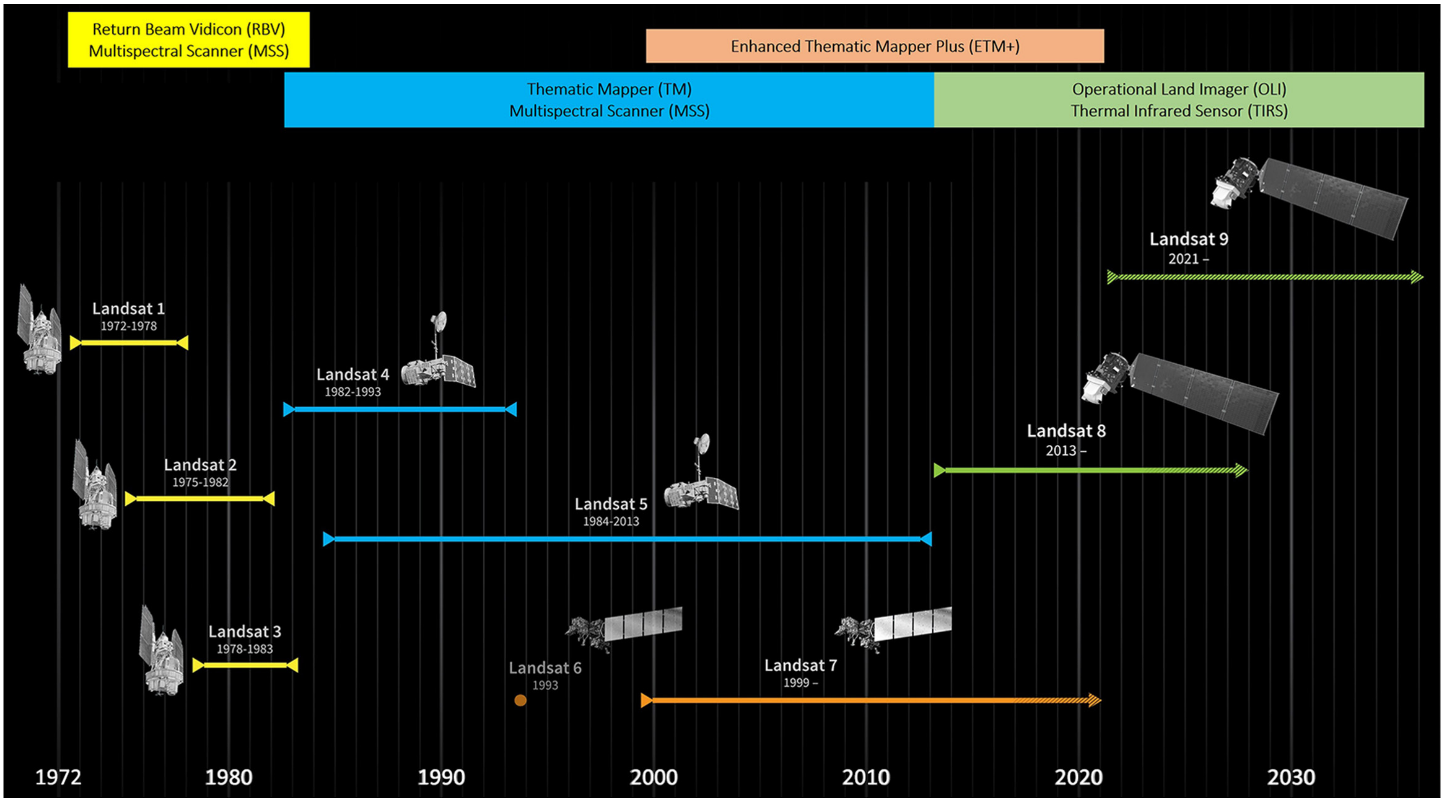

Figure 1. Landsat satellite platforms from 1972 to 2021. Note that Landsat 6 was lost at launch. Landsat 8 and 9 are projected to continue observations in the coming years, and planning is underway for missions beyond that period. The key sensor packages utilized on these Landsat satellites are listed along the top portion of the figure. While sensors have been enhanced considerably over time, great efforts have been made to allow for continuous temporal analyses from the beginning of this program, although the original MSS observations by Landsats 1–3 still present some challenges. Figure originally developed by NASA's Scientific Visualization Studio (https://svs.gsfc.nasa.gov/11433) and modified by S Goward.

In the late 1990s, DeFries and her colleagues combined Landsat analysis with global tree cover from Advanced Very High Resolution Radiometer (AVHRR) data to calibrate a carbon emissions product (DeFries and Townshend 1999). Following this, in 2008 Matt Hansen and his team used a combination of Moderate Resolution Imaging Spectroradiometer (MODIS) imagery and Landsat imagery to analyze forest conversion globally, developing a fused data product of the two sets of observations. This important application promoted efforts to automate the processing stream and exploit massive amounts of digital Landsat imagery and pixel selection (Hansen *et al.* 2013), which continues today as Global Forest Watch (www.globalforestwatch.org). As part of NASA's Earth Observing System Project, these interdisciplinary studies enabled ecologists to study land-cover changes and evaluate climate and carbon-cycle changes affecting the Earth system.

The launch of Landsat 7 in 1999 provided some additional upgrades with the inclusion of the Enhanced Thematic Mapper Plus (ETM+) sensor, which offered high spatial resolution with a panchromatic band and additional spectral bands, and maintained the continuity of core measurements. The Landsat 7 science team also developed several long-term procedures to integrate past Landsat observations with imagery from current and future missions.

After more lenient data policies were introduced by USGS in 2008, an explosion in the use of Landsat data followed. Free and unrestricted access to the TM datasets allowed researchers to expand their studies of land-surface changes to larger regional domains over the period of data collection. Increased reliance on the Landsat data archive was also associated with the Analysis Ready Datasets (ARDs) created by the USGS Earth Resources Observation and Science (EROS) Data Center in 2018 and the ARD developed by the University of Maryland's Global Land Analysis and Discovery laboratory in 2019. These datasets facilitate use by creating a spatially consistent, geometrically and atmospherically corrected, cloud-free data collection for the detection of land-cover change.

Landsat data continue to be used and advanced by groups such as Jody Vogeler's research team at Colorado State University. She and her colleagues are incorporating data from the recent spaceborne-lidar (light detection and ranging) mission – NASA's Global Ecosystem Dynamics Investigation (GEDI) – along with Landsat and other Earth observations to characterize forest structure across broad spatial and temporal extents for a variety of applications. The synergistic use of lidar imagery of forest structure and topography around the world will enhance the interpretative power of the long-term data available through Landsat observations. Further collaborations

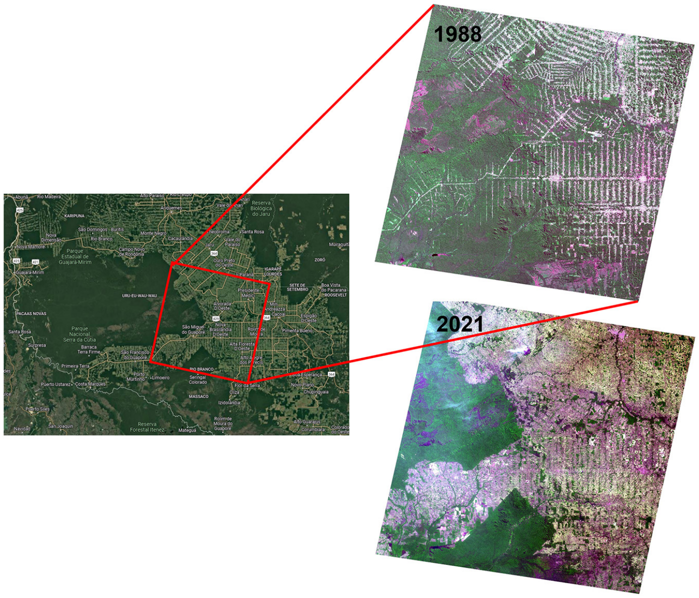

Figure 2. Extent of deforestation within the Amazon Basin, in the State of Rondônia, Brazil, utilizing Landsat observations for 1988 and 2021. Observations such as these are still used to monitor deforestation rates across the Amazon. The early analysis, in the 1990s, was used to establish the rapid loss of tropical forest across the basin (Skole and Tucker 1993). Figure created by D Skole. Basemap source: Google Earth using NASA Landsat imagery as back coverage. Imagery source: Landsat images from the USGS EROS Data Center, processed by the TRFIC Data Center at the Global Observatory for Ecosystem Services at Michigan State University.

with other (multi-)national initiatives, such as the Sentinel Program of the European Space Agency (the *other* ESA), are integrating Landsat's long-term imagery with additional multispectral observations to advance our understanding of changes occurring across the Earth's terrestrial surfaces.

The Landsat mission continued its saga with the launch of Landsat 8 in 2013, which introduced next-generation Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) instruments (www.usgs.gov/landsat-missions/landsat-8). Likewise, Landsat 9 became operational in 2021 and plans for Landsat 10 are nearing completion, to ensure years of consistent, uninterrupted observations.

The ecological community has greatly benefitted from the vision and fortitude of the researchers, developers, and mission managers to maintain this valuable set of observations, and we are grateful for their continued diligence in preserving the observations' continuity while simultaneously making technological advancements.

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