






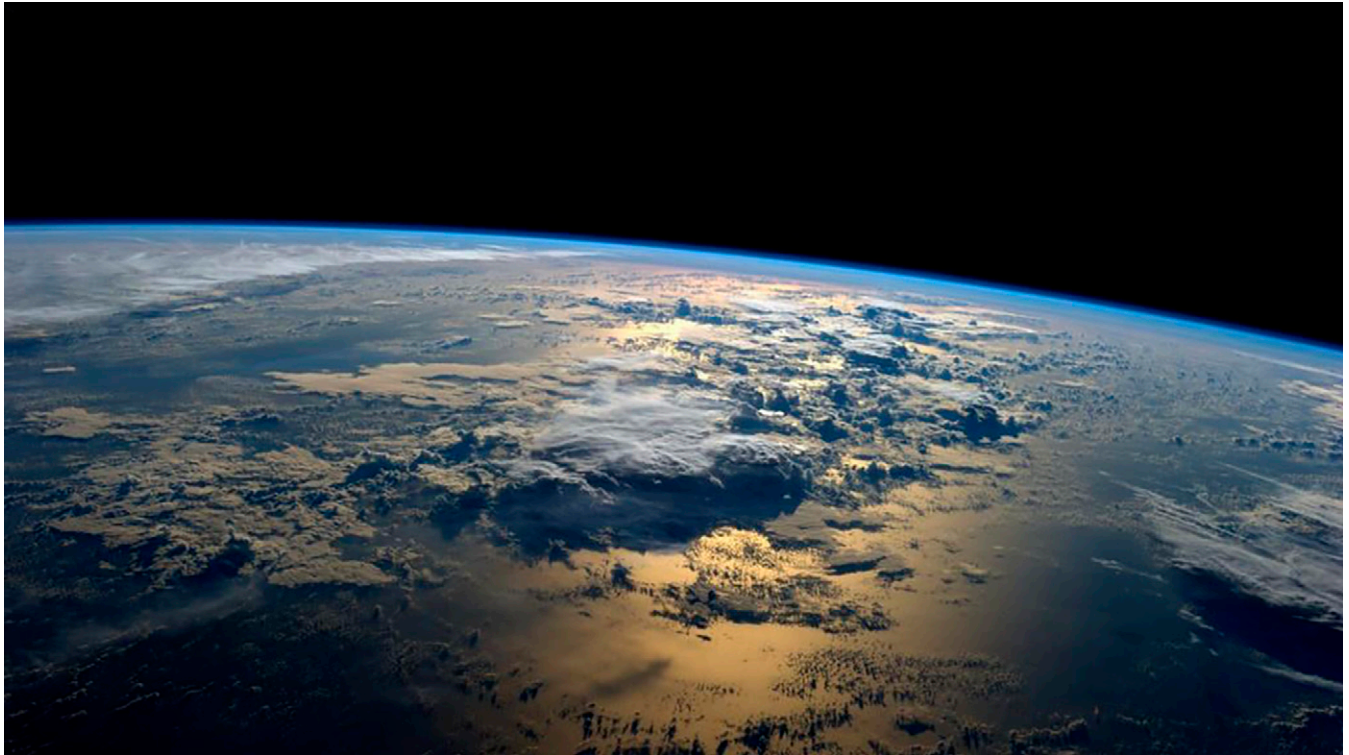


## Creating an Earth Archive

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Changes to the Earth's biosphere have reached a critical point. It's abundantly clear that we can no longer halt those changes that have resulted from human-induced modifications to the Earth's systems (1, 2). The climate crisis will fundamentally disrupt weather patterns, raise sea levels, alter biogeographic distributions, and much more.

Research across disciplines from archaeology to zoology shows that terrestrial environments comprise irreplaceable archives of past human and evolutionary activity. Our rapidly changing Earth presents a grand challenge for humanity: We must preserve or record our cultural and ecological heritage, along with information about habitats critical for biodiversity, before they are lost completely.

But this challenge brings up a profoundly important question: How best do we accomplish this recording, as quickly and with as much detail as possible? Some of this documentation is already underway. For example, there are archives of multi-spectral remote sensing products that are freely open to all, most notably the U.S. Geological Survey (USGS) archives ([earthexplorer.usgs.gov](https://earthexplorer.usgs.gov)) that include Landsat multi-spectral images dating back to the 1970s for much of the Earth's surface, as well as aerial photographs that date to earlier. What's missing from these archives is three-dimensional data that record the structure of the Earth's forest cover as well as the cultural and ecological features found beneath forest canopies.

There have been calls to use remote sensing technologies, such as light detection and ranging (Lidar), to fill in this gap and record these broad areas of the

**A rapidly changing Earth presents a grand challenge for humanity: We must preserve or record our cultural and ecological heritage, along with information about habitats critical for biodiversity—before they are lost completely.** Image credit: NASA/Reid Wiseman.

The authors declare no competing interest.

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Earth's surface (3), along with several national initiatives such as the 3D Elevation Program (3DEP) in the United States (4) and Canada's state-level programs (5). However, these efforts are limited in geographic scope, and they propose or use technical solutions that are inadequate to collect, at the spatial resolution needed, the information that must be preserved.

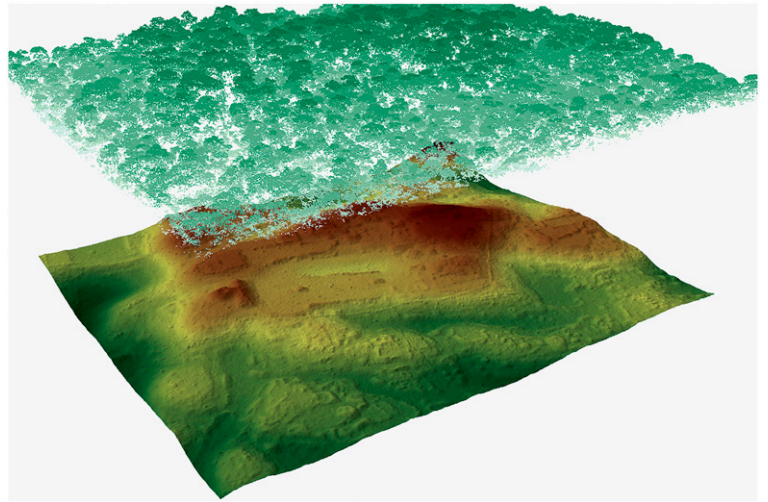
Thus, we call for a massive international effort to three-dimensionally scan, using airborne Lidar, the entire land mass of the planet (29.2%) to create a digital Earth Archive in combination with other open source data such as the Landsat archives and field-based measurements, such as the National Ecological Observatory Network [NEON (5)]. This will provide a comprehensive baseline database of the Earth's surface, and everything on it, at a very high resolution that exceeds standards used by current national scanning initiatives, which is stored as an open access database. The ultimate goal: create a high-resolution, three-dimensional digital model of the Earth's land surface for use by future generations.

### Our Ecological and Cultural Heritage

One of the key challenges we face in the 21st century is that so much of the Earth's surface remains poorly documented and understood by Western science—even as the ecological and cultural heritage found there face unprecedented threats from the climate crisis and the expansion of humanity's global footprint. Over the last decade, millions of forested acres have been lost, including habitat for endangered species, and incalculable numbers of archaeological sites have been looted and destroyed. These losses have occurred with such scale and speed that it will be impossible to ever fully account for what has been destroyed or to understand what profound ecological landscape and cultural insights have been lost. Such losses include accurate estimates of species distributions, continental-scale compositions of plants and animals, human demographic reconstructions for past societies such as pre-contact America, and knowledge about past environmental transformations.

Humanity has long shared a commitment to the preservation of the earth's heritage. Museums serve as collectors of rare and endangered items; zoos have a mission to preserve biodiversity; and archives preserve original documents and records. Since the 1970s, this desire to preserve has expanded to other realms: for example, CGIAR, formerly the Consultative Group for International Agricultural Research, along with international and national centers, has established the Seed Vault on Svalbard Island in Norway to collect and store rare and endangered plant cultivars; human microbiota are being collected and preserved by the Microbiota Vault Trust; and Cyark.org is leading an effort to collect three-dimensional Lidar scans of monumental buildings. Surprisingly, there is no analogous worldwide program to document and preserve a valuable heritage resource: the Earth's natural and pre-historical human-influenced landscapes.

We need a coordinated global effort of multi-disciplinary scientists to collect a three-dimensional record of the global



**Fig. 1.** This animation illustrates one use of Lidar, showing tree cover lifting from the archaeological site of Angamuco, Michoacán, Mexico. The scan revealed house mounds and a pyramid at the site of a previously unrecorded pre-Contact city.

landscape. This will allow for future analysis, appreciation, and use of these records, while complementing ongoing collection and archiving of above-canopy multi-spectral images collected by satellite sensors and other means. This goal is currently achievable with new digital tools and geospatial technologies, such as Lidar (Fig. 1). Lidar rapidly and accurately provides researchers with below-canopy information, down to the earth's surface, digitally preserving three-dimensional information about both the land cover and the landscapes of these areas at a very high spatial resolution.

Applications of Lidar technology have already informed major revisions of population estimates across the ancient world (6), transformed our understanding of long-term socio-ecological dynamics (7, 8), helped to determine carbon sequestration (9), acted as baseline data for forest and other resource management (10), mapped geological faults and other landforms (11), and helped elucidate changing ice distributions (12). But the spatial distribution and aerial coverage of this work has been limited and uneven, and the data are often not freely available to other researchers. In this era of a rapidly changing earth, we are losing more information than we are collecting.

### An Earth Archive

The solution we propose is an "Earth Archive Initiative" that entails the acquisition of very high-resolution Lidar over large areas; the data would be stored in an open access repository for future generations. In conjunction with current efforts to collect above-canopy multi-spectral data and in situ field data, the resulting datasets will serve both as a focus for current scientific analyses and an archive of the landscapes in their current form.

Recent Lidar applications have made its impact clear. In the last decade, archaeologists have performed landscape-scale scans using airborne Lidar to document legacy cultural landscapes and their associated geology and ecological habitats. Some studies have fundamentally altered understandings of long-term trajectories of coupled human/natural

systems. These records also contain important information about the ecology of these sites that future researchers might analyze. One of the key problems we face is that airborne Lidar scans are currently being conducted on an ad hoc basis without standard protocols for data collection (e.g., nominal pulse density and other specifications) or for creating metadata and archiving the resulting datasets as open access resources.

But we now have the technology to expand and coordinate these scattered efforts and systematically collect and archive global landscape data to well-defined standards. Already the Norwegian government has initiated such an effort, procuring high-resolution satellite imagery for tropical rainforest areas over the next 4 years and making those data freely available to researchers and nongovernmental organizations for monitoring and analysis of land change. One of the key limitations of this effort, however, is that high-resolution satellite imagery records only the top of the canopy—what’s under the canopy (i.e., any structural and land surface information) is not documented.

The Earth Archive Initiative would carry out Lidar scans of the entire land surface of the planet, excluding Antarctica, beginning with the areas that are the most threatened by the climate crisis, such as the Amazon and public lands within the United States. The initiative has three main goals.

The first is to create a baseline record of the land surface of the earth as it is today. The only way to measure change is to compare two sets of data, before and after. Currently, there is no very high-resolution, three-dimensional “before” dataset for the land surface of most of the planet. We therefore are not able to monitor change over time and assess whether efforts to mitigate the impacts of the expanding human footprint and of climate change are making a positive impact.

The second goal is to build a digital twin of the planet’s surface through the storage of these data to preserve a record of the earth for future generations as a means to access their cultural and ecological heritage. The data will be accessible to all scientists and researchers, and, in combination with archived multispectral imagery and in situ field measurements, archaeologists can discover undocumented settlements; ecologists can study forest composition, tree size, age, and distribution; geologists can study hydrology, faults, and disturbance; and researchers can monitor carbon sequestration. There are many other potential applications across disciplines, including using these data toward addressing the United Nation’s Sustainable Development Goals (13).

The third goal is to encourage the use of the resulting open access digital archives as a “digital seed bank” by supporting explorations of these voluminous datasets through developing technologies, protocols, visualization, and analyses based on artificial intelligence/machine learning (AI/ML) as well as developing improved data storage and sharing technologies. As science and technology advance, tools, algorithms, and other technical capabilities will also advance in ways that we can’t anticipate. These advances may be applied to the archived Lidar data, facilitating ongoing analyses and meeting future “grand challenges” related to planning and resource use that will face the Earth as the human population continues to expand.

Across many disciplines, we find examples of new technologies being applied to old datasets in ways that are unpredictable and not foreseen by the original collectors of the data. Examples range from moon rocks recovered during NASA Apollo missions (14), to imagery in the Landsat archives, originally collected in the 1970s and 1980s, being used for Google Earth today (15). The Earth Archive will preserve landscape records of critically endangered areas.

There are three major technical and social challenges involved in the creation of the Earth Archive. They are: 1) the need for large unmanned aerial vehicles capable of multi-hour flights to optimize the collection of data; 2) the use of AI/ML to accelerate processing times of the collected data; and 3) the development of open access storage and dissemination infrastructures that have the capacity and connectivity to both store and provide access to the data on a global scale, including indigenous and underserved populations. (Regarding this last challenge, the data dissemination infrastructure in use by USGS and the Landsat Archive should provide a model.)

Another critical obstacle is the sequential methodology of collection, storage, management, and analysis that is conventionally followed by researchers in many disciplines. Generally, researchers first collect and store a partial dataset, then analyze and publish that dataset, before starting the next collection phase. In contrast, the proposed Earth Archive Initiative will focus initially on collection, management, and storage, so that we can maximize the amount of data collected before the destruction of more landscapes and further loss of critical land surface records.

A major priority of the initiative will be identifying the critical landscapes that researchers should focus on first. The storage of the data, in an appropriate open access form, will ensure that it’s analyzed quickly. Data analysis and publication will occur on an ongoing basis; but the process of collection will take precedence, rather than analysis and incremental “discovery.”

The other major challenge will be working together. For the Earth Archive Initiative to be successful, it must entail the involvement of, and collaboration with, researchers across disciplines, as well as the support of international research groups. Only by reaching across disciplines, embracing the technological tools at our disposal, and devoting the necessary resources will we be able to record the Earth’s biological and cultural heritage in high resolution. Given the dire climatic circumstances we face, it could turn out to be one of the most important endeavors of our time.

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