POLICY FORUM

FOREST LOSS

Combating deforestation: From satellite to intervention

Near–real-time monitoring and response are possible

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Tropical forests are critically important for human livelihoods, climate stability, and biodiversity conservation but remain threatened (*1*). Recent years have seen major strides in documenting historical and annual tropical forest loss with satellites (*2*). Now, a convergence of satellite technologies and analytical capabilities makes it increasingly possible to monitor deforestation in near real time, on the scale of days, weeks, or months, rather than years (*3*, *4*). This advance creates greater potential for near–real-time action as well and could play a key role in achieving local, national, and international forest, biodiversity, and climate policy goals, as there is a global imperative to address deforestation. Challenges remain, however, to attaining effective policy action based on the new technology. On the basis of lessons learned from pioneering work in Brazil and Peru, we suggest at least two key factors for successfully linking the technical and policy realms. On the technical side, it is critical to capitalize on continually improving satellite technology to better detect, understand, and prioritize deforestation events. On the policy side, institution building, along with related civil-society engagement, is needed to facilitate effective action within complex government frameworks. We outline a five-step protocol for near–real-time tropical deforestation monitoring, with the goal of bridging the gap between technology and policy.

MORE AND BETTER EYES IN THE SKY

The number of Earth observation satellites, and the quality and accessibility of the imagery they provide, has greatly improved in recent years (see the first figure) (*5*), making satellite imagery the most consistent and effective tool for large-scale forest monitoring. Satellite-based monitoring has four key considerations: spatial resolution, temporal resolution, sensor type, and data access. Spatial resolution (that is, pixel size) has been steadily increasing since the 1970s (see the first figure), trending from coarse (>250 m) to medium (10 to 30 m) to high (<5 m). Temporal resolution (frequency of imagery for any given location) has also improved. Until recently, there had been a trade-off between spatial and temporal resolution, with higher-resolution sensors covering less area per day. For example, NASA's coarse-resolution MODIS (Moderate Resolution Imaging Spectroradiometer) sensor collects optical imagery of every point daily, whereas medium-resolution Landsat has a revisit time of 16 days. However, constellations of miniature satellites (such as the 175 satellites of the company Planet) address the trade-off, by providing high-resolution (3 m) optical imagery with near-daily frequency (*6*).

Though cloud cover often limits the availability of usable optical satellite imagery, radar sensors can penetrate clouds. The European Space Agency's new Sentinel-1 satellites offer medium-resolution radar data on a regular basis for every point on Earth (for example, every 12 days in the Amazon), regardless of the weather conditions.

Cost can limit access to some imagery. Although coarse- and medium-resolution imagery from U.S. and European governments is freely available (MODIS, Landsat, and Sentinel), high-resolution imagery from companies such as Planet (including RapidEye), DigitalGlobe, and Airbus is available commercially and tends to be costly. However, the public- versus commercial-access gap is closing. For example, Europe's new Sentinel-2 satellite freely offers 10-m-resolution optical imagery every 4 days (*7*), and Sentinel-1 is the first radar satellite that provides freely available data. Planet now displays monthly 5-m-resolution cloud-free mosaics online.

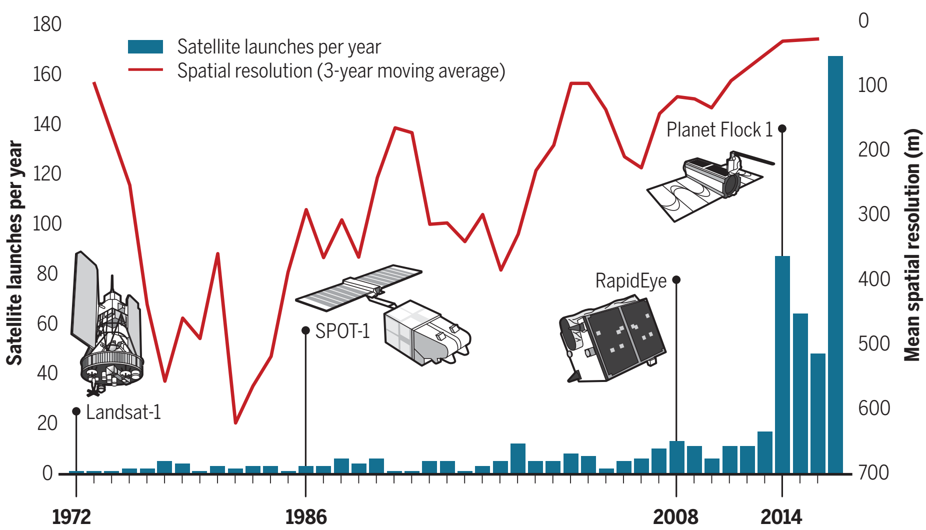
Along with improvements in resolution and access, increased computing power, such as by Google Earth Engine, has enabled effective processing of the massive amounts of satellite data.

POWER IN THE PROTOCOL

The challenge remains to harness improving satellite technology and unprecedented data streams into a strategic and effective monitoring system that can ultimately be used by decision-makers to reduce defor-

Trends in earth observation satellites

Data reflect 488 earth observation satellites launched since 1972 by commercial and government providers (excluding military). We followed methods established in (5) and added satellites from the Union of Concerned Scientists database and public launch information from SpaceFlightNow and Planet. See the supplementary materials for details.



GRAPHIC: ADAPTED BY KELLIE HOLOSKI/*SCIENCE*

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estation. We propose a five-step near–real-time deforestation-monitoring protocol designed primarily for government and civil society. This comprehensive protocol, based on recent monitoring initiatives in the Amazon (*8*, *9*) and insights from the international Global Forest Watch partnership, is particularly aimed at tropical countries that are designing strategies to confront deforestation. One of our main motivations is to help convert cutting-edge technological data into actionable information, a transformation that has thus far been lacking on a global scale.

Forest loss detection

The first step is to detect forest loss as precisely and quickly as possible. Advances in automated forest-loss detection have followed those of satellites. The original near–real-time detection systems, starting in the early 2000s, utilized coarse-resolution MODIS imagery, including well-known systems in Brazil [DETER (Real-Time System for Detection of Deforestation; government) and SAD (Deforestation Alert System; civil society)] and Terra-i and FORMA (Forest Monitoring for Action) from international organizations.

More recently, detection systems have incorporated medium-resolution Landsat imagery. In 2009, researchers at the Carnegie Institution for Science developed CLASlite (Carnegie Landsat Analysis System–Lite), pioneering Landsat-based forest-loss detection software. In 2016, researchers at the University of Maryland developed GLAD (Global Land Analysis and Discovery), the first fully automated, Landsat-based alert system (*10*). In 2017, the Peruvian government, which previously used GLAD, developed its own Landsat-based alert system.

Most recently, the Brazilian SAD alerts were further innovated by incorporating Sentinel imagery, both optical and radar. Thus, sensing capability for automated forest-loss alerts has improved resolution by two orders of magnitude (from 1000 to 10 m) in less than a decade and can see through clouds. Future alerts may improve to 3 m, with Planet imagery.

Given the widespread nature of small-scale deforestation events (*11*), medium-resolution (Landsat and Sentinel)–based alerts have replaced coarse-resolution (MODIS)–based alerts as the standard. As a practical option, GLAD alerts now cover more than 20 tropical countries, essentially providing pantropical coverage. These alerts are free datasets, updated weekly, that indicate 30 m–by–30 m pixels of likely forest loss. For Brazil and Peru, there are also more specialized alerts.

Prioritization of data

Alerts may yield thousands, even millions, of raw data points (pixels) on a regular basis and can quickly become overwhelming, especially at larger scales. Thus, prioritizing alert data is often necessary, for example, by incorporating important spatial data such as protected areas, indigenous territories, or any specific area of interest. Kernel density analysis identifies deforestation hot spots, allowing users to focus on geographic areas with the highest concentrations of recent forest loss (*12*). Other prioritization techniques include visually scanning for large clusters or linear features that indicate anthropogenic clearing and adding river and terrain information to screen for forest loss that is likely due to natural causes. In the future, machine learning may aid prioritization by highlighting the most important alerts on the basis of pattern (size and density), shape (linear), and location (overlap with areas of interest).

"...effective government institution building is the key element to ensuring that near-real-time forest monitoring information is utilized."

Identification of drivers

To convert priority alerts to actionable information, they need to be validated, to verify that the highlighted pixels are indeed deforestation, and investigated, to determine the driver (cause).

Alerts can typically be validated by visually checking the underlying medium-resolution imagery (Landsat or Sentinel). Also, new mobile apps, such as Forest Watcher, facilitate field verification. Drones, which can fly targeted missions under cloud cover, will likely play increasing roles in providing local information.

After validation, visual analysis of high-resolution imagery is an effective and efficient technique to determine the driver. Our protocol focuses on identification of the direct driver, the immediate action at the local level that is causing the forest loss. For example, important direct drivers in the Amazon include agriculture (both large and small scale), logging roads, and gold mining (see second figure). In turn, identification of the direct driver aids identification of the indirect driver, such as a market force, that often determines the appropriate policy action. For example, the response to a new mining operation will be different, and involve different government agencies, than the response to a new oil palm plantation.

In cases where high-resolution imagery is cost-prohibitive, there are improving free alternatives. At 10-m resolution, Sentinel-2 is sufficient to distinguish most drivers. Further, Planet now offers 5-m-resolution visual maps online, updated monthly.

In the future, machine learning could greatly enhance identification of major deforestation drivers (such as mining and agriculture) and even identify specific crop types (oil palm, cacao, coffee, soy, and so on) from satellite imagery.

Timely communication of results

The next challenge is to communicate important results when traditional methods, such as published reports or peer-reviewed articles, are not time-effective options. Although the operative audience is government officials, as described in the next step below, there is scientific, educational, and governance (transparency) value in reaching a wider public audience that includes civil society, journalists, researchers, and the private sector. It is often difficult to predict the exact group of actors that will seize on any given set of new findings, so it is strategic to cast a wide net, as this step is important in bridging the gap between the technical and policy components.

Civil society has developed approaches that may serve as a model. Launched in 2015, Monitoring of the Andean Amazon Project (MAAP) specializes in publishing concise, timely, web-based reports about ongoing near–real-time monitoring efforts in the Andean Amazon. Reports often feature high-resolution imagery both before and after recent deforestation events. All reports are reviewed by preselected expert committees before publication. Particularly sensitive findings, such as illegal activity that may be subject to an intervention, are passed directly to relevant government entities before being made public.

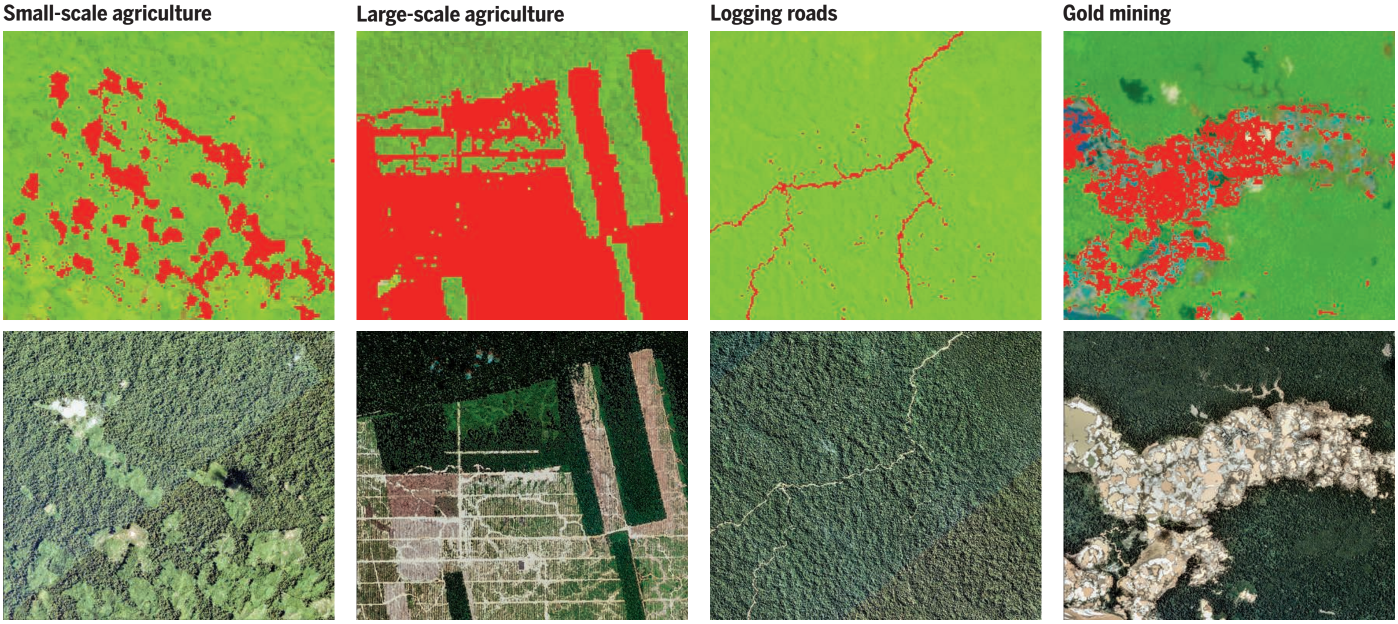
Global Forest Watch has recently built off this approach, expanding to a global scale with the "Places to Watch" initiative (*13*). Brief, web-based reports highlight the most consequential cases of recent deforestation identified by GLAD alerts around the tropics.

Impact to reduce deforestation

The ultimate goal is that the steps above lead to actual policy or conservation action. On the basis of recent experience in the Amazon, first in Brazil and now also in Peru, effective government-institution building is the key element to ensuring that near–real-time forest monitoring information is utilized.

Detecting deforestation and identifying drivers in the Peruvian Amazon

Detecting forest loss with Landsat-based GLAD alerts (top) and identifying deforestation drivers with high spatial and temporal resolution Planet imagery (bottom).



IMAGES: (TOP ROW) GLOBAL FOREST WATCH; (BOTTOM ROW) PLANET

Streamlined coordination between the array of government ministries and agencies to process and respond to the technical information is critical. In a pioneering effort, the effective use of MODIS-based deforestation alerts (DETER) was widely credited with helping to curb surging deforestation in the Brazilian Amazon in the early 2000s. Notably, the Brazilian government increased its capacity to physically and legally respond to the alerts by improving coordination across 15 ministries (including the federal police, army, and public prosecutor) (*14*, *15*).

Similar institution building is now taking place in Peru, which is constructing a National System of Monitoring and Control, led by the National Forest Service and Wildlife Authority (SERFOR), to coordinate actions related to the generation, analysis, and response to deforestation information among government entities. This system is specifically designed to build the government infrastructure for efficient, data-driven policy action, including laying out responsibilities and pathways for the complex array of actors. Notably, in addition to generating and receiving forest-loss information (that is, detection), SERFOR conducts both a technical and legal analysis of the data before sending the information to decision-makers. This technical and legal analysis also provides detailed guidance to authorities on how to prioritize deforestation events, on the basis of factors such as driver, area, and land designation, to facilitate prompt decision-making.

Although Brazil and Peru are the most advanced examples, other countries are making progress as well. Colombia is now producing quarterly early-warning reports to identify the most-active deforestation fronts across the country. These reports are an input for the strengthening of coordinated actions between the environment ministry, regional authorities, and the military. The Indonesian government is also using near–real-time monitoring data as an additional source of information to improve law enforcement in the forestry sector.

Civil society has also emerged as a key actor related to institution building. Brazil, again, led the way with the development of an independent alert system (SAD) in addition to the government-generated alerts. This independent data generation and analysis by civil society set an important precedent, with implications for improving transparency, spurring innovation, and creating public pressure.

In Peru, the civil society–designed protocol presented in this paper served as an initial model for the emerging National System of Monitoring and Control. The protocol was modified and expanded on to fit Peru's complex government structure but serves as a good example of how civil society, and the protocol itself, may assist institution building. In Uganda, civil society (led by the Jane Goodall Institute) is training government rangers to use GLAD alerts to identify and respond to new deforestation fronts.

Advancing satellite technology has made near–real-time deforestation monitoring increasingly feasible for a growing number of countries and actors. Our protocol may serve as a foundation for efforts to effectively link the technological advances with the ultimate goal of policy action to reduce deforestation. ■

REFERENCES AND NOTES

1. J. Barlow *et al.*, *Nature* **535**, 144 (2016).
2. M. Hansen *et al.*, *Science* **342**, 850 (2013).
3. J. Lynch, M. Maslin, H. Balzter, M. Sweeting, *Nature* **496**, 293 (2013).
4. A. K. Pratihast *et al.*, *PLOS ONE* **11**, e0150935 (2016).
5. A. S. Belward, J. O. Skøien, *ISPRS J. Photogramm. Remote Sens.* **103**, 115 (2015).
6. D. Butler, *Nature* **505**, 143 (2014).
7. J. Li, D. P. Roy, *Remote Sens.* **9**, 902 (2017).
8. M. Finer, S. Novoa, "Patterns and Drivers of Deforestation in the Peruvian Amazon. MAAP: Synthesis #2" (Monitoring of the Andean Amazon Project, 2017).
9. E. Worsham, C. Clark, R. Fehrman, "Scaling pathways: Case study. Imazon: Using data and partnerships to save the Amazon" (Innovation Investment Alliance and CASE at Duke, 2017).
10. M. C. Hansen *et al.*, *Environ. Res. Lett.* **11**, 034008 (2016).
11. M. Kalamandeen *et al.*, *Sci. Rep.* **8**, 1600 (2018).
12. N. L. Harris *et al.*, *Environ. Res. Lett*. **12**, 024012 (2017).
13. M. J. Weisse, R. Petersen, S. Sargent, S. Gibbes, "Places to watch: Identifying high-priority forest disturbance from near-real time satellite data" (World Resources Institute, Washington, DC, 2017).
14. D. Nepstad *et al.*, *Science* **344**, 1118 (2014).
15. J. Assunção, C. Gandour, R. Rocha, *Environ. Dev. Econ.* **20**, 697 (2015).

ACKNOWLEDGMENTS

This work was partially funded by the International Conservation Fund of Canada and the Norwegian Agency for Development Cooperation. We thank C. Garcia, J. Swenson, and M. Silman for reviewing the manuscript.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/360/6395/1303/suppl/DC1

10.1126/science.aat1203

Science

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Science **360** (6395), 1303-1305.
DOI: 10.1126/science.aat1203

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