PERSPECTIVE

Revisiting the status of forest carbon stock changes in the context of the measurement and monitoring needs, capabilities and potential for addressing reduced emissions from deforestation and forest degradation

Scott Goetz\textsuperscript{1}, Ralph Dubayah\textsuperscript{2} and Laura Duncanson\textsuperscript{3}

\textsuperscript{1} School of Informatics, Computing and Cyber Systems, Northern Arizona University, Flagstaff, AZ, United States of America
\textsuperscript{2} Department of Geographical Sciences, University of Maryland, College Park, MD, United States of America

Keywords: monitoring, reporting, verification, UNFCCC REDD+, climate change, mitigation, forests

In December 2015 Goetz et al reviewed the measurement and monitoring needs, capabilities and potential for addressing reduced emissions from deforestation and forest degradation (REDD+) formulated under the United Nations Framework Convention on Climate Change (UNFCCC). REDD+ policies were adopted that same month at the UNFCCC Conference of the Parties to the Convention (COP21) as part of the Paris Agreement, a breakthrough climate change treaty that went into effect beginning November 2016. Goetz et al (2015) assessed the current status of capabilities at the time for various needs of REDD+ including (a) estimating and monitoring emissions from deforestation, (b) emissions from degradation, (c) removals by regrowth, (d) safeguards on biodiversity and separation of natural forest from plantations, and (e) various policies and measures such as attribution and enforcement. Each of these were considered broadly in the context of national reporting and meeting needs for monitoring, reporting and verification (MRV), but particularly in the context of refining activity data (i.e. forest cover change) and emission factors (forest carbon stocks in areas undergoing change). Here we revisit that paper focusing on how satellite remote sensing capabilities have, since then, advanced key components of national reporting and MRV, specifically how capabilities in measuring aboveground forest biomass (AGB) have progressed to the point they can now meet operational needs associated with the first three of the five key needs (i.e. improving estimated emissions from deforestation and forest degradation, and assessing gains in forest carbon stocks). Meeting these needs is notable because it means that countries participating in REDD+ could be eligible for performance-based payments related not only to reducing emissions (by avoiding deforestation and forest degradation) but also for increasing the carbon stocks in existing forests through management, reforestation and afforestation.

A key to the advance in meeting these REDD+ operational needs was the launch of the Global Ecosystem Dynamics Investigation (GEDI) in December 2018 (Dubayah et al 2020). GEDI is a laser instrument based on the principle of Light Detection and Ranging (Lidar) and is currently operating on the International Space Station (ISS). GEDI became operational in March 2019 and is the first space mission designed to produce three-dimensional metrics of forest canopy height and structure along with robust but straightforward estimates of AGB (i.e. forest carbon stocks), including accuracy and uncertainty metrics using established statistical inference (Dubayah et al 2022). GEDI was specifically designed to penetrate even the densest tropical forest canopies and retrieve a ground return beneath them. Canopy height products are already operationally used in mapping forest cover change by augmenting canopy cover estimates from optical satellite imagery with minimum canopy height thresholds derived from GEDI (Potapov et al 2022). Estimates of the precision of forest extent and reported AGB is central to MRV activities yet are often missing from jurisdictional reporting. In this sense, GEDI technology and data address several of the REDD+ priority research topics of the Global Forest Observations Initiative (GFOI 2020). In essence, GEDI has launched a new era of inferring, mapping and monitoring forest carbon stock changes from space.

GEDI data products are freely available from the Land Processes Distributed Active Archive Center (DAAC) and the Oak Ridge National Laboratories DAAC. The AGB data products alone have already been downloaded more than 1.5 million times (as of
October 2022). They are available in two forms; as ∼25 m ‘footprints’ densely sampled across the surface of the earth between 51.9° north and south latitudes, and as 1 km grids across that same domain. GEDI data products cover all of the tropical forest biome and the vast majority (∼90%) of the temperate forest biome. Further, a suite of additional GEDI-derived data products complements those focused on canopy height and AGB, including foliage height diversity, plant area volume density, and vertical profiles of related forest properties (e.g. cover, leaf area index). These data thus provide unique opportunities for not only mapping and monitoring changes in forest carbon stocks but also for addressing the ecological integrity of forests (Hansen et al 2020) and their suitability for sustaining other aspects in REDD+ such as safeguards on biodiversity (Pillay et al 2022) and separation of natural forest from plantation (Potapov et al 2022). GEDI data products have also been incorporated in data processing streams that fuse them with data from other earth observation satellites to produce seamless global maps of canopy height at fine spatial resolution (Potapov et al 2021, Lang et al 2022) and similar maps for AGB are underway that will provide global benchmark data sets with well quantified uncertainty.

GEDI AGB data, in particular, fill the need for globally consistent emission factors to combine with long-term optical satellite monitoring of activity data (i.e. forest conversion and degradation). Thus, losses of forest cover can now be assigned spatially explicit, well quantified emissions factors from the AGB products, enabling a step change in forest monitoring and verification of reported emissions (i.e. MRV). Moreover, past emissions can be estimated through fusion of GEDI and longer-term time series imagery documenting cover change, including the nearly 40 year Landsat record at 30 m spatial resolution (e.g. Francini et al 2022). Further applications of GEDI data for mapping and monitoring forest carbon stock changes will undoubtedly expand rapidly in the near future.

Even though the community has anticipated this capability for over two decades, GEDI is a NASA Earth Ventures Instrument project, and as such was designed and funded to meet targeted investigational goals over a nominal 2 year mission length, which was later extended to 4 years. To meet the needs of MRV and REDD+ requires sustaining the observational capabilities of GEDI with longer-term satellite missions designed to operate over a decade or more. Work on such follow-on missions has been initiated, but they will likely take at least a decade to reach orbit and start producing continuous data products to extend the GEDI legacy. Although the GEDI mission shows virtually no signs of degradation, it is currently (as of this writing) scheduled to be removed from the ISS in February of 2023, unless the mission is again extended. Such an extension would provide continued data acquisition but also, importantly, coincident coverage with new satellite missions planned for launch in 2023 and beyond. These notably include new L-band and P-band synthetic aperture radar (SAR) missions, which would extend GEDI’s samples for wall-to-wall mapping at higher spatial resolution while also being able to acquire imagery through cloud cover. This is particularly important in perpetually cloudy areas such as the Tropics where REDD+ is focused.

NASA and the Indian Space Agency, ISRO, are scheduled to launch the NASA ISRO L-band SAR (NISAR) mission in 2024, which will produce its own forest biomass stock and change products with a high temporal repeat (global coverage every 12 d). While AGB estimates from SAR data often saturate at moderate to high biomass levels, physically-based and machine learning models may extend the useful range of biomass mapping by training on the billions of structure and biomass estimates GEDI provides (Khati et al 2021). Another complementary satellite mission called BIOMASS, developed by the European Space Agency (ESA) primarily for mapping and monitoring forest biomass, primarily in tropical forest ecosystems, is scheduled for launch in late 2023. This P-band SAR mission is novel from a space technology perspective and will be the first SAR mission launched with the longer P-band wavelengths that are capable of penetrating deeper into forest canopies than L-band data. The BIOMASS mission will also use GEDI data to calibrate its AGB estimation algorithm (Banda et al 2020). Taken together, the confluence of GEDI, NISAR and BIOMASS enables more accurate, higher spatial resolution, cloud-free, wall-to-wall, global biomass maps.

The time series of the SAR missions will also enable detailed quantification of the biomass losses associated with deforestation and degradation, thus contributing directly to REDD+ needs. For example, the TanDEM-X satellites (Kugler et al 2014) have provided interferometric, x-band SAR observations since 2010. There have been two global coverages of the Earth’s forests to date from the 2010 and 2020 epochs, with a potential new coverage in 2023. GEDI data have been combined with TanDEM-X to map forest height and canopy structure at high spatial resolutions (Qi et al 2019, Guliaev et al 2021), and their fusion provides the opportunity for mapping biomass change across 15 years.

One challenge that will emerge with these next generation SAR missions is related to data dissemination and processing. This is particularly true of NISAR, which is anticipated to collect upwards of 140 petabytes of data in the first 3 years on-orbit.
A second challenge relates to transparency of data products and associated algorithms. REDD+ requires not only reliable products, but transparency in their generation and uncertainty estimation. To address these challenges, NASA has adopted an Open Science approach that requires all mission algorithm code to be publicly available. Indeed, the NISAR and BIOMASS algorithms for forest biomass mapping are already generated following Open Science standards (e.g. Banda et al 2020). Moreover, ESA and NASA have partnered to create a new open science tool to help enable researchers to both handle the large data volumes expected from the new missions and develop open source algorithms across agencies. This capability, called the Multi-mission Algorithm and Analysis Platform (MAAP, Albinet et al 2019), is currently in a pilot phase but will be available for researchers to conduct global-scale biomass mapping in anticipation of GEDI-calibrated NISAR and BIOMASS data.

Meeting the needs for REDD+ MRV is dependent on both new satellite missions and new capabilities development to sustain the advances made over the past decade, thus enabling implementation and success of REDD+ as well as related international programs such as the UN Convention on Biological Diversity. Moreover, they will inform global efforts towards data harmonization for the UNFCCC’s 2023 and 2028 objective of taking stock, i.e. Global ‘Stocktakes’ (unfccc.int/topics/global-stocktake/global-stocktake) assessing progress on implementing the 2015 Paris agreement. We anticipate the public availability of next generation earth observation datasets in an online open-source platforms (such as the MAAP) will greatly bolster these capabilities.

Data availability statement

No new data were created or analysed in this study.

ORCID iD

Scott Goetz  https://orcid.org/0000-0002-6326-4308

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