nature reviews biodiversity

https://doi.org/10.1038/s44358-026-00178-6

Review article

Check for updates

Remote sensing delivers tropical forest resilience monitoring for the Global Biodiversity Framework

Jesús Aguirre-Gutiérrez[1,2,3,4] ✉, Isamar Cortes[1,2], Matheus Henrique Nunes[5], Moses Azong Cho[6,7], Ryuichi Takeshige[8,9] & Yadvinder Malhi[10]

Abstract

Tropical forests sustain a disproportionate share of global biodiversity and of nature's contributions to people, yet they are increasingly destabilized by interacting pressures from climate change, land-use change and intensifying disturbance regimes. Understanding and monitoring forest resilience — the capacity to resist, absorb, recover from and adapt to disturbance — requires scalable approaches that integrate biodiversity, ecosystem structure and function across space and time. In this Review, we discuss how the essential biodiversity variables (EBV) framework, enabled by satellite remote sensing, has improved understanding of forest resilience under global environmental change. Remotely sensed EBV proxies derived from multispectral, thermal, hyperspectral, radar, light detection and ranging (LiDAR) and solar-induced fluorescence observations capture multiple facets of biodiversity and ecosystem dynamics. However, scale dependence, observational biases and the limited capacity of current EBVs to resolve fine-grained biological and mechanistic processes underpinning resilience (particularly species turnover and functional reassembly) are critical limitations. Emerging opportunities, including data fusion, next-generation satellite missions and integration with in situ observations, will advance the operationalization of EBV-based resilience monitoring, particularly in the context of the Kunming–Montreal Global Biodiversity Framework.

Sections

Introduction

Relevant remote sensing methods

Remote sensing of biodiversity facets

Methodological advances and sensor limitations

From resilience to ecosystem health

Summary and future directions

A full list of affiliations appears at the end of the paper. ✉e-mail: jeaggu@gmail.com

Introduction

Tropical forests contain a large proportion of Earth's terrestrial biodiversity and have a central role in regulating global carbon, water and energy cycles[1,2]. However, they are undergoing rapid transformation under interacting pressures from climate change, land-use change and intensifying disturbance regimes such as droughts and fires[1–5]. Specifically, increasing disturbance frequency and severity are altering forest structure, composition and functioning, raising concerns about their long-term resilience and capacity to maintain ecological processes under environmental change[6,7]. Tropical forests are considered highly vulnerable to climate change as many of their species evolved under relatively stable climatic conditions[8], and low-elevation forests are especially at risk because species have limited opportunities to migrate when climatic thresholds are exceeded[9]. Understanding how biodiversity contributes to tropical forest resilience, and how these dynamics can be monitored consistently across space and time, have therefore become a major challenge in ecology and conservation science.

As ecosystem degradation increases, the loss of ecosystem functioning and its slow recovery become increasingly pronounced. For example, following droughts and fire disturbances, tropical forests can require several decades to recover pre-disturbance biomass levels, resulting in prolonged reductions in carbon storage capacity[10–12]. In response to these accelerating changes and their consequences for ecosystem function and services, a growing body of research has focused on forest resilience, seeking to understand the mechanisms by which forests cope with, adapt to and recover from climatic and anthropogenic disturbances. Multiple biodiversity facets (in other words, complementary dimensions of biodiversity, including taxonomic, functional, phylogenetic and genetic diversity) are now recognized to underpin several components of resilience, such as the capacity of tropical forests to resist, absorb, recover from and adapt to disturbance.

In an effort to monitor the state, trends and changes of biodiversity consistently across spatial and temporal scales, the Group on Earth Observations Biodiversity Observation Network (GEO BON) established a suite of essential biodiversity variables (EBVs)[13,14]. EBVs comprise six core classes: genetic composition, species populations, species traits, community composition, ecosystem structure and ecosystem function. Importantly, EBVs offer a unifying framework for translating biodiversity science into policy-relevant metrics[13,15], explicitly serving as a bridge between scientific observations and reporting requirements under the Kunming–Montreal Global Biodiversity Framework (GBF) and the biodiversity-related Sustainable Development Goals (SDGs, in particular SDG 15 'Life on land'). Remote sensing, the acquisition of information about Earth's surface using sensors mounted on satellites, aircraft or unmanned aerial vehicles (UAVs), aids EBV implementation by enabling systematic, repeatable and spatially continuous observations, which are combined with ecological models to extrapolate from local measurements to regional and global scales[16,17].

Remote sensing has emerged as a cornerstone of forest ecosystem monitoring[18–20], complementing field-based monitoring by enabling consistent tracking of biodiversity facets and ecosystem processes across space and time. Crucially, remote sensing underpins the assessment of forest resilience in several ways: through the tracking of resistance (as, for example, how much ecosystem functions such as productivity or gas exchange decline during disturbance); through the tracking of structural changes (vegetation structural composition and landscape fragmentation); and by quantifying recovery (how quickly ecosystem functions return to pre-disturbance levels). Long-term satellite missions, such as Landsat, have been useful in monitoring ecosystem change through consistent multispectral observations over several decades. Newer spaceborne missions are now capable of capturing key dimensions of ecosystem structure and function. For example, the Global Ecosystem Dynamics Investigation (GEDI) provides full-waveform light detection and ranging (LiDAR) measurements that improve characterization of forest vertical structure[21], and ESA (European Space Agency)'s BIOMASS mission aims to enhance the accuracy of global estimates of forest carbon dynamics. Together, products derived from these missions have substantially improved the ability to observe forest change and infer proxies of resilience across regional to global scales. However, despite these advances, important limitations remain. In particular, uncertainties persist at local scales owing to spatial resolution constraints, as well as the scarcity of field observations required for robust calibration and validation in many tropical regions. More fundamentally, the extent to which remotely sensed observations can capture the multidimensional and process-based nature of forest resilience, especially its biological and mechanistic components, remains an open question.

In this Review, we address this challenge by assessing to what extent the EBV framework, enabled by remote sensing, has improved understanding of tropical forest resilience to global change. Moving beyond a general overview, we focus specifically on how remotely sensed proxies for key biodiversity facets, taxonomic, functional, phylogenetic and genetic (Fig. 1), have contributed to diagnosing, monitoring, and, increasingly, anticipating resilience dynamics in tropical forests. We evaluate the major advances achieved through remote sensing for the generation of EBVs, while critically examining their limitations in capturing the complexity and multiscale nature of resilience, particularly with respect to species turnover, functional reorganization, and ecological processes that remain only partially observable from space. Finally, we identify persistent conceptual and methodological gaps and highlight emerging opportunities, including data fusion (integration of information from multiple sensors or datasets to improve biodiversity monitoring, reduce uncertainty and enhance ecological interpretation), next-generation satellite missions and stronger integration with in situ observations, to strengthen the role of EBVs in resilience assessment across tropical forest ecosystems. These developments are essential for advancing more robust, scalable and policy-relevant monitoring frameworks in support of international commitments such as the GBF, particularly in the context of rapidly intensifying global environmental change.

Relevant remote sensing methods

Remote sensing provides a multiscale suite of tools for monitoring tropical forest biodiversity from individual species to entire biomes. In this section, we review the principal sensing systems used in biodiversity research, from spaceborne passive and active platforms to airborne (crewed) and drone-based (uncrewed) instruments. We situate the methods within the EBV framework by discussing their integration into standardized EBV monitoring pipelines.

Sensors and associated EBV products

Remote sensing systems are broadly divided into active and passive approaches. Active systems, such as LiDAR, emit their own energy and measure returned signals to retrieve 3D vegetation structure.

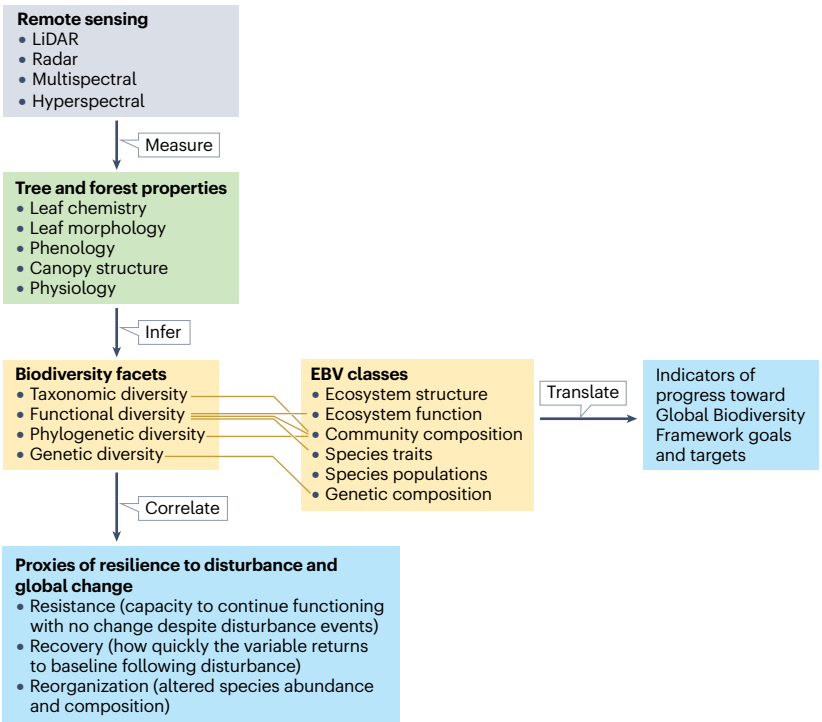


Fig. 1 | Conceptual framework for linking vegetation remote sensing to tropical forest resilience and the Kunming–Montreal Global Biodiversity Framework. Remote sensing platforms can measure several properties of trees and forests, which are then used to infer biodiversity facets and essential biodiversity variables (EBVs). When monitored over time and across space, these biodiversity variables can be correlated with several proxies of forest resilience. The variables can also be translated into indicators of progress toward Kunming–Montreal Global Biodiversity Framework targets. LiDAR, light detection and ranging.

Spaceborne examples include GEDI, which provides near-global measurements of canopy height, vertical structure and estimates of above-ground biomass through laser sampling of forest profiles[21,22]. By contrast, passive remote sensing systems rely on reflected solar radiation to derive spectral information[23]. Multispectral sensors (such as Sentinel-2 and Landsat) capture discrete spectral bands and are widely used to measure land cover, vegetation condition and their changes across time and space. Hyperspectral sensors operate on the same physical principle but offer substantially higher spectral resolution, acquiring data in hundreds of narrow, contiguous bands, thereby enabling more detailed characterization of morphological, biochemical and physiological vegetation properties than multispectral sensors.

Recognizing the growing role of satellite observations in biodiversity monitoring, the concept of satellite remote sensing EBVs was introduced as a unifying framework for integrating satellite, airborne and in situ observations into harmonized biodiversity indicators[24] (Table 1). However, the six main EBV classes have been studied to a varying extent in the context of remote sensing, and important gaps remain (Box 1). Advancing the use of remote sensing to quantify biodiversity resilience requires close collaboration between ecologists, conservationists and the Earth observation community, particularly to improve ecological models with enhanced predictive and explanatory capacity.

Spatial, spectral and temporal scaling

One of the primary advantages of spaceborne remote sensing is its ability to provide repeat sampling over large spatial extents (Table 1). For example, Sentinel-2 offers ~10-m spatial resolution with global revisit times of ~5 days since 2015, enabling high-frequency monitoring of tropical forest condition and disturbance. This temporal resolution is particularly important because tropical forests occur in persistently cloud-prone environments where frequent observations increase the likelihood of acquiring usable data. When combined with Landsat imagery, Sentinel-2 contributes to continuous multidecadal data (from 1972), supporting long-term monitoring of tropical forest change. Such change detection approaches typically rely on pixel-based and band-based classification techniques to identify forest resilience through trends in forest dynamics, disturbance and recovery[25].

Spatial resolution strongly influences biodiversity inference. Although satellite sensors provide moderate resolution, airborne platforms and UAVs offer centimetre-level detail, enabling fine-scale mapping of forest heterogeneity and individual canopy features. Drone-based multispectral systems (typically 3–10 bands) can resolve local species or functional variation, but remain limited in spatial coverage, repeatability and operational scalability. They are therefore most valuable for calibration, validation and linking field data to satellite-scale products in multiresolution frameworks[26].

Remote sensing of biodiversity facets

Multiple aspects of biodiversity together determine forest resilience, including the capacity to resist disturbance, recover from stress, and reorganize under novel environmental conditions (Fig. 2). Framing these facets as EBVs clarifies not only their ecological roles in sustaining resilience, but also what dimensions are currently monitorable at scale and where observational gaps persist. In this section, we discuss how four key biodiversity facets (taxonomic, functional, phylogenetic and genetic diversity) that are part of the EBVs framework underpin different components of resilience and to what extent remote sensing can detect, quantify and track its dynamics at operationally relevant spatial and temporal scales.

Table 1 | Remote-sensing-derived essential biodiversity variables (relevant to tropical forest monitoring)

EBV class	Spatial extent	Representative indicators	Remote sensing measurements
Ecosystem structure	Local to global	Vegetation structure; habitat structure and pattern; forest disturbances; vegetation classification and land use change	Spectral indicators from optical imagery (NDVI, EVI, texture metrics)[135,136]; SIF for land use detection[127,137]; LiDAR-based height metrics, canopy cover, PAI, canopy vertical complexity[138–146]; L-band, P-band of SAR for AGB, and ground penetrating radar for below-ground biomass[147]; fusion of radar/optical with spaceborne LiDAR (for example, GEDI-Tandem-X or Landsat-GEDI)[148,149]
Ecosystem function	Regional to global	Gross or net primary productivity; carbon stocks; carbon emissions; carbon sink; evapotranspiration; canopy water content; canopy nitrogen content; ecosystem phenology (photosynthesis, respiration, green-up)	SIF from OCO-2/OCO-3, Sentinel-5P as a proxy for photosynthesis, capturing GPP, carbon flux and responses to drought[127,137,150–152]; multispectral imagery-based NDVI, EVI, fAPAR, LAI, phenology and VHI from MODIS, Sentinel-2 or Landsat[153–155]. Thermal infrared-based land surface temperature and evapotranspiration from MODIS thermal, Landsat TIR, ECOSTRESS; passive microwave-based vegetation water content from SMAP/SMOS and VOD[128,156–158], LiDAR and radar-based AGB recovery and carbon sink/source[159]
Community composition	Regional	Plant functional types; species assemblages; floristic composition; species richness; taxonomic, functional and phylogenetic diversities; community homogenization	Optical imagery for NDVI, EVI, FCVI, SAVI, texture metrics from Landsat, Sentinel-2, PlanetScope, WorldView-2/-3 and MODIS[160,161]. Canopy surface temperature, thermal heterogeneity and heat stress frequency from Landsat TIR and ECOSTRESS; SAR for backscatter, polarimetric decomposition, and canopy penetration differences from Sentinel-1, ALOS PALSAR and Polarimetric SAR[162]; canopy-level reflectance data using UAV-borne, airborne and spaceborne hyperspectral sensors, for example, AVIRIS/AVIRIS-NG, DESIS, HyMap, APEX, Hyperion; LiDAR-based canopy height metrics, canopy rugosity, gap fraction, vertical foliage profile and complexity, including terrestrial, airborne and spaceborne LiDAR[163,164]. SIF-based maximal photosynthesis[165]
Species traits	Local to regional	Morphological, physiological, ecological and reproductive plant traits	Hyperspectral reflectance for biochemical and physiological traits retrieval from airborne (for example, CAO-2, AVIRIS, AVIRIS-NG, HyMap, AISA Eagle, APEX, CASI) and spaceborne (for example, Hyperion (EO-1), DESIS, PRISMA)[166–170]; terrestrial and airborne LiDAR for architectural and structural plant traits, and individual tree crown trait mapping[124,171–173]; optical multispectral LAI, deciduousness, flowering based on Sentinel-2, Landsat, MODIS, PlanetScope and WorldView[174–178]
Species populations	Local to regional	Species distributions, species abundances, species presence and absence; seedling establishment, colonization, invasive species dominance, population turnover; survival rate, mortality rate, population decline, extinction risk, local extinction	Optical imagery, including very-high-resolution WorldView-2/WorldView-3, Pléiades 1A, Sentinel-2 MSI and Landsat (TM, ETM+, OLI)[179–184]; hyperspectral and LiDAR (see 'Species traits' above)[185,186]
Genetic composition	Local to regional	Genetic diversity, genetic variance; allelic richness, heterozygosity, polymorphism, genetic bottleneck; genetic differentiation (number of genetic units and genetic distance), effective population size and inbreeding, genetic connectivity and gene flow, adaptive evolution	Leaf-level spectral reflectance and imaging hyperspectroscopy[69,92–97]; complementary optical imagery for landscape connectivity, fragmentation, and species occurrence; LiDAR supports crown segmentation and tree architecture[187]

Further details regarding the example studies are provided in Supplementary Table 1. AGB, above-ground biomass; AISA, Airborne Imaging Spectrometer for Applications; ALOS PALSAR, Advanced Land Observing Satellite Phased Array L-band Synthetic Aperture Radar; APEX, Airborne Prism Experiment; AVIRIS, Airborne Visible/Infrared Imaging Spectrometer; AVIRIS-NG, Airborne Visible/Infrared Imaging Spectrometer–Next Generation; CAO-2, Carnegie Airborne Observatory 2; CASI, Compact Airborne Spectrographic Imager; DESIS, DLR Earth Sensing Imaging Spectrometer; EBV, essential biodiversity variable; ECOSTRESS, Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station; EVI, Enhanced Vegetation Index; ETM+, Enhanced Thematic Mapper Plus; fAPAR, fraction of absorbed photosynthetically active radiation; FCVI, Forest Canopy Vegetation Index; GEDI, Global Ecosystem Dynamics Investigation; GPP, gross primary productivity; Hyperion, Hyperion imaging spectrometer onboard EO-1 (Earth Observing-1); LAI, leaf area index; LiDAR, light detection and ranging; MSI, MultiSpectral Instrument; MODIS, Moderate Resolution Imaging Spectroradiometer; NDVI, Normalized Difference Vegetation Index; OCO-2, Orbiting Carbon Observatory-2; OCO-3, Orbiting Carbon Observatory-3; OLI, Operational Land Imager; PAI, plant area index; PRISMA, Precursore Iperspettrale della Missione Applicativa; SAR, synthetic aperture radar; SAVI, Soil-Adjusted Vegetation Index; Sentinel-5P, Sentinel-5 Precursor; SIF, solar-induced fluorescence; SMAP, Soil Moisture Active Passive; SMOS, Soil Moisture and Ocean Salinity; TM, Thematic Mapper; TIR, thermal infrared; UAV, unmanned aerial vehicle; VHI, Vegetation Health Index; VOD, vegetation optical depth.

Taxonomic diversity

Taxonomic diversity is a fundamental dimension of biodiversity and a key determinant of forest resilience. High species richness (α-diversity) and heterogeneous species composition across space (β-diversity) buffer ecosystems against climate extremes, facilitate post-disturbance regeneration and promote long-term stability through functional complementarity and redundancy[27]. Temporal changes in β-diversity can reveal forest homogenization following repeated disturbance, indicating resilience loss[28,29]. Within the EBV framework and specifically within the community composition EBV class, taxonomic diversity is central to understanding how forest communities reorganize under disturbance and climate change[30].

Taxonomic diversity can be monitored through surrogate- and count-based remote sensing approaches. Surrogate approaches infer taxonomic diversity patterns from spectral or structural heterogeneity. Hyperspectral data, for example, use relationships between spectral variability and species turnover to estimate α-diversity and β-diversity[31]. Based on the spectral species concept and the spectral-variation hypothesis[32], whereby pixels with similar spectra are clustered to estimate α-diversity and β-diversity, these approaches have been applied using airborne, UAV and satellite data in tropical forests[33–35]. Although they do not estimate absolute species richness, they provide robust proxies of taxonomic diversity and identify areas of high species turnover associated with ecological resilience[36]. Count-based approaches aim

to directly map species distributions using high-spatial-resolution optical imagery. Their application in tropical forests remains challenging owing to extreme species richness and difficulties in delineating individual tree crowns (but see recent work[37]). A notable exception is French Guiana, where 169 species were mapped using airborne hyperspectral imagery and automated crown segmentation[38].

Broad-scale, wall-to-wall mapping of taxonomic diversity with remote sensing can complement field inventories typically biased towards accessible areas[39]. Progress in this field is driven by (1) the spectral species concept, the spectral-variation hypothesis and spectranomics[40], where canopy spectral heterogeneity reflects chemical and structural variations linked to potential single species and species diversity, and (2) multisensor fusion and individual-tree approaches that combine spectral, structural and contextual data to map α-diversity and β-diversity across scales[41]. At fine scales, UAV platforms equipped with hyperspectral and LiDAR sensors support individual-tree crown delineation and species assignment, providing high-resolution maps of α-diversity and β-diversity[41].

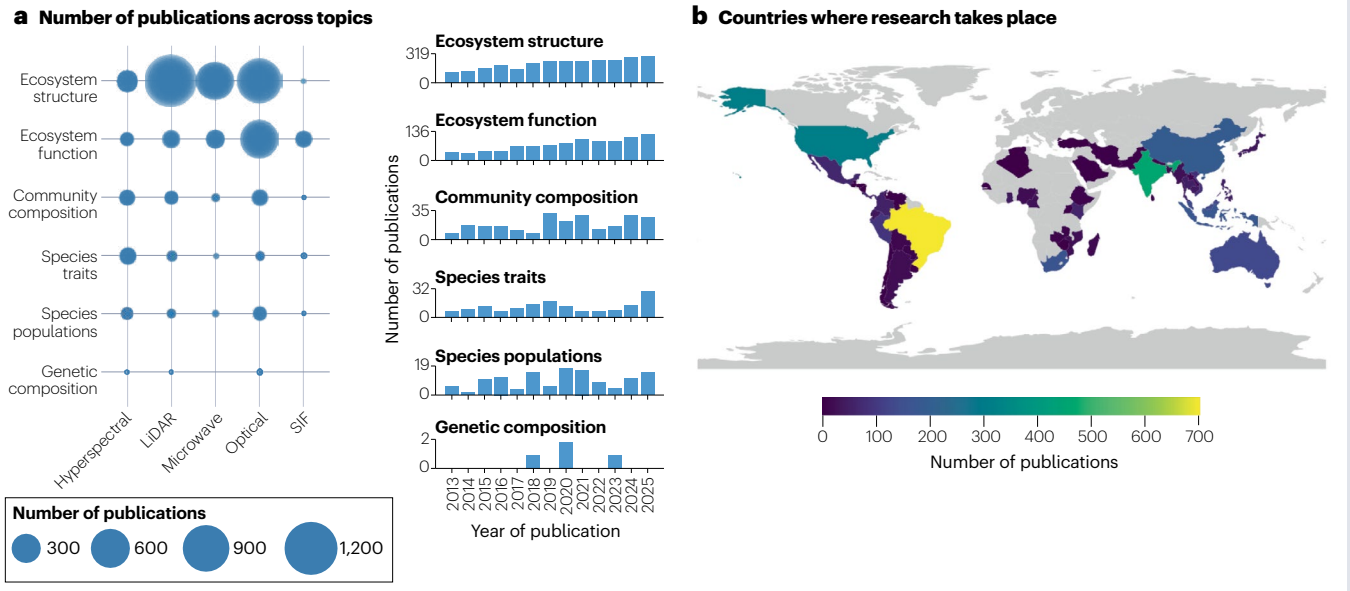
Imaging spectroscopy, primarily from airborne and increasingly from spaceborne platforms, has been used to retrieve foliar traits that can be clustered or modelled to infer species richness and turnover. Studies in tropical and subtropical forests show that imaging spectroscopy reliably captures α-diversity and β-diversity when integrated with plot inventories[42]. In parallel, high-resolution multispectral sensors (for example WorldView and Planet), together with Sentinel-2 and Landsat time series, are used to map community types and diversity proxies using calibration data and multitemporal metrics. Other approaches further partition γ-diversity into α-components and β-components using multispectral or hyperspectral data within ordination frameworks, enabling spatially explicit diversity assessments[43].

Box 1 | Gaps in the use of remote sensing to study EBVs

Some essential biodiversity variable (EBV) classes have been better studied in the remote sensing literature than others. To illustrate patterns in data gaps, we retrieved articles (n=4,481) published between January 2013 and December 2025 that used hyperspectral, LiDAR, microwave, optical and solar-induced fluorescence (SIF) sensors to measure or predict indicators within the six EBV classes: ecosystem structure, ecosystem function, community composition, species traits, species populations and genetic composition (methods details in Supplementary Information).

Studies of ecosystem structure are most abundant in the remote sensing literature, with nearly 1,200 publications, far exceeding all other EBV classes. Ecosystem structure is followed distantly by ecosystem function, whereas genetic composition remains almost entirely unstudied via remote sensing (part **a** of the figure, left panel). Further, different sensor types have been used to different extents in the detection of EBVs. Optical and hyperspectral sensors account for the largest share of publications across most biodiversity dimensions, whereas LiDAR shows strength specifically for ecosystem structure. Publication output has increased substantially since 2013 for ecosystem structure and function, whereas EBV classes related to biodiversity have seen little to no growth (part **a** of the figure, right panel).

Strong geographical biases are also evident, with most remote sensing studies of EBVs having focused on Brazil (mainly the Cerrado, the Atlantic Forest and the Amazon). Conversely, most of tropical Africa remains poorly studied in this context (part **b** of the figure). As in many other fields of biodiversity science, the locations of study and the locations where the authors are based differ; in this case, research on tropical ecosystems is conducted primarily by researchers based in the USA, UK, Brazil, China and India (Supplementary Fig. 1). These disparities highlight persistent gaps in both observational coverage and scientific capacity that continue to shape what can currently be inferred about tropical forest resilience via remote sensing.



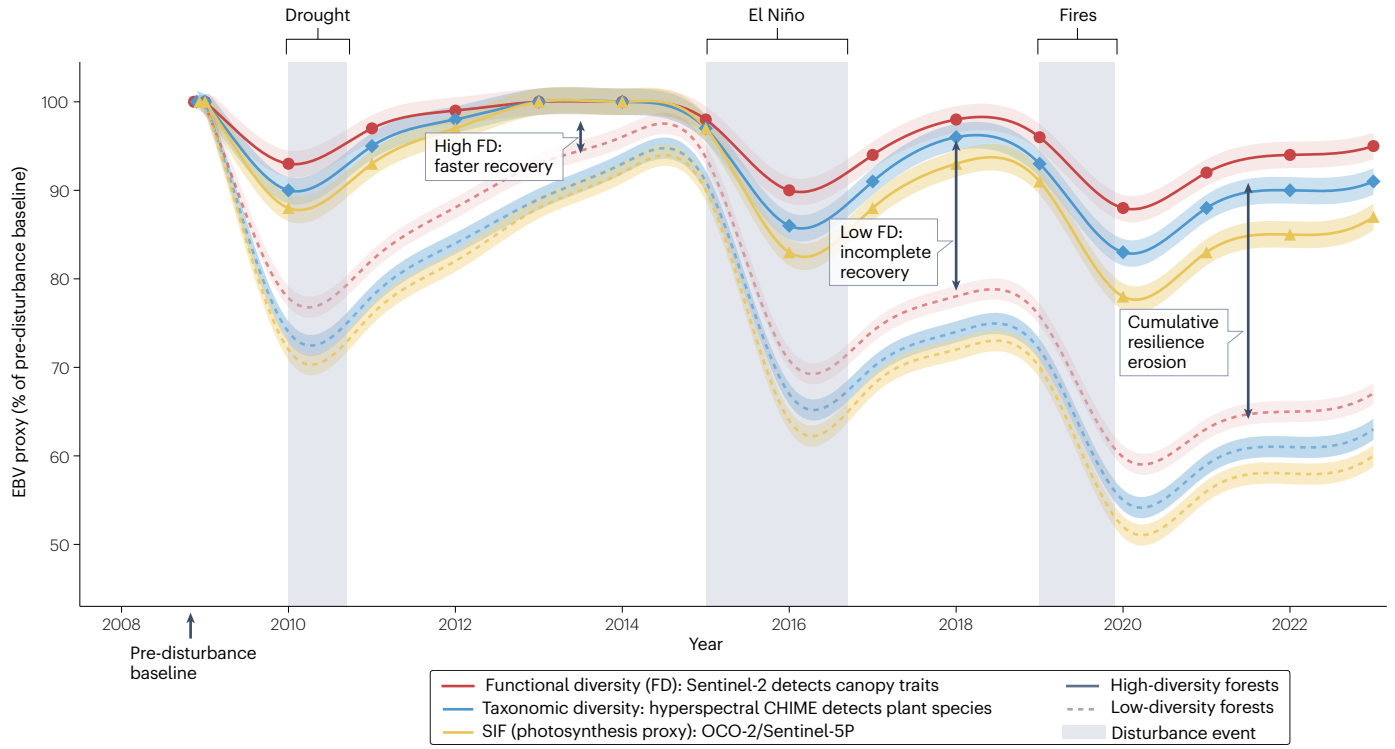


Fig. 2 | Biodiversity facets tracked by remote sensing as predictors of tropical forest resilience. Stylized time series to illustrate how satellite-derived essential biodiversity variable (EBV) proxies could differ between high-diversity (solid lines) and low-diversity (dotted lines) tropical forests in response to three successive disturbance events in the Amazon (vertical shaded columns): the 2010 drought[10,27], the 2015–2016 El Niño event[128,152] and the 2019–2020 fire season[144,145]. Functional diversity (FD; red lines) can be derived from Sentinel-2 canopy trait mapping following the pixel-level community-weighted mean trait method[55], capturing morphological, structural and chemical functional traits linked to drought tolerance, hydraulic strategy and post-disturbance recovery capacity. Taxonomic diversity (blue lines) can be approximated from airborne and uncrewed aerial vehicle hyperspectral imagery using the spectral species concept and spectranomics framework[32,40], whereby spectral heterogeneity serves as a proxy for species turnover and compositional diversity. Sun-induced fluorescence (SIF; yellow lines) can be derived from OCO-2 and Sentinel-5P observations as a proxy for gross primary productivity and canopy photosynthetic capacity[127,152]. Double-headed arrows highlight the growing divergence in recovery rates between high-diversity and low-diversity forests following each event, illustrating the biodiversity insurance effect whereby higher functional diversity and functional redundancy buffer against disturbance and accelerate recovery[27,52]. The progressive failure of low-diversity forests to return to pre-disturbance baselines across successive events is consistent with cumulative resilience erosion under intensifying global change[128,157]. CHIME, Copernicus Hyperspectral Imaging Mission for the Environment.

Three major methodological families have been used to determine plant taxonomic diversity levels using remote sensing: spectral diversity approaches that cluster spectra or compute heterogeneity indices; direct classification methods using random forest, support vector machine and convolutional neural networks for species assignment; and trait-based spectranomics approaches linking biochemical and biophysical traits to diversity[44]. However, scaling taxonomic monitoring remains challenging because trait–spectrum relationships vary across environments, training inventories are limited in tropical regions, and multilayer canopies obscure understorey species, where much tropical diversity and regeneration occur[45]. Emerging satellite missions and improved modelling pipelines nevertheless position remote sensing to deliver operational and repeatable taxonomic diversity maps at regional to continental scales.

Functional diversity and redundancy

Functional traits — the physiological, phenological, morphological, chemical, and structural characteristics of organisms[46–49] — determine responses to drought, heat, pests and disturbance, thereby shaping both resistance (capacity to continue functioning with no change despite disturbance events) and recovery (how quickly function returns). Functional diversity describes the range, distribution, and relative abundance of functional traits within communities, whereas functional redundancy reflects the extent to which multiple species share similar trait values. Both dimensions are central to ecosystem resilience: functional diversity promotes complementarity and niche differentiation, whereas functional redundancy provides insurance by maintaining ecosystem processes when species decline or are lost[50,51]. Across tropical forests, high functional diversity combined with high functional redundancy has been associated with reduced biomass loss and faster recovery following drought and El Niño events[27]. Mechanistically, functional diversity enables communities to exploit diverse resources and micro-niches, while functional diversity maintains ecosystem processes such as carbon sequestration, nutrient cycling and biomass accumulation during disturbance[50,52]. Functional diversity and functional redundancy are relevant to the community composition and functional traits EBV classes, and they could be monitored as indicators related to several of the GBF targets (such as Target 2, restoring 30% of degraded ecosystems).

Advances in passive and active remote sensing now allow estimation of functional diversity and functional redundancy at operational scales. Imaging spectroscopy captures canopy traits linked to biochemistry (including nitrogen, phosphorus and pigments), structure (specific leaf area) and phenology; LiDAR provides 3D vegetation structure, including canopy height, foliage distribution and gap fraction, which relate to structural traits and above-ground biomass proxies[53]. Their fusion allows derivation of community-level trait distributions used to compute functional diversity and functional redundancy, validated across tropical and temperate forests[54]. At larger scales, Sentinel-2 and other multispectral sensors estimate canopy traits and functional diversity using field trait databases[55], and spaceborne LiDAR (GEDI, ICESat-2) improves structural trait retrieval and enhances trait–diversity mapping when combined with spectral data[15,56]. Emerging missions such as ESA's Copernicus Hyperspectral Imaging Mission for the Environment (CHIME), combined with spaceborne LiDAR, are expected to improve retrieval of biochemical and structural traits, and to enable routine functional diversity and functional redundancy monitoring.

It is expected that greater diversity and redundancy levels increase ecosystem resilience because functionally diverse and redundant communities are more likely to maintain ecosystem processes under environmental change, disturbance or species loss through mechanisms such as complementarity, redundancy and insurance effects[57]. Therefore, temporal dynamics in trait composition, including shifts in functionally redundant groups detected from repeat hyperspectral data, can reveal declining ecosystem insurance before structural degradation becomes visible. Key challenges remain, including context-dependent trait–reflectance relationships, uncertainty propagation into diversity metrics, and the need for species identity and abundance data to robustly estimate redundancy. Practical workflows combining field networks, airborne campaigns, satellite time series and uncertainty-explicit validation will remain essential for delivering robust, policy-relevant functional diversity and functional redundancy predictions that can detect functional erosion and declining resilience capacity before forests cross critical thresholds.

Phylogenetic diversity

Phylogenetic diversity quantifies evolutionary breadth by summing branch lengths among co-occurring species[58]. Phylogenetic diversity captures deep evolutionary differences that correspond to variation in ecological strategies and functional traits that can influence resilience[59,60]. Communities with high phylogenetic diversity comprise distantly related lineages that exploit complementary niches, thereby enhancing ecosystem stability and resilience through niche complementarity[61]. Because many traits that influence drought tolerance, defence and demographic performance, such as wood density, hydraulic architecture, leaf morphology and defence chemistry, are phylogenetically conserved[62–64], phylogenetic diversity reflects the range of strategies available to buffer climate extremes and disturbance impacts and hence could be associated with higher forest resilience. These traits underpin key ecosystem processes, including decomposition, nutrient cycling, carbon sequestration[65,66] and population dynamics[59]. Consequently, phylogenetic diversity often predicts ecosystem productivity and stability more effectively than species richness alone[67,68] and can be used to quantify potential ecosystem resilience.

Remote sensing enables scalable estimation of phylogenetic diversity by linking evolutionary relationships to observable spectral and structural signals. Imaging spectroscopy captures leaf chemistry, phenology and structural traits with strong phylogenetic signal, allowing spectral similarity to approximate evolutionary relatedness across taxa[69,70]. LiDAR provides complementary 3D structural traits, tree height, crown geometry and vertical foliage profiles, which also reflect phylogenetic conservatism in growth forms and architectural strategies[71]. Integrating spectroscopy and LiDAR can improve the discrimination of taxa and evolutionary lineages and enables mapping of phylogenetically structured β-diversity[72,73]. However, phylogenetic diversity retrieval remains challenging owing to spectral convergence among unrelated taxa, phenological and illumination effects, mixed pixels, and incomplete phylogenetic and field datasets. Emerging missions such as ESA's CHIME and advanced spaceborne LiDAR might facilitate integrating spectral–structural approaches that can enable global-scale phylogenetic diversity mapping. This can aid in revealing evolutionary patterns in β-diversity[73] that are directly relevant to assessments of community reorganization under climate change.

Genetic diversity

Genetic diversity — heritable variation within populations — underpins adaptive capacity, the ability of populations to persist and evolve under disturbances associated with warming, altered rainfall, pests and pathogens[74,75]. It affects resilience across scales: reducing extinction risk and inbreeding depression at the population level[76]; stabilizing competitive interactions and reducing invasibility at the community level[77–79]; and influencing productivity, nutrient cycling and recovery at the ecosystem level when dominant or keystone species harbour substantial genetic variation[80–82]. Genetic diversity is typically quantified through allelic richness, heterozygosity and effective population size[83]. Anthropogenic disturbances rapidly erode genetic diversity through population size reductions, disrupted reproduction and allele loss[84], with allelic richness being particularly sensitive to disturbance[85,86]. Adaptive genetic variation, revealed through genotype–environment associations, captures fitness-related genetic differences across gradients[87,88], whereas neutral diversity reflects demographic history and gene flow rather than adaptive capacity[89].

Despite its central importance for resilience and growing evidence of widespread decline across taxa[90], genetic diversity remains underrepresented in biodiversity monitoring and conservation efforts[91]. Similarly, mapping genetic diversity with remote sensing remains far less developed than taxonomic or functional monitoring (Box 1). Empirical links between spectra and within-species genetic variation are limited and mostly from temperate forests[92–94]; we are unaware of published examples from tropical regions. Airborne and field spectra have predicted genetic differentiation in *Quercus*[69] and genetic diversity in *Fagus sylvatica*[95,96]. Spectral reflectance has been linked to gene expression related to temperature and drought stress, pest and pathogen interactions, and plant defence[92,97]. Spectral reflectance captures variation in plant physiological status, including chlorophyll concentration, leaf water content and photosynthetic activity, traits that are influenced by both genetic variation and environmental stressors such as drought, disturbance and nutrient limitation[98]. However, these relationships are largely established at fine scales and are difficult to transfer to satellite observations owing to canopy mixing and dominant community-level signals[97].

Remote sensing cannot yet directly measure genetic diversity; instead, genetic diversity must be inferred through trait-mediated pathways or integrated with genomic data. Emerging approaches combining landscape genomics with hyperspectral and LiDAR data offer promise for linking genetic variation to environmental gradients

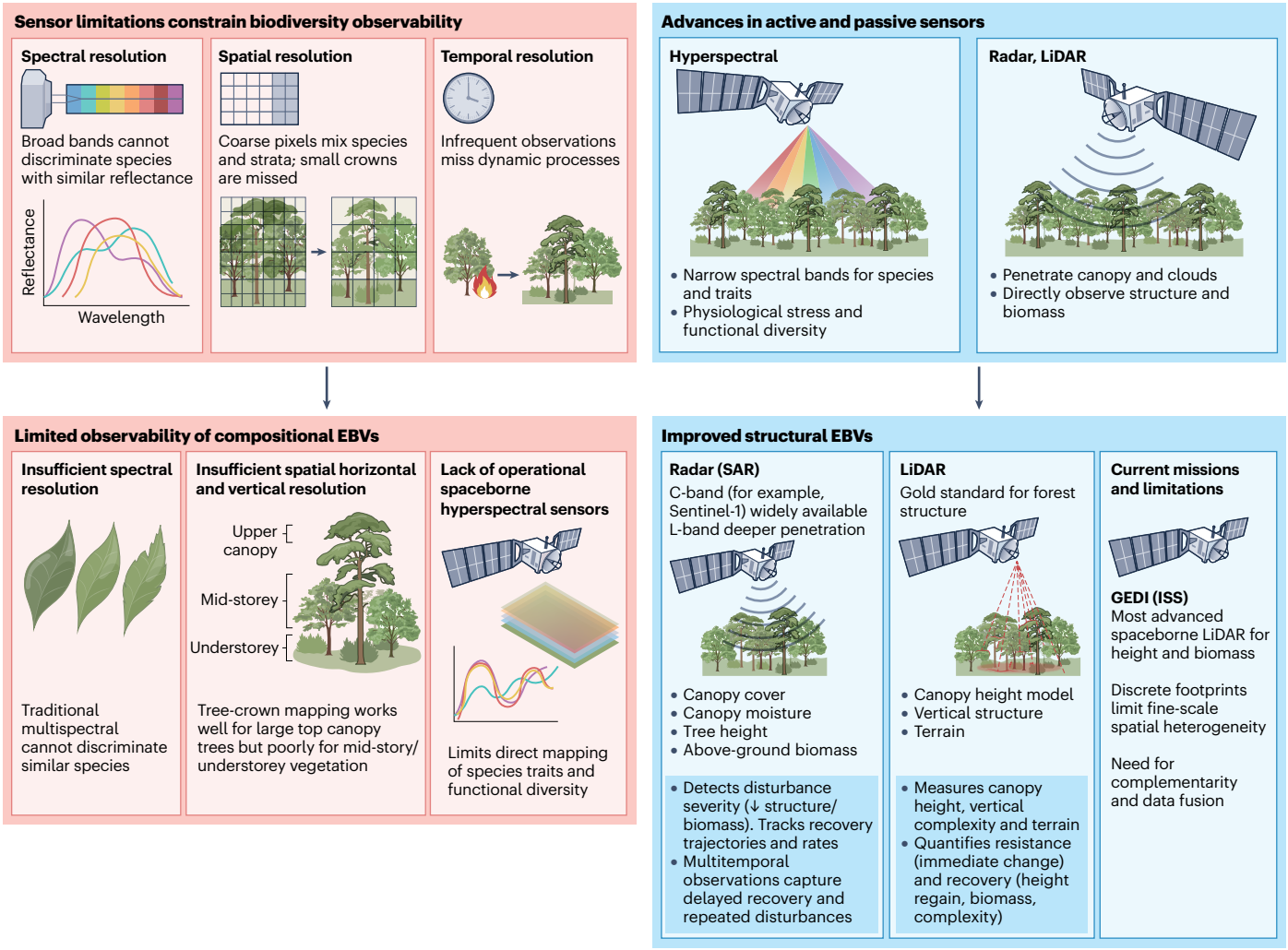


Fig. 3 | Sensor limitations and advances for tropical forest EBV monitoring. Current sensor constraints, insufficient spectral and spatial resolution, and the absence of operational spaceborne hyperspectral coverage limit observability of compositional and trait-based essential biodiversity variables (EBVs), restricting detection of species turnover, functional diversity and early-warning signals of resilience decline. Active sensors — radar and light detection and ranging (LiDAR) — provide comparatively robust structural EBVs, enabling quantification of disturbance severity and recovery trajectories, although spatial coverage gaps persist. GEDI, Global Ecosystem Dynamics Investigation; ISS, International Space Station; SAR, synthetic aperture radar.

and disturbance regimes[99]. In parallel, optical remote sensing provides information on fragmentation, connectivity and isolation[100], helping to identify populations with reduced gene flow or adaptive capacity. Together, these advances point toward an integrated framework for assessing genetic resilience in forest landscapes under global change. Future progress will rely on integrative workflows combining landscape genomics, hyperspectral imaging, terrestrial and airborne LiDAR, and models capable of scaling leaf-level and crown-level genetic signals to broader landscapes[99].

Methodological advances and sensor limitations

As we have discussed in the prior sections, current limitations in biodiversity monitoring largely reflect gaps in observability rather than analytical capability. Although ecosystem structure and function EBVs are now routinely derived from satellite observations, species, trait, and genetic-related EBVs remain only partially observable, and phylogenetic dimensions are still largely inferred. These differences in observability directly constrain the ability to quantify resilience processes, including resistance to disturbance, recovery trajectories and long-term compositional reorganization (Fig. 3). Understanding the capabilities and limitations of these tools is fundamental to evaluate how effectively remote sensing can detect and track climate-driven changes in forest ecosystems.

Constraints on species, trait and compositional EBVs

Compared with the ecosystem structure and ecosystem function EBV classes, the EBVs related to species (species traits, species populations, genetic composition) and community composition remain the most constrained in terms of observability. In species-rich tropical forests, multispectral sensors lack the spectral resolution to separate co-occurring taxa with similar reflectance signatures, whereas spatial resolution limits the detection of individual crowns, particularly in

mid-storey and understorey layers. Consequently, species mapping is largely restricted to dominant upper-canopy trees, using object-based or crown delineation approaches, which limits robust estimation of species turnover and compositional heterogeneity — key indicators of resilience loss and ecosystem reorganization[33,34,101].

Similarly, trait-based EBVs from satellite observations remain largely indirect. Although airborne imaging spectroscopy has demonstrated strong potential for retrieving biochemical and physiological traits, the absence of operational spaceborne hyperspectral coverage limits direct scaling of these approaches[55,102–104]. As a result, functional diversity (calculated with species traits) and adaptive capacity, which can be potentially quantified via genetic diversity, are often inferred rather than directly observed, constraining early detection of functional homogenization and erosion of drought- or disturbance-adaptive trait diversity.

Advances in structural EBVs from active sensing

By contrast, ecosystem structure EBVs (canopy structure and biomass) can be observed more readily owing to advances in active remote sensing. Radar systems provide consistent, large-scale estimates of canopy structure and biomass, enabling monitoring of disturbance severity and recovery dynamics as proxies of resilience. L-band systems offer improved canopy penetration in dense forests and reduced saturation effects compared with C-band systems[105,106], and the long-term Sentinel-1 archive enables multitemporal monitoring of degradation, disturbance frequency and recovery trajectories[107]. Multitemporal radar approaches have further improved structural retrievals, in some cases achieving performance comparable to L-band systems in savanna and open-canopy systems[108,109]. However, saturation in high-biomass forests and biome-dependent performance remain persistent constraints.

Spaceborne LiDAR provides the most direct measurements of structural EBVs, including canopy height, vertical complexity and terrain, which are strongly linked to forest resistance and recovery potential[110–113]. The GEDI mission has advanced global structural monitoring by providing near-global sampling of canopy height and above-ground biomass[21,22], but its discrete footprint limits representation of fine-scale spatial heterogeneity and localized disturbance effects (Fig. 4). Planned missions such as JAXA's (Japan Aerospace Exploration Agency) MOLI[114,115] and NASA's (National Aeronautics and Space Administration) EDGE swath LiDAR[116,117] are expected to improve spatial continuity and sampling density, enabling more complete characterization of structural dynamics.

Emerging hyperspectral–LiDAR integration and next-generation missions

Methodological advances in the past 10 years have increasingly focused on spectral–structural data fusion to improve inference of biodiversity across EBVs. Integrating imaging spectroscopy and LiDAR reduces ambiguity in trait–structure relationships and improves discrimination of vegetation composition and function across scales.

This capability will expand substantially with upcoming satellite missions (Table 2). CHIME (~2028) will provide global hyperspectral observations enabling improved retrieval of vegetation traits, functional diversity and physiological stress indicators, strengthening the species traits, community composition and ecosystem functioning EBVs. The ESA BIOMASS mission (2026), operating in P-band radar, will deliver unprecedented estimates of woody biomass and forest structure in dense tropical forests, improving structural EBVs linked to disturbance impacts and recovery processes[105,118]. The NASA–ISRO NISAR mission (2025) provides systematic L-band SAR observations for monitoring forest degradation, canopy water dynamics and recovery trajectories across biomes[119].

Together, these emerging capabilities mark a transition from largely inferential biodiversity monitoring toward more direct, multidimensional observation of EBVs. Structural EBVs are already operational at scale, and functional, compositional and species-related

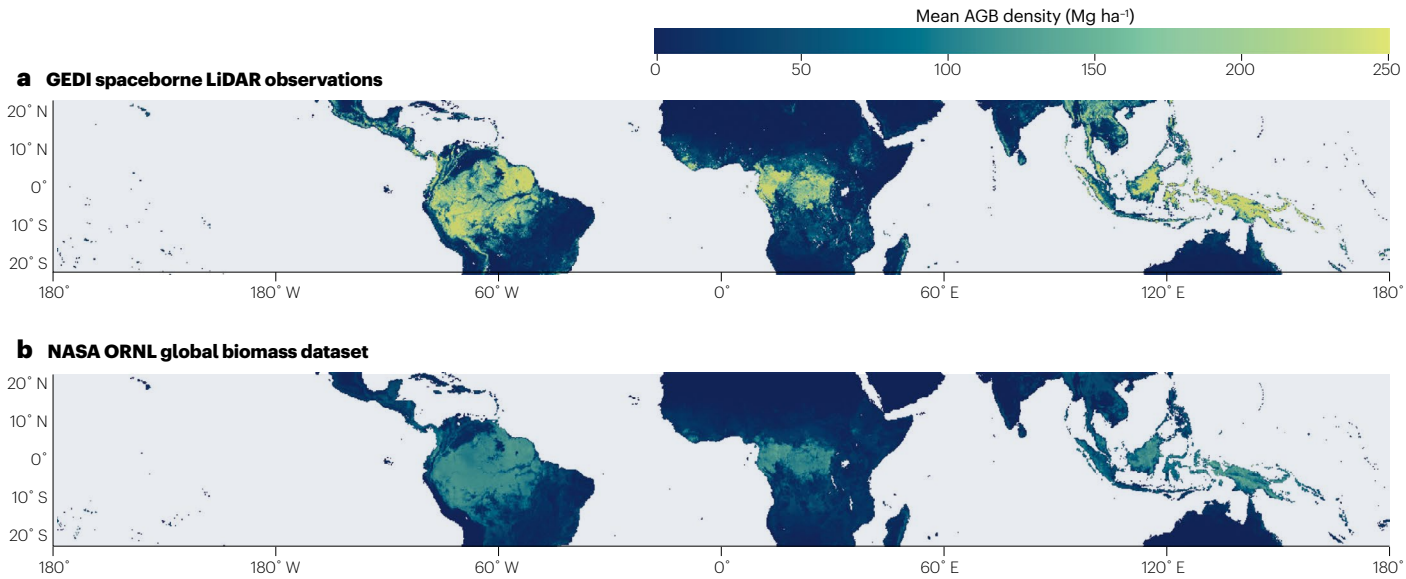


Fig. 4 | Comparison of above-ground biomass density estimates across tropical forests. a, Mean above-ground biomass (AGB) density derived from Global Ecosystem Dynamics Investigation (GEDI) spaceborne LiDAR observations at 25-m spatial resolution, revealing fine-scale spatial variability in forest structure. **b**, AGB density from the NASA ORNL global biomass dataset for the year 2010 at 300-m spatial resolution, illustrating the effects of coarser spatial resolution on biomass representation. GEDI biomass data from https://ceos.org/gst/GEDI-biomass.html and NASA ORNL biomass data from https://www.earthdata.nasa.gov/.

Table 2 | Ongoing and upcoming satellite missions with enhanced capabilities for observing tropical forest characteristics relevant to the development of essential biodiversity variables

Lead agency	Name	Sensor	Application	Launch year
NASA–ISRO	NISAR	L-band SAR	Degradation, disturbance regimes, canopy water dynamics, recovery	2025
ESA — Copernicus	BIOMASS	P-band SAR	Woody biomass and forest structure	2026
JAXA	MOLI	LiDAR	Forest structure	2027
ESA — Copernicus	CHIME	Hyper-spectral	Plant traits, functional diversity, taxonomic diversity, physiological stress indicator	2028
NASA	EDGE	Swath-imaging LiDAR	Forest structure	2030

CHIME, Copernicus Hyperspectral Imaging Mission for the Environment; EDGE, Ecosystem Dynamics and Geohazards Explorer; ESA, European Space Agency; JAXA, Japan Aerospace Exploration Agency; LiDAR, light detection and ranging; MOLI, Multi-footprint Observation Lidar and Imager; NASA, National Aeronautics and Space Administration; NISAR, NASA–ISRO synthetic aperture radar; SAR, synthetic aperture radar.

EBVs are becoming increasingly observable through hyperspectral imaging, radar and LiDAR integration. However, persistent challenges remain, including spectral convergence among taxa[104], mixed-pixel effects in complex canopies, phenological variability and incomplete ground-truth datasets[120–122]. Addressing these constraints through integrated field–airborne–satellite frameworks will be essential for delivering robust, operational monitoring of forest resilience (or proxies thereof) under global change.

From resilience to ecosystem health

Ecosystem health is best understood as an emergent property of forest resilience rather than a separate concept: healthy forests are those that retain the biodiversity configurations — taxonomic, functional, phylogenetic and genetic diversity — that collectively enable resistance, recovery and reorganization under global change[50,123,124]. In this framing, ecosystem health does not precede resilience but emerges from it; a forest is healthy to the extent that its biodiversity underpins continued functioning, productivity, and nature's contributions to people, across disturbance events or cycles. Declines in one or more biodiversity facets, detectable through EBVs before major structural losses occur, therefore signal deteriorating ecosystem health, not merely compositional change[50,52,125,126].

Remote sensing operationalizes this integrated view of ecosystem health by enabling simultaneous tracking of the structural, functional and compositional EBVs through which resilience, and thus ecosystem health, is expressed. For instance, LiDAR and radar-derived structural EBVs capture physical organization and biomass recovery capacity[21,22], whereas optical and SIF-based functional EBVs reflect photosynthetic performance and stress responses[42]. Spectral diversity, trait-based models based on spectral reflectance, and sensor fusion can also be used to approximate taxonomic and functional diversity and redundancy facets[69,70]. Importantly, ecosystem health arises from the combined interpretation of these signals, with sustained productivity without functional diversity, or intact canopy structure without compositional recovery, being insufficient indicators of a resilient system. Multiscale remote sensing, integrating satellite time series with airborne and UAV calibration, therefore provides a powerful way to identify the health of tropical forests. We are now able to quantify biodiversity, functioning and overall health of forests in great detail, which allows us to understand and predict their capacity to persist, adapt and continue contributing to people's livelihoods under accelerating global environmental change.

Summary and future directions

This Review has synthesized how satellite and airborne remote sensing of biodiversity facets and EBVs can advance understanding of tropical forest resilience under global environmental change. Remote sensing is an effective tool for monitoring ecosystem structure and function, quantifying resistance, recovery and reorganization through structural EBVs derived from LiDAR and radar[21,22], and functional EBVs from optical, SIF and microwave observations[127,128]. Progress in observing compositional EBVs — taxonomic, functional, phylogenetic and genetic diversity — has been more uneven, with functional diversity now measurable at pantropical scales through Sentinel-2 trait mapping[53,55], but taxonomic richness, phylogenetic diversity and genetic composition remaining only partially or indirectly observable from space[69,92,97]. Together, these facets underpin an integrated view of tropical forest ecosystem health as an emergent property of resilience: forests that retain high and diverse configurations of biodiversity across multiple EBV dimensions are better positioned to resist disturbance, recover rapidly and adapt to new conditions, sustaining their structure, function and nature's contributions to people over the long term[27,50,129].

A central unresolved challenge is whether remote sensing can reliably estimate the number of species in a tropical forest area and their functional composition at operationally relevant scales. Individual tree crown delineation and species assignment have been demonstrated locally using fused hyperspectral and LiDAR data[38,41,130], but scaling these approaches to the extraordinary species richness of Amazonian, Congolian or Southeast Asian forests demands large, georeferenced, crown-matched species inventories, which remain scarce outside a handful of well-studied regions. Closing this gap requires systematic expansion of permanent plot networks and taxonomic inventories across undersampled regions, including the Congo Basin, the Guiana Shield, and Southeast Asian dipterocarp forests, through initiatives such as GEO-TREES (www.geo-trees.org) and ForestPlots (www.forestplots.net), combined with UAV-borne hyperspectral acquisitions to build the training libraries that species mapping pipelines require[37,131]. Importantly, this work cannot succeed without deep and equitable collaboration with local scientists, forest managers and communities who hold irreplaceable knowledge of species identities, forest histories and site conditions. Botanists and taxonomists working in tropical countries are the indispensable partners for ground-truthing remote sensing models, and their systematic under-representation in global EBV research (Supplementary Fig. 1) must be actively reversed if monitoring frameworks are to be globally credible and locally meaningful.

Operationalizing functional diversity EBVs at the scales needed to track resilience change requires closing the gap between field trait measurements and spaceborne retrievals. The imminent launch of ESA's CHIME mission (~2028) will potentially enable the retrieval of leaf nitrogen, phosphorus, chlorophyll, water content and leaf mass per area across the full visible to shortwave infrared domain, traits that determine drought tolerance, hydraulic strategy, and post-disturbance recovery capacity[27,132,133]. Realizing this potential

will require coordinated hyperspectral and field campaigns across all three major tropical forest regions, explicitly designed to build trait–spectra calibration datasets that span the full gradients of climate, soil, and disturbance history. Integration of CHIME with GEDI, NISAR and the forthcoming MOLI and EDGE LiDAR missions[114–117] will allow simultaneous retrieval of chemical, structural and architectural traits, enabling functional diversity indices to be updated annually across disturbance chronosequences and detecting functional homogenization as an early warning of declining resilience[27,51] before structural losses become apparent.

Phylogenetic and genetic EBVs remain the largest challenge for remote sensing-based resilience monitoring. Phylogenetic diversity is now approachable through spectral–phylogenetic frameworks exploiting the conservatism of biochemical and architectural traits across lineages[69,70,134], and the combination of CHIME data with well-resolved molecular phylogenies, increasingly available through global initiatives such as Global Biodiversity Information Facility (GBIF)-linked phylogenomic databases, offers a realistic pathway to operational phylogenetic diversity mapping within this decade. For genetic diversity, the most actionable advance lies in integrating landscape genomics datasets, allelic richness, heterozygosity and genotype-environment associations for widespread tropical tree species[74,75,92,97], with high-resolution spectral and structural remote sensing, to test whether spectrally detectable trait variation can serve as a scalable proxy for adaptive genetic diversity and long-term population viability under climate change[99]. Again, these efforts are entirely dependent on primary field data collected with and by local research teams, whose capacity to conduct repeated sampling across fragmentation and disturbance gradients must be supported through sustained, long-term research partnerships rather than extractive data collection models.

Translating EBV-based resilience monitoring into policy action under the GBF requires both standardization and equity. The current geographical concentration of EBV research leaves the Congo Basin, Southeast Asian insular forests, and West and Central Africa profoundly underrepresented in global resilience assessments, precisely the regions where biodiversity and data gaps are largest (Box 1). Standardized EBV reporting pipelines, combining Sentinel-2 functional diversity products[55], GEDI structural metrics[21,22] and national forest inventory data through open-access platforms, should be developed explicitly for GBF indicator reporting under Targets 1, 2, 4 and 15[13,16]. The next 5 to 10 years offer a genuinely transformative window with the convergence of next-generation spaceborne sensors, expanding field networks built in partnership with tropical country institutions, and growing political urgency around biodiversity loss. This creates the conditions under which operationalizing EBVs as real-time indicators of tropical forest resilience and ecosystem health for the GBF is not only possible, but necessary.

Published online: 8 July 2026

References

1. Wright, S. J. The future of tropical forests. *Ann. N. Y. Acad. Sci.* **1195**, 1–27 (2010).
2. Gatti, R. C. et al. The number of tree species on Earth. *Proc. Natl Acad. Sci. USA* **119**, e2115329119 (2022).
3. Díaz, S. et al. Assessing nature's contributions to people. *Science* **359**, 270–272 (2018).
4. Steffen, W. et al. Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 1259855–1259855 (2015).
5. Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
6. Guz, J. & Kulakowski, D. Forests in the Anthropocene. *Ann. Am. Assoc. Geogr.* **111**, 869–879 (2020).
7. Randhir, T. O. & Erol, A. Emerging threats to forests: resilience and strategies at system scale. *Am. J. Plant Sci.* **04**, 739–748 (2013).
8. Deutsch, C. A. et al. Impacts of climate warming on terrestrial ectotherms across latitude. *Proc. Natl Acad. Sci. USA* **105**, 6668–6672 (2008).
9. Colwell, R. K., Brehm, G., Cardelús, C. L., Gilman, A. C. & Longino, J. T. Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science* **322**, 258–261 (2008).
10. Silva, C. V. J. et al. Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics. *Philos. Trans. R. Soc. B Biol. Sci.* **373**, 20180043 (2018).
11. Berenguer, E. et al. Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. *Proc. Natl Acad. Sci. USA* **118**, e2019377118 (2021).
12. Hubau, W. et al. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* **579**, 80–87 (2020).
13. Pereira, H. M. et al. Essential biodiversity variables. *Science* **339**, 277–278 (2013).
14. What are EBVs? *GEO BON* https://geobon.org/ebvs/what-are-ebvs/ (2026).
15. Skidmore, A. K. et al. Environmental science: agree on biodiversity metrics to track from space. *Nature* **523**, 403–405 (2015).
16. Skidmore, A. K. et al. Priority list of biodiversity metrics to observe from space. *Nat. Ecol. Evol.* **5**, 896–906 (2021).
17. Fassnacht, F. E., White, J. C., Wulder, M. A. & Næsset, E. Remote sensing in forestry: current challenges, considerations and directions. *For. Int. J. For. Res.* **97**, 11–37 (2023).
18. Cleemput, E. V. et al. Scaling-up ecological understanding with remote sensing and causal inference. *Trends Ecol. Evol.* **40**, 122–135 (2025).
19. Chambers, J. Q. et al. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends Ecol. Evol.* **22**, 414–423 (2007).
20. Sader, S., Stone, T. & Joyce, A. Remote sensing of tropical forests — an overview of research and applications using non-photographic sensors. *Photogramm. Eng. Remote Sens.* **56**, 1343–1351 (1990).
21. Duncanson, L. et al. Aboveground biomass density models for NASA's Global Ecosystem Dynamics Investigation (GEDI) lidar mission. *Remote Sens. Environ.* **270**, 112845 (2022).
22. Dubayah, R. et al. The Global Ecosystem Dynamics Investigation: high-resolution laser ranging of the Earth's forests and topography. *Sci. Remote Sens.* **1**, 100002 (2020).
23. Wulder, M. A. et al. Fifty years of Landsat science and impacts. *Remote Sens. Environ.* **280**, 113195 (2022).
24. Pettorelli, N. et al. Framing the concept of satellite remote sensing essential biodiversity variables: challenges and future directions. *Remote Sens. Ecol. Conserv.* **2**, 122–131 (2016).
25. Nguyen, T. H., Jones, S., Soto-Berelov, M., Haywood, A. & Hislop, S. Landsat time-series for estimating forest aboveground biomass and its dynamics across space and time: a review. *Remote Sens.* **12**, 98 (2019).
26. Komatsu, K. et al. Quantifying carbon stock and tree community composition in tropical forests through combining satellite and UAV analyses. *Sci. Rep.* https://doi.org/10.1038/s41598-025-34938-9 (2026).
27. Aguirre-Gutiérrez, J. et al. Functional susceptibility of tropical forests to climate change. *Nat. Ecol. Evol.* **6**, 878–889 (2022).
28. Yano, S. et al. Effects of logging on landscape-level tree diversity across an elevational gradient in Bornean tropical forests. *Glob. Ecol. Conserv.* **29**, e01739 (2021).
29. Takeshige, R. et al. Influences of fern and vine coverage on the above-ground biomass recovery in a Bornean logged-over degraded secondary forest. *J. For. Res.* **28**, 260–270 (2023).
30. Jetz, W. et al. Essential biodiversity variables for mapping and monitoring species populations. *Nat. Ecol. Evol.* **3**, 539–551 (2019).
31. Wang, R. & Gamon, J. A. Remote sensing of terrestrial plant biodiversity. *Remote Sens. Environ.* **231**, 111218 (2019).
32. Féret, J.-B. & Asner, G. P. Mapping tropical forest canopy diversity using high-fidelity imaging spectroscopy. *Ecol. Appl.* **24**, 1289–1296 (2014).
33. Gastauer, M. et al. Spectral diversity allows remote detection of the rehabilitation status in an Amazonian iron mining complex. *Int. J. Appl. Earth Obs. Geoinf.* **106**, 102653 (2022).
34. Kishore, B. S. P. C., Kumar, A., Saikia, P. & Khan, M. L. Alpha and beta diversity mapping in Indian tropical deciduous forests using high-fidelity imaging spectroscopy. *Adv. Space Res.* **73**, 1413–1426 (2024).
35. Banerjee, S., Sarker, S. K. & Pijanowski, B. Remotely sensed mapping of plant diversity in Earth's largest mangrove forests: developing a spectral diversity metric with DESIS hyperspectral data and the 'spectral species' concept. *Remote Sens. Appl.: Soc. Environ.* **39**, 101676 (2025).
36. Rocchini, D. et al. The spectral species concept in living color. *J. Geophys. Res. Biogeosci.* **127**, e2022JG007026 (2022).
37. Laliberté, E. et al. Seeing the forest and the trees: a workflow for automatic acquisition of ultra-high resolution drone photos of tropical forest canopies to support botanical and ecological studies. Preprint at *bioRxiv* https://doi.org/10.1101/2025.09.02.673753 (2026).
38. Ball, J. G. C. et al. Towards comprehensive individual tree species mapping in diverse tropical forests by harnessing temporal and spectral dimensions. Preprint at *bioRxiv* https://doi.org/10.1101/2024.06.24.600405 (2025).
39. Carvalho, R. L. et al. Pervasive gaps in Amazonian ecological research. *Curr. Biol.* **33**, 3495–3504 (2023).

40. Asner, G. P. & Martin, R. E. Airborne spectranomics: mapping canopy chemical and taxonomic diversity in tropical forests. *Front. Ecol. Environ*. https://doi.org/10.1890/070152 (2009).
41. Almeida, D. R. A. de et al. Monitoring restored tropical forest diversity and structure through UAV-borne hyperspectral and lidar fusion. *Remote Sens. Environ.* **264**, 112582 (2021).
42. Asner, G. P. & Martin, R. E. Spectranomics: emerging science and conservation opportunities at the interface of biodiversity and remote sensing. *Glob. Ecol. Conserv.* **8**, 212–219 (2016).
43. Guo, Y. et al. Plant species richness prediction from DESIS hyperspectral data: a comparison study on feature extraction procedures and regression models. *ISPRS J. Photogramm. Remote Sens*. **196**, 120–133 (2023).
44. Rocchini, D. et al. From local spectral species to global spectral communities: a benchmark for ecosystem diversity estimate by remote sensing. *Ecol. Inform*. **61**, 101195 (2021).
45. Lutz, J. A. et al. Global importance of large-diameter trees. *Glob. Ecol. Biogeogr.* **27**, 849–864 (2018).
46. Violle, C. et al. Let the concept of trait be functional! *Oikos* **116**, 882–892 (2007).
47. Díaz, S. et al. Functional traits, the phylogeny of function, and ecosystem service vulnerability. *Ecol. Evol.* **3**, 2958–2975 (2013).
48. Wright, S. J. et al. Functional traits and the growth–mortality trade-off in tropical trees. *Ecology* **91**, 3664–3674 (2010).
49. Rüger, N. et al. Demographic trade-offs predict tropical forest dynamics. *Science* **368**, 165–168 (2020).
50. Eisenhauer, N., Hines, J., Maestre, F. T. & Rillig, M. C. Reconsidering functional redundancy in biodiversity research. *npj Biodivers.* **2**, 9 (2023).
51. Aguirre-Gutiérrez, J. et al. Long-term droughts may drive drier tropical forests towards increased functional, taxonomic and phylogenetic homogeneity. *Nat. Commun.* **11**, 3346 (2020).
52. Cadotte, M. W., Carscadden, K. & Mirotchnick, N. Beyond species: functional diversity and the maintenance of ecological processes and services. *J. Appl. Ecol.* **48**, 1079–1087 (2011).
53. Aguirre-Gutiérrez, J. et al. Pantropical modelling of canopy functional traits using Sentinel-2 remote sensing data. *Remote Sens. Environ.* **252**, 112122 (2021).
54. Aguirre-Gutiérrez, J. et al. Tropical forests in the Americas are changing too slowly to track climate change. *Science* **387**, eadl5414 (2025).
55. Aguirre-Gutiérrez, J. et al. Canopy functional trait variation across Earth's tropical forests. *Nature* https://doi.org/10.1038/s41586-025-08663-2 (2025).
56. Schneider, F. D. et al. Towards mapping the diversity of canopy structure from space with GEDI. *Environ. Res. Lett.* **15**, 115006 (2020).
57. Yachi, S. & Loreau, M. Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. *Proc. Natl Acad. Sci. USA* **96**, 1463–1468 (1999).
58. Faith, D. P. Conservation evaluation and phylogenetic diversity. *Biol. Conserv.* **61**, 1–10 (1992).
59. Souza, F. C. de et al. Evolutionary heritage influences Amazon tree ecology. *Proc. R. Soc. B Biol. Sci.* **283**, 20161587 (2016).
60. Souza, F. C. de et al. Evolutionary diversity is associated with wood productivity in Amazonian forests. *Nat. Ecol. Evol.* **3**, 1754–1761 (2019).
61. Wiens, J. J. et al. Niche conservatism as an emerging principle in ecology and conservation biology. *Ecol. Lett.* **13**, 1310–1324 (2010).
62. Ackerly, D. D. & Reich, P. B. Convergence and correlations among leaf size and function in seed plants: a comparative test using independent contrasts. *Am. J. Bot.* **86**, 1272–1281 (1999).
63. Chave, J. et al. Regional and phylogenetic variation of wood density across 2456 Neotropical tree species. *Ecol. Appl.* **16**, 2356–2367 (2006).
64. Swenson, N. G. & Enquist, B. J. Ecological and evolutionary determinants of a key plant functional trait: wood density and its community-wide variation across latitude and elevation. *Am. J. Bot.* **94**, 451–459 (2007).
65. Vitousek, P. M. *Nutrient Cycling and Limitation: Hawai'i as a Model System* (Princeton Univ. Press, 2004).
66. Weedon, J. T. et al. Global meta-analysis of wood decomposition rates: a role for trait variation among tree species? *Ecol. Lett.* **12**, 45–56 (2009).
67. Cadotte, M. W., Cardinale, B. J. & Oakley, T. H. Evolutionary history and the effect of biodiversity on plant productivity. *Proc. Natl Acad. Sci. USA* **105**, 17012–17017 (2008).
68. Finke, D. L. & Snyder, W. E. Niche partitioning increases resource exploitation by diverse communities. *Science* **321**, 1488–1490 (2008).
69. Cavender-Bares, J. et al. Associations of leaf spectra with genetic and phylogenetic variation in oaks: prospects for remote detection of biodiversity. *Remote Sens.* **8**, 221 (2016).
70. Schweiger, A. K. et al. Plant spectral diversity integrates functional and phylogenetic components of biodiversity and predicts ecosystem function. *Nat. Ecol. Evol.* **2**, 976–982 (2018).
71. Jucker, T. et al. The global spectrum of tree crown architecture. *Nat. Commun.* **16**, 4876 (2025).
72. Zhao, Y., Zeng, Y., Zhao, D., Wu, B. & Zhao, Q. The optimal leaf biochemical selection for mapping species diversity based on imaging spectroscopy. *Remote Sens.* **8**, 216 (2016).
73. Schneider, F. D. et al. Mapping functional diversity from remotely sensed morphological and physiological forest traits. *Nat. Commun.* **8**, 1441 (2017).
74. Hughes, A. R., Inouye, B. D., Johnson, M. T. J., Underwood, N. & Vellend, M. Ecological consequences of genetic diversity. *Ecol. Lett.* **11**, 609–623 (2008).
75. Perry, A. et al. Resilient forests for the future. *Tree Genet. Genomes* **20**, 17 (2024).
76. Chaves, M. M., Maroco, J. P. & Pereira, J. S. Understanding plant responses to drought — from genes to the whole plant. *Funct. Plant Biol.* **30**, 239–264 (2003).
77. Booth, R. E. & Grime, J. P. Effects of genetic impoverishment on plant community diversity. *J. Ecol.* **91**, 721–730 (2003).
78. Frieley, J. D., Grime, J. P. & Bilton, M. Genetic identity of interspecific neighbours mediates plant responses to competition and environmental variation in a species-rich grassland. *J. Ecol.* **95**, 908–915 (2007).
79. Lankau, R. A. & Strauss, S. Y. Mutual feedbacks maintain both genetic and species diversity in a plant community. *Science* **317**, 1561–1563 (2007).
80. Whitham, T. G. et al. Community and ecosystem genetics: a consequence of the extended phenotype. *Ecology* **84**, 559–573 (2003).
81. Whitham, T. G. et al. A framework for community and ecosystem genetics: from genes to ecosystems. *Nat. Rev. Genet.* **7**, 510–523 (2006).
82. Hughes, A. R. & Stachowicz, J. J. Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance. *Proc. Natl Acad. Sci. USA* **101**, 8998–9002 (2004).
83. Hartl, D. L. & Clark, A. G. *Principles of Population Genetics* Vol. 116 (Sinauer, 1997).
84. Jennings, S. B., Brown, N. D., Boshier, D. H., Whitmore, T. C. & Lopes, J. do C. A. Ecology provides a pragmatic solution to the maintenance of genetic diversity in sustainably managed tropical rain forests. *For. Ecol. Manag.* **154**, 1–10 (2001).
85. Vilas, A., Pérez-Figueroa, A., Quesada, H. & Caballero, A. Allelic diversity for neutral markers retains a higher adaptive potential for quantitative traits than expected heterozygosity. *Mol. Ecol.* **24**, 4419–4432 (2015).
86. González, A. V., Gómez-Silva, V., Ramírez, M. J. & Fontúrbel, F. E. Meta-analysis of the differential effects of habitat fragmentation and degradation on plant genetic diversity. *Conserv. Biol.* **34**, 711–720 (2020).
87. Kort, H. D., Mergeay, J., Jacquemyn, H. & Honnay, O. Transatlantic invasion routes and adaptive potential in North American populations of the invasive glossy buckthorn, *Frangula alnus*. *Ann. Bot.* **118**, 1089–1099 (2016).
88. Jordan, R., Hoffmann, A. A., Dillon, S. K. & Prober, S. M. Evidence of genomic adaptation to climate in *Eucalyptus microcarpa*: implications for adaptive potential to projected climate change. *Mol. Ecol.* **26**, 6002–6020 (2017).
89. Charlesworth, B., Charlesworth, D. & Barton, N. H. The effects of genetic and geographic structure on neutral variation. *Annu. Rev. Ecol. Evol. Syst.* **34**, 99–125 (2003).
90. Shaw, R. E. et al. Halting genetic diversity loss, from local to international action and policy. *Nat. Rev. Biodivers.* https://doi.org/10.1038/s44358-026-00162-0 (2026).
91. Hoban, S. et al. Global commitments to conserving and monitoring genetic diversity are now necessary and feasible. *BioScience* **71**, 964–976 (2021).
92. Corbin, J. P. M. et al. Hyperspectral leaf reflectance detects interactive genetic and environmental effects on tree phenotypes, enabling large-scale monitoring and restoration planning under climate change. *Plant Cell Environ.* **48**, 1842–1857 (2025).
93. Blonder, B. et al. Remote sensing of ploidy level in quaking aspen (*Populus tremuloides* Michx.). *J. Ecol.* **108**, 175–188 (2020).
94. Blonder, B. et al. Remote sensing of cytotype and its consequences for canopy damage in quaking aspen. *Glob. Change Biol.* **28**, 2491–2504 (2022).
95. Czyż, E. A. et al. Intraspecific genetic variation of a *Fagus sylvatica* population in a temperate forest derived from airborne imaging spectroscopy time series. *Ecol. Evol.* **10**, 7419–7430 (2020).
96. Czyż, E. A. et al. Genetic constraints on temporal variation of airborne reflectance spectra and their uncertainties over a temperate forest. *Remote Sens. Environ.* **284**, 113338 (2023).
97. Chen, Y., Monks, L., Rubio, V. E., Cox, A. J. & Swenson, N. G. Linking leaf hyperspectral reflectance to gene expression. *Commun. Earth Environ.* **6**, 694 (2025).
98. Ollinger, S. V. Sources of variability in canopy reflectance and the convergent properties of plants. *N. Phytol.* **189**, 375–394 (2011).
99. Aitken, S. N. & Bemmels, J. B. Time to get moving: assisted gene flow of forest trees. *Evol. Appl.* **9**, 271–290 (2016).
100. Hernández, M. et al. Population structure and genetic diversity of *Magnolia cubensis* subsp. *acunae* (Magnoliaceae): effects of habitat fragmentation and implications for conservation. *Oryx* **54**, 451–459 (2020).
101. Rocchini, D. et al. Measuring β-diversity by remote sensing: a challenge for biodiversity monitoring. *Methods Ecol. Evol.* **9**, 1787–1798 (2018).
102. Asner, G. P., Martin, R. E., Anderson, C. B. & Knapp, D. E. Quantifying forest canopy traits: imaging spectroscopy versus field survey. *Remote Sens. Environ.* **158**, 15–27 (2015).
103. Chadwick, K. D. & Asner, G. P. Tropical soil nutrient distributions determined by biotic and hillslope processes. *Biogeochemistry* **127**, 273–289 (2016).
104. Singh, A., Serbin, S. P., McNeil, B. E., Kingdon, C. C. & Townsend, P. A. Imaging spectroscopy algorithms for mapping canopy foliar chemical and morphological traits and their uncertainties. *Ecol. Appl.* **25**, 2180–2197 (2015).
105. Toan, T. L. et al. The BIOMASS mission: mapping global forest biomass to better understand the terrestrial carbon cycle. *Remote Sens. Environ.* **115**, 2850–2860 (2011).
106. Saatchi, S., Marlier, M., Chazdon, R. L., Clark, D. B. & Russell, A. E. Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass. *Remote Sens. Environ.* **115**, 2836–2849 (2011).
107. Torres, R. et al. GMES Sentinel-1 mission. *Remote Sens. Environ.* **120**, 9–24 (2012).
108. Bussinguer, J. et al. Understanding the spatio-temporal behavior of Sentinel-1 SAR vegetation indices over the Brazilian savanna. *IEEE Trans. Geosci. Remote Sens.* **62**, 1–18 (2024).
109. Reiche, J., Hamunyela, E., Verbesselt, J., Hoekman, D. & Herold, M. Improving near-real time deforestation monitoring in tropical dry forests by combining dense Sentinel-1 time series with Landsat and ALOS-2 PALSAR-2. *Remote Sens. Environ.* **204**, 147–161 (2018).

110. Lefsky, M. A., Cohen, W. B., Parker, G. G. & Harding, D. J. Lidar remote sensing for ecosystem studies. *BioScience* **52**, 19–30 (2002).
111. Johnstone, J. F. et al. Changing disturbance regimes, ecological memory, and forest resilience. *Front. Ecol. Environ.* **14**, 369–378 (2016).
112. Senf, C. et al. Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nat. Commun.* **9**, 4978 (2018).
113. Vierling, K. T., Vierling, L. A., Gould, W. A., Martinuzzi, S. & Clawges, R. M. Lidar: shedding new light on habitat characterization and modeling. *Front. Ecol. Environ.* **6**, 90–98 (2008).
114. Mitsuhashi, R. et al. in *Tropical Peatland Eco-evaluation* (eds Osaki, M. et al.) 271–293 (Springer Nature, 2023).
115. Sakae, T., Sakaizawa, D., Imai, T. & Sumita, T. Development status of MOLI project. In *Proc. SPIE Sensors, Systems, and Next-Generation Satellites XXIX*, 136670P (SPIE, 2025).
116. Dubayah, R., Armston, J. D. & Blair, J. B. Advancing ecosystem structure observation: insights from GEDI and the path to EDGE. *AGU Fall Meeting Abstracts* https://ui.adsabs.harvard.edu/abs/2024AGUFMGC13W..01D (2024).
117. Fricker, H. A. & Armston, J. D. Advances in tracking global change: insights from NASA's satellite laser altimetry missions (ICESat, ICESat-2, and GEDI) and the path to EDGE I. *AGU2024* https://agu.confex.com/agu/agu24/meetingapp.cgi/Session/229145 (2024).
118. Quegan, S. et al. The European Space Agency BIOMASS mission: measuring forest above-ground biomass from space. *Remote Sens. Environ.* **227**, 44–60 (2019).
119. Rosen, P. et al. The NASA-ISRO SAR (NISAR) mission dual-band radar instrument preliminary design. In *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* https://doi.org/10.1109/igarss.2017.8127836 (IEEE, 2017).
120. Asner, G. P. et al. Spectroscopy of canopy chemicals in humid tropical forests. *Remote Sens. Environ.* **115**, 3587–3598 (2011).
121. Jetz, W. et al. Monitoring plant functional diversity from space. *Nat. Plants* **2**, 16024 (2016).
122. Zanne, A. E. et al. Three keys to the radiation of angiosperms into freezing environments. *Nature* **506**, 89–92 (2014).
123. Malhi, Y. et al. New perspectives on the ecology of tree structure and tree communities through terrestrial laser scanning. *Interface Focus* **8**, 20170052 (2018).
124. Nunes, M. H. et al. Edge effects on tree architecture exacerbate biomass loss of fragmented Amazonian forests. *Nat. Commun.* **14**, 8129 (2023).
125. Nunes, M. H. et al. Forest fragmentation impacts the seasonality of Amazonian evergreen canopies. *Nat. Commun.* **13**, 917 (2022).
126. Martínez-García, E. et al. Drought response of the boreal forest carbon sink is driven by understorey–tree composition. *Nat. Geosci.* **17**, 197–204 (2024).
127. Pinagé, E. R. et al. Forest structure and solar-induced fluorescence across intact and degraded forests in the Amazon. *Remote Sens. Environ.* **274**, 112998 (2022).
128. Wigneron, J.-P. et al. Tropical forests did not recover from the strong 2015–2016 El Niño event. *Sci. Adv.* **6**, eaay4603 (2020).
129. Hernández-Blanco, M. et al. Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature. *Glob. Change Biol.* **28**, 5027–5040 (2022).
130. Kamoske, A. G. et al. Towards mapping biodiversity from above: can fusing lidar and hyperspectral remote sensing predict taxonomic, functional, and phylogenetic tree diversity in temperate forests? *Glob. Ecol. Biogeogr.* **31**, 1440–1460 (2022).
131. Manfreda, S. et al. On the use of unmanned aerial systems for environmental monitoring. *Remote Sens.* **10**, 641 (2018).
132. Anderegg, W. R. L. et al. Hydraulic diversity of forests regulates ecosystem resilience during drought. *Nature* **561**, 538–541 (2017).
133. Langan, L., Scheiter, S., Hickler, T. & Higgins, S. I. Amazon forest resistance to drought is increased by diversity in hydraulic traits. *Nat. Commun.* **16**, 8246 (2025).
134. Griffith, D. M. et al. Capturing patterns of evolutionary relatedness with reflectance spectra to model and monitor biodiversity. *Proc. Natl Acad. Sci. USA* **120**, e2215533120 (2023).
135. Hansen, M. C. et al. High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853 (2013).
136. Diniz, C. G. et al. DETER-B: the new amazon near real-time deforestation detection system. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **8**, 3619–3628 (2015).
137. Zeng, Y. et al. Structural complexity biases vegetation greenness measures. *Nat. Ecol. Evol.* **7**, 1790–1798 (2023).
138. Asner, G. P. et al. A universal airborne LiDAR approach for tropical forest carbon mapping. *Oecologia* **168**, 1147–1160 (2012).
139. Doughty, C. E. et al. Satellite derived trait data slightly improves tropical forest biomass, NPP and GPP estimates. *J. Geophys. Res. Biogeosci.* **129**, e2024JG008108 (2024).
140. Conto, T., de, Armston, J. & Dubayah, R. Characterizing the structural complexity of the Earth's forests with spaceborne lidar. *Nat. Commun.* **15**, 8116 (2024).
141. Satapathy, T. & Dutta, D. Characterizing the vertical variability of canopy structure from space: implications for biodiversity, productivity, and ecosystem functioning. *Agric. For. Meteorol.* **372**, 110710 (2025).
142. Wu, Y., Chen, Y., Tian, C., Yun, T. & Li, M. Estimation of subtropical forest aboveground biomass using active and passive sentinel data with canopy height. *Remote Sens.* **17**, 2509 (2025).
143. Bourgoin, C. et al. Human degradation of tropical moist forests is greater than previously estimated. *Nature* **631**, 570–576 (2024).
144. Holcomb, A., Burns, P., Keshav, S. & Coomes, D. A. Repeat GEDI footprints measure the effects of tropical forest disturbances. *Remote Sens. Environ.* **308**, 114174 (2024).
145. Forkel, M. et al. Burning of woody debris dominates fire emissions in the Amazon and Cerrado. *Nat. Geosci.* **18**, 140–147 (2025).
146. Lima, R. B. de et al. Mapping the density of giant trees in the Amazon. *N. Phytol.* **249**, 152–168 (2026).
147. Lei, Y. et al. Quantification of selective logging in tropical forest with spaceborne SAR interferometry. *Remote Sens. Environ.* **211**, 167–183 (2018).
148. Qi, W. et al. Mapping large-scale pantropical forest canopy height by integrating GEDI lidar and TanDEM-X InSAR data. *Remote Sens. Environ.* **318**, 114534 (2025).
149. Potapov, P. et al. Mapping global forest canopy height through integration of GEDI and Landsat data. *Remote Sens. Environ.* **253**, 112165 (2021).
150. Guan, K. et al. Photosynthetic seasonality of global tropical forests constrained by hydroclimate. *Nat. Geosci.* **8**, 284–289 (2015).
151. Giardina, F. et al. Tall Amazonian forests are less sensitive to precipitation variability. *Nat. Geosci.* **11**, 405–409 (2018).
152. Koren, G. et al. Widespread reduction in sun-induced fluorescence from the Amazon during the 2015/2016 El Niño. *Philos. Trans. R. Soc. B Biol. Sci.* **373**, 20170408 (2018).
153. Moura, Y. M. de et al. Seasonality and drought effects of Amazonian forests observed from multi-angle satellite data. *Remote Sens. Environ.* **171**, 278–290 (2015).
154. Moura, Y. M. de et al. Spectral analysis of amazon canopy phenology during the dry season using a tower hyperspectral camera and MODIS observations. *ISPRS J. Photogramm. Remote Sens.* **131**, 52–64 (2017).
155. Zhou, L. et al. Widespread decline of Congo rainforest greenness in the past decade. *Nature* **509**, 86–90 (2014).
156. Liu, L. et al. The novel microwave temperature vegetation drought index (MTVDI) captures canopy seasonality across Amazonian tropical evergreen forests. *Remote Sens.* **13**, 339 (2021).
157. Tao, S. et al. Increasing and widespread vulnerability of intact tropical rainforests to repeated droughts. *Proc. Natl Acad. Sci. USA* **119**, e2116626119 (2022).
158. Bernardino, P. N. et al. Estimating vegetation water content from Sentinel-1 C-band SAR data over savanna and grassland ecosystems. *Environ. Res. Lett.* **19**, 034019 (2024).
159. Pinagé, E. R. et al. Surface energy dynamics and canopy structural properties in intact and disturbed forests in the southern Amazon. *J. Geophys. Res. Biogeosci.* **128**, e2023JG007465 (2023).
160. Sumoinen, L., Ruokolainen, K., Pitkänen, T. & Tuomisto, H. Similar understorey structure in spite of edaphic and floristic dissimilarity in Amazonian forests. *Acta Amaz.* **45**, 393–404 (2015).
161. Medeiros, E. S. e S., Machado, C. C. C., Galvíncio, J. D., Moura, M. S. B. de & Araujo, H. F. P. de Predicting plant species richness with satellite images in the largest dry forest nucleus in South America. *J. Arid Environ.* **166**, 43–50 (2019).
162. Fagua, J. C. et al. Mapping tree diversity in the tropical forest region of Chocó-Colombia. *Environ. Res. Lett.* **16**, 054024 (2021).
163. Marselis, S. M. et al. Evaluating the potential of full-waveform lidar for mapping pan-tropical tree species richness. *Glob. Ecol. Biogeogr.* **29**, 1799–1816 (2020).
164. Marselis, S. M., Keil, P., Chase, J. M. & Dubayah, R. The use of GEDI canopy structure for explaining variation in tree species richness in natural forests. *Environ. Res. Lett.* **17**, 045003 (2022).
165. Cao, R. et al. Global evidence for a positive relationship between tree species richness and ecosystem photosynthesis. *Nat. Plants* **11**, 1429–1440 (2025).
166. Asner, G. P. et al. Landscape biogeochemistry reflected in shifting distributions of chemical traits in the Amazon forest canopy. *Nat. Geosci.* **8**, 567–573 (2015).
167. Chadwick, D. K. & Asner, G. P. Organismic-scale remote sensing of canopy foliar traits in lowland tropical forests. *Remote Sens.* **8**, 87 (2016).
168. Swinfield, T. et al. Imaging spectroscopy reveals the effects of topography and logging on the leaf chemistry of tropical forest canopy trees. *Glob. Chang. Biol.* **26**, 989–1002 (2020).
169. Liu, S. et al. Mapping foliar photosynthetic capacity in sub-tropical and tropical forests with UAS-based imaging spectroscopy: scaling from leaf to canopy. *Remote Sens. Environ.* **293**, 113612 (2023).
170. Schimel, D. et al. Pan-tropical plant functional trait variation from space. Preprint at https://doi.org/10.48550/arxiv.2505.19199 (2025).
171. Gauci, V. et al. Global atmospheric methane uptake by upland tree woody surfaces. *Nature* **631**, 796–800 (2024).
172. Burt, A. et al. New insights into large tropical tree mass and structure from direct harvest and terrestrial lidar. *R. Soc. Open Sci.* **8**, 201458 (2021).
173. Han, T. et al. Taller trees experienced less crown damage during a severe hurricane in a tropical forest. *Glob. Change Biol.* **32**, e70709 (2026).
174. Huechacona-Ruiz, A. H. et al. Mapping tree species deciduousness of tropical dry forests combining reflectance, spectral unmixing, and texture data from high-resolution imagery. *Forests* **11**, 1234 (2020).
175. Laurin, G. V. et al. Discrimination of tropical forest types, dominant species, and mapping of functional guilds by hyperspectral and simulated multispectral Sentinel-2 data. *Remote Sens. Environ.* **176**, 163–176 (2016).
176. Cross, M. D., Scambos, T., Pacifici, F. & Marshall, W. E. Determining effective meter-scale image data and spectral vegetation indices for tropical forest tree species differentiation. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **12**, 2934–2943 (2018).
177. Wagner, F. H. The flowering of Atlantic Forest *Pleroma* trees. *Sci. Rep.* **11**, 20437 (2021).
178. Miura, T. et al. Utility of commercial high-resolution satellite imagery for monitoring general flowering in Sarawak, Borneo. *Ecol. Res.* **38**, 386–402 (2023).
179. Ferreira, M. P., Wagner, F. H., Aragão, L. E. O. C., Shimabukuro, Y. E. & Filho, C. R. de S. Tree species classification in tropical forests using visible to shortwave infrared WorldView-3 images and texture analysis. *ISPRS J. Photogramm. Remote Sens.* **149**, 119–131 (2019).

180. Cho, M. A., Malahlela, O. & Ramoelo, A. Assessing the utility WorldView-2 imagery for tree species mapping in South African subtropical humid forest and the conservation implications: Dukuduku forest patch as case study. *Int. J. Appl. Earth Obs. Geoinf.* **38**, 349–357 (2015).
181. Ferreira, M. P. et al. Accurate mapping of Brazil nut trees (*Bertholletia excelsa*) in Amazonian forests using WorldView-3 satellite images and convolutional neural networks. *Ecol. Inform.* **63**, 101302 (2021).
182. Chaves, P. P., Ruokolainen, K. & Tuomisto, H. Using remote sensing to model tree species distribution in Peruvian lowland Amazonia. *Biotropica* **50**, 758–767 (2018).
183. José-Silva, L. et al. Improving the validation of ecological niche models with remote sensing analysis. *Ecol. Model.* **380**, 22–30 (2018).
184. Deblauwe, V. et al. Remotely sensed temperature and precipitation data improve species distribution modelling in the tropics. *Glob. Ecol. Biogeogr.* **25**, 443–454 (2016).
185. Thomas, R. Q., Kellner, J. R., Clark, D. B. & Peart, D. R. Low mortality in tall tropical trees. *Ecology* **94**, 920–929 (2013).
186. Barber, C. et al. Species-level tree crown maps improve predictions of tree recruit abundance in a tropical landscape. *Ecol. Appl.* **32**, e2585 (2022).
187. Khan, G. et al. Weak population structure and no genetic erosion in *Pilosocereus aureispinus*: a microendemic and threatened cactus species from eastern Brazil. *PLoS ONE* **13**, e0195475 (2018).

Acknowledgements
The authors are supported by the European Union (ERC, ADAPTA, 101231095), the Natural Environment Research Council (NERC; NE/T011084/1 and NE/Z504191/1), the Royal Society (RG\R1\251370), the Leverhulme Trust (RPG-2024-342), and the National Aeronautics and Space Administration (NASA; contract NNL 15AA03C).

Author contributions
The authors contributed to all aspects of the article.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44358-026-00178-6.

Peer review information *Nature Reviews Biodiversity* thanks Haidi Abdullah and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

© Springer Nature Limited 2026

[1]Biodiversity and Earth Observation Lab, Environmental Change Institute, University of Oxford, Oxford, UK. [2]Leverhulme Centre for Nature Recovery, University of Oxford, Oxford, UK. [3]Georgina Mace Centre for the Living Planet, Imperial College London, Ascot, UK. [4]Facultad de Ciencias Forestales y Ambientales, Universidad Juárez del Estado de Durango, Durango, Mexico. [5]NASA Global Ecosystem Dynamics Investigation (GEDI), Department of Geographical Sciences, University of Maryland, College Park, MD, USA. [6]Department of Plant and Soil Sciences, University of Pretoria, Hatfield, South Africa. [7]Precision Agriculture Research Group, Council for Scientific and Industrial Research (CSIR), Hatfield, South Africa. [8]Graduate School of Science, Osaka Metropolitan University, Sugimoto, Osaka, Japan. [9]Biodiversity Division, National Institute for Environmental Studies, Onogawa, Tsukuba, Japan. [10]Environmental Change Institute, University of Oxford, Oxford, UK.