The PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA): Scoping a NASA-Sponsored Field Campaign

Tropical forests are the most biodiverse on the planet and account for 40% of Earth's terrestrial biomass and 20% of annual global methane (CH_4) emissions. They pump water vapor into the atmosphere cooling the tropics while watering farms in the temperate zone. Tropical forests have historically been significant carbon sinks, but deforestation, extreme droughts and storms, and increasingly frequent wildfires are turning some regions into net carbon sources. Critically, this reversal is not uniform. Tropical forest landscapes differ in their recent carbon flux trends, sensitivity to extreme events, and interactions with climate shifts and land-use change. Different evolutionary histories and enormous heterogeneity in environmental conditions and human interactions underpin potentially significant regional variation in tropical forest resilience, with consequences for the entire Earth system. However, major data gaps prevent us from confirming this and utilizing satellite datasets to their fullest. Regional changes have global impacts on carbon cycle dynamics and biodiversity loss that require regionally tailored actions to mitigate these outcomes and conserve the globally important tropical forest biomes. PANGEA is urgently needed to bridge critical knowledge gaps concerning rapid and large-scale climate shifts and land-use changes that are already underway in tropical forests.

PANGEA will investigate whether tropical forests - with a particular emphasis on Africa and the Americas - will share the same fate or vary in their response to change.

In 2022, NASA called for scoping studies to guide selection of a new Terrestrial Ecology field campaign. *The PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA) responded to this call, proposing a multi-scale tropical forest campaign to:

- **Answer** globally relevant and urgent science questions emphasizing comparisons among the major tropical forest formations on our planet through effective analyses and interpretation of remote sensing observations (satellite and airborne) combined with ground-based measurements and environmental and ecosystem modeling.
- **Provide** information that will contribute to tropical forest conservation and regeneration, and climate change mitigation and adaptation.
- **Ensure** transdisciplinary collaborations and the building of new relationships among diverse partners, including scientists from the US and countries with tropical forests, international space agencies, Indigenous peoples and local communities, decision-makers, and action-taking communities in the tropics.
- **Train and Educate** the next generation of scientists and the broader workforce from the US and from tropical countries where field research will be based.
- **Establish** a legacy of open data and open science to strengthen partnerships among scientists and institutions in the US, tropical countries, and other countries as the basis for future research and applications.

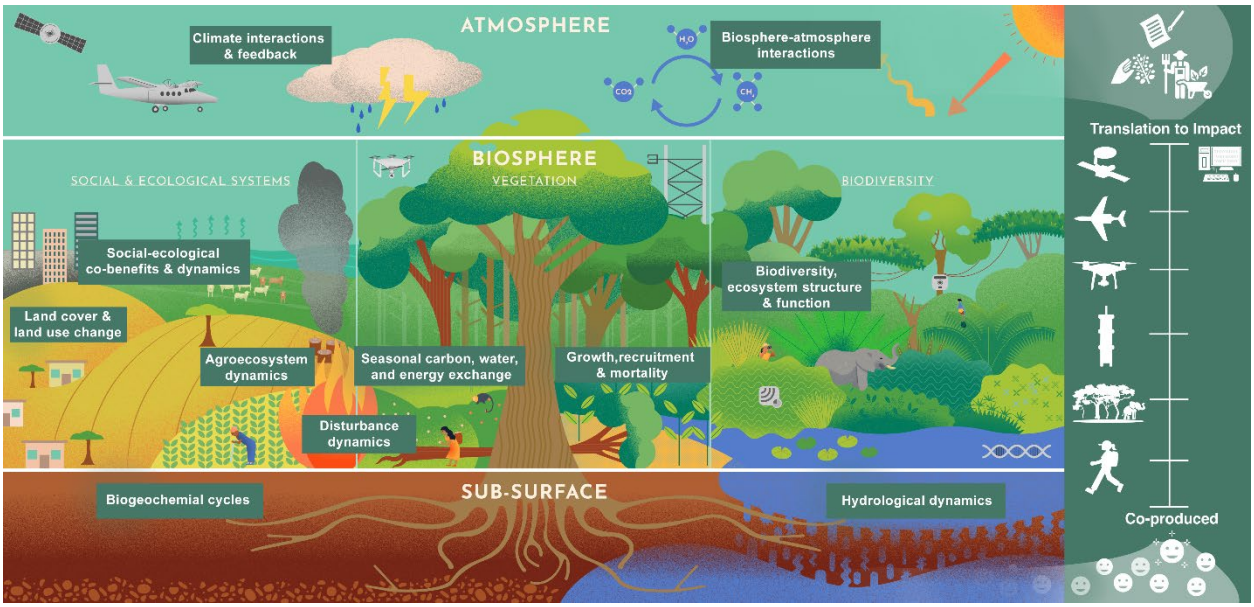
We are in an unprecedented data-rich, model-rich, and computationally advanced moment. With new and forthcoming satellites observations using lidar, radar, and imaging spectroscopy, there is an opportunity to study and observe tropical forest biomass, carbon fluxes, biodiversity, and ecosystem functions in greater detail than ever before. Yet major knowledge, data, and methodological gaps in the tropics need to be overcome to fully benefit from current and future satellite missions to answer critical science questions, PANGEA is essential to enable coordinated ground, airborne, and satellite measurements operating simultaneously to overcome these limitations.

PANGEA will investigate variation between and within Earth's two largest tropical forests in the **Americas** and **Central Africa** while integrating datasets and research from existing and complementary activities across the tropics. PANGEA's research questions focus on five thematic areas, **Biogeochemical Cycles**; **Biodiversity**; **Climate Interactions and Feedbacks**; **Social-Ecological Systems**; and **Disturbance Dynamics**. Informing climate mitigation and adaptation strategies and biodiversity conservation requires answering three critical questions:

1. What are the **patterns** of recent (5-30 years) and ongoing change in tropical forest landscape states, dynamics, and feedbacks, and how do they vary geographically?
2. What **processes** control heterogeneity in the vulnerability of tropical forest landscapes to structural and functional change in the Anthropocene?
3. How will ongoing and **projected** future changes in tropical forest landscapes alter feedbacks to local, regional, and global climates and social-ecological systems?

To address the above questions, **PANGEA's objectives** are to:

1. **Characterize and quantify** heterogeneous tropical forest responses to climate shifts and land-use changes;
2. **Address** calibration, validation, and algorithm development needs to ensure measurements can be accurately retrieved from satellite remote sensing datasets over tropical forests, ultimately advancing the global utility of satellite missions;
3. **Constrain** model uncertainty of predictions of tropical carbon fluxes and other biogeochemical cycles, biodiversity, and forest-climate feedbacks by improving process understanding and advancing remote sensing data-model integration.
4. **Develop** new capabilities for monitoring carbon, biodiversity, and agriculture using satellite remote sensing and support the development of tools to translate science into action.
5. **Train** the next generation of scientists and leaders to continue this work beyond PANGEA.



PANGEA measurements and scaling. PANGEA takes an integrated approach to science and applications, with ground, tower, drone, and aircraft measurements in tropical forest landscapes across Africa and the Americas. Modeling and satellite remote sensing analyses integrate pan-tropically

Pan-tropical forest structure and biomass can now be studied using spaceborne lidar from **GEDI** and upcoming radar missions including the NASA-ISRO **NISAR** mission and the ESA **BIOMASS** mission. Today, we can study detailed foliar diversity and chemistry of ecosystems and crops using high-fidelity spectroscopy from current missions including NASA's **EMIT** and **PACE** missions and Italian Space Agency **PRISMA** and forthcoming NASA **SBG** and ESA **CHIME** missions. Canopy solar induced fluorescence (SIF), a correlate of gross primary productivity (GPP), is now measured by instruments on several satellite platforms including **OCO-2** and **OCO-3** and **TROPOMI**. Land surface temperature has long been available at coarse resolution from weather satellites and is now measured at 70 m resolution from **ECOSTRESS** providing new insights into evapotranspiration. Satellite observations of total column CO_2 (e.g. from **GOSAT**, **OCO-2/3** and **TROPOMI**) and gravitational anomalies (**GRACE** and **GRACE-FO**) provide regional constraints on atmospheric carbon and water budgets. Similarly, surface water stage measurements are now available from space through **SWOT**. High spatial and temporal resolution data on the land surface are now available from sources such as Planet and the geostationary **GOES-R** series of missions. Many of these sources of information have barely been employed for tropical forest studies. **PANGEA supports the calibration and validation, algorithm and product development, and global utility of these current and forthcoming satellites from NASA and partner space agencies**. PANGEA's coordinated multi-scale campaign integrates drone and aircraft measurements (e.g., AVIRIS, LVIS, small-footprint lidar, UAVSAR, CARAFE) with ground measurements (e.g., flux tower and chamber measurements, trait measurements, animal movement, bioacoustics, and Indigenous Ecological Knowledge) to advance understanding of tropical forest systems and the utility of satellite remote sensing to measure and monitor them.

Tropical forests are the least investigated of all of Earth's major terrestrial biomes. The scarcity of observations in tropical regions makes it difficult to scale up findings from individual research sites to broader regional, pan-tropical, and global levels.

PANGEA stands on the shoulders of highly successful NASA field and airborne campaigns to Africa and South America, including but not limited to **SAFARI 2000**, **LBA**, **AfriSAR-1 and -2**, **BioSCape**, and several Earth Venture Suborbital (EVS) missions. PANGEA will build on these precedents to enable NASA funded investigators to answer crucial scientific questions by comparison among major tropical forest systems. Recent achievements that demonstrate feasibility include the highly successful AfriSAR-2 campaign that collected airborne L- and P-band UAVSAR data over Cameroon, the Democratic Republic of Congo (DRC), Gabon, Ghana, the Republic of Congo, and Sao Tome and Principe. These campaigns provide valuable initial data, yet there remains a critical need for collocated and coincident ground, airborne, and satellite measurements across the highly variable tropical landscapes, to capture variation in ecosystem structure and function within and across continents. These coincident measurements are particularly important in Africa, where data gaps are the greatest, and process-based understanding is poorest.

The PANGEA campaign would be executed over 6 to 9 years, beginning in 2026 following the science definition phase. We obtain the **Baseline, Threshold and Descope Essential Scientific Measurements** from the PANGEA Science Objectives:

- **Baseline:** PANGEA measurements encompass ~3-6 tropical African and ~3-6 tropical American landscapes that capture the end of the wet season and the end of the dry season.
- **Threshold:** PANGEA measurements encompass 2 tropical African and 2 tropical American landscapes that capture the end of the wet season and the end of the dry season.
- **Descope:** PANGEA measurements encompass 2 tropical African landscapes that capture the end of the wet and dry seasons, which will be compared with information for the American tropics collated from existing data, other projects and campaigns led by collaborators, commercial data-buys, and deployable drones. This descope option partially meets PANGEA objectives while accounting for potential funding restrictions or geopolitical uncertainty.

PANGEA will include a core and extended domain. The extended domain will encompass pan-tropical forests and will be prioritized for satellite remote sensing and modeling analyses. PANGEA's core domain will focus on tropical biomes in Africa and the Americas. Both the core and extended domains will encompass moist tropical forests, including flooded forests, wetlands, and peatlands. The extended domain will enable the inclusion of existing datasets and opportunistic collection in Asia and Australia.

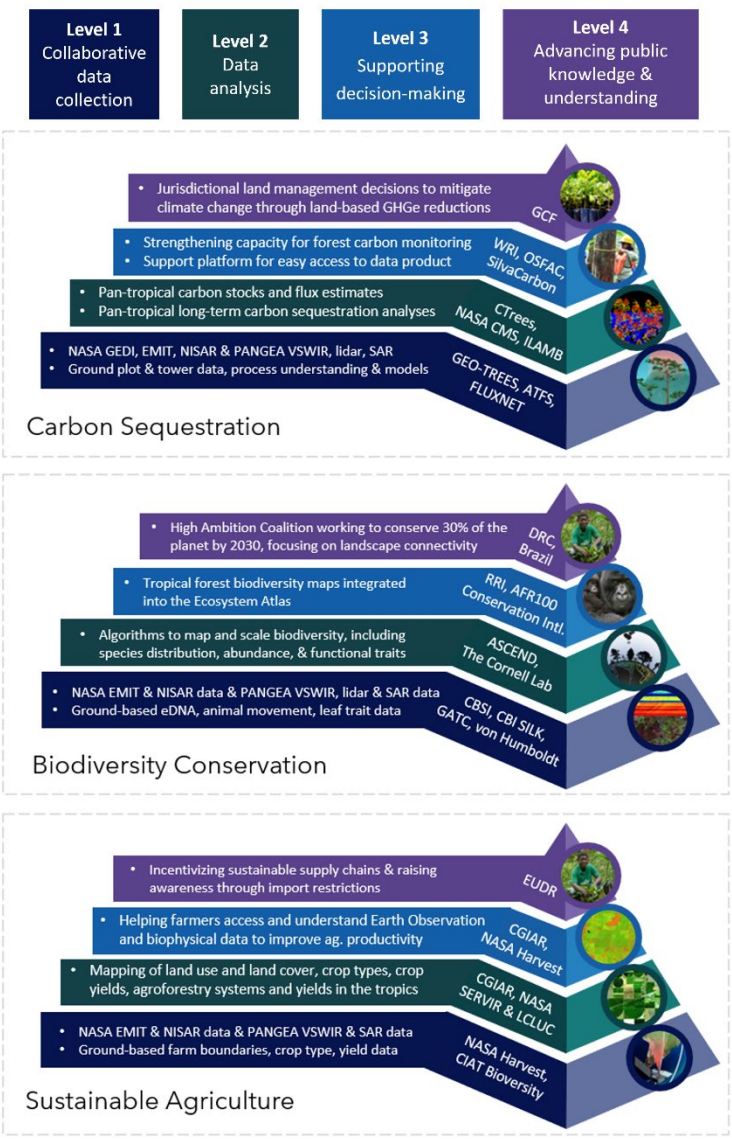
PANGEA will coordinate landscape selection closely with efforts that are actively in the process of selecting sites for complementary data collection and investment in infrastructure. These include GEO-TREES, the INPE-ESA Amazon campaign, One Forest Vision Initiative, Moore Foundation and NSF funded tropical methane and peatland field measurements, as well as multiple Schmidt Science Virtual Institute for the Carbon Cycle proposals focusing on the tropics. A landscape selection process will be formalized as part of the Concise Experimental Plan to ensure transparency. This process will build on ongoing discussions with local institutional partners and site managers that began during the scoping process and will include co-design with Indigenous Peoples and Local Communities.

In partnership with local institutions, PANGEA will prioritize training, capacity building, and education that prepares the next generation to continue this work well after the PANGEA campaign. PANGEA is an important opportunity to increase understanding of Earth observations and expand the use of NASA Earth data, products, and services around the world. As PANGEA advances knowledge of tropical forests and their vulnerability and resilience to climate shifts, PANGEA will develop innovative methods, compile valuable datasets, and produce critical findings that can help scientists, governments, Indigenous peoples and local communities, conservation practitioners, private companies, and more understand their environmental impacts and take urgent actions to mitigate and adapt to climate shifts and biodiversity loss.

PANGEA shares NASA Earth Science's strategic goal of advancing and integrating Earth science knowledge to empower humanity to create a more resilient world over the next decade. Strengthening capacity and investing in education associated with PANGEA is central to this aim, and critical to preparing the next generation with the necessary expertise and tools. Critically, PANGEA capacity building, training, and education will target US-based research and workforce communities, as well as local and national communities in tropical forest countries partnering with PANGEA. PANGEA will partner with existing NASA programs, as well as with local and international collaborating institutions, to plan and execute training activities that are appropriate for a range of potential trainees, including students, early career scientists, the broader workforce, and Indigenous Peoples and Local Communities.

The 2017 Decadal Survey directs us to "pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observations and analysis to the nation and to the world in a way that delivers great value." Now is the time for strategic investment in ambitious international collaborations to bridge the gap between rapid advancements in science and technology and society's ability to harness them for a more resilient world. PANGEA is highly relevant to NASA's strategic goal to advance and integrate Earth science knowledge to empower humanity to create a more resilient world. Specifically, PANGEA supports NASA's Earth Science to Action strategy by:

- Investigating the risks of crossing tipping points with potential cascading impacts.
- Supporting efforts to enhance Earth's resilience through mitigation and adaptation.
- Facilitating development of efficient, interactive end-to-end tools, models, and assessment systems with appropriate latencies, temporal and spatial scales, and uncertainty quantification to enable science-based actions for communities, decision-makers, and policymakers.



PANGEA Earth Science to Action implementation strategy, with potential focal areas in carbon sequestration and climate mitigation, biodiversity conservation, and sustainable agriculture.

PANGEA will develop new capabilities for monitoring carbon, biodiversity, and agriculture using satellite remote sensing and support the development of tools to translate science into action through partnership with diverse partners, including governments, IPLCs, civil society, and private industry. These include advances in: 1) **long-term carbon sequestration stability mapping**, 2) **methane flux monitoring**; 3) **biodiversity conservation**; 3) **sustainable agriculture**. PANGEA engages diverse communities to address PANGEA's science questions and applications, identify synergies with local research priorities, and implement PANGEA in a manner that is broadly beneficial in the landscapes and countries targeted for research. The strategy draws upon the knowledge, expertise, and experiences shared throughout PANGEA's scoping campaign, and will complement and expand upon many existing efforts but is likewise urgently needed to fill gaps left unfilled by these other activities.

Co-production is at the heart of PANGEA's transdisciplinary science and applications and training the next generation of scientists and leaders.