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1. Introduction and Motivation

In response to a call from the NASA Terrestrial Ecology Program, we present the scope of a terrestrial ecology community field campaign, *The PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA), that will focus on tropical forest biomes.

PANGEA will:

- **Answer** globally relevant and urgent big science questions emphasizing comparison among the major tropical forest formations on our planet through effective interpretation and analysis of space-based measurements and through a combination of ground, airborne, and satellite-based science investigations.
- **Foster** collaborations and build new relationships within the scientific community, with an emphasis on interactions between US scientists and researchers from countries with tropical forests, as well as strengthening relationships with partners from international space agencies and decision-making and action-taking communities.
- **Provide** opportunities for training and educating the next generation of scientists and the broader workforce, including scientists and trainees from countries where field research will be based.
- **Establish** a legacy of open data, open science, and strengthened partnerships between the US, tropical institutions, and international partners as the basis for future research and applications.

Tropical forests account for globally significant carbon, water, and energy fluxes, and a large proportion of Earth's biodiversity. Tropical forests also store vast amounts of carbon; moist tropical forests in particular comprise about 40% of global biomass (Xu et al., 2021) and are currently a globally important carbon sink (Pan et al., 2024). Tropical forests also regulate climate locally, regionally, and globally.

Critically, the biogeochemical response of tropical forests to changing climate forcing and climate extremes varies strongly across the tropics in ways that urgently require improved understanding.

Forests in the equatorial regions will soon experience the highest known temperatures since the Eocene which, combined with land-use change, will lead to increasing atmospheric dryness and water stress (Barkhordarian et al., 2019). Tropical tree mortality rates are rising differentially across the tropics due to increases in drought duration and severity and storm intensity (Allen et al., 2010, McDowell et al., 2018, Choat et al., 2012). Rising temperatures are approaching hypothesized thermal limits of leaf function, although those limits remain much debated (Smith et al., 2020, Doughty et al., 2023, Winter 2024). Unprecedented rates of anthropogenic land-use change in recent decades (DeFries et al., 2004, Gibbs et al., 2010a, Hosonuma et al., 2012) have resulted in some tropical forests becoming net sources of carbon to the atmosphere (Gatti et al., 2021). Prolonged hot and dry conditions increase forest vulnerability to fires and already burned forests in turn become hotter and drier leading to a positive feedback that has been called a “gathering firestorm” (Brando et al., 2020). Deforestation, forest degradation, direct exploitation (e.g., hunting, harvesting), and climate change threaten many tropical species with extinction (Feeley et al., 2012; Barlow et al., 2016; Benitze-Lopez et al., 2017; Alroy 2017), and this biodiversity loss could in turn compromise tropical forest structure and function as well as goods and services (Bunker et al., 2005; Peres et al., 2016).

Even as regrowing, secondary tropical forests continue to sequester large amounts of carbon from the atmosphere, tropical deforestation and degradation accounted for 22% of annual anthropogenic carbon dioxide (CO_2) emissions, while intact tropical forest sinks weakened from 1284 TgCyr-1 in the 1990s to 881 TgC in the 2010s, an estimated 31% in the past two decades (Pan et al., 2024). Tropical forests and floodplains, interspersed with wetland and aquatic ecosystems, also play a critical role in the global methane (CH_4) and CO_2 budgets (Sjögersten et al., 2014; Peng et al., 2022). CH_4 contributes an estimated 30% of the increase in radiative forcing from anthropogenic emissions and is 25 times more potent as a greenhouse gas (GHG) compared to CO_2 (Masson-Delmotte et al., 2021). CH_4 has experienced recent atmospheric growth rates inconsistent with our current understanding of global sources and sinks of this critical greenhouse gas (GHG) (Turner et al., 2019). Tropical wetland and inland freshwater systems contribute the vast majority of global aquatic CH_4 emissions and make up roughly 20% of the total global CH_4 budget of ~575 Tg CH_4 yr^{-1} (Saunois et al., 2020; Peng et al., 2022). These tropical CH_4 sources are the most uncertain component of the global carbon budget (Saunois et al., 2020, 2024).

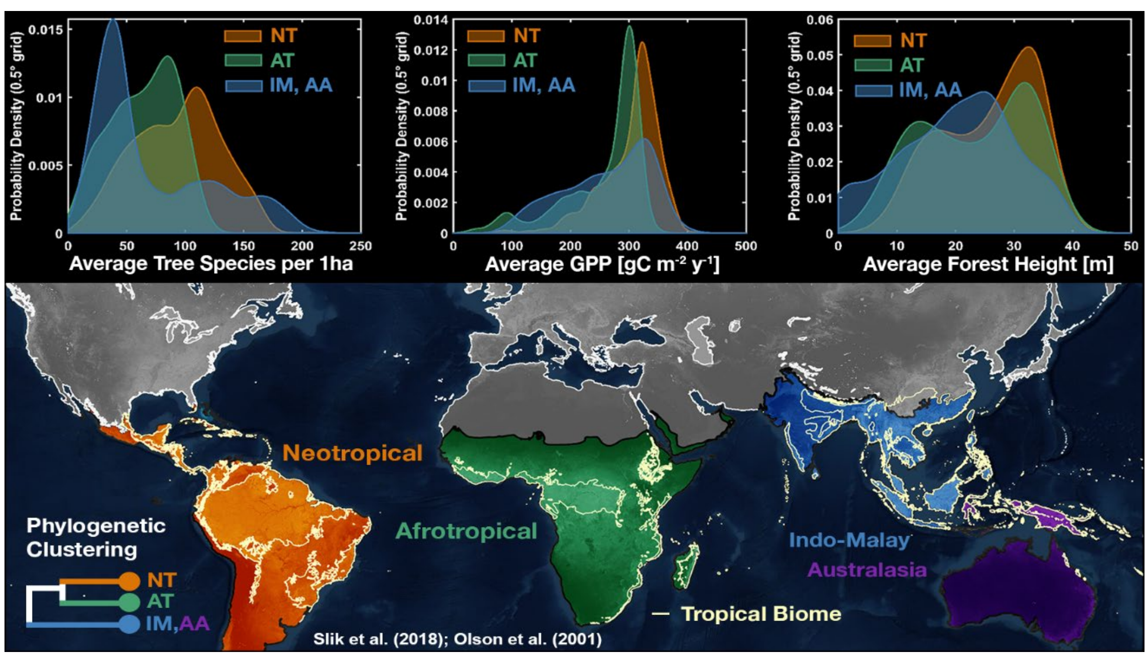


Figure 1 Tropical forests vary strongly in structure (height), function (GPP), and diversity within and among major floristic regions (mapped colors), shaping responses to climate and land-use change. The brightness of each color indicates mapped GPP.

Current research has revealed our lack of understanding of how differences in the heterogeneity of tropical forests' species composition, structure, functional traits, and human interactions across continents control responses to climate change and other anthropogenic changes. This knowledge gap is greater in the humid tropics than in other biomes (e.g., boreal or temperate forest ecosystems). Differences in the evolutionary history of tropical ecosystems across continents have produced major variation in species and functional composition, structure, and biogeochemical cycling that directly affects their vulnerability and resilience (**Figure 1**). In other words, the ability to withstand and recover from changes is directly linked to the conditions under which these systems evolved. From 1985-2015, the carbon sink of intact African lowland tropical forests measured in forest inventory plots was effectively constant, while the carbon sink in Amazonian lowland tropical forests declined by one-third from 2005 through 2015 compared to the 1990s (Hubau et al., 2020; Brienen at al., 2015). Under El Niño conditions during 2015-2016, tropical America, Africa, and Asia, all temporarily became net sources of CO_2 emissions to the atmosphere (Liu et al., 2017).

However, these net carbon losses appear to be underpinned by distinct mechanisms that indicate differences in the stability of the carbon sink and will require regionally specific understanding and management to mitigate. The sources of atmospheric CO_2 concentrations, as measured by the Orbiting Carbon Observatory-2 (OCO-2), suggest that in the tropical Americas, reduced photosynthesis led to reduced carbon uptake reversing the balance to net emissions. In Africa, increased temperatures led to increased respiration, outweighing the sequestration benefits of Central African tropical forests (Liu et al., 2017). In Asia, a hotter and drier land surface resulted in more emissions from fires. However, we cannot confidently explain differences among tropical forest biomes in responses to climate forcing, nor do our current scaling tools fully reconcile differences between ground and satellite measurements in the tropics.

NASA satellite missions require validation in tropical forests.

NASA satellites play a critical role in advancing understanding of how forest ecosystems respond to environmental changes such as climate variability and land-use change. However, before satellite data can be useful for scientific analysis or operational use, ground-based observations are critical to validate these measurements. Yet, the scarcity of such observations in tropical regions has led to significant challenges in improving satellite products **and interpreting scientific findings learned from these products**. For instance, the carbon and water cycles in the tropics are strongly dependent on soil moisture dynamics, however, recent ground-based observations revealed that the Soil Moisture Active Passive (SMAP) satellite exhibits strong biases in tropical ecosystems (Cho et al., 2024). Importantly, these same ground-based data have provided an opportunity to improve SMAP's soil moisture measurements in tropical forests (Wang et al., 2024). Another example is the lack of ground-based validation data for space-based CO2 measurements over the tropics, especially tropical Africa, which led to an ongoing unsettled debate about the magnitude of net biosphere exchanges over tropical Africa (Palmer et al., 2019; Gaubert et al.,2023). Reducing biases in measurements such as soil moisture and atmospheric column CO_2 is critical for enhancing our understanding of the water cycle, carbon fluxes, and ecosystem dynamics in this globally important region. Validating satellite measurements with ground and airborne observations is essential to the success of NASA's Earth observation missions, particularly with the advent of an exciting new and forthcoming fleet of sensors that have the potential to capture the multi-dimensionality of these systems (e.g., GEDI, EMIT, SWOT, NISAR, SBG). The development of more accurate satellite products, particularly in understudied tropical regions, directly supports NASA's mission to improve global environmental monitoring and advance predictive models.

Future predictions of the role of the tropical land carbon flux in the Earth system remain highly uncertain (Arora et al., 2020; Friedlingstein et al., 2014; Friedlingstein et al., 2006).

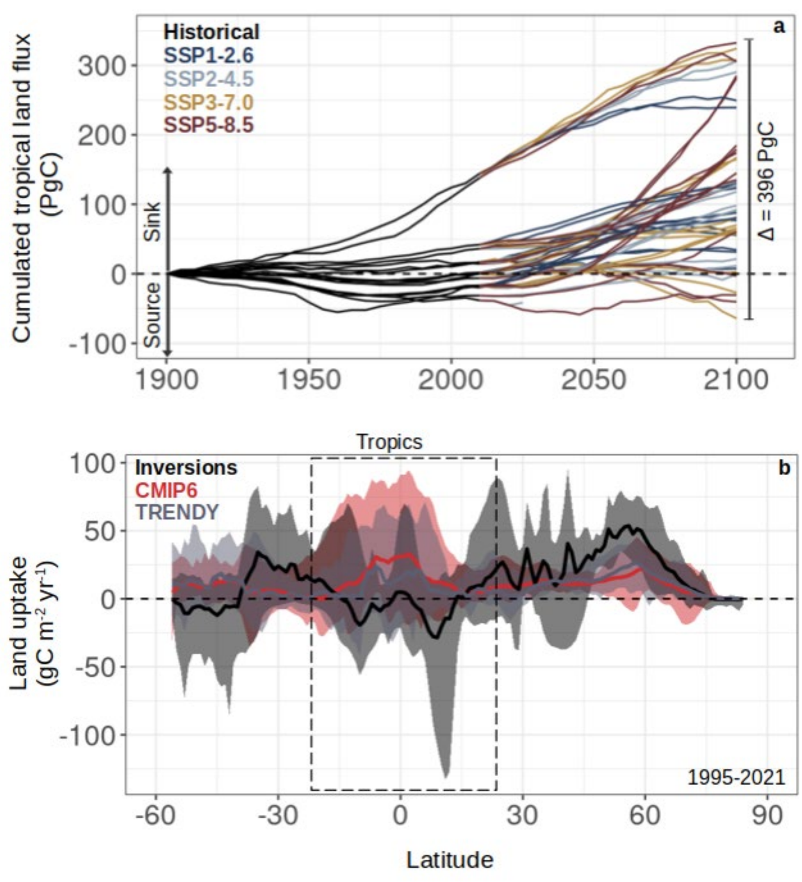


Figure 2. Historical and future cumulative land carbon flux from the tropics according to CMIP6 models with dynamic vegetation and multiple emission scenarios (a). Zonal mean of the land carbon uptake according to inversion models (black), CMIP6 models with dynamic vegetation models, and TRENDY land surface models for the recent period (b). The extent of the tropical region and its high uncertainty is highlighted with the dashed rectangle. Panel (a) was adapted from Friedlingstein et al. 2014 (update from CMIP5 to CMIP6) while panel (b) was redrawn from the IPCC sixth assessment report with recent data.

The current uncertainty in terrestrial carbon flux predictions across Earth System Models (ESMs) (Negron-Juarez et al., 2015) is three times greater in the tropics than at any other latitude (**Figure 2**, Cavaleri et al., 2015). While model development between Coupled Model Intercomparison Project (CMIP) Phase 5 and Phase 6 resulted in a major step toward constraining tropical carbon flux uncertainty, these reductions were primarily linked to the inclusion of nutrient limitations in models (Friedlingstein et al., 2023). Traditionally, Earth System Models (ESMs) ignore most biodiversity and represent tropical vegetation in simple and aggregated ways that directly contribute to model failure to capture tropical forest responses to climate variation and disturbance (Levine et al., 2016; Yang et al., 2023; Sakchewski et al., 2016). Constraining this uncertainty requires improved representation of ecological processes of diverse ecosystems (Bonan et al., 2024). Newer generations of terrestrial biosphere models—vegetation demography models (Fisher et al., 2018) – such as ED and FATES—include more structurally and functionally diverse forest canopies (Longo et al., 2019; Koven et al., 2020). Although vegetation demography models represent forest dynamics processes more directly, the additional complexity creates two challenges for regional and global simulations. First, initial conditions require detailed forest structure and composition data that can be derived from forest plots only for small domains (Marvin et al., 2014). Second, existing model benchmarking systems, such as the International Land Model Benchmarking (ILAMB; Collier et al., 2018) are insufficient, because the newer generation of models may predict reasonable aggregated properties (e.g., total aboveground biomass) via compensating errors in process representation (e.g., overly high productivity and mortality). Recent advances in remote sensing provide a unique opportunity to collect data on the structure, composition, and diversity of tropical ecosystems over large areas and thereby better inform models (Schimel et al., 2019).

Tropical forests are also the least investigated of all of Earth's major terrestrial biomes.

Few tropical forest countries maintain systematic repeated forest inventories because inventories are costly and require technical and management expertise. Networks of research plots provide valuable insights into forest dynamics (e.g., ForestPlots.net et al., 2021; Anderson-Teixeira et al., 2014, Davies et al., 2021), but their distribution is sparse and extrapolation from potentially biased plot locations may lead to significant uncertainties and biases (Saatchi et al., 2015). The latitudinal distribution of both forest inventory plots and eddy covariance flux towers is nearly inversely proportional to gross primary productivity, demonstrating the underrepresentation of sampling in these critical ecosystems (Baldocchi et al., 2020, Schimel et al., 2015) (**Figure 3**).

Earth Action Relevance: PANGEA has relevance to Earth Action programs, Climate & Resilience, Water Resources, Ecological Conservation, and Agriculture. Halting tropical deforestation and forest degradation and conserving and restoring tropical forests can be a cost-effective tool for mitigating climate change, with co-benefits that extend beyond carbon sequestration (e.g. Heinrich et al., 2023). Tropical forests maintain high levels of evaporation and transpiration

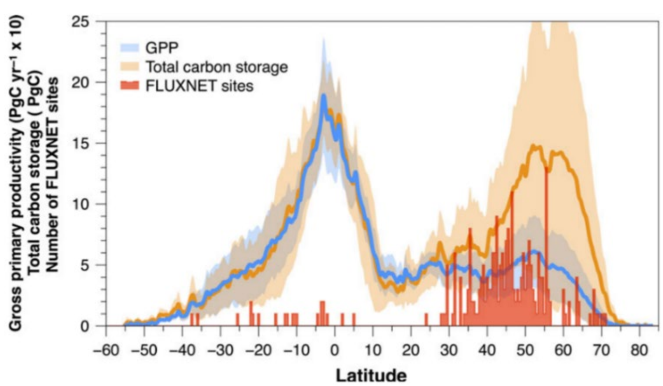


Figure 3. Forest function refers to the ecological roles of forests, such as regulating climate, supporting biodiversity, cycling nutrients, and providing habitat, which contribute to the overall health and stability of ecosystems. Forest functions include gross primary productivity (GPP), woody productivity, ecosystem respiration, and evapotranspiration.

throughout the year, transferring energy and water to distant latitudes and maintaining high rates of regional precipitation through rainfall recycling (Salati et al., 1979; Worden et al., 2021; Worden et al., 2024, van der Ent et al., 2010, Staal et al., 2018). Tropical deforestation and forest degradation reduce evapotranspiration in the dry season (Sampaio et al., 2007; Longo et al., 2020; Zemp et al., 2017) potentially leading to forest mortality and a positive feedback loop resulting in impacts to water resources and agricultural productivity, and possible forest ecosystem collapse that could result in tipping points (Xu et al., 2022; Lovejoy and Nobre 2018). Accelerating biodiversity loss, declining populations and changes in species composition directly impact ecosystem function and services (Ceballos et al., 2002; Gaston et al., 2008), although the full impacts of biodiversity loss are likely underestimated (Dirzo et al., 2014). Connected to all of this is the immense pressure on tropical forests from agricultural expansion due to rising global demand for food, fiber, and biofuels (Erb et al., 2024; Pendrill et al., 2022). Tropical regions are expected to play a growing role in global agriculture (Alexandratos and Bruinsma 2012). Agricultural intensification to support global demands and local livelihoods in the region stands to greatly benefit from precision agriculture methods and biogeochemical cycle monitoring (e.g., phosphorus and nitrogen) to ensure sustainable solutions. These elements cut across PANGEA's Science Questions (*Section 3*) and Earth Science to Action Strategy (*Section 8*).

PANGEA aims to determine whether tropical forests will share the same fate or vary in their responses to the effects of climate change, with a particular emphasis on the two largest tropical forests.

Implementing PANGEA is urgent due to our limited understanding of tropical forest ecosystems. Experts suggest the potential collapse of these ecosystems within decades, which could drastically impact the global carbon and water cycles, exacerbating climate change (Lovejoy and Nobre 2018). Second, the lack of knowledge necessary to fully utilize existing and upcoming satellite data hinders progress. To fully benefit from current and future satellite missions and take effective, regionally tailored action to mitigate these outcomes and conserve this globally important biome, immediate action is essential. PANGEA will bridge critical knowledge gaps, enabling timely advancements that directly support NASA's Carbon Cycle and Ecosystems Focus Area, in alignment with the Water and Energy Cycle and Climate Variability and Change Focus Areas, as well as global climate and biodiversity commitments.

1.1 Questions, Objectives, and Science Themes

Tropical forests have been a globally important carbon sink in recent decades, absorbing large amounts of CO_2 from the atmosphere. However, deforestation, increases in extreme weather events, frequent wildfires, and other disturbances are reversing this trend, with some regions now acting as net carbon sources. Moreover, forest regrowth following these disturbances does not fully restore the original carbon sink capacity. This reversal is not uniform: tropical forest landscapes differ in their recent carbon sink trends, sensitivity to extreme events, and interactions with climate and land-use change. Understanding controls on tropical forest carbon flux trends and the resilience of tropical forest carbon sinks to extreme events is crucial to accurately projecting the future of the Earth system and requires an improved understanding of patterns and processes. Critically, continued monitoring of these dynamics at pan-tropical and global scales urgently requires filling data and methods gaps to effectively harness the new era of satellite remote sensing capabilities available now and in the next 1-10 years. PANGEA will study the complex interactions of the carbon cycle and social-ecological systems in the tropics to answer: **How vulnerable or resilient are tropical forest landscapes and their feedbacks to the global carbon cycle and climate?**

Addressing this knowledge gap to inform 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?

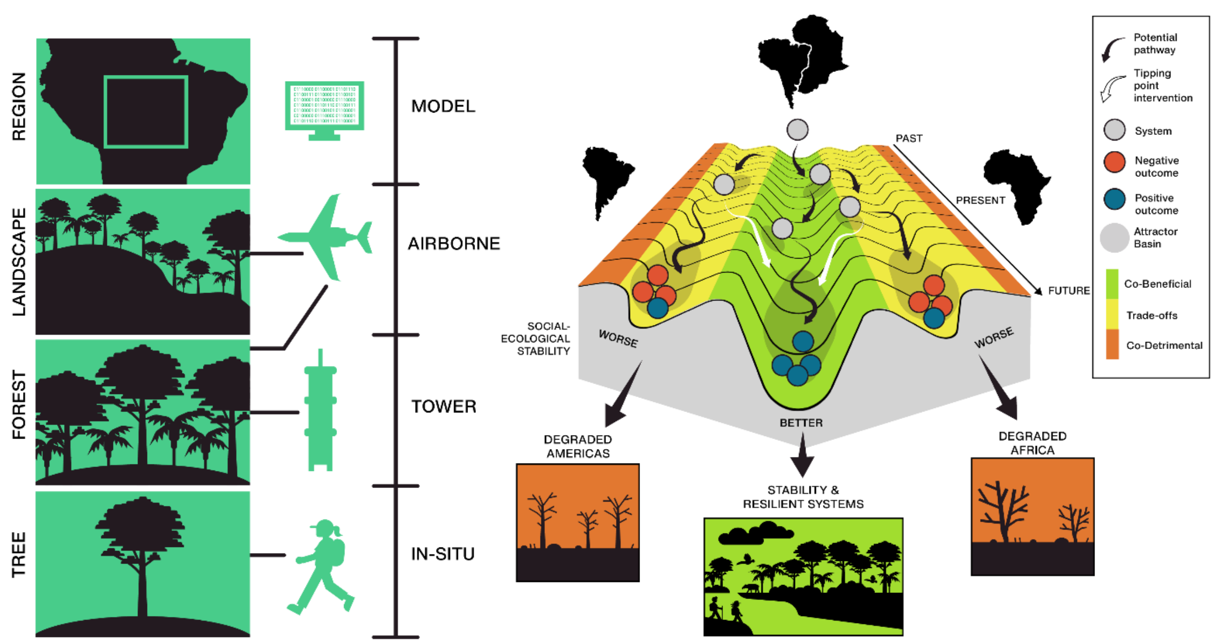


Figure 4. PANGEA examines how vulnerable or resilient tropical forest landscapes are, as well as and their feedbacks to the global carbon cycle and climate. PANGEA's science and applications and international collaborations employ an integrated approach to bridge the gap between rapid advancements in science and technology and society's ability to harness them for a more resilient world.

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

1. **Characterize and quantify heterogeneous tropical forest responses** to anthropogenic changes;
2. **Constrain model uncertainty of future tropical carbon flux predictions** by improving process understanding and advancing remote sensing data-model integration;
3. **Address calibration, validation, and algorithm development needs** to ensure measurements can be accurately retrieved from satellite remote sensing datasets over the tropics, ultimately supporting the global utility of satellite missions.

PANGEA research and activities will prioritize the investigation of variation between Earth's two largest tropical forests in the **Amazon** and **Central Africa** while integrating datasets and research from existing and complementary activities across the tropics wherever possible (**Figure 4**). PANGEA's research questions focus on resolving uncertainties related to **multidecadal trends** and **responses to extreme events** across five thematic areas:

- **Biogeochemical Cycles** encompass the movement and transformation of essential elements (e.g., carbon, nitrogen, and phosphorus) through Earth's biosphere, atmosphere, hydrosphere, and lithosphere. In tropical forests, these cycles are highly dynamic, with rapid nutrient turnover and a significant role in global carbon storage.
- **Biodiversity** is the variety of life on Earth, including its variation at the level of genes, species, functional traits, and ecosystems. In tropical forests, biodiversity is exceptionally high within and across forests, supporting complex interactions and ecosystem function, and causing heterogeneity in climate responses and resilience.
- **Climate Interactions and Feedbacks** are the interactions between climate systems and ecosystems, where changes in one influence the other. In tropical forests, these interactions are significant, as the forests regulate carbon, water and energy cycles. Climate changes (like temperature and rainfall shifts) and land-use and land cover changes (like fires and forest degradation) can alter forest ecosystem dynamics, creating feedback loops that affect global climate stability.
- **Social-Ecological Systems** are interconnected systems of humans and nature, where ecological and social components interact and influence each other. In tropical forests, these systems are shaped by the livelihoods, cultural practices, and resource use of local communities, while ecological changes impact social well-being, creating complex feedbacks between human activities and ecosystem stability.
- **Disturbance Dynamics** vary by type, intensity, and frequency, and involve natural or human-induced events, such as fires, storms, drought, and logging, that disrupt ecosystems and affect their structure and function. In tropical forests, these disturbances can lead to shifts in biodiversity, biogeochemical cycling, and feedbacks to climate and to social-ecological systems.

1.2 The urgent need for PANGEA

Implementing PANGEA is urgent for two reasons; both relate to our lack of knowledge of tropical forest ecosystems.

First, PANGEA is urgent because recent scientific results find real potential for the collapse of tropical forest ecosystems in the next few decades (Malhi et al., 2009; Boulton et al., 2022; Wunderling et al., 2022). Because of the importance of these ecosystems in the global carbon and water cycles, the collapse of tropical forest ecosystems would have potent effects on the whole Earth System exacerbating current trends in climate change (Wunderling et al., 2024). To take effective, regionally tailored action to mitigate these outcomes and conserve this globally important biome, action requires improved understanding of the varied ways in which different tropical forests are responding to change.

The second urgent reason for implementing PANGEA now is the lack of knowledge to adequately understand existing and forthcoming satellite data. The tropical forest biomes are woefully understudied compared to other biomes on Earth because of their inaccessibility and because much of the tropical forest area is in moderately poor or extremely poor nations that have limited resources to devote to the study of tropical forests. To fully benefit from current (e.g., EMIT, GEDI, OCO-2/3) and future (e.g., NISAR, SBG) satellite missions, we urgently need studies with field and airborne resources to understand the signals from those missions.

Immediate implementation of PANGEA as a Terrestrial Ecology Field Campaign is essential to fill knowledge gaps, and coordinate with well-timed international efforts. Delaying efforts to intensively study tropical forests will lead to a mismatch between the abundant data coming from our satellite assets and our ability to interpret those data.

PANGEA will advance scientific understanding and remote sensing capabilities across thematic areas that directly address the goals of NASA's Carbon Cycle and Ecosystems Focus Area, in alignment with the Water and Energy Cycle and Climate Variability and Change Focus Areas.

1.3 Role of Remote Sensing Observations

We are in an unprecedented data-rich, model-rich, and computationally advanced moment. We now have remote sensing capabilities that allow for more direct measurement of structural, functional, and in some cases taxonomic diversity. In tropical forest regions, surface observations are scarce. Few tropical forest countries have regularly repeated, systematic forest inventories. The limited number of research sites provide critical information on biogeochemical and ecological processes, but because of the scarcity of information it is challenging to scale up to regional, biome-wide, or pan-tropical analysis.

Remote sensing, and especially satellite remote sensing is the primary source of information for regional and pan-tropical studies.

PANGEA represents a unique opportunity for advancing NASA satellite-based studies of tropical forests. The previous tropical forest campaign, LBA, began in1998 before the launch of EOS Terra and Aqua satellites. Landsat was the prime tool for monitoring deforestation (Skole and Tucker 1993) and through the first decade of LBA research it would be applied to estimate logging (Asner et al., 2005) and understory forest fires (Morton et al., 2011). Remote sensing in early ecological models, such as the Carnegie-Ames-Stanford (CASA) biosphere model (Potter et al., 1993) that used satellite data, were originally designed to incorporate NDVI data from polar orbiting weather satellites (AVHRR) calibrated to net primary production. Among the earliest major results of LBA, was the recognition that tower-based estimates of NEE had very different seasonality than the predictions of models at the time (Saleska et al., 2003). Understanding this mismatch motivated new linkages with more sophisticated remote sensing data. Interpreting MODIS data led to the observation that the Amazon region has a distinct seasonal signal of green-up and brown-down (Huete et al., 2006). Part of this signal resulted from land-use change because pastures and crops are senescent (brown) in the dry season. Forests showed a seasonal pattern of green up, however, even during droughts (Saleska et al., 2007). Subsequent studies showed that BRDF induced artifacts magnified the dry season green-up signal (Morton et al., 2014). However, after these artifacts are removed a seasonal signal remains. Part of the seasonal signal is related to the annual replacement of old leaves with new leaves at the beginning of the dry season (Wu et al., 2016). Researchers are still untangling the signal of Amazon phenology that has multiple causes, including seasonal changes in the vertical distribution of leaves visible in spaceborne lidar data (IceSat GLAS) (Tang and Dubayah 2017) and variable spatial patterns of leaf replacement inferred from SIF data from TROPOMI (Doughty et al., 2019). New technologies moving beyond *greenness* estimates are providing deeper insights into the function of tropical forests.

The constellation of Earth observing satellites available today, those nearing launch, and those in early stages of implementation and planning offer many dimensions of information not previously available and not widely used in tropical forest studies.

Pan-tropical forest structure and biomass can now be studied using spaceborne lidar from GEDI (Dubayah et al., 2020) and upcoming radar missions including the NASA-ISRO NISAR mission and the ESA BIOMASS mission. There is now opportunity to study detailed foliar chemistry of ecosystems and crops using high-fidelity spectroscopy from current missions including NASA's EMIT mission and Italian Space Agency PRISMA (Tagliabue et al., 2022; Rogers et al. 2024) and forthcoming SBG and CHIME missions. Canopy solar induced fluorescence, a close correlate of gross primary productivity (GPP), is now measured instruments on several satellite platforms including OCO-2 and OCO-3 and TROPOMI (Köhler et al. 2018). Land surface temperature has long been available at coarse resolution from weather satellites but is now measured at 70 m resolution from ECOSTRESS (Fisher et al., 2020; Li et al., 2021) providing new insights on evapotranspiration and GPP. Satellite observations of total column carbon dioxide (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, river stages 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 GOES-R series of missions. Many of these sources of information have barely been employed for tropical forest studies.

The knowledge gaps that PANGEA will address cannot be answered without pan-tropical satellite observations, integrative analyses, and models. However, we are currently unable to fully leverage these satellite datasets without coordinated calibration and validation measurements. Major data gaps and process uncertainties in tropical forests currently limit algorithm and product development, preventing the global utility of these sensors from being fully realized.

Scale mismatches exist for desired retrievals from nearly all of these satellites. For example, differences need reconciliation between the approximately 1 km footprint of tower-based eddy covariance fluxes and >2 km resolution satellite retrievals of gross primary productivity, methane fluxes, and ecosystem respiration. Functional trait maps still require estimation using models calibrated to specific sites based on in situ leaf trait measurements (e.g., Chadwick & Asner 2016). Calibration and validation data in the tropics are currently lacking to test the generalizability of existing algorithms. Similarly, retrieval of tree- and crown-level structural attributes from lidar is necessary to link organismal processes and dynamics to ecosystem responses observed at landscape scales. In addition, vertical variation in forest structure has been shown to vary with ecosystem function even when vertically integrated metrics like leaf area index (LAI) does not (Ordway et al., 2022). Spaceborne lidar yields community scale observations that, although incredibly valuable, remain insufficient to pair with tree level in situ measurements. Because these data are sampled across forests, they do not support retrieval of crown and tree-level metrics, or fine-scale ecosystem metrics like canopy gap detection and tree mortality. Reconciling these scale mismatches requires collocated ground, tower, drone, aircraft, and satellite measurements in combination with advances in understanding of processes that underpin scaling theory.

The abundance of new satellite data can now be paired with new capabilities for data analysis. We have a far greater ability to do numerically intensive analyses with cloud computing, advanced computational resources, and rapidly evolving machine learning and AI. We see great opportunities for numerical models that represent processes that mediate forest diversity, and the interactions of structurally heterogeneous forests with climate, land use and biogeochemical cycles.

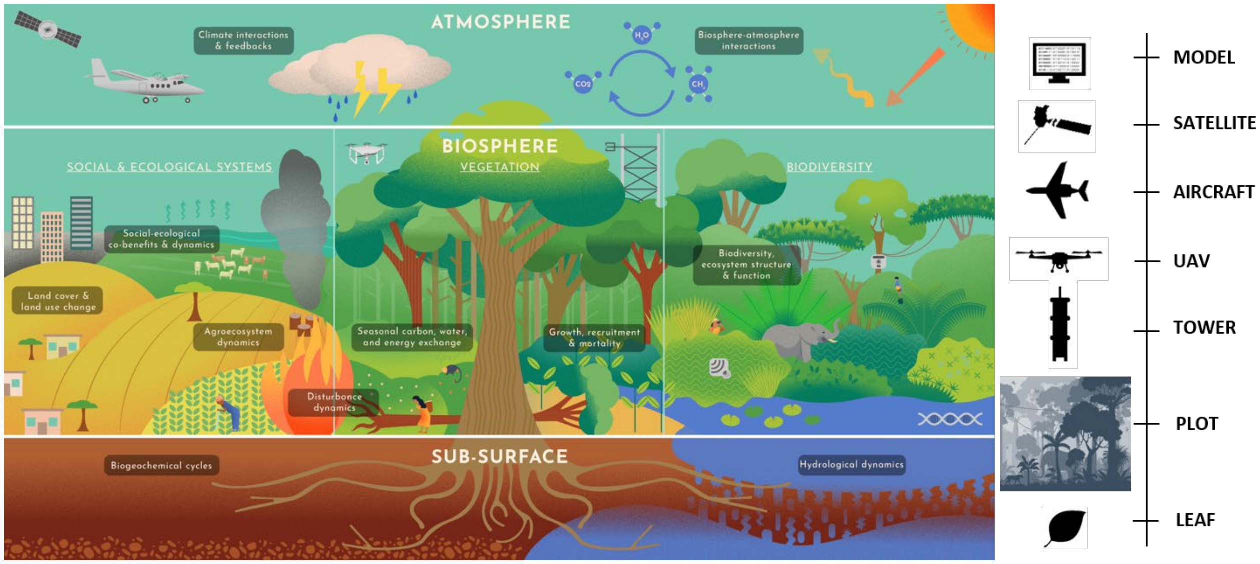


Figure 5. PANGEA measurements and scaling. PANGEA takes an integrated approach to science and applications, with ground, tower, drone, and aircraft measurements in tropical forest landscapes across Africa and the Americas. Modeling and satellite remote sensing analyses integrate pan-tropically.

However, information gathered from satellites has important limitations over the tropics. Persistent cloud cover can be an important limitation for optical sensors in tropical forests (e.g., OCO-2/3). In addition, aspects of the enormous biodiversity of tropical forests may be studied from space, but it is unlikely that spaceborne observations will soon supplant species inventories from ground-based studies. Non-plant taxa are unlikely to ever be revealed by satellite-based investigations in tropical forests, though some aspects of non-plant biodiversity may be predictable from satellite data. The dense plant canopy of tropical forests can also block our view of the soil and other belowground dynamics. PANGEA will improve our ability to push the limits of what we can observe with satellite sensors and better define the limitations, enabling the research community to focus efforts and resources where we need information to complement remote sensing research in order to gain greater understanding of tropical forest function.

1.4 The PANGEA Terrestrial Ecology Field Campaign

PANGEA leverages Terrestrial Ecology investment for its core resources. The Optimal, Baseline, and Threshold measurements defined in *Section 6.2.1* represent stand-alone NASA campaign. However, given the urgency and importance of the topic, and such widespread interest from the community, there is strong potential to augment or even exceed NASA's contributions (see *Section 7.3* for more details). We derive the **Optimal**, **Baseline, and Threshold Essential Scientific Measurements** from the PANGEA Science Objectives to: 1) understand differences in tropical carbon stocks and fluxes and the forces driving heterogeneity, 2) resolve scaling issues between field and satellite data by advancing process understanding and scaling methods, and 3) forecast varying tropical forest ecosystem responses to climate and land-use change:

- **Optimal:** measurements that capture the dry season onset and the dry season end for more than 2 African and more than 2 American landscapes.
- **Baseline:** measurements that capture the dry season onset and the dry season end for only 2 African and 2 American landscapes.
- **Threshold:** measurements that capture the dry season onset and the dry season end for 2 African landscapes, relying on existing data, planned missions in the American tropics, commercial data-buys, and deployable drones, to utilize satellite data over the Americas for comparisons.

The proposed airborne data (e.g., VSWIR, lidar, SAR, carbon fluxes) has only been collected in a few locations across the tropics to date, at different points in time, by different organizations, and with differing methods. PANGEA allows for direct comparisons and evaluations of the role of tropical forest heterogeneity in ecosystem dynamics (**Figure 5**). These data include CARAFE data to measure CO_2, CH_4, sensible heat, and latent heat fluxes at high spatial resolution, VSWIR reflectance and small footprint lidar to measure canopy leaf traits, vegetation structure, thus allowing us to model functionally distinct forest types, and SAR data to measure inundation and disturbance dynamics. PANGEA integrates these with ground measurements and Indigenous and Local Ecological Knowledge on floristic, faunal, and phylogenetic diversity, species interactions, disturbance dynamics, land-use activities, and hydrological and meteorological dynamics. These ground and airborne measurements will advance process-based understanding, the calibration and validation of satellite remote sensing datasets and products, and constrain model uncertainty, including by advancing remote sensing data-model integration to generalize mapping capabilities across the tropics, and model carbon, water, and energy fluxes to examine the stability of tropical forests under future climate projections.

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. While the potential applications resulting from PANGEA science are many, the PANGEA campaign will focus on supporting monitoring capabilities to advance:

- Carbon sequestration stability and methane fluxes
- Biodiversity conservation
- Sustainable agriculture and livelihoods

PANGEA will engage with 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, which engaged with over 500 individuals and 150 organizations from 42 countries across five continents through consultative workshops, outreach events, working group discussions, bilateral meetings, and web surveys. PANGEA research and applications will complement and expand upon many existing efforts, but is likewise urgently needed to fill gaps left unfilled by these other efforts. PANGEA is actively engaging with partners to avoid duplication, and to ensure complementarity, coordination, and reinforcement.

1.5 PANGEA Study Domain

PANGEA will include a core and extended domain (**Figure 6**). 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, peatlands, and mangroves in lowland tropical forests, and highland tropical forests where possible. The PANGEA study region covers the major ecosystems and landscapes found in the tropics and the spatial scale required to address the primary questions in the 5 science themes (see *Section 2*). The extended domain will enable the inclusion of existing datasets and opportunistic collection in Asia and Australia.

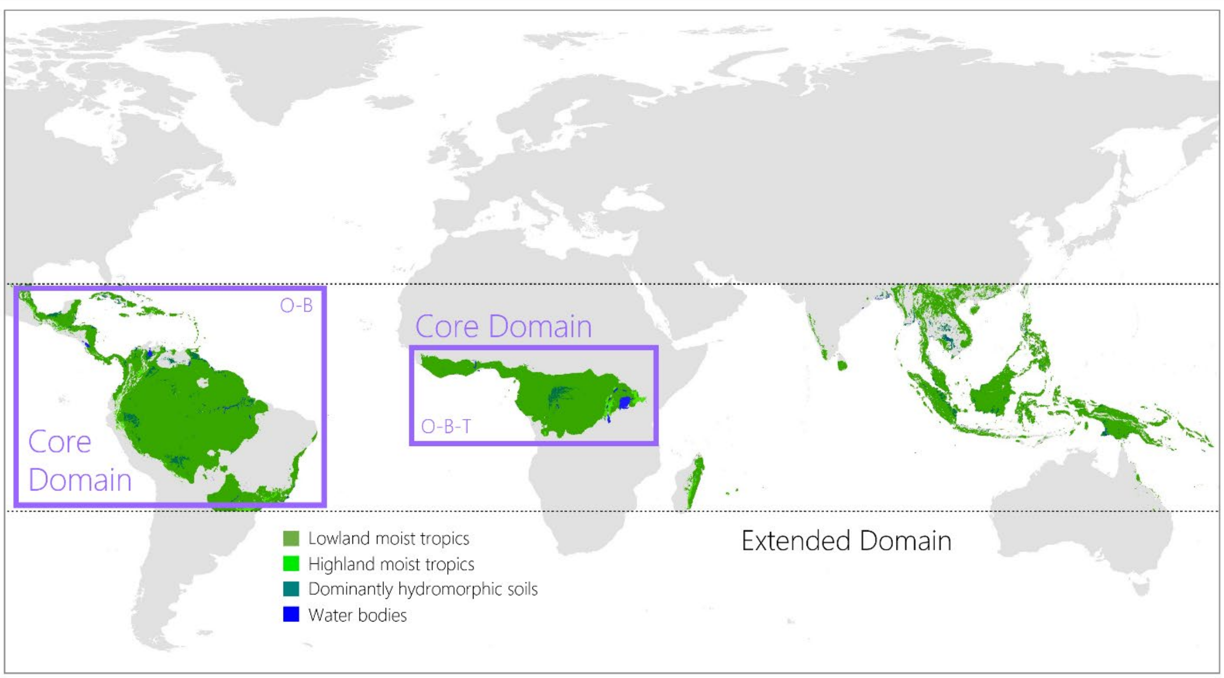


Figure 6. PANGEA core (solid purple lines) and extended (dashed black line) domains. O: Optimal, B: Baseline, T: Threshold. Boundaries were sourced from the following GAEZv4 agroecological zones: lowland humid tropics, highland humid tropics, dominantly hydromorphic soils, and land with severe soil/terrain limitations.

The focus of PANGEA's coordinated ground, tower, drone, and aircraft measurements will be at landscapes in the core domain (see *Section 6.3* for more information on *Candidate Landscapes*). PANGEA's Optimal Investigation will include a minimum of two priority landscapes in Africa and two priority landscapes in the Americas. The Baseline Investigation will include exactly two landscapes on each continent, while PANGEA's Threshold

Investigation will include two landscapes in Africa only. The Threshold Investigation will rely on existing data, planned missions in the American tropics, commercial data-buys, and deployable drones, to utilize satellite data over the Americas for comparisons. The location of these primary research areas will be based on opportunities to conduct integrated research across science themes, the existence of ongoing or planned research funded by NASA, as well as relationships and ongoing activities conducted by local and international partner agencies and organizations. See *Section 6* for more information the PANGEA Research Strategy and Study Design.

Note: A variability analysis will be included in the final white paper, highlighting key geographic domains that vary with respect to biotic, abiotic, and disturbance dynamics.

1.6 The need for coordinated teamwork

Individual investigator science excels in testing singular hypotheses. However, Earth system science is inherently multifaceted and complex. Recognizing this complexity, NASA scientific leadership embraced the multi-investigator team approach to Earth System Science decades ago (Asrar et al., BAMS v 82, pp.1309-1330, 2001). The Terrestrial Ecology Program has promoted the multi-investigator model for decades of field campaigns that span FIFE, BOREAS, LBA, and ABoVE. Multiple drivers and interacting processes that cannot be isolated in controlled experiments characterize Earth system investigations. Numerous variables require expert knowledge for acquisition and measurement whether it be through the operation of a high-performance spectrometer or botanical identification of a tree species. No single individual or small group of individuals possesses all the knowledge and tools demanded by an Earth system science investigation. Fulfilling the needs of integrative analyses of the tropical biomes for many variables and models that incorporate the complex interactions of those variables requires a large team of specialists working together. Equitable collaboration is required to assure that measurements are coordinated in time and space to maximize their value in interpretation and modeling. This can only be achieved by a cooperative, coordinated, interdisciplinary team.

It is also important to note that there is real risk that a campaign like PANGEA could perpetuate parachute and flyover science (Culotta et al., 2024). Recognizing the deep imprint of colonialism on tropical forest research, PANGEA takes an interwoven approach to equitable and ethical engagement with researchers, governments, institutions, and Indigenous Peoples and Local Communities (IPLCs). Several sections describe PANGEA's approach to community engagement (*Section 7.2*), an inclusive organizational structure (*Section 7.1*), Earth Action (*Section 8*), capacity building (*Section 9*), open science and data management (*Section 7.4*), and international agreements when conducting airborne campaigns (*Section 6.2.3*).

1.7 Earth Science to Action

The interconnected geophysical, biological, and social Earth System is experiencing a particularly unique moment in its history that demands decisive action from incredible advancements in modern tools and infrastructure. Accelerating rates of land-use change and globally consequently climate feedbacks in the tropics drive urgency to apply insights from the frontiers of NASA Earth Science to support climate mitigation, adaptation, and resilience, biodiversity conservation, forest landscape restoration, food security, water security, and human health around the planet. Since the inception of the Earth Science Enterprise Applications program in 2001 (ESE Strategic Plan) to the launch of the Earth Science to Action strategy in 2024 (ES2A Strategic Plan), NASA has innovated a systems approach to facilitate the collection of Earth Observations and predictions into decision and management support tools for diverse users and collaborators to advance their local initiatives that provide essential services to society.

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" (Decadal Survey). 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 and the potential for cascading environmental and societal impacts.*
- *Supporting efforts to enhance Earth's resilience through mitigation strategies, adaptation, and the assessment of risks and contingencies from global change*
- *Developing 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.*

2. PANGEA Science Themes

Owing to the inherent complexity of tropical terrestrial ecosystems and their feedbacks with the Earth system, PANGEA takes an integrated, interdisciplinary approach across five science themes. Understanding patterns and processes and constraining prediction uncertainty requires diverse expertise and coordinated collaboration. PANGEA bridges disciplines and ways of knowing to co-produce science that will address specific knowledge gaps and support urgently needed applications.

In this section, we parse the current state-of-the-science by thematic area. In *Section 3*, we present PANGEA's integrated science questions in response to knowledge gaps related to pattern, process, and future projections. *Section 4* describes how addressing these questions will yield major, scientific advancements.

2.1 Biogeochemical Cycles

This PANGEA Science Theme will investigate patterns of spatial and temporal variability in carbon stocks and fluxes–including interactions with other biogeochemical cycles–as well as processes that control heterogeneous changes and will improve future projections.

The terrestrial biosphere is a large sink of atmospheric CO_2 with a present-day global net ecosystem exchange (NEE) estimated at 3.3 GtC yr^{-1}, offsetting ~30% of the CO_2 emitted by fossil fuels annually (Friedlingstein et al., 2023), where NEE refers to the total balance of carbon dioxide (CO_2) exchanged between an ecosystem and the atmosphere. Tropical terrestrial ecosystems are estimated to contribute up to 0.6±0.4 GtC yr^{-1} of this sink (Friedlingstein et al., 2023). Tropical landscapes are also a controlling factor of atmospheric global CO_2 interannual variability (Ahlström et al., 2015; Friedlingstein et al., 2023), implying vulnerability of the tropical carbon sink to future climate change. Over the past three decades an estimated two-thirds of the benefit from the global forest sink was negated by tropical deforestation (2.2±0.5 Pg C yr^{-1}, 1990-2019) (Pan et al., 2024). In addition, according to the most recent Global Carbon Project CH_4 budget synthesis (Saunois et al., 2024), the tropics contribute roughly 65% of total (anthropogenic + natural) global methane (CH_4) emissions to the atmosphere (364 Tg CH_4 yr^{-1}). A significant portion of total CH_4 emissions from the tropics are from wetland, floodplains, and inland freshwater ecosystems sources (151 Tg CH_4 yr^{-1}), contributing to roughly 20% of the total global CH_4 budget.

Due to the improved observational coverage of column integrated CO_2 (XCO_2) and CH_4 (XCH_4) compared to ground-based and airborne in situ measurement networks, satellite remote-sensing retrievals have been used in inverse atmospheric models to estimate tropical GHG budgets. The tropical CO_2 terrestrial budget has been constrained using satellite remote-sensing XCO_2 data from GOSAT, OCO-2, and TanSat (e.g., Liu et al., 2016; Lunt et al., 2019; Crowell et al., 2019; Palmer et al., 2019; Yang et al., 2021; Liu et al., 2020; Gaubert et al., 2023; Wang et al., 2023; Liu et al., 2024; Byrne et al., 2023). These studies have made critical breakthroughs in understanding the spatiotemporal distributions of regional carbon budgets and how climate, hydrology, and vegetation characteristics impact the tropical carbon budget across multiple temporal scales. Simultaneously, these studies have also revealed observational gaps that limit our full understanding of the tropical carbon cycle. The most recent OCO-2 top-down model intercomparison project (MIP), based on 14 models, has revealed the complex spatial distributions of sources and sinks across the tropical continents: net carbon sources over the northeast Amazon and northern tropical Africa, contrasted with net carbon sinks over western Amazon and the Congo basin (Bryne et al., 2023). The net biosphere exchange over tropical South America is close to carbon neutral (Liu et al., 2024), while the tropical African terrestrial biosphere is a net carbon source.

However, the lack of a comprehensive validation dataset for the tropics has fueled debate around satellite-based inversion results. For instance, GOSAT and OCO-2 atmospheric inversion results consistently show a significant carbon source in northern tropical Africa (Palmer et al., 2019), driven by considerable carbon releases during the dry season, when these satellites have better observational coverage of the region. On the other hand, a recent study using an emergent constraint approach – which combined four instances of aircraft measurements with satellite-based inversions – suggested that northern tropical Africa is close to carbon neutral (Gaubert et al., 2023). These apparently conflicting findings underscore the urgent need for validation data to resolve such discrepancies. Until these datasets are available, the utility of satellite-based inversions for national carbon inventory quantifications will remain limited.

Despite the debate surrounding mean flux estimates based on OCO-2/3 and GOSAT, these satellite observations have provided new insights into the seasonal cycles and interannual variability of the tropical carbon cycle (Lei et al., 2024; Philip et al., 2022; Liu et al., 2017; 2024; Wang et al., 2023). Interestingly, the seasonal cycle of net biosphere exchange over the tropics, as inferred from OCO-2, exhibits a much larger amplitude than that simulated by state-of-the-art biogeochemical models, suggesting that the tropical terrestrial biosphere responds to seasonal climate variations more dynamically than previously understood (Lei et al., 2024; Philip et al., 2020). Satellite observations have also greatly improved the process-level understanding of the tropical carbon cycle's response to interannual climate variability (Liu et al., 2017; 2024; Wang et al., 2023). For example, Wang et al. (2023) showed that

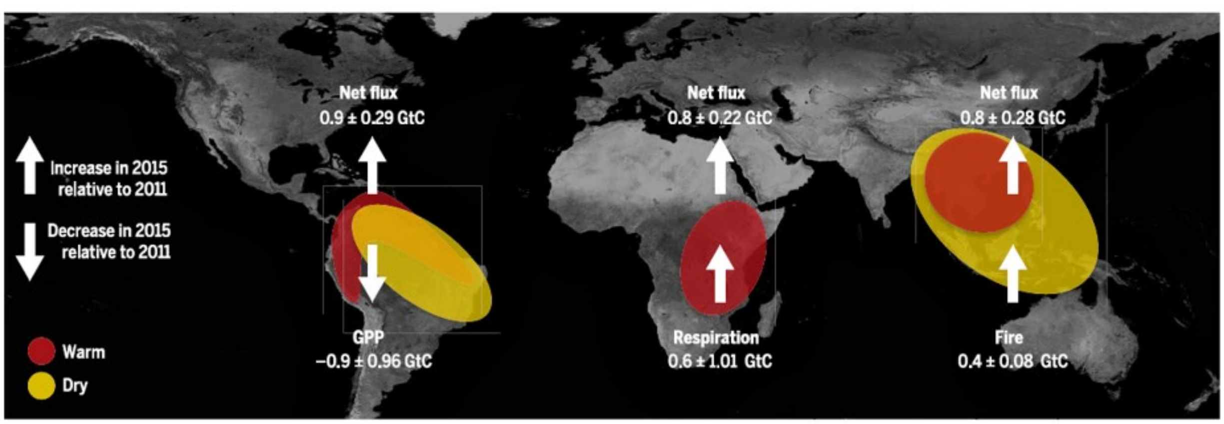


Figure 7 Analyses of Orbiting Carbon Observatory 2 (OCO-2) data over tropical continents revealed that each became a net source of carbon emissions to the atmosphere in response to the 2015 El Niño. Critically, each continent exhibited distinct regional pathways that require improved understanding. Adapted from (Liu et al. et al. 2017).

variability in total water storage drives the spatial heterogeneity of the Amazon's carbon cycle response to the 2015-2016 drought, while temperature plays a more important role in influencing carbon flux variability across the entire tropical region. More holistic measurements from the PANGEA mission will further enhance our understanding of the tropical carbon cycle. Comprehensive PANGEA datasets, incorporating measurements from multiple platforms and technologies, will help resolve current uncertainties and deepen our knowledge of how tropical carbon flux dynamics respond to both short-term climate anomalies and long-term environmental changes.

Tropical wetland emissions of CH_4 have been estimated using satellite retrievals of XCH_4 from GOSAT and TROPOMI (e.g., Parker et al., 2018; Ma et al., 2021; Feng et al., 2022; Yu et al., 2023). These studies have made critical findings about how climate, hydrology, and vegetation characteristics impact the tropical carbon budget across multiple temporal scales. These major findings are a result of satellite XCH_4 observations filling a critical gap in ground-based measurements in the tropics and allowing for better constraint on regional emissions. Using spaceborne XCH_4 retrievals it has been determined that our current estimates of tropical wetland and aquatic emissions are largely underestimated (Yu et al., 2023) and spatiotemporal variability in these natural CH_4 sources are driven by environmental characteristic such as vegetation type/amount, temperature, and inundation extent (Parker et al., 2018; Ma et al., 2021). Furthermore, using satellite XCH_4 data, it was determined that tropical wetlands are a primary driver of global interannual variability in the global atmospheric CH_4 growth rate (Feng et al., 2022).

A critical challenge relates to how much tropical carbon stocks and fluxes vary enormously in space and time (Sullivan et al. 2020, Xu et al., 2021, Muller-Landau et al., 2021, Wang et al. 2023).

Intact, disturbed, and regrowing forests differ dramatically in their ability to uptake carbon, with strong variation geographically and within each group. From 1990 to 2019, regrowing tropical forests increased in area, resulting in a 29±8% increase in their ability to sequester carbon, while intact forest areas shrank, directly reducing their ability to store carbon by 31±7% (Pan et al., 2024). The tropical carbon sink has weakened in recent years, a trend widely attributed to climate and land-use change (Hubau et al., 2020; Pan et al., 2024). Tropical forests also differ in their sensitivity to extreme events (**Figure 7**) and responses to climate and land-use change, with some evidence suggesting a more rapidly weakening carbon sink in the Amazon compared to Central Africa (Bennett et al., 2015; Poorter et al. 2016; Verbesselt et al., 2016, Liu et al., 2017; Hubau et al. 2020).

Climate plays a critical role in driving the tropical carbon cycle. For example, regions with high rainfall typically support dense, evergreen forests with high productivity and large carbon stocks, while areas with seasonal or lower rainfall harbor partially or fully deciduous forests with more seasonal variation in carbon fluxes and relatively lower productivity and carbon stocks (Malhi et al., 2002; Bonan et al., 2008; Muller-Landau et al., 2021).

Temperature affects forest carbon cycling, both directly and in interaction with water availability (Taylor et al., 2017; Muller-Landau et al., 2021). Tropical forests also exhibit enormous variation in geomorphology, and thus in soil physical properties and soil fertility (Townsend et al., 2008). Geomorphological variables are often correlated, making it more difficult to tease apart their relationships with productivity and biomass. For example, across the Amazon Basin, lower soil fertility is often associated with deeper, more stable, well-aggregated, and well-drained soils (Quesada et al., 2010). Regardless, productivity typically increases with soil fertility, although there are no consistent relationships between soil fertility and biomass, likely because turnover increases and woody residence time decreases with soil fertility (Muller Landau et al., 2021).

A large proportion of tropical forests are permanently or seasonally flooded wetlands, which include forested peatlands, swamps, and floodplains (Aselmann and Crutzen 1989). For instance, Amazon River floodplain forests represent areas up to 250,000 km^2 with most flooded six months of the year (Richey et al., 2002; Goulding et al., 2003). Further, the Amazon floodplain represents the greatest natural CH_4 emission source in the tropics and rivals CH_4 sources from the Arctic (Pangala et al., 2017). In addition to the significant ebullitive CH_4 source from inundated soil and vegetation, Amazon floodplain tree stems are also contributing non-ebulitive CH_4 emissions which are estimated to be 200 times larger than from temperate wet forests (Pangala et al., 2017). These tropical forest wetlands play a critical role in the global CH_4 and CO_2 budgets (Sjögersten et al., 2014; Peng et al., 2022). Tropical wetlands are a moderate source and sink of CO_2 to the atmosphere depending on environmental characteristics (Sjögersten et al., 2014; Helfter et al., 2021). However, tropical wetland and inland water systems contribute the vast majority of global total wetland/aquatic CH_4 emissions and make up ~20% of the overall global CH_4 budget (Saunois et al., 2020; Peng et al., 2022). CH_4 contributes ~30% of the increase in radiative forcing from anthropogenic emissions and is 25× or more effective as a GHG compared to CO_2 (Masson-Delmotte et al., 2021). Methane has experienced recent atmospheric growth rates inconsistent with our current understanding of global sources and sinks of this critical greenhouse gas (GHG) (Turner et al., 2019). As CH_4 concentrations soar past all-time record levels, climate scientists worry that climate change itself could be contributing to these elusive sources of CH_4 (Tollefson, 2022). Tropical forest wetlands, floodplains, and inland waters like lakes, reservoirs, and rivers are significant sources of CH_4 and are sensitive to changes in climate yet remain the most uncertain contributors to the global CH_4 budget (Saunois et al., 2020).

Furthermore, organic-rich tropical peatlands store the largest and highest-density irrecoverable carbon reserves (Noon et al., 2021). Tropical peatlands store approximately 100 Pg (100,000 Tg) of soil carbon, but there remain large uncertainties in the spatial extent and associated carbon stocks in tropical peatlands. For example, the extensive peatland carbon stocks of the central Congo Basin were only recently mapped, despite accounting for nearly a third of the carbon stored in tropical peat soils (Dargie et al., 2017; Crezee et al., 2022). Land use change, through deforestation or drainage, and climate change threaten the carbon sink capacity of tropical peatlands (Page et al., 2022; Wang et al., 2018). For example, in Southeast Asia extensive peatland drainage has turned peatlands of this region into a CO_2 source on par with regional fossil fuel emissions (Hoyt et al., 2020). As anthropogenic disturbances continue to threaten tropical peatlands (Hastie et al., 2022; Page et al, 2022), a better understanding of the distribution and carbon stock density of tropical peatlands and associated GHG emissions is needed to predict which areas should be prioritized for conservation efforts (Roucoux et al, 2017; Deshmukh et al, 2021). While large peat complexes such as the Cuvette Central in the Congo Basin and Pastaza-Marañón Foreland Basin in the Peruvian Amazon have been recently mapped (Lahteenoja et al, 2012; Dargie et al, 2017), other peatlands remain poorly characterized and substantial undocumented peatland areas likely remain (Hastie et al, 2024). The wide diversity of tropical peatland vegetation and flooding dynamics (Lahteenoja and Page, 2011; Flores Llampazo et al, 2022) makes mapping peatland ecosystems particularly difficult (Minasny et al, 2019). Furthermore, additional process understanding of tropical peatland carbon cycling is needed to predict how CO_2 and CH_4 emissions from these diverse ecosystems will respond to climate and land use change. Improved tropical peatland maps, carbon stock estimates, and process understanding are all critical to identify priority areas for conservation and restoration efforts aimed at protecting the carbon storage capacity of tropical peatlands.

2.2 Biodiversity

This PANGEA science theme will investigate how tropical biodiversity varies spatially at local, regional, and continental scales, how it shapes ecosystem function and responses to climate and anthropogenic change, and how it thereby contributes to heterogeneity in forest resilience and feedbacks to global climate and socio-ecological systems.

Tropical biomes are the most biodiverse on Earth. Biodiversity is the variability among all living organisms and ecosystems, including taxonomic, phylogenetic, functional, and genetic diversity within and among species, as well as within and among sites. Tropical forests are home to more than half of Earth's described species diversity, even though they encompass only about one-fifth of terrestrial areas, and many tropical species remain undocumented (Lewis et al., 2015; Barlow et al., 2018; Dinerstein et al., 2017; Pillay et al., 2022; Gatti et al., 2022). The high total number of species found in tropical forests (high gamma diversity) reflects both extraordinarily high numbers of species within sites (alpha diversity), as well as substantial turnover of species among sites (beta diversity) (Condit et al., 2002; Basset et al., 2012; Jenkins et al., 2013; Slik et al. 2015). At small scales, among-site compositional variation largely reflects environmental filtering and stochasticity (Condit et al., 2002; Fyllas et al., 2009; Condit et al., 2013; Asner et al., 2014; Chadwick and Asner 2016; Chadwick and Asner 2018). At the largest scales, the divergent evolutionary histories of different tropical continents have resulted in very different species assemblages and phylogenetic composition (Slik et al., 2018). The high taxonomic and phylogenetic diversity of tropical forests is accompanied by high functional diversity, with species displaying a wide range of life history strategies, functional traits, and environmental responses (Fyllas et al., 2009; Condit et al., 2013; Slot and Winter 2017; Ruger et al., 2018; Homeier et al., 2021).

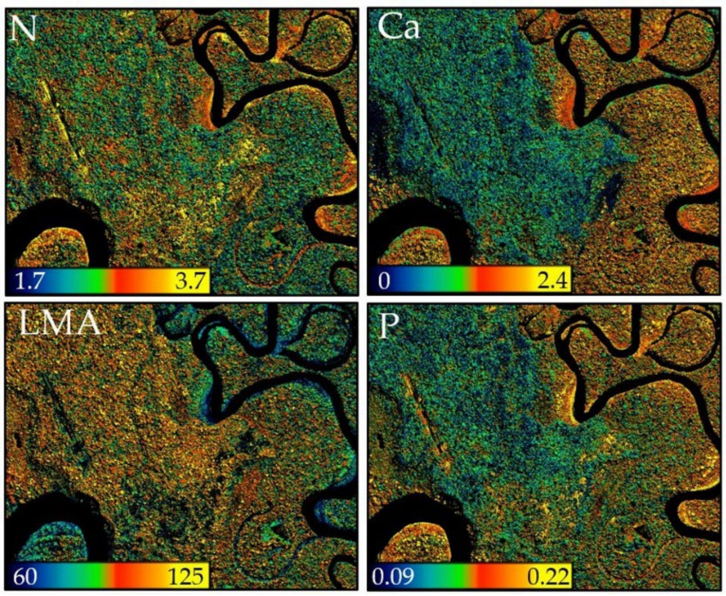


Figure 8. Landscape scale variation in nitrogen (N), calcium (Ca), leaf mass per area (LMA) and phosphorus (P) in the Peruvian Amazon. Example of trait maps created from VSWIR imaging spectroscopy data from (Chadwick & Asner 2016). No data of this type exist for Central Africa.

Tropical biodiversity is critically important to the functioning of tropical ecosystems and their feedbacks to the earth system (Cardinale et al., 2012; Dirzo et al., 2012; Sakschewski et al., 2016; Berzaghi et al., 2018; Schmitt et al., 2020). Which species are present in an area, and their traits and abundances, affects forest structure, function, resilience, and interactions with local and global climate and social-ecological systems (e.g., Dirzo et al., 2014; Del-Claro and Dirzo 2021). The wide variation in structure and function among tropical forests is closely linked to variation in biodiversity, reflecting not only the influences of abiotic environmental factors on biodiversity, structure, and function, but also feedbacks *between* biodiversity and structure and function (Muller-Landau et al., 2021). The species and functional composition of woody plants is particularly important in shaping forest structure and function, which in turn affects microclimates, habitat, and food resources for animals and microbes.

Leaf phenological strategy is an important aspect of plant functional trait variation in tropical forests, which plays a major role in stand-level productivity, responses to climate variation, and the seasonal availability of food resources for animals and microbes (Hutyra et al., 2007; Christoffersen et al., 2014; Xu et al., 2016; Wu et al., 2017; Longo et al., 2018; Manoli et al., 2018). Tropical trees and lianas display a large diversity of leaf phenological strategies, from evergreen to deciduous, with variation in the duration, timing, and completeness of deciduousness, and whether deciduousness is obligate or facultative (Borchert 1994; Eamus 1999; Kushwaha and Singh 2005; Williams et al., 2008; Kearsley et al., 2024). Leaf lifespans and the seasonal timing of leaf production also vary widely, with implications for seasonal variation in leaf quality and photosynthetic capacity (Wu et al., 2016; Lopes et al., 2016; Wu et al., 2017; Albert et al., 2018). The relative abundance of different phenological strategies varies systematically among tropical forests in relation to climate, geomorphology, soils, and other factors (e.g., Condit et al., 2000) and contributes importantly to strong stand-level variation in leaf phenology among sites (Bohlman 2010; Guan et al., 2015; Fisher et al., 2020; Fadrique et al., 2021; Yang et al., 2021). Leaf phenology also varies substantially among years within sites, contributing to interannual variation in forest function (Pau et al., 2010; Detto et al., 2018; Lamjiak et al., 2021). Year-to-year variation in leaf phenology on short time scales is due mainly to responses of plants to climate variation, though it can also arise from temporal shifts in species composition and abundance due to disturbances, succession, or other factors, which become increasingly important at longer timescales. Climate drivers of leaf phenology include water availability and light. Many tropical trees, species, and stands "green up" at times of year when they receive the most light (fewer clouds), even if more light is accompanied by drier conditions (Wright and van Schaik 1994; Lopes et al., 2016; Wagner et al., 2017; Li et al., 2021).

Tropical forest structure and function is also strongly influenced by other dimensions of woody plant functional trait composition, including the fast-slow axes of plant life history, adult stature, and self-supporting vs. climbing strategies to reach the canopy. The fast-slow axis extends from plant species with fast resource acquisition and processing, fast growth, high resource needs, high mortality rates, and low shade-tolerance to species with slow resource acquisition and processing, slow growth, low resource needs, low mortality rates, and high shade-tolerance (Reich 2014; Ruger et al., 2018). Variation in functional composition among stands thus relates to forest successional status, woody productivity, and woody residence time. The fast-slow axis encompasses variation in leaf traits such as leaf mass per area (LMA) and leaf nutrient content (e.g., nitrogen, phosphorus, and calcium) that can be measured with hyperspectral imaging, enabling quantification of this dimension of plant functional composition from remote sensing (**Figure 8**) (Asner et al., 2016; Chadwick and Asner 2016). Recent work has also explored functional diversity and redundancy trends using multispectral imagery (Aguirre-Gutiérrez et al., 2021).

Another major axis of variation among tropical trees is adult stature, which ranges from small shrubs to giant emergent trees above the main canopy (Ruger et al., 2018; Maynard et al. 2022). Forest carbon stocks, structure, and productivity are intimately related to the relative abundances of trees of different sizes, which in turn depends on functional composition with respect to this axis and ultimately influences entire ecosystem structure. Lidar can provide information on canopy height and even tree size distributions, thus providing important information on this dimension of plant and ecosystem structural variation (Stark et al., 2012). For example, vertical variation in forest structure has been shown to vary with ecosystem function even when vertically integrated metrics like leaf area index (LAI) does not (**Figure 9**) (Ordway et al., 2022).

Finally, tropical woody plants may be self-supporting like trees and shrubs or be structural parasites like lianas (woody vines) that rely on other plants for support (Muller-Landau and Pacala 2020). Lianas reduce tree growth and increase tree mortality via competition, and thereby alter forest structure and function (Estrada-Villegas et al., 2022). Increasing CO_2 concentrations appear to be increasing tree growth (Phillips et al., 2009, Brienen et al., 2015), which is expected to increase tree mortality rates by increasing tree competition, which may favor fast-growing woody vines like lianas. Interestingly, lianas have increased in abundance in many tropical forests (Phillips et al., 2002; Schnitzer and Bongers 2011, Rueda-Trujillo et al., 2024) due in part to increasing disturbance rates (Schnitzer and Bongers 2011, Schnitzer et al., 2021). Higher liana abundance leads to slower carbon accumulation in secondary forests, lower woody productivity, lower forest stature, and lower biomass carbon stocks (van der Heijden et al. 2015). Liana abundance varies widely among tropical forests in relation to climate, disturbance history, and other factors (Dewalt et al., 2015), and is on average increasing, for reasons that remain unclear (Schnitzer and Bongers 2011, Rueda-Trujillo et al., 2024). Lianas differ from trees in their leaf angles and in the distributions of their leaf traits, making it possible to quantify liana abundance with remote sensing (van der Heijden et al., 2022).

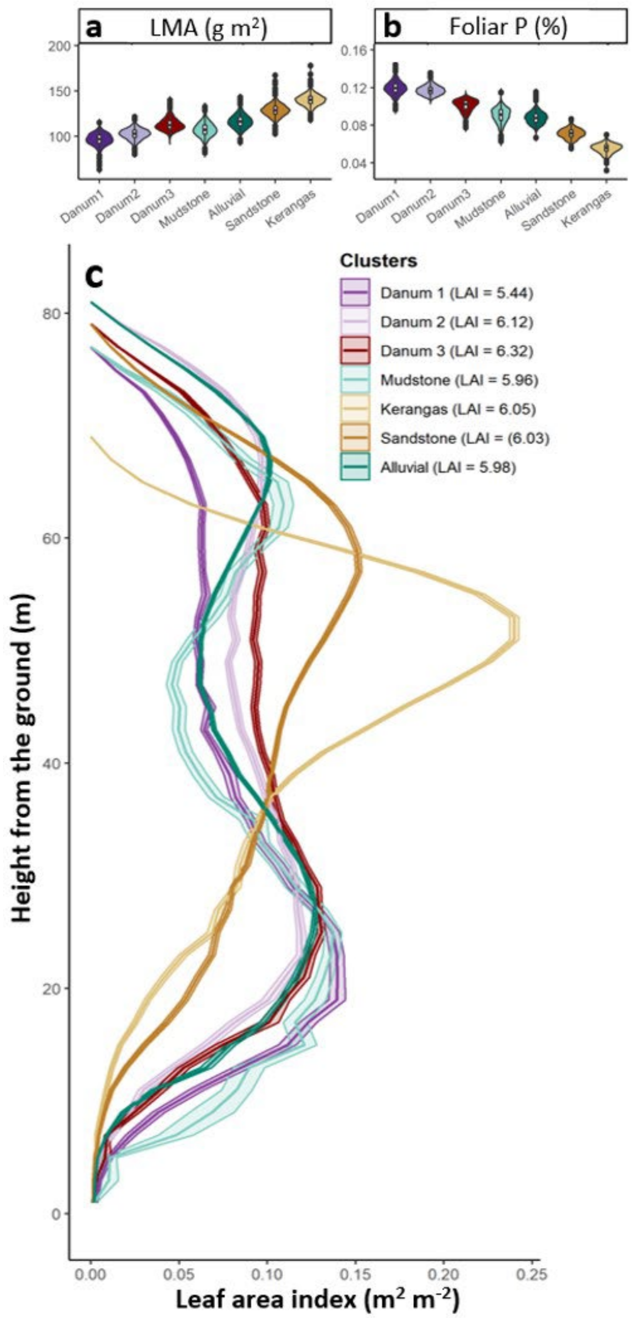


Figure 9. Variation in leaf mass per area (LMA), leaf phosphorus (P), and vertical leaf area index (LAI) in seven functionally distinct forest types mapped using airborne VSWIR and lidar data in Malaysian tropical forests (Ordway et al., 2022).

Understanding the influence of functional diversity on ecosystem functioning, such as carbon sequestration and storage, is critical in the face of climate change, since it remains uncertain whether or not tropical forests will remain a carbon sink (Arora et al., 2020; Brienen et al., 2015; Hubau et al., 2020; Sabatini et al., 2019). High biodiversity may help mitigate negative effects of climate change through increased ecosystem stability and resilience (Schmitt et al., 2020) but changing climate regimes could also negatively impact levels of biodiversity that might feedback on climate through decreased carbon sequestration (Thomas et al. 2004; Cavanaugh et al., 2014). In a review of 258 studies of naturally assembled communities, van der Plas (2019) found that, while most studies focused on the effects of taxonomic diversity, metrics of functional diversity were generally stronger predictors of ecosystem functioning. Several possible mechanisms for this phenomenon exist that need to be tested outside of experimental set-ups and in tropical forests. Furthermore, although the tropics host immense tree species diversity, most species are rare. In fact, based on forest inventory plot data, 2% of species comprise 50% of the tropical trees in the Americas (n = 174 species), Africa (n = 77 species), and Southeast Asia (n = 172 species) (Cooper et al., 2024). Characterizing the functional diversity of these hyperdominant species is tractable and within the scope of PANGEA.

Though studies of the importance of biodiversity for forest function have focused largely on plants, animals and microbes also drive function. They contribute to essential services such as pollination, seed dispersal, and nutrient cycling, and shape plant biodiversity and forest structure and function both via these mutualistic interactions, as well as through antagonistic interactions including herbivory and disease (Dirzo et al., 2014). Megafauna like elephants (found in Africa, but not the Americas) have particularly important effects in determining forest structure due to their browsing and physical disturbance, as well as their redistribution of nutrients across the landscape (Berzaghi et al., 2018; 2019), and dispersal of large seed, high wood density tree species (Campos-Arceiz and Blake 2011). Experimental vertebrate exclosures resulted in an increase in understory plant density and seedling abundance (Beck et al., 2013; Camargo-Sanabria et al., 2015; Kurten and Carson 2015). A large majority of tropical tree species and approximately half of liana (woody vine) species depend on vertebrates for seed dispersal, with most of the remaining species relying on wind for seed dispersal (Muller-Landau and Hardesty 2005). Defaunation of tropical forests by hunting and other human activities thus threatens plant regeneration and has the potential to shift plant species composition and carbon cycle dynamics (Wunderly 1997; Estrada-Villegas et al., 2023). Because plant species dispersed by large vertebrates tend to have larger seeds and higher wood densities, some have argued that defaunation will ultimate lead to a shift towards lower forest carbon stocks, although debate continues (Brodie and Gibbs 2009; Jansen et al., 2010; Bello et al., 2015; Osturi et al., 2016; Peres et al., 2016). Among sites in Panama, increased defaunation was associated with compositional shifts in the seedling layer including more abiotically dispersed species and more lianas (Wright et al., 2007; Kurten et al., 2015). In general, defaunation tends to increase the dominance of some plant species, and decrease plant diversity (Kurten 2013). Other changes in animal communities, whether due to anthropogenic pressures via hunting, habitat alteration and fragmentation, or changing climate, also have the potential to shift plant communities via these interactions.

2.3 Climate Interactions and Feedbacks

This PANGEA science theme will investigate the complex feedbacks and interactions between tropical forests and the climate system, as well as how changes in these processes will determine whether tropical forests will act as a future carbon sink or source.

Tropical rainforest land-atmosphere interactions play key roles in modulating climate conditions both locally and regionally. Tropical forest moisture recycling provides large proportions of atmospheric moisture for rainfall locally and in areas downwind, and in some regions, influences the onset and timing of their own rainy seasons (Wright et al., 2017; Sori et al., 2022; Worden et al., 2021; van der Ent et al., 2010; Staal et al., 2018; Dirmeyer et al., 2009, Zemp et al., 2017; Nyasulu et al., 2024). Additionally, emitted biogenic volatile organic compounds influence cloud formation and albedo, affecting the amount and quality of light available for vegetation (Artaxo et al., 2022). Tropical forests also alter surface properties, including land surface albedo, latent and sensible heat fluxes, and roughness, which in turn exert biophysical climate feedbacks (Bonan, 2008; Chen et al., 2020; Lee et al., 2011). For example, belowground rooting systems and soil texture regulate soil moisture (Fan et al., 2017), exerting strong impact on surface energy and water balances (Seneviratne et al., 2010; Zhou et al., 2021).

Climate systems, in turn, strongly influence vegetation structure and function. For example, mesoscale convective systems provide large proportions of rainfall within central Africa and the Amazon (Andrews et al., 2024; Rehbein et al., 2017), while also influencing tree mortality via windthrow (e.g., Negrón-Juárez et al., 2018; Feng et al., 2023). Precipitation controls flooding cycles within the African and Amazon rainforests (Alsdorf et al., 2016; Hawes and Peres 2016), which in turn, affects lowland floodplain forests as they adapt to long periods of submersion and water-logging that can lower oxygen availability, reduce photosynthesis, and decrease water conductance (Parolin et al., 2004; Parolin et al., 2016; Hawes and Peres 2016) and support conditions for microorganisms to produce CH_4. Indirectly, rainfall can also influence local nutrient cycles via wet nutrient deposition onto forest canopies (Bauters et al., 2018, 2021), altering the amount and quality of light available for photosynthesis via clouds and fog (Philippon et al., 2019; Pohl et al., 2021), and evapotranspiration and photosynthesis via dew deposition (e.g., Gerlein-Safdi et al., 2018; Binks et al., 2019).

As a result of tightly coupled land-atmosphere interactions in tropical forests, anthropogenic disturbances can alter local and regional climate conditions. Deforestation and degradation have significant surface warming effects due to decreases in evaporative cooling (Devaraju et al., 2018; Li et al., 2015), with the magnitude of this effect influenced by the declined forest cover fraction (Alkama and Cescatti 2016). Interestingly, forest gain and loss may have asymmetric effects on land surface temperature (Su et al., 2023; Zhang et al., 2024). Higher temperatures can subsequently increase tree respiration, which may reduce net primary productivity (NPP) and change how tropical forests cycle carbon (Choury et al., 2022; Das et al., 2023; Liu et al., 2017; Lloyd et al., 2023). In addition, deforestation and degradation can increase streamflow and sediment fluxes (Levy et al., 2018) due to reductions in evapotranspiration and infiltration (Costa et al., 2003; Souza-Filho et al., 2016), leading to changes in the surface water balance.

Tropical rainfall magnitude and patterns are also tightly linked to LCLUC activities (Xu et al., 2022; Bell et al., 2015; Smith et al., 2023) that change land surface heterogeneity at various spatial scales (Khanna et al., 2017; Lawrence & Vandecar, 2014; Leite-Filho et al., 2021; Smith et al., 2023). Along with atmospheric circulation, local and regional moisture and heat anomalies will be transferred to generate teleconnection on downstream circulation patterns (Mahmood et al., 2014; Snyder, 2010) and cross-continental nutrient cycles (Li et al., 2021; Barkley et al., 2019). Additionally, extensive biomass burning releases large amounts of aerosols into the atmosphere. Subsequent aerosol-cloud and aerosol-radiation interactions can alter cloud formation and life time (Liu et al., 2020), induce subsidence (Zhang et al., 2008), and change temperature gradients controlling regional dynamic systems (Chaboureau et al., 2022), ultimately limiting convection and rainfall (Tosca et al., 2015).

Tropical climate systems are also changing in other important ways. Changes in sea surface temperature (SST) patterns can alter cross-equatorial (Cook and Vizy 2015) and land-ocean energy transport and temperatures (Zhou et al., 2019). This affects tropical precipitation and moisture patterns via changes to the intertropical convergence zone (ITCZ; Schneider et al., 2014, Byrne et al., 2018), monsoons (Cook and Vizy 2019) and regional-scale dynamic systems (Cook and Vizy 2019; Creese et al., 2019; Montini et al., 2019). Climate phenomena such as ENSO, the Madden-Julian Oscillation, the Indian Ocean Dipole, and Atlantic Meridional Overturning Circulation can also alter tropical convection and induce climate variability (Raghavendra et al., 2020; Dias et al., 2017; Gu and Adler 2018). As a result, tropical forests can experience significant changes in their water cycle over a variety of time scales, including droughts (Marengo et al., 2016; Ndehedehe et al., 2018; Jiménez-Muñoz et al., 2016) , increases in dry season lengths and intensity (Jiang et al., 2019; Staal et al., 2020), variability in wet season onsets (Yin et al., 2014), decadal-scale declines in rainfall (Zhou et al., 2014), and changes to the timing and intensity of mesoscale convective systems and cyclonic storms (Taylor et al., 2018; Rehbein and Ambrizzi 2023; Balaguru et al., 2018). This can alter ecosystem structure and function in many ways, including higher tree mortality rates, loss of canopy cover, and subsequent changes in species composition and ecosystem processes (Uriarte et al. 2019; Liu et al., 2017). However, tropical forests are showing different responses to changes in their water cycle. For example, Central African tropical forests appear less responsive to drought conditions compared to the Amazon rainforests (Tao et al., 2022; Asefi-Najafabady and Saatchi 2013; Saatchi et al., 2012; Bennett et al., 2021), and in general, intact, wetter tropical forests seem better able to withstand these changing climatic conditions (Bennett et al., 2023).

Due to climate change and projected increases in the intensity and frequency of extreme events, vegetation temperature and water thresholds are being tested (Esquivel-Muelbert et al., 2019). Reductions in moisture recycling can exacerbate drying in both local and nonlocal regions (Zemp et al., 2017), and delay the rainy season onsets (Marengo et al. 2011; Leite-Filho et al., 2019), eventually leading to critical transition points and possibly even tipping points (Flores et al., 2024). However, vegetation sensitivity differs among tropical continents, and complex interactions with other changes, such as increased atmospheric CO_2, may alter vegetation response (Doughty et al., 2023; Smith et al., 2020). For example, African forests, particularly those in West Africa, are often exposed to higher temperatures and may be more adapted to heat stress compared to the relatively cooler, more humid regions of Southeast Asia (Malhi et al., 2013). However, this adaptation might come at the cost of reduced overall photosynthetic capacity under extreme conditions. Overall, exceeding these climate thresholds could lead to subsequent shifts to alternative states, such as savannas, which are less capable of supporting globally important tropical forest ecosystem services (Aguirre-Gutiérrez et al., 2020; Flores et al., 2024; Nobre et al., 2016; Scheffer et al., 2001).

2.4 Social-Ecological Systems

This PANGEA science theme will investigate the interactions and feedbacks between social and ecological systems related to food production and security, cultural practices, livelihoods, and resilience of tropical systems.

Tropical forests are important not only for biodiversity, carbon storage, and climate regulation but also for food security, cultural diversity, and the livelihoods of millions of people. Tropical forests are of particular importance to Indigenous Peoples and Local Communities (IPLCs), whose lives and cultures have long shaped and been shaped by forests. PANGEA will conduct integrated social-ecological systems research to better understand the patterns and influence of land use and its change, including deforestation, degradation, restoration, and fire regimes across tropical biomes. PANGEA will also study the feedbacks between social and ecological systems, spanning modern industrial systems to traditional, local, and Indigenous forest management, and how these systems affect ecosystem resilience and the provision of ecosystem services. PANGEA integrates social and ecological data into existing and new models to capture the feedbacks within social-ecological systems under different economic, cultural, environmental, and governance conditions.

Social-ecological systems in the tropics have been shaped by complex interactions among a diverse range of actors, each with distinct values, capacities, and objectives that mediate their interactions with and influence over natural ecosystems (Meyfroidt et al., 2018; 2022). Despite their critical role in climate regulation, biodiversity conservation, and provision of essential benefits to human well-being, tropical ecosystems are increasingly threatened by environmental changes and overexploitation (Koellner et al., 2008), leading to shifts in species composition, altered ecosystem function, reduced resilience, and diminished productivity (Siyum, 2020). These shifts have local to planetary scale impacts (Houghton and Castanho 2022, Mendoza-Ponce et al., 2020).

Several conceptual frameworks have been developed to understand the relationships between and within social and ecological systems, including the sustainable livelihoods framework (Scoones 1998), and various models of social-ecological systems (Anderies et al., 2004; Folke 2006; Ostrom 2009). Other frameworks focus on coupled human-nature systems (Liu et al., 2007), socionature (Swyngedouw 1999), ecosystem services (Costanza et al., 2017; Daily 1997), nature's contributions to people (Díaz et al., 2018; Pascual et al., 2017), and social-ecological co-benefits (Levis et al., 2024). While these frameworks may differ in their definitions (Colding and Barthel 2019), they converge on key principles and variables that describe the social-ecological system, facilitating comparability often through the use of remote sensing, field-based surveys, and ancillary data. PANGEA adopts a systems perspective that integrates human and environmental processes, interactions, and feedbacks, which is critical for assessing the sustainability of natural systems (Ostrom 2009), and charting effective solutions for a more resilient planet.

In tropical social-ecological systems, feedbacks play a critical role in maintaining resilience and guiding the trajectory of these systems (Dearing, et al. 2010). Changing social-ecological systems dynamics in tropical forests are driven by a combination of direct and indirect forces (Lambin & Geist 2002, Lambin et al. 2003) including, deforestation and degradation, restoration and reforestation, international policy initiatives, market forces, agriculture and commodity crop expansion, infrastructure development, and local and Indigenous forest management (Potapov et al., 2022; Lapola et al., 2023; Bourgoin et al., 2024; Crouzeilles et al., 2017; Jackovak et al., 2021; Gatti et al., 2023; Lambin et al., 2018, Grass et al., 2020, Bennett et al., 2018; Geist and Lambin 2002; Shapiro et al., 2023; Tyukavina et al., 2018; Garrett et al., 2018; Robbins et al., 2015, Michon et al., 2007; Sze et al., 2022, 2024; Fent et al., 2019; Bennett et al., 2018). Each of these interacts with changing climate dynamics to impact carbon stocks, hydrological regimes, seasonality, phenology, ecosystem function, plant-animal interactions, species composition and biodiversity, fire regimes, food security, and local livelihoods (Liu et al., 2017; Hubau et al., 2020; Bennett et al., 2021; Staal et al., 2018; Karam et al., 2023; Wolh et al., 2012; Fu et al., 2013; Couralet et al., 2013; Koltunov et al., 2009; Aguirre-Gutiérrez et al., 2022; Schmitz et al., 2018; Tyukavina et al., 2022, Williamson et al. 2024; Whitfield et al., 2019; Sonwa et al. 2012). While these drivers are similar across the tropics, place-specific political, economic, cultural, and management conditions influence the response, resiliency, and adaptations of tropical forests and local communities to global change dynamics (Liu et al., 2017; Hubau et al., 2020; Saatchi et al., 2021; Geist and Lambin 2002; Bennett et al., 2018; Turner 2014).

Tropical forests are also regions of cultural and biological diversity, home to a vast array of ecosystems and communities of people that have coexisted for millennia (Nobre et al., 2021). Small-scale and subsistence agriculture, which has traditionally been practiced sustainably by many Indigenous and local communities, is now often driven to unsustainable levels. Additionally, the expansion of commercial agriculture, driven by growing global demands for commodities like beef, palm oil, soy, chocolate (cocoa), and coffee, has led to widespread deforestation and habitat fragmentation, severely impacting biodiversity and ecosystem functions (Curtis et al., 2018, Haddad et al., 2024). In the Amazon, traditional management practices are increasingly being complemented or replaced by industrial soybean cultivation and cattle ranching (Barlow et al., 2018, Londres et al., 2023). Land-use intensification for soy cultivation is altering biogeochemical (e.g., nitrogen and phosphorus) and water cycles and fire frequency and intensity. Cattle ranching for beef production in the Amazon is a significant driver of deforestation in the tropics, with vast tracts of forest cleared annually (Mapbiomas 2023). These impacts not only contribute to major and irreversible losses of biodiversity, they alter the global carbon cycle, exacerbating climate change (Nobre et al., 2016). Illicit activities, such as unregulated mining, further degrade the environment by contaminating water sources, destroying habitats, and displacing local communities (Tellman et al., 2020). Similar large-scale clearing has resulted from oil palm expansion in Southeast Asia (Carlson et al., 2012). However, Central Africa sits in contrast to these other two regions, with land-use change and deforestation primarily resulting from small-scale rotational agriculture to meet food security and local livelihood needs (Tyukavina et al. 2018; Shapiro et al. 2023), and timber harvesting (Hosonuma et al., 2012). Different patterns and intensities of land-use and change likely have distinct feedbacks on vegetation dynamics and the tropical carbon cycle, although this remains severely understudied.

These human activities create complex feedbacks between social and ecological systems, resulting in a cascade of environmental and social impacts (Lambin & Meyfroidt, 2010). A better understanding of the diverse social-ecological feedbacks across tropical geographies and communities can improve our understanding of tropical heterogeneity and inform the development of place-based and culturally sensitive management plans and policies while supporting the livelihoods and cultures of the people who depend on them. Recent research efforts, for example, are focused increasingly on understanding and scaling social-ecological 'hope spots' (Levis, et al., 2024). Hope spots reimagine conservation as a process that integrates both ecological and cultural dimensions, recognizing that Indigenous peoples and local communities have long influenced biodiversity through land management practices. The case of the Upper Xingu, located in the Brazilian Amazon's arc of deforestation, demonstrates the power of such integration (Levis, et al., 2024). Indigenous groups like the Kuikuro have enriched biodiversity through millennia of landscape management, including the creation of anthropogenic soils, domestication of diverse crops, and the cultivation of cultural forests. Rather than degrading ecosystems, these practices have created resilient systems that benefit both nature and people. By engaging Indigenous knowledge alongside remote sensing technologies, the Upper Xingu hope spot offers a model for how conservation can benefit from Two-Eyed Seeing or the integration of Indigenous knowledge and Western science.

PANGEA will advance research on social-ecological feedbacks in the tropics to improve understanding and enable more accurate predictions of the long-term impacts of human actions. This work is essential for forecasting future trajectories of the tropical carbon sink, species loss, changes in ecosystem services, and the resilience of these ecosystems to external pressures (Leclère et al., 2020). Accurate predictions are needed to identify potential tipping points, where small changes could lead to irreversible damage, and to design interventions that might prevent or mitigate such outcomes (Staal et al., 2020; Liu et al., 2024; Flores et al. 2024). PANGEA activities will also empower local communities and decision-makers with the information they need to govern these ecosystems effectively. Tropical regions are home to many Indigenous and local communities whose livelihoods are intimately tied to the health of their surrounding environment. By understanding the feedbacks between human activities and ecosystem health, people can make more informed decisions about land-use, resource management, and conservation efforts that align with both ecological sustainability and their socio-economic needs (Aguiar et al., 2020). Decision-makers at regional and national levels can also use this information to craft policies that balance development goals with the conservation of biodiversity and ecosystem services, ensuring that the benefits of these ecosystems are equitably shared and sustained for future generations (Pörtner et al., 2021). Ultimately, the ability to predict and manage the complex feedbacks in tropical ecosystems is key to fostering both environmental and social resilience in these critical regions.

2.5 Disturbance Dynamics

This PANGEA Science Theme will investigate how disturbance regimes are changing and altering carbon cycle feedbacks via climate, biodiversity, and hydrologic cycling.

There are two primary modes of forest disturbance: (1) direct human disturbance resulting from human action, such as deforestation, degradation, and fire, and (2) natural disturbance that is largely associated with water stress, storms, and biotic agents, and is increasingly being exacerbated by indirect human action as a result of climate change. These two modes of disturbance contribute enormously to total forest turnover and carbon emissions from tropical forests (Espírito-Santo et al., 2014; Qin et al., 2021), but they have distinct spatial distributions, intensities, frequencies, and consequences for tropical forests.

The primary risk to tropical forest persistence and function is direction human disturbance. People clear vast tracts of tropical forest each year and cause degradation through selective logging, hunting, and fire. Direct human disturbances typically involve intense and enduring impacts, such as extensive biomass removal, animal extirpation, and conversion of land to non-forested ecosystems (Lewis 2005; Gibson et al., 2011, Wearn et al., 2012; Brodie et al., 2014; Silva Junior et al., 2020, Brando et al., 2024, Flores et al., 2024). Satellite remote sensing has revolutionized rapid detection and quantification of direct human disturbance and deeper understanding of the drivers (see *Section 2.4* for details). Deforestation and land cover change is now actively being mapped in high spatial resolution across the tropics and in association with specific industries and practices driving these trends (Curtis et al., 2018; Maxwell et al., 2019; Longo et al., 2020; Qin et al., 2021; Harris et al., 2021; Lapola et al., 2023; McGregor et al., 2024). With the advent of small-satellite arrays (e.g., PlanetScope), it is now also possible to quantify both deforestation and degradation within days-to-months (Welsink et al., 2023; Dalagnol et al., 2023). These advances have demonstrated that degradation contributes as much, or more, than deforestation to total tropical forest disturbance regimes (Maxwell et al., 2019; Qin et al., 2021), highlighting the importance of high-resolution and high-frequency data for understanding and monitoring these dynamics. However, like many tropical forest dynamics, we know much more about the effects of degradation and deforestation in American tropical forests than in other regions.

Fire dynamics often interact with deforestation and degradation in moist tropical forests, where naturally ignited fires are essentially non-existent, and human-ignited fires are common practice (Brando et al., 2019). From 2003-2018, an estimated 41 ± 14% of all forest loss in primary humid tropical forests was fire-related, although this varied considerably between continents (van Wees et al., 2020). Of all tropical fire-related forest loss during this period, 69% occurred in the tropical Americas, 22% in Southeast Asia, and only 8% in sub-Saharan Africa. However, significant decreases in the fraction of fire-related forest loss were found in the Amazon and Indonesia, where high deforestation rates peaked in the early 2000s, as fire-related forest loss increased in tropical forests in Africa. Satellite and ground measurements have revealed the widespread effects of fires and their major contributions to pan-tropical carbon cycling (Cochrane 2001; Berenguer et al., 2021). Human-ignited fires commonly spread into the understory of intact tropical forests where they directly cause tree mortality and indirectly make forests more susceptible to subsequent wind-caused disturbance (Barlow et al., 2003; Brando et al., 2014; Silvério et al., 2019; Berenguer et al., 2021). Additionally, periodic droughts amplify the effects of fire by increasing fuel flammability, and thus climate-driven increases in severe droughts are expected to increase the effects of fire (Alencar et al., 2009; Brando et al., 2014; 2019).

Natural disturbances - primarily drought, storms, and biotic agents - present distinct challenges for detection, quantification, and attribution relative to deforestation and forest degradation (although defaunation remains essentially impossible to detect using remote sensing). Nearly all natural disturbances occur at small spatiotemporal scales, with over 98% of biomass mortality in the Amazon attributable to events less than 0.1 ha in area (Espírito-Santo et al., 2014). Although natural disturbance events are typically small, they collectively cause about 1.5-2% of biomass turnover annually, indicating that natural disturbances release the equivalent to the entire tropical forest carbon pool every 50-75 years (Galbraith et al., 2013; Espírito-Santo et al., 2014). However, natural disturbances vary tremendously in space and time (Galbraith et al., 2013; Sullivan et al., 2020; Hubau et al., 2020; Dalagnol et al., 2021, Csillik et al., 2024), with distinct drivers in different regions and strong evidence that natural disturbance regimes are shifting with climate change (Gloor et al., 2013; McDowell et al., 2018, Gora et al., 2020a; Sullivan et al., 2020; Gora and Esquivel-Muelbert 2021; Fang et al., 2022). Given their tremendous contributions to tropical forest carbon cycle dynamics, even small changes in natural disturbance regimes would have a tremendous impact on tropical forest function and the global carbon budget.

Drought and storm events are major drivers of natural disturbance in tropical forests. Atmospheric water stress associated with high temperatures and vapor pressure deficits has been increasing the past several decades (Fang et al., 2022), and periodic droughts are occurring with increasing severity and frequency (Boiser et al., 2015; Duffy et al., 2015; Trenberth et al., 2014). Drought related water stress is associated with increases in tree mortality and decreases in tree growth detectable with both forest inventory plots and satellite remote sensing (Phillips et al., 2009; Saatchi et al., 2013; Qie et al., 2017; Hammond et al., 2022; Bauman et al., 2022; Bennett et al., 2023; Chen et al., 2024). Detailed physiological and anatomical work has revealed much about the mechanisms underlying forest resilience to water stress (McDowell et al., 2008; McDowell 2011; Trugman et al., 2018; Smith-Martin et al., 2023; Tavares et al., 2023). Drought research in tropical forests provides strong evidence of its importance, but also reveals that the effects of drought are highly variable among ecosystems. For example, the 2015-2016 El Niño had strong effects on the Amazon (Bennett et al., 2023), but only a marginal effect in African tropical forests (Bennett et al., 2021) and caused a substantial increase in GPP in central Panama (Detto and Pacala 2022). Although the differences between drought and non-drought years are clear, the contributions of drought to decadal trends in forest dynamics and the future trajectories of tropical forests remain highly uncertain.

Cyclonic storms (hurricanes and typhoons) are increasing in intensity and are a dominant form of disturbance in tropical forests 10° north and south of the equator (Hoyos et al., 2006; Lugo 2008), although they play a limited role in pan-tropical disturbance regimes. By contrast, there is abundant evidence that wind and lightning associated with local and mesoscale convective storms are dominant drivers of tree mortality and forest biomass dynamics (Chambers et al., 2013; Negrón-Juárez et al., 2018; Gora et al., 2020a; 2021). Specifically, temporal variation in storm activity predicts canopy disturbance rates (Araujo et al., 2021) and spatial variation in storm activity is a strong correlate of spatial variation in forest biomass, biomass mortality rates, and species composition (Gora et al., 2020a; Gorgens et al., 2021; de Lima et al., 2023; Feng et al., 2023). For example, low storm activity is associated with high biomass in the Guiana Shield, whereas high storm frequency is associated with lower biomass and higher disturbance rates across the western Amazon (Gorgens et al., 2021). Storms likely play a similar role across other tropical forests, but storm disturbance analyses from the African and Indomalayan tropical forests are nearly non-existent. This knowledge gap is concerning because all existing data suggest that convective storms have increased in frequency by 5-25% per decade of the past century, and continued increases are expected (Taylor et al., 2018; Raghavendra et al., 2018; Lavigne et al., 2019; Harel and Price 2020).

The patterns and processes underlying disturbance dynamics are among the largest sources of uncertainty for the future of the global carbon budget (Pugh et al., 2020). Information about these disturbances is primarily from American tropical forests. This geographic bias is highly problematic as the sparse, existing data suggest that disturbance regimes and forest responses to these disturbances are distinct from other continents (Hubau et al., 2020; Bennett et al., 2021; 2023). PANGEA will advance mechanistic understanding of these disturbances, how they are regulated by social-ecological systems (*Section 2.4*), and how their effects are modulated by local biodiversity (*Section 2.2*) to predict the future trajectory of tropical forests and their contributions to the Earth system (*Sections 2.1 and 2.3*).

3. Knowledge Gaps & Questions

In spite of the global importance of tropical forests, there remains great uncertainty about basic patterns and processes, limiting our ability to effectively forecast their future role in the Earth system. PANGEA science questions are interdisciplinary and cut across multiple themes. For this reason, questions addressing key knowledge gaps that relate to the PANGEA Science Themes described in *Section 2* are organized below according to **pattern** (*Section 3.1*), **process** (*Section 3.2*), and **projected future change** (*Section 3.3*). Corresponding measurements are described briefly in this section, and referenced in more detail in **Table 1** in *Section 6.2*.

3.1 Pattern

3.1.1 Carbon Stocks and Fluxes

Tropical carbon stocks and fluxes vary enormously in space and time (Sullivan et al., 2020; Xu et al., 2021; Muller-Landau et al., 2021; Wang et al., 2023). Variation in geomorphology, climatic conditions, human activities, water and nutrient availability, and plant species composition, and phenology drive wide variation in rates of photosynthesis, respiration, tree mortality, woody productivity, and carbon flux across the tropics (Sullivan et al., 2020; Muller-Landau et al., 2021; Wang et al., 2023). As a result, tropical forests vary enormously within and among tropical continents, including over relatively small spatial scales. This variation encompasses species composition and species interactions, land-atmosphere feedbacks, hydrological dynamics, forest productivity, and the carbon storage capacity and flux of these landscapes. However, most studies are based on ground-based data that represent a small fraction of tropical forest area, raising key questions regarding the generalizability of these findings, especially given that monitoring plots constitute a very small and biased subset of tropical landscapes (Malhi et al., 2014; Marvin et al., 2014; Schimel et al., 2019; Hughes et al., 2021; Chapman et al., 2024).

Critically, tropical forests appear to vary in their carbon sink strength response to extreme events and longer-term climate and land-use change trends. However, long-term trend data of tropical carbon stocks and fluxes is rare and attribution of drivers to the temporal trends remains unknown. Despite advances in satellite remote sensing, higher temporal resolution of carbon, energy, and water fluxes are still critical for going beyond stocks to understand how fluxes respond to environmental drivers and extreme events. In particular, fluxes from respiration, methane emissions, and lateral flows of carbon, have been shown to be substantial in tropical forests. The observational coverage of CH_4 fluxes from the tropics is extremely limited compared to temperate and boreal regions (Johnson et al., 2022; Melack et al., 2022; Stanley et al., 2023). Tropical forest wetlands are an uncertain component of the global CH_4 budget due to the: a) complexity of the meteorology, hydrology, ecology, land-use practices, and CH_4 emission drivers in these regions; and b) extreme data limitations amplified by cloud cover prevalence that inhibits satellite retrievals (Ganesan et al., 2019; Melack et al., 2022). The lack of flux observations for use in mechanistic model development and statistical upscaling has led to poorly quantified tropical wetland and inland water system CH_4 emissions (Ganesan et al., 2019; Rosentreter et al., 2021). Existing mechanistic models have large differences in tropical CH_4 emissions (Melton et al., 2013; Bloom et al., 2017) and do not capture observed CH_4 seasonality in tropical regions dominated by forested wetlands (Melack et al., 2022). Much of this difference is driven by the lack of fine-scale measurements detailing the drivers of wetland and aquatic emissions (Melack et al., 2022) and the threefold difference in wetland/inundation extents applied in individual models (Peng et al., 2022).

Disturbance regimes play a crucial role in shaping tropical forest dynamics, influencing tree mortality, biomass turnover, and carbon cycling. The effects of drought, storms, increasing temperatures, and deforestation are highly variable among ecosystems and can impact tree mortality, respiration, methane emissions and more. However, there is a severe lack of intercomparison between different tropical ecosystems, despite strong evidence that different forests exhibit distinct responses to disturbance and experience distinct disturbance regimes. Current research is geographically biased towards American tropical forests, underscoring a need for more research efforts in African tropical forests and beyond. Moreover, disturbances are typically studied in isolation and interactions among disturbances are poorly understood. Yet the reality is that tropical forests are facing multiple interacting and changing agents of disturbance. The few studies that have investigated interactions among disturbances typically find that their effects are multiplicative, rather than additive, meaning that we need to explicitly quantify their interactions to understand their effects. Examples include drought amplifying the effects of fire (Brando et al., 2014), deforestation amplifying the effects of wind (Schwartz et al., 2017), and lianas amplifying the effects of lightning (Gora et al., 2023). Concurrent quantification of the effects of all types of disturbance across variation in forest composition, climate, and edaphic factors is needed to understand these interactions and the consequences for forest carbon cycling. **Effectively and accurately using satellite measurements to map and monitor spatial and temporal variation in carbon stocks and fluxes and disturbances over the tropics requires filling major data and methodological gaps.** To address knowledge gaps directly related to variation in carbon stocks and fluxes, PANGEA will answer the following questions:

- ***Q1.*** *How does spatial variation in tropical forest* ***carbon stocks and fluxes*** *relate to spatial variation in climate, hydrological cycling, soils, geomorphology, and social-ecological interactions?*

- ***Q2.*** *How does **temporal variation** in tropical landscape carbon fluxes relate to temporal variation in climate change trends and extreme events?*
- ***Q3.*** *How do tropical forests vary in their **disturbance regimes**?*
- ***Q4.*** *How does geographic and temporal variation in **tropical forest phenology** covary with carbon stocks and fluxes, and how is this changing in relation to systematic shifts in forcing processes, including climate, land-use, and disturbance regimes?*

PANGEA will employ polar-orbiting satellite sensors like the **Orbiting Carbon Observatory (OCO-2/3), TROPOMI, Carbon Mapper**, and geostationary satellites like **GOES-R** to estimate CO_2 natural net biosphere exchanges and CH_4 emissions, terrestrial GPP, and ecosystem respiration (Crisp et al., 2017; Lorente et al., 2021; Khan et al., 2021; Ranjbar et al., 2023). Inundation from **NISAR** and **BIOMASS** will support tropical forest wetland mapping and will be integrated with measures of surface water flows from **SWOT**, enabling direct measurements of lateral carbon fluxes from tropical systems. Additionally, CO_2 and CH_4 concentration measurements by PANGEA will fill a critical validation gap in OCO-2/3 and TROPOMI missions. The TCCON network that is routinely used to validate the column CO2 and CH4 measurements from these missions has no site over Africa, which has contributed to the ongoing debates about the magnitude of sources and sinks derived from these missions. To overcome complexities in the main CH_4 flux drivers (e.g., meteorology, hydrology, biomass, vegetation type, soil moisture, edaphic factors, aquatic constituents/quality, etc.) and the persistent cloud coverage in the tropics inhibiting our understanding of tropical forest GHG fluxes, PANGEA will acquire airborne and in situ measurements coincident with ground-based observations to improve regional CH_4 model capabilities and emission budget estimates.

Understanding and scaling processes linked to heterogeneous carbon stocks and fluxes from forests also requires ground and airborne observations. PANGEA will prioritize landscapes that have eddy covariance flux towers wherever possible, and extend CO_2 and CH_4 measurements with chambers. Eddy covariance flux measurements are one of the few ways to measure the ecosystem-scale exchange of carbon, water, and energy across time (hours to decades) and space (leaves to communities) (Baldocchi 2020). Long-term eddy covariance flux measurements, inclusive of CO_2 and CH_4 fluxes and ecosystem respiration, also enable direct monitoring of changing forcings, including warming temperatures, shifting rainfall regimes and soil moisture, rising atmospheric CO_2 concentrations, changing phenology, compositional shifts resulting in changing structural and functional plant traits, and land-use change (Keenan et al., 2013; Keenan et al., 2014; Stocker et al., 2018; Fernández-Martínez et al., 2014; Magnani et al., 2007; Balzarolo et al., 2016; Chen et al., 2018; Luyssaert et al., 2007; Thornton et al., 2002). The long-term data and ability to capture extreme events facilitated critical findings during LBA, revealing the previously unknown late dry season increases in GPP (Doughty and Goulden 2008; Saleska et al., 2003).

Eddy covariance towers capture areas ranging from tens to hundreds of meters. For this reason, they play a critical role in ground-truthing remote sensing measurements. Despite the advances and growing number of planned eddy covariance flux towers in the tropics, they are still underrepresented globally (Schimel et al., 2015) due to the high cost of installation and maintenance, making scaling a must. Only one, recently built, flux tower exists in Central Africa (Sibret et al., 2022). While there have been about 21 towers across the Amazon, most flux tower data ended around 2014, and they are geographically biased towards the lower precipitation and lower soil fertility gradient in the central Amazon (Villarreal and Vargas 2021; Quesada et al., 2012). This leads to discrepancies in both our understanding of environmental drivers of variation, and also our ability to predict how fluxes will respond to large perturbations. For example, models project that about half the precipitation within the Amazon Basin comes from evapotranspiration carried via trade winds to the Andes (van der Ent et al., 2010), but towers in the western Amazon to ground-truth these estimates have been lacking, making it difficult to model future precipitation. PANGEA's advances in process understanding and airborne observations will reconcile the scale mismatch between flux tower footprint measurements and spaceborne observations, extending their capabilities to larger spatial areas.

Satellite remote sensing also makes it possible to map annual forest-related emissions and removals from changes in biomass at a range of spatial resolutions (e.g., 4m - 10km) (Harris et al., 2021; Xu et al., 2021; Csillik et al., 2019). However, estimates of the carbon stocks, as well as the magnitude of fluxes, require spatial maps of tropical forest biomass generated by integrating ground-based inventory plots with airborne and satellite data using statistical relationships. Forest plot-derived carbon stocks, based on allometry, can miss variation due to the lack of species-specific allometric equations, buttressed trees, and errors with missing woody biomass in branches. Terrestrial lidar offers opportunities for more accurate ground data, but is labor-intensive to process. GEO-TREES, a PANGEA partner effort, is developing a biomass reference system across forests globally, with "strong priority placed on the tropics" to improve the calibration and validation of satellite-derived biomass mapping. This will include coordinated ground measurements (forest inventory plot censuses), terrestrial laser scanning, and drone and aircraft lidar data collection. PANGEA will prioritize collocating landscapes with GEO-TREES sites and support upscaling efforts using **GEDI, NISAR, BIOMASS**, and **EDGE***.

Finally, tropical forest leaf phenology can be quantified with field observations of focal trees, litter traps, phenocams, drone-based or airborne imaging, and satellite remote sensing (e.g., Williams et al., 2008; Detto et al., 2018; Park et al., 2019; Yang et al., 2021; Albertson et al., 2023). Satellite remote sensing using **Landsat, Sentinel-2** and **Planet** has greatly expanded the geographic area for which tropical forest phenology data are available, enabling mapping of stand-level phenology over large areas, and analyses of its relationship with climate (Guan et al., 2015; Yang et al., 2021; Wang et al., 2023). However, high cloud cover and sensor artifacts complicate satellite-based studies of tropical forest phenology

(Chambers et al., 2007; Chirabi et al., 2021), which also mainly provide information on overstory phenology, although lidar approaches have been used to glean data on understory phenology as well (Tang and Dubayah 2017). PANGEA ground, tower-based PhenoCams, and high-repeat UAV RGB and lidar measurements will address knowledge gaps related to the divergent leaf phenological responses of individual species and functional types, which requires data linked to individual plants of known species identity, a link that is difficult to make for most satellite remote sensing (but see Bush et al., 2020).

3.1.2 Biodiversity & Functional Composition

Given the enormous biodiversity in the tropics and major geographic differences in biodiversity within and among tropical continents, understanding the interactions between and carbon cycle dynamics is critical. Despite this complexity, tropical forests are often represented as a single biome and a small number of plant functional types in global Earth system models, generally ignoring differences between tropical continents and differences in species and functional diversity within continents due in large part to the lack of data and knowledge to inform better representation (Zhou et al., 2021; Wei et al., 2022). Biodiversity varies significantly between tropical continents, not just due to climatic differences, but also due to their evolutionary past. Continents have shifted over deep time, and plant lineages and species interactions have radiated and adapted leading to phylogenetic differences linked to the paleoclimatic and geologic history of our planet (Corlett and Primack 2006; Slik et al., 2018). This leads to important differences in species diversity and composition (Raven et al., 2020). However, whether the relationships of biodiversity with ecosystem structure, productivity and function vary in strength and scale-dependence within and among continents is poorly understood.

Mapping, monitoring and understanding changes in biodiversity and its role in the Earth system under climate change is critically important. The advent of new and forthcoming spaceborne sensors (e.g., imaging spectroscopy, radar, lidar) will be crucial in helping to fill important data and knowledge gaps by providing spatially explicit and continuous data at spatial scales otherwise unattainable, including in remote regions that are hard to reach. Understanding and monitoring biodiversity still requires ground measurements, as remotely sensed biodiversity variables do not replace understanding of functional and genetic composition, species-interactions, or species discovery (Cavender-Bares et al., 2022). However, combining several remote sensing tools in combination with ground measurements (e.g., trait measurements, animal movement, bioacoustics, and Indigenous Ecological Knowledge) can yield novel insights into the structural and functional diversity of tropical forest ecosystems, and reveal new insights into how the taxonomic, functional and phylogenetic components of biodiversity are linked to changes in the environment. Leveraging this integrated approach, PANGEA is well positioned to address knowledge gaps related to patterns of biodiversity by answering the following questions:

- ***Q5.*** *How does tropical* ***biodiversity*** *vary spatially with forest structure and function?*

- ***Q6.*** *What are the plant* ***functional trait distributions of tropical forests*** *on different continents, and how do these differences affect forest carbon cycle responses to extreme events and across disturbance and climatic gradients?*
- ***Q7.*** *To what degree are changing tropical carbon cycle dynamics caused by shifts in* ***plant functional composition****?*

PANGEA will employ **EMIT, PRISMA, DESIS** and **PACE** for satellite measurements using imaging spectroscopy, and advance calibration and validation and algorithm development supporting the **SBG** mission. Imaging spectroscopy has led to major advances in taxonomic, functional and phylogenetic diversity mapping of tropical forests (Feret and Asner, 2011; Asner et al., 2014; Asner et al., 2017). Still, understanding of phenotypic variability within and among tropical forest regions and covariation with differences in ecosystem function remains severely lacking. The enormous variation in tropical forests can lead to high uncertainties in distinguishing tree species using purely remote sensing tools, and requires in situ data collection to calibrate local models for upscaling physiological, morphological and reproductive characteristics of each species, clade, or functional group. Several studies have shown that the combination of extensive field sampling with airborne imaging spectroscopy and lidar is a powerful tool for estimating plant functional traits at the individual-tree level to estimate the functional composition and diversity of tropical forest ecosystems (Asner et al., 2017; Chadwick and Asner 2020; Ordway et al., 2022). Additionally, spectral methods have been used to characterize differences in species communities in terms of beta diversity, i.e., the spatial turnover in species composition (Feret and Asner 2014; Draper et al., 2018; Draper et al., 2020). PANGEA will employ similar methods by collecting coincident ground and airborne measurements to extend these types of mapping capabilities more broadly across the tropics and evaluate scaling capabilities from airborne to spaceborne resolutions across functional composition and disturbance gradients.

Another dimension of ecosystem diversity relates to forest structure, defined by the three-dimensional arrangement of branches, leaves and trunks, which has been frequently measured with lidar. Structural complexity is strongly linked to ecosystem functioning, influencing light interception, productivity, faunal and flora diversity, microclimate regulation, as well as nutrient and water cycling (Coverdale and Davies 2023). More complex forests often support higher plant species diversity due to architectural diversity among species (Kent et al., 2015; Milodowski et al., 2021). However, the links between structural complexity and functional diversity have been little explored, as the understanding of these links requires the combined use of multiple remote sensing techniques that offer complementary perspectives. PANGEA will characterize forest structural diversity and 3D complexity using terrestrial and UAV-based, airborne, and spaceborne lidar (**GEDI, EDGE***) at individual-tree to ecosystem scales (e.g. Decuyper et al., 2018; Terryn et al., 2022; Schneider et al., 2019; Ferraz et al., 2016; Jucker et al., 2018; Schneider et al., 2020; De Conto et al., 2024).

3.1.3 Land-Atmosphere Interactions and Thresholds

Characterizing patterns of functional trait distributions and functional composition at large spatial scales and across gradients will offer unprecedented opportunities to evaluate important vegetation trait-tradeoffs linked to growth and hydraulic strategies, thermal tolerance, and critical thresholds. Plant- and ecosystem-scale thermal and hydraulic tolerances and thresholds remain major open questions as do fire-related ecosystem scale thresholds, for example linked to live fuel moisture content and soil moisture. Variability in vegetation thermal and water content also directly influences important land-atmosphere interactions.

The impacts of changes in climate feedbacks remains highly uncertain pan-tropically. Though transport pathways for recycled atmospheric moisture, consequences of deforestation on moisture recycling, and potential thresholds for transition have been extensively investigated in the Amazon, there are few if any such studies for Central Africa (Staal et al., 2023; Zemp et al., 2017; Xu et al., 2022; Flores et al., 2024; Theeuwen et al., 2023; Baker and Spracklen 2022; Te Wierik et al., 2022; Nyasulu et al., 2024; van der Ent et al., 2010). However, based on recent evidence, Central African tropical forests appear to rely more heavily on moisture recycling to provide atmospheric moisture for rainfall than the Amazon (Worden et al., 2021; Baker and Spracklen 2022). In addition, variability in regional and cross-continental climate conditions and cloudiness (e.g., Phillipon et al., 2018; Pohl et al., 2022; Martins et al., 2018; Chakraborty et al., 2019; Jonard et al., 2022), as well as the magnitude, type, and location of anthropogenic disturbances (for example, large-scale deforestation within the southeastern Amazon versus massive biomass burning in semi-arid regions directly north and south of Central African forests) necessitates regionally-specific investigations of how changing environmental conditions affect carbon fluxes via climate feedbacks (Braghiere et al., 2020; Durand et al., 2021; Adebiyi and Zuidema 2016).

Hydroclimatic conditions in tropical forests vary significantly along disturbance gradients, from intact forests to heavily fragmented landscapes (Gutierrez-Cori et al., 2021), and are unique across tropical regions as they are heavily shaped by local climate and disturbance histories. The effects of these disturbances can happen at small spatial scales or be hard to measure, such as changes in local winds (Staal et al., 2020). Additionally, they can depend on the geographic distribution and spatial extent of deforestation (Butt et al., 2023), on background climate conditions, or interact with other factors such as climate change or natural fluctuations (Staal et al., 2020). The role of these disturbances pushing tropical regions past water and temperature thresholds is thus highly uncertain. To address knowledge gaps related to hydroclimate thresholds and land-atmosphere interactions, PANGEA will answer the following questions:

- ***Q8.*** *How do changes in **land-atmosphere interactions**, including moisture recycling and carbon fluxes, vary with climate feedbacks, carbon storage capacity, and resilience of tropical forests under changing environmental conditions?*

- ***Q9.*** *Do* ***hydroclimatic thresholds****, such as critical soil moisture levels or thermal boundaries, vary within and between tropical continents, and how do hydroclimatic conditions vary along disturbance gradients?*

PANGEA will employ satellites including **SMAP, SMOS, NISAR, AMSR-E, EMIT, ECOSTRESS**, and **FLEX**, to measure soil moisture, canopy water content, hydraulic traits, and thermal stress. To more accurately characterize differences in land-atmosphere interactions and hydroclimatic thresholds across tropical forests, PANGEA will build on measurements used to address previous questions. Additional ground measurements will include meteorological and weather station data, soil moisture, canopy ecophysiological measurements, and live fuel moisture. Recent ground-based observations revealed that the Soil Moisture Active Passive (SMAP) satellite exhibits strong biases in tropical ecosystems (Cho et al., 2024). Ground-based data from PANGEA will further improve SMAP's soil moisture measurements in tropical forests, building on work by Wang et al., 2024.

Retrievals of canopy water content from airborne VSWIR data have illustrated ecologically meaningful patterns related to water stress in Mediterranean systems (e.g., Brodrick et al., 2019; Paz-Kagan and Asner 2017), however, much work is needed to evaluate these patterns in the tropics. Work using spaceborne VOD measurements revealed that leaf surface water, not plant water stress, was the main driver of diurnal variation in tropical forest canopy water content (Xu et al., 2021). Far more work is required to fully leverage these sensors in the tropics before mapping of plant water content and stress is possible. PANGEA will collect canopy leaf-level ecophysiological measurements, as well as tower-based VOD retrieval methods using GNSS microwave signals (Humphrey and Frankenberg 2023) to monitor diurnal and seasonal changes across gradients.

3.2 Process

3.2.1 Species Interactions and Resilience

Beyond variation in plant biodiversity, there is enormous variation in the biodiversity of non-plant taxa within and between tropical continents, resulting in important differences in species interactions (e.g., seed dispersal, pollination, browsing) that undoubtedly influence variation in carbon stocks and fluxes. Although we know that animals matter, there is very limited research to determine how much, and in what direction for carbon stocks and fluxes of intact and regenerating forests. We expect the form of the relationship of biodiversity with ecosystem structure, productivity and functionality to vary in strength and scale dependence, but knowledge of these patterns, and more importantly the underlying mechanisms, remain highly uncertain.

PANGEA is well poised to leverage advances in remote sensing capabilities alongside a revolution in measurement technologies, and machine learning and AI for scaling biodiversity-driven processes. These include imaging spectroscopy, DNA sequencing, camera trap image recognition, animal tracking capabilities, and bioacoustics sensors. This is also an important opportunity to evaluate how Indigenous and local ecological knowledge (IEK and LEK) can reinforce and support remote sensing analyses of biodiversity and processes. For example, how can mapping Indigenous ecological knowledge make the invisible, visible? At the same time, understanding the limits of remote sensing in these complex, highly diverse systems is in many ways just as important as advancing remote sensing capabilities through the type of data-integration approach PANGEA will take. To address these knowledge gaps, PANGEA will answer the following questions:

- ***Q10.*** *What is the role of* ***biodiversity*** *in driving the variation in tropical forest carbon stocks and fluxes at local, regional, and continental scales?*
- ***Q11.*** *How do* ***plant-animal interactions*** *mediate the vulnerability or resilience of tropical forest carbon stocks and fluxes?*
- ***Q12.*** *How vulnerable or resilient are the* ***species interactions*** *underpinning tropical forest function to climate and land-use change?*
- ***Q13.*** *What* ***plant functional traits and structural attributes*** *confer carbon cycle resilience, and how do they vary across forest types, environmental gradients, and vertically within forests?*

Similar to previous questions, PANGEA will employ **EMIT, PRISMA, DESIS** and **PACE** for satellite measurements using imaging spectroscopy, and **GEDI**, **NISAR***, and **BIOMASS*** to characterize structural diversity, all of which will rely on aircraft measurements for scaling. Measurements and information from Indigenous and Local Ecological Knowledge (IEK, LEK), animal movement tracking, bioacoustics sensors, camera traps, and environmental DNA sequencing will be utilized to advance understanding of the role of biodiversity and species interactions in carbon stocks and fluxes across gradients of diversity (plant and animal species diversity), carbon stocks and fluxes, and abiotic conditions. PANGEA will advance scaling methods to integrate these data, evaluating what biological processes and biodiversity metrics are scalable, as well as what temporal and spatial frequencies matter for both ground and satellite measurements.

3.2.2 Mortality, Recovery, and Management

Changing disturbance regimes, including drought, fires, storms, and land-use change, are reshaping tropical forests. Tropical regions differ in their responses to similar disturbance events. For example, measurements from the Orbiting Carbon Observatory-2 (OCO-2) satellite indicate that while the South American, African, and Asian tropics all exhibited net carbon emissions following the 2015 El Niño event, each region responded differently to the impacts of the El Niño and via different mechanisms (Liu et al., 2017). Such differences are associated with variation in forest resilience to both human action and climate change. However, the mechanisms underlying differences in forest vulnerability to shifting disturbance regimes remain elusive. Advancing understanding of distinct ecosystem responses to dynamics requires integrated data on tree mortality, carbon- and water-use efficiency, and post-disturbance recovery rates spanning disturbance regimes, patterns of functional composition, and land-use.

Fundamentally, we lack large-scale quantification of the drivers of tree mortality, as well as attribution to increased tree mortality, across different continents. Although we know what *can* kill trees, we know surprisingly little about what *actually* kills trees. For example, we know little about small-scale storm events (<0.1 ha) that represent nearly all of storm-caused disturbance (Espírito-Santo et al., 2014; Negrón-Juárez et al., 2018; Negron-Juarez et al., 2023) because they are too small to be reliably detected with contemporary satellite methods (Cushman et al., 2021) and cannot be reliably attributed using traditional forest plot methods because of their long census intervals. Corresponding with the lack of data on patterns of storm-caused mortality, data describing the mechanisms underlying tree vulnerability to storm-associated winds and lightning are also limited (Gora et al., 2017; 2020b; Jackson et al., 2019; 2021a, 2021b; Feng et al., 2023). Overall, the relative contributions of natural agents of disturbance to trends in biomass turnover or tree death remains poorly understood (McDowell et al., 2018; Gora and Esquivel-Muelbert 2021), particularly with respect to how these vary over space and time. This substantial knowledge gap hinders our ability to explain divergent trends of tree mortality across tropical continents (Hubau et al., 2020; Bennett et al., 2021), or the long-term consequences. Because most natural disturbance events are small in scale (Espírito-Santo et al., 2014; Negron-Juarez et al., 2023), addressing this knowledge gap requires agent-attributed and high-resolution, high-frequency data on tree mortality at scale (>10km), including the relative role of carbon-use efficiency and water-use efficiency in mortality associated with drought and extreme heat events. To understand how these trends vary over space and time, these measurements need to be continued for several years and replicated across multiple sites. PANGEA addresses these knowledge gaps by asking:

- ***Q14.*** *How are changing disturbance regimes impacting the* ***carbon-use efficiency (CUE)*** *and* ***water-use efficiency (WUE)*** *of different tropical forests?*
- ***Q15.*** *How do* ***tree mortality*** *rates and patterns vary within and across tropical forests in response to systematic shifts in forcing processes, including climate, land-use change, and disturbance regimes, and how well do these differences explain variation in tropical carbon stocks and fluxes?*

Given recent successes quantifying fine-scale degradation from space (e.g., Dalagnol et al., 2023), it is likely possible to integrate multiple sources of satellite remote sensing to advance monitoring of tree mortality and natural disturbance regimes from space. However, we still need high-quality, validated, field data at scale to produce the training datasets required for developing these methods. PANGEA will integrate ground-based inventories, and drone and aircraft RGB and lidar measurements with **Planet**, **Landsat** and **Sentinel-1 and 2** data, **NISAR***, **BIOMASS***, and **GEDI**.

In addition to the need for improved understanding of tree-level responses to disturbance, there is a need to improve understanding of how forest stands recover from disturbance, particularly in terms of post-disturbance recovery time scales and rates. As climate change leads to more natural disturbances, the cycle of damage and regrowth of trees –the disturbance regime– is expected to occur more frequently, reshaping the forest dynamics and eventually posing a real threat of passing ecological tipping points. On the other hand, recovering tropical secondary and degraded forests now cover about 10% of the tropical forest area and have a large carbon sink potential (Heinrich et al., 2023). Hence, understanding the regrowth rates of disturbed forests is essential for monitoring long-term carbon dynamics and predicting the long-term carbon sequestration potential of the tropics as a whole, as well as their role in climate change mitigation. By incorporating constraints on recovery, models could better simulate forest regrowth with the complex interactions between species composition, forest structure, and environmental factors, which ultimately would enhance their ability to project future shifts in carbon stock under an altered disturbance regime and inform conservation and restoration efforts (Hérault and Piponiot, 2018; de Paula et al., 2015; Shi et al., 2024; Zhang et al., 2022). PANGEA addresses this need and knowledge gap by answering the following question:

- ***Q16.*** *How do disturbance type and intensity - including different patterns of land use - influence* ***post-disturbance recovery time scales*** *of forest structure, composition, and function?*

Much research has focused on patterns and drivers of deforestation and forest degradation (Armenteras et al. 2006; Portela & Rademacher 2001; Jusys 2018; Hosonuma et al. 2012). Far less research has examined the drivers of forest resilience (but see Verbesselt et al. 2016). This requires targeted methodological efforts to advance understanding of complex social-ecological systems dynamics to uncover why deforestation and degradation is *not* occurring. Understanding drivers of forest resilience also requires advances in mapping forest gain to be able to monitor and understand where human activities (e.g., shifting from intensive cropping systems to agroforestry systems) and management (e.g., Indigenous stewardship) result in restoration or increased resilience of systems relative to adjacent areas. Extending this type of work beyond protected areas is critical to understand these dynamics in broader landscape mosaics which hold most forested lands. Emerging research is starting to address which factors contribute to avoiding deforestation with the aim of finding local, regional and global scale examples of social-ecological processes that enable forest resilience (e.g. Auckland et al., 2011; Santika et al. 2017). Avoided deforestation analyses are a very important way forward to understand the options for land use, intensity and delivery of the livelihoods that tropical forests support locally and globally. Traditional land use and land cover pattern description and modeling efforts enable to identify options for current and future land use based on a combination of remote sensing and in situ data, individual choices, economic and land price information and protection and development policies. Yet, despite the many benefits of 'avoided deforestation' interventions that enable forest resilience and co-benefits (Ebeling & Yasué 2008), many have resulted in leakages (Ewers & Rodrigues 2008, Gan & McCarl 2007), i.e. resulted in higher than expected deforestation in other geographies. In the tropics, a recent analysis has shown that these leakages occur within a 10km buffer of protected areas (Ford et al. 2020), but also can be transnational (Gan & McCarl 2007). Leakages can be typically detected using change detection techniques, less trivial, however, is attribution of leakages to processes in vicinity or telecoupled across regions (Henders & Ostwald 2014), but also the potential cascading effects and alternative options to counteract leakages (e.g. Buchadas et al. 2022) and learn from scaling interventions aimed at conservation and restoration (e.g. Mills et al. 2019, Pienkowski et al., 2024), and in particular how social-ecological processes and feedbacks, including governance (Bastos Lima et al. 2019), affect future adoption of strategies (Pienkowski et al., 2024). PANGEA will build on this small but growing body of work, for example research led by the Rights & Resources Initiative in collaboration with the GATC and Woodwell Climate Research Center that quantified the carbon uptake potential on lands held by Indigenous peoples and local communities in 24 countries across the tropics (Research Report, Policy Brief). To address this knowledge gap, PANGEA will answer the following question:

- ***Q17.*** *What **human activities and management practices** support the resilience of the tropical carbon sink, including protected areas and other effective area-based conservation measures (OECMs) such as Indigenous and territorial community practices, agroforestry practices, and selective logging practices?*

PANGEA will leverage ongoing efforts to detect human activities, such as for example a set of innovations that enable detection, mapping and monitoring natural resources needed to enable livelihoods and human well-being (Meemken et al. 2024). Further, to address the diversity of practices across actors in tropical systems as well as different options for management, PANGEA will build on existing global categorization of management regimes (Lesiv et al. 2022) together with local context information on diversity of implementation options for these different regimes, as well as recent approaches on how to extract socio-economic information from satellite data (Yeh et al., 2020F), which together with in situ and other auxiliary data can not only enable PANGEA to define tropical social-ecological system components and causal diagrams, fundamental to examine whether SES feedbacks deliver and support the resilience of tropical carbon sink and other ecosystem processes.

By addressing these questions, PANGEA will advance mechanistic understanding of tree mortality, in turn supporting model development efforts, understanding of future carbon sequestration capacity, and guiding science-based restoration efforts.

3.3.3 Hydrological Cycle Feedbacks

Human activities in the form of agriculture, cattle ranching, and fire, interact with climate change to exert significant feedbacks on terrestrial hydrological cycles (Li et al., 2022). This includes changes at the surface such as river discharge and floods (Ndehedehe et al., 2022; Bogning et al., 2022; Oliveira et al., 2021), as well as changes in convective development or atmospheric boundary layer dynamic and thermodynamic conditions (Taylor et al., 2022; Commar et al., 2023; Sierra et al., 2023; Wright et al., 2017; Leite-Filho et al., 2019; Jiang et al., 2019). Changes in these atmospheric dynamics lead to shifts in tropical storm activity, which has increased by 5-25% per decade over the past half century and seems likely to continue in the future (Taylor et al., 2018; Raghavendra et al., 2018; Lavigne et al., 2019; Harel and Price 2020). Concurrent with increasing storm activity, tropical forests are experiencing longer dry seasons, greater atmospheric water stress, and more frequent droughts (Fang et al., 2022; Boiser et al., 2015; Duffy et al., 2015; Trenberth et al., 2014). Despite the crucial role of rainfall in tropical forests, ESMs fail to reproduce the observed spatial distribution of rainfall, due to their poor performance in reproducing extreme rainfall events (Negron-Juarez et al. 2024).

Research is needed to advance understanding of the hydrological cycle consequences of deforestation, forest degradation, and regrowth using remote sensing (Lapola et al., 2023; Heinrich et al., 2021). This requires understanding both the process of disturbance impacts on land surface biophysical properties, including carbon cycle dynamics, and their climate feedback mechanisms (Li et al., 2022). Previous observational and modeling studies have shown that changes in canopy structure associated with severe forest degradation can produce hotter and drier microenvironments that result in reduced evapotranspiration and gross primary productivity and increased sensible heat flux (Brando et al., 2014; Jucker et al., 2018; Longo et al., 2020; de Oliveira et al., 2021; Rangel Pinagé et al., 2023). Yet, to date, most studies have focused on a single or a few sites. The regional impacts of forest conversion, degradation, regrowth and shifting disturbance regimes on interconnected carbon and water cycles at large scales remains unknown.

Specifically, the mechanisms controlling tropical forest land-atmosphere interactions represent one of the most uncertain aspects of the terrestrial climate system, in part due to the complex pathways through which they can take place and large variations in the spatial scales at which they occur (Lintner and Neelin, 2009; Betts and Silva Dias, 2010; Gentine et al., 2019). Investigating these interactions currently requires the extensive use of models and reanalysis products that vary significantly within the tropics in their accuracy due to factors such as heavy over-parameterization, the lack of ground-based data to constrain estimates, and different representations of key processes (e.g., Fisher et al., 2009; Sibret et al., 2022; Lopez-Ballesteros et al., 2018; Seinfeld et al., 2016). For example, large variations exist in current carbon, water, and energy fluxes that cannot be measured directly over large scales, such as evapotranspiration and gross primary productivity (e.g., Baker et al., 2021; Weerasinghe et al., 2020; Zhang and Ye 2021). Meanwhile, studies investigating how land-atmosphere interactions influence large-scale atmospheric thermodynamic and dynamic conditions, as well as water and energy cycling, must heavily rely on climate models and reanalysis products (e.g., Staal et al., 2023, Xu et al., 2022; Brown et al., 2021; Te Wierik et al., 2022; Sori et al., 2022; Seinfeld et al., 2016; Liu et al., 2020). To address these knowledge gaps, PANGEA will answer the following questions:

- ***Q18.*** *How are climate and land-use change altering* ***land surface biophysical properties*** *that influence the strength of land-atmosphere feedbacks and teleconnections?*
- ***Q19.*** *What are the direct and indirect* ***hydroclimate controls*** *on tropical forests and how does this influence the resilience or vulnerability of their carbon balance with shifting disturbance regimes, land cover and land-use change, and increasing atmospheric* CO_2*?*
- ***Q20.*** *How do* ***deforestation****,* ***degradation****, and* ***forest regrowth*** *alter regional* ***hydrological cycles*** *in tropical regions, including precipitation regimes, freshwater resources, and water quality, and river connectivity?*

PANGEA will employ satellites including **SMAP**, **SMOS**, **NISAR**, **AMSR-E**, **EMIT**, **ECOSTRESS**, and **FLEX** to measure soil moisture, canopy water content, hydraulic traits, and thermal stress. To further quantify land surface biophysical properties, PANGEA will also measure surface albedo, and other surface radiation fluxes by leveraging satellites such as **VIIRS** and **GOES-R**. Surface hydrological measurements from **SWOT** will be used to characterize tropical terrestrial water bodies (lakes, reservoirs, wetlands) and assess freshwater resources. To develop high resolution maps of extensive land use activities including deforestation, degradation, and forest regrowth, PANGEA will also derive land use information from **Planet**, **Landsat** and **Sentinel-1** and **2** data, **NISAR***, **BIOMASS***, and **GEDI**. These satellite observations will be combined to constrain the performance of models (*Section 6.4*) and to simulate the hydroclimate feedback from deforestation, degradation, and forest regrowth in the tropics.

3.3 Projections

Projecting how ongoing and future changes in tropical forest landscapes will alter feedbacks to local, regional, and global climates and social-ecological systems requires integrating pattern and process understanding and improved measurement capabilities with modeling and upscaled metrics derived from airborne and satellite remote sensing datasets that capture landscape scale dynamics.

Projecting the future productivity of tropical forests relies on understanding interactions of increasing temperature, CO_2, and extreme events with soil nutrient availability and plant functional composition. The low soil nutrient availability from highly weathered tropical soils are expected to constrain CO_2 fertilization as more nutrients are bound up in plant tissues

(Fleischer and Terrer 2022). For example, phosphorus is expected to constrain forest growth responses to increased CO_2 by about half (Fleischer et al., 2019; Braghiere et al., 2022), while potassium plays a critical role in regulating plant responses to drought (Manu et al., 2024). Furthermore, land-use change can further induce nutrient limitation by displacing large quantities of nutrients (Bauters et al., 2022, 2018, 2021; Kauffman et al., 1995), leading to local nutrient losses and redistribution of some elements. While phosphorus is largely assumed to be the most limiting nutrient across the lowland tropics (e.g. Cunha et al., 2022), recent observations reveal the heterogeneity of nutrient limitation across tropical forests, including limitation and colimitation by nitrogen, phosphorus, potassium and calcium (Davidson et al., 2004, Wright et al., 2011, Manu et al., 2022). However, it is challenging to scale results from highly localized manipulative experiments testing where and when nutrient limitation affects productivity because of the high biodiversity and spatial heterogeneity of tropical forests (Townsend et al., 2008). Remote sensing offers opportunities to capture variation in foliar chemistry, functional traits, and canopy structure across large scales (Townsend et al., 2008, Chadwick and Asner 2016; 2018, Martins et al., 2018), as well as projecting the type of nutrient losses based on the disturbance event. Better spatial understanding may allow us to identify where and when different nutrients may interact with disturbance events to constrain productivity.

Changes in climate, land cover and land use will likely increase the frequency of natural and anthropogenic disturbances, potentially altering the structure, composition, and function of most remaining tropical forests. Earth system simulations indicate that warming trends will increase vapor pressure deficit and favor frequent drought conditions, even if total precipitation remains similar to current climate (Ukkola et al., 2020; Vogel et al., 2020). Similarly, ongoing increases in atmospheric CO_2 will reduce stomatal conductance, which could potentially reduce transpiration in tropical forests (Sampaio et al., 2021), especially if nutrient limitation prevents increases in total LAI. The expansion of deforestation and forest degradation across the tropics (Assis et al., 2022, Rosan et al., 2024) will likely expose forests to more frequent fire ignitions, fragmentation and logging. Similarly, typical intensity of tropical storms will likely increase (Kossin et al., 2020), which will result in more severe disturbances even if the total number of storms does not increase. To address these knowledge gaps, PANGEA will answer the following questions:

- ***Q21.*** *How will increasing temperatures, atmospheric CO_2, and extreme events impact **nutrient availability** and **soil-vegetation interactions**?*
- ***Q22.*** *Which **functionally distinct forest types** are most vulnerable to becoming net sources of carbon to the atmosphere in a changing climate, which are resistant, and why?*
- ***Q23.*** *How will climate warming and shifting extreme events interact with land cover and land-use change to influence **shifting fire regimes** and their feedbacks with forest function and the climate?*

Widespread shifts in disturbance regimes would have profound effects on ecosystem structure, composition and function, and in turn on the many local, regional, and global ecosystem services that tropical forests provide. For example, the drier conditions combined with forest fragmentation may increase the flammability of forests (Fonseca et al., 2019), potentially leading to persistent canopy losses across the tropics (Brando et al., 2020) and permanent reductions in tropical forest carbon stocks. Land-atmosphere feedbacks are already shifting the timing, duration, and intensity of rainfall regimes with implications for ecosystems and people living in these regions (Feng et al., 2013; Mamalakis et al., 2021). Projecting the emergent shifts in carbon stocks and structural and functional properties of tropical forests to global changes, and their feedbacks on water and energy cycles will require models that can reliably predict the impacts of natural and anthropogenic disturbances on plant functional composition, the ecosystem recovery trajectories from disturbances, and the ecosystem responses to changes in climate and CO_2. In addition, knowledge and modeling capabilities are severely lacking when it comes to future projections of these changes on the direct provisioning of ecosystem services and co-benefits (Agudelo et al. 2020). To address these knowledge gaps, PANGEA will answer the following questions:

- ***Q24.*** *How will changes in precipitation patterns (e.g., ITCZ displacement), increasing temperatures, and shifting disturbance dynamics in tropical forests alter the* ***terrestrial water balance*** *via changes in seasonal rainfall timing and duration, evapotranspiration, and soil water?*
- ***Q25.*** *How will* ***future changes in vegetation****, including deforestation, degradation, and regrowth, impact local, regional, and cross-continental climate and hydrology?*
- ***Q26.*** *How will these future changes in climate and extreme events impact carbon cycling within tropical rainforests, and at what point will this lead to a* ***large-scale transition*** *in functional composition and/or the regions becoming a net carbon source?*
- ***Q27.*** *How will climate and land-use change interact with the changing vulnerability of tropical forests to influence the provisioning of and access to* ***social-ecological co-benefits,*** *including water availability, agricultural production, human health, disaster risk reduction, and cultural practices?*

PANGEA projections questions will be addressed using multiple remote sensing datasets to provide initial and boundary conditions to models, as well as reference values for uncertainty reduction. For example, to initialize cohort- and individual-based mechanistic models with realistic, observed forest structure and composition across environmental gradients, we will integrate multispectral, lidar, radar, and imaging spectroscopy data collected both through PANGEA airborne campaigns and from satellite measurements (**GEDI**, **EMIT**, **VIIRS**, **Sentinel-3**, **NISAR***, **SBG VSWIR***). Similarly, the predicted emergent relationships between forest structure and ecosystem function metrics will be constrained by combined data streams from SIF (**TROPOMI**, **OCO-2/3, FLEX***) and thermal infrared measurements (**ECOSTRESS, GOES-R**, **MTG-I**) co-located with airborne and spaceborne lidar. These combined datasets will also provide constraints on the effects of forest degradation and forest management on ecosystem response to extreme events such shifts in plant water-use efficiency during droughts and shifting fire regimes. The observed impacts of disturbances on forest structure at landscape and regional scales derived from multi-temporal observations of forest structure and composition metrics will inform and provide parameters to models on the magnitude of impacts by disturbance type and disturbance intensity. Space-for-time datasets of forest structure, composition and ecosystem function derived from airborne and spaceborne sensors will serve as benchmarks for the recovery trajectory of forests as functions of age since last disturbance and disturbance type.

4. Scientific and Technical Advancement from PANGEA

PANGEA will leverage decades of scientific efforts, including large programs such as LBA (Davidson et al., 2012), expanded international forest inventory plot networks (ForestPlots.net et al., 2021) and NGEE-Tropics E3SM-FATES model development efforts (Tollefson 2015, Powell et al., 2018; Koven et al., 2020). Despite these efforts, attempts to assess the stability of tropical forests to changes have garnered inconsistent results. Field studies suggest Central African forests may be more resistant or resilient to changing climatic conditions and may offer a longer-term carbon sink compared to other tropical forests (Hubau et al., 2020; Bennett et al., 2021). However, satellite remote sensing studies indicate that Central African forests are just as sensitive to climate anomalies as the Amazon and other tropical forest regions (Liu et al., 2017; Palmer et al., 2019). Inconsistencies between field measurements and satellite observations must be reconciled to predict the impact of climate change on the role of these forests in global carbon and water cycles. Among the hypotheses that may explain these inconsistencies are: 1) changing rates of tree mortality, 2) varying sensitivity of photosynthesis, respiration rates, and other ecosystem processes that alter net carbon and water fluxes, to natural and anthropogenic disturbances, 3) differing intensities and patterns of deforestation and degradation on ecosystem structure and function, and 4) different evolutionary trajectories that have resulted in unique biodiversity and species interactions that directly influence ecosystem resilience (e.g., varying megafauna abundances across tropical forests).

PANGEA will investigate these hypotheses and others by adding a pan-tropical view gaining new knowledge from enhanced multidimensional remote sensing measurements and analyses. The PANGEA view emphasizes integration of ground measurements, remote sensing datasets, and models, supporting remote sensing algorithm development and model-data integration in tropical forests. We foresee significant scientific advances from a coordinated campaign.

PANGEA will:

- **Elucidate** the patterns of recent (5-30 years) and ongoing change in tropical forest landscapes, dynamics, and feedbacks, and their geographic variation with an emphasis on comparisons between the Americas and Africa.
- **Increase** our understanding of processes that control heterogeneity in the vulnerability of tropical forest landscapes to structural and functional change.
- **Provide** improved projections of future changes in tropical forest landscapes encompassing the feedbacks in local, regional, and global climates and social-ecological systems.

*These scientific advances will be enable*d by technical advances in:

- **Integration** of ground and remote sensing measurements leading to more reliable calibrations of remote sensed variables;
- **Development** of data-model-integration that improves the representation of the functionally important components of tropical forest diversity that are scalable with remote sensing.

PANGEA will characterize ecosystem structure and function across multiple dimensions, from intact to degraded and low- to high-diversity tropical forest ecosystems. PANGEA will measure floristic and phylogenetic diversity as well as demographic rates, using existing ground data from permanent inventory plots, and functional and structural diversity using airborne lidar. Coincident airborne VSWIR data and in situ leaf trait measurements will map canopy traits and distinct functional communities, in addition to evaluating scalable models leveraging satellite measurements. Using this output, we will characterize differences across abiotic, land-use, and animal abundance gradients. The resulting improvements in our understanding of trait distributions will improve our models of ecosystem fluxes under climate change and land-use change forcings and evaluate differences in ecosystem responses. With this combination of measurements and models, PANGEA will address how varying tropical forest structure and function influences tropical forest stability in the face of land-use and climate change impacts.

Through model and data integration, PANGEA will advance our understanding of climate interaction, including studies to determine (1) how increased CO_2 levels and rising temperatures specifically affect carbon sequestration rates in tropical forests; (2) the impacts of extreme weather events, such as severe droughts, on forest health and carbon emission; (3) the consequences of land use changes—like deforestation for agriculture—on forest fragmentation and its effects on biodiversity and ecosystem services; (4) how altered forest cover influences both biophysical variables (e.g., albedo changes) and biochemical processes (e.g., nutrient cycling) to clarify their role in climate feedbacks; (5) evaluate the effectiveness of various forest restoration strategies in improving resilience and mitigating climate impacts essential for developing practical responses to ecosystem degradation and climate change.

5. Critical Role of NASA Remote Sensing

PANGEA aims to determine whether different tropical forests will share the same fate or vary in their responses to the effects of climate and land-use change, with a particular focus on Earth's two largest tropical forests.

Identifying processes that result in tropical forest stability is paramount for constraining uncertainty in predictions of future terrestrial carbon flux dynamics. To reconcile differences between ground and satellite measurements and improve scaling strategies to advance future monitoring, coordinated airborne measurements are necessary to characterize how and why Central African and American tropical forests differ in their ability to remain stable in the face of rapid climate change. For example, sufficiently high spatial resolution (~2-5 m) is needed to adequately scale organismal level leaf and tree dynamics to landscapes, serving as an intermediary between field and satellite observations (**Figure 5**). PANGEA builds directly upon the scaling developments and successes from the NASA Arctic Boreal Vulnerability Experiment (ABoVE) in North America (e.g., Virkkala et al., 2021; Peltola et al., 2019; Braghiere et al., 2023), which shed new light on previously understudied Arctic systems.

PANGEA leverages NASA's Airborne Science Program to obtain high-resolution data from VSWIR imaging spectroscopy, small footprint lidar, synthetic aperture radar (SAR), and other remote sensing systems over tropical forests in Central Africa and the Americas to facilitate a PANGEA science team that will address PANGEA's science objectives. Obtaining high spatial and spectral resolution data in these regions supports unprecedented evaluation of forest dynamics, including fluxes, growth, mortality, and functional strategies (e.g., nutrient- and water-use efficiency, phenology) at the resolution of individual trees across large landscapes that vary in their species composition, soil characteristics, topography, disturbance regimes, and human interactions.

Persistent cloud coverage is a significant issue when using space-based XCO_2 and XCH_4 to constrain tropical greenhouse gas fluxes (e.g., Rayner et al., 2002; Qu et al., 2021). Even at the higher spatial resolution of the current low earth orbiting satellite sensors retrieving XCH_4 (e.g., TROPOMI [3.5 km x 7.0 km]) and XCO_2 (e.g., OCO-2 [1.3 km x 2.2 km]) over 95% of retrieved information is filtered due to clouds in the tropics (Qu et al., 2021). Higher spatial resolution XCO_2 and XCH_4 satellite sensors such as the recently launched MethaneSat (100 m x 400 m) will greatly improve the ability to retrieve tropical flux measurements through cloud gaps. Other point-source mapping satellite sensors (e.g., EMIT, GHGSat, Carbon Mapper, PRISMA) have been launched with very high spatial resolution (<100 m x 100 m). However, these target mode observations will not provide the global coverage needed to constrain tropical greenhouse gas budgets.

PANGEA will obtain a large variety of airborne and ground-based observations coincident with overpasses of existing NASA (e.g., OCO-2/3, EMIT, PACE, VIIRS, SMAP, GRACE, SWOT, AMSR-E, AMSR2, ICESat-II, Landsat), international (e.g., TROPOMI, GOSAT, GOSAT-2, CO2M, RADARSAT, Envisat, PRISMA, DESIS), and commercial (e.g., GHGSat, MethaneSat, WorldView, Planet) satellite products. These observations will aid in validation of these satellite's retrievals of terrestrial vegetation, inundation, precipitation, disturbance dynamics, and atmospheric composition. They will also assist in assessing the capability of future planned satellite sensors (e.g., NISAR, SBG, BIOMASS, CHIME, GLIMR, FLEX, Carbon Mapper) and observation strategies. PANGEA will allow for investigating the required instrument characteristics (e.g., precision, accuracy, spatial/spectral resolution) and observational strategies (e.g., low Earth orbit versus geostationary) for monitoring greenhouse emissions and the many variables driving tropical source-sink dynamics.

6. Research Strategy and Study Design

6.1 Overall Study Design

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, and BioSCape and several Earth Venture Suborbital (EVS) programs. PANGEA will build on these precedents to enable NASA funded investigators to answer crucial scientific questions by comparison among major tropical forest systems. Research will integrate ground, airborne, and satellite-based science investigations such that the study design will enable effective interpretation of present and future satellite-based science investigations. The PANGEA strategy will facilitate collaborations and build new relationships within the scientific community, with a special emphasis on interactions among US scientists and scientists from tropical forest countries. PANGEA research and future NASA studies will benefit from opportunities for training and educating the next generation of scientists, including scientists from tropical countries where field research will be based. The strategy will leave a legacy of open data, open science, and strengthened partnerships between the US and tropical institutions, providing a basis for future research.

To initiate PANGEA, we will define our scientific study design during a preliminary phase that will last, ideally, one to two years. During this science definition phase, a science definition team will refine the general strategy presented below, by selecting specific landscapes for studies and refining the ground, airborne, and satellite measurements and analyses to be used to answer the campaign science questions. During this science definition phase, resources will be broadly matched to activities. The refined strategy developed in the science definition phase will inform NASA managers, enabling the development of a NASA announcement of opportunity to recruit and select the PANGEA campaign Phase 1 science team. Based on previous field campaigns, NASA nominally will solicit proposals for science team participation every three years.

The PANGEA campaign will be executed over 6 to 9 years following the science definition phase and the selection of a Phase 1 science team. The first year of the campaign will focus on development of the research capacity through the establishment and augmentation of field sites including installation of new instrumentation. PANGEA will be co-designed with local institutions and partners to collaboratively build upon decades of past, present, and ongoing research efforts. Data analysis and synthesis will not be restricted to later campaign phases, but will be carried out from Phase 1, starting with satellite-based analyses that can begin immediately in the first year, along with model studies that facilitate and inform effective measurement design. Early campaign model development and the execution of model-based studies and analysis of existing data will be used to reveal the greatest sensitivities that will guide the implementation details and scientific emphases of campaign measurements. Peak data acquisition would occur in years 2 to 4 of a six-year campaign or between years 2-7 of a nine-year campaign. A longer campaign will permit more intermediate analysis. While there is often pressure to acquire as much data as possible as soon as possible, the TE program is sufficiently mature to value intermediate analysis of early data and the role of these activities in the overall success and cost-effectiveness of a campaign.

All PANGEA science team members will either directly conduct or participate in integrative analysis (including modeling). Building an interdisciplinary science team from the earliest stages which effectively brings together the expertise and experience of the team will result in deeper insights into tropical systems. Data collected through funded PANGEA activities will be made available to the full team as soon as possible, always following NASA requirements for open science as a minimum. Open science practices will make integrative analyses and model studies as transparent as possible to both the selected science team, as well as the broader PANGEA community. The PANGEA campaign will benefit from years of field-campaign experience in the TE program including ABoVE, LBA, EVS's, and numerous earlier campaigns. Moreover, the team will learn from experience outside of NASA through collaboration with partner projects and institutions and the use of existing protocols for data collection. Examples abound from NASA projects and facilities (e.g. BioSCape, SHIFT, EMIT, GEDI, NISAR), as well as outside organization (e.g. CEOS, NEON, ICOS, AmeriFlux, FLUXNET, Forestplots.net, GEO-TREES, and more) (Baldocchi et al., 2024; Delwiche et al., 2024; ForesPlots.net et al., 2021; Ordway et al., 2021; Nagy et al., 2021; Phillips 2023).

6.2 Essential Scientific Measurements

PANGEA's overarching science goal is to understand differences in tropical forest ecosystem stability in terms of pattern and process, and reduce uncertainties in projected tropical forest responses to climate and land-use change.

Addressing this gap requires a coordinated ground and airborne campaign spanning the two largest tropical forests in Africa and the Americas.

PANGEA leverages NASA's history of successful field and airborne campaigns in the tropics to measure ecosystem dynamics and status at the onset (and end) of the dry season, when tropical forest systems are least (and most) stressed and differences in function are most apparent (Yang et al., 2021). 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 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. Achieving PANGEA's objectives therefore requires flight campaigns that meet the measurement requirements described in *Section 6.2.1*, based out of multiple countries in Central Africa and the tropical Americas, to span the range of environments present in these systems. These observations provide an essential scaling bridge linking high resolution, process measurements (forest plots, chamber measurements, flux towers, eDNA, animal movement data, Indigenous ecological knowledge) with spatially extensive measurements (satellite) which are becoming increasingly spectrally resolved with new sensors. Combined measurements will provide a baseline snapshot through which we can understand sustained field and spaceborne measurements, as well as hindcast and contextualize previous studies.

PANGEA will establish a network of centrally coordinated field and airborne campaigns that are distributed across targeted tropical forest ecosystems to fill data gaps and enable scaling between field and remotely sensed datasets, as well as regional and pan-tropical scale modeling.

PANGEA provides a framework for scaling and integrating airborne and satellite measurements with in-situ field observations, eddy-covariance flux tower measurements, and models to advance scientific understanding and remote sensing capabilities across thematic areas that directly address the goals of NASA's Carbon Cycle and Ecosystems Focus Area, in alignment with the Water and Energy Cycle and Climate Variability and Change Focus Areas.

Using PANGEA measurements, differences will be characterized across biotic, abiotic, and land-use gradients. Integrated output from ground, airborne, and satellite measurements will then be used to model ecosystem structure, function, and fluxes under climate and land-use change scenarios to evaluate differences in ecosystem responses. In doing so, PANGEA addresses how varying tropical forest dynamics influences tropical forest stability in the face of climate and land-use change impacts.

6.2.1 Optimal, Baseline, and Threshold Measurements

We derive the **Optimal**, **Baseline, and Threshold Essential Scientific Measurements** from the PANGEA Science Objectives to: 1) understand differences in tropical carbon stocks and fluxes and the forces driving heterogeneity, 2) resolve scaling issues between field and satellite data by advancing process understanding and scaling methods, and 3) forecast varying tropical forest ecosystem responses to climate and land-use change. The PANGEA Investigation Functional Requirements are described below.

The **Optimal Investigation** fulfills all Science Objectives (*Section 1.1*) and all Science Questions (*Section 3*) at a minimum of 2 American and 2 African tropical forest landscapes. To meet these Optimal Investigation Objectives, we establish the following requirements:

- Collect aircraft measurements via wall-to-wall flightline mosaics and sampling transects over a minimum of two priority landscapes in Africa and two priority landscapes in the Americas.
    - **Note:** Landscapes will be selected from candidate sites during the development of the Concise Experimental Plan.
    - Airborne measurements will include one successful capture of the wet-to-dry transition and one successful capture of dry-to-wet transition at each landscape. Wet-to-dry and dry-to-wet captures can occur in different years on different continents.
    - **Note:** A variability analysis is underway, which will inform important endmembers to capture. This will be included in the final white paper, and will contribute to landscape selection during the development of the Concise Experimental Plan.
- Collect coincident ground measurements during airborne acquisitions for required measurements (e.g., chemical leaf traits, chamber flux measurements).
- Collect ongoing ground measurements at required temporal frequencies throughout the campaign (e.g., monthly drone- and ground-based tree mortality and phenology acquisitions, sub-hourly flux measurements)
- Develop data-model integration algorithms for scaling and evaluate model generalizability.
- Model carbon, water, and energy fluxes, using terrestrial biosphere models parameterized and benchmarked with airborne and satellite data, at regional scales under future climate scenarios.
- Model tropical forest stability within and among all investigation landscapes and regionally based on terrestrial biosphere and social-ecological systems model results.
- Model the relative role of climate, soils, and divergent evolutionary histories in determining variation in tropical forests' stability in the face of climate change impacts.

The **Baseline Investigation** fulfills all Science Objective (*Section 1.1*) and the core Science Questions (TBD) at only 2 American and 2 African tropical forest landscapes. **Note:** The core Science Questions are actively being selected among the Science Questions outlined in *Section 3* and will be included in the final white paper). The Baseline Investigation requires one successful airborne capture of the wet-to-dry transition and one successful airborne capture of the dry-to-wet transition at each landscape.

Our **Threshold Investigation** fulfills all Science Objective (*Section 1.1*) and the core Science Questions (TBD) at two landscapes in Africa only. Our Threshold Investigation will rely on existing data, planned missions in the American tropics (see *Section 6.2.3*), commercial data-buys, and deployable drones, to utilize satellite data over the Americas for comparisons.

Temporal revisit requirements: Two focused airborne campaigns with wall-to-wall mosaics and transects at multiple landscapes, as opposed to higher repeat frequency airborne measurements at one landscape, are necessary to capture shoulder-season (wet-to-dry and dry-to-wet) variation across landscapes that span important within and among continental heterogeneity in a standardized way. Single airborne campaigns during the wet-to-dry and during the dry-to-wet season transitions will capture necessary endmembers for scaling seasonal differences in fluxes, stocks, traits, plant-animal interactions, hydrodynamics, land-atmosphere interactions, and fire and agricultural land-use activities. The time elapsed between the two captures and between different landscapes will not affect the ability to capture these endmembers, building in valuable airborne campaign flexibility. Within landscape level subsections of these airborne acquisitions (e.g., 10-20 km^2), high-frequency (≤ monthly) drone measurements of forest structure and spectra will allow for quantification of fine-scale temporal trends (e.g., mortality, phenology) and provide calibration and validation data for the development of satellite methods to monitor these dynamics. In addition, while we are unable to predict whether an extreme event will happen during PANGEA, the likelihood of a major fire, drought, or ENSO event is high. Over a 6- to 9-year campaign, it is essentially inevitable that there will be one or more extreme events that the team will be able to analyze.

Spatial variability requirements: Ecosystem structure, function, fluxes, and biodiversity are characterized across multi-dimensional gradients of intact to degraded, low- to high-diversity, and low- to high- carbon stock tropical forest systems. **PANGEA implements a sampling-to-scale approach, with a nested sampling design.** Ground and airborne measurements will span gradients within a landscape, and landscapes span climatic and biodiversity gradients within a continent (**Figure forthcoming**). PANGEA data collection will be conducted at landscapes that encompass intact, disturbed, and degraded forests, peatland and wetland ecosystems (and mangroves where nearby coastal data acquisition allows), as well as adjacent agro-ecosystems. Coordinated, coincident ground data collection on fluxes, foliar traits, forest structure, tree mortality, faunal diversity, species interactions, soil moisture, and more will be collected across these gradients within each landscape. See *Section for 6.3 Candidate Landscapes* and *Section 6.2.4 Field Observations and Studies* for more information.

Table 1. Description of ecological and geophysical variables relevant to this campaign, with corresponding observing requirements and existing or forthcoming Earth Observation assets. ET: evapotranspiration; LST: land surface temperature; SIF: solar-induced fluorescence. Purple text indicates satellites from non-US federal agencies. *Indicates missions that have not yet launched and/or may still be under competitive consideration. ** Indicates recently ended missions.

Variable(s)	Science Q's	Ground Measurements	Observing Technology	Earth Observation Assets	
				Satellite (planned/proposed*)	**Airborne (drone & aircraft)**
GPP	Q1, Q2, Q4-Q8, Q10, Q11, Q13-Q15, Q17, Q18, Q20, Q22, Q26	Flux towers, leaf-level spectra	Infrared Spectroscopy	OCO-2/3, TROPOMI, GOES-R ABI, AHI, MTG-I, NASA GHG ESE*, Sentinel 5P/5*, FLEX*, CO2M*, GOSAT-2, GOSAT-GW*	NASA AVIRIS-NG/3 + HyTES, MASTER
ET	Q1, Q2, Q4-Q8, Q10, Q11, Q13-Q15, Q17, Q18, Q20, Q22, Q24-Q26	Flux towers	Thermal	Landsat, ECOSTRESS, SBG*, CHIME*, TRISHNA*, LSTM*, VIIRS, Sentinel-3, Commercial*, GEO weather satellites	NASA HyTES, MASTER
Ecosystem Respiration	Q1, Q2, Q4-Q8, Q10, Q13, Q15, Q17, Q18, Q20, Q22, Q26	Flux towers	Infrared Spectroscopy	GOES-R ABI, AHI, MTG-I	NASA AVIRIS-NG/3 + HyTES, MASTER
CO2 & CH4 Fluxes	Q1, Q2, Q4-Q8, Q10, Q11, Q13, Q14, Q18, Q20, Q22, Q26	Flux towers, chamber measurements	Imaging Spectroscopy	EMIT, MethaneSat, SBG*, Carbon-i*, CarbonMapper*	NASA AVIRIS-NG/3, UZH ARES, NEON AOP, GAO
			Airborne Eddy Covariance (AEC)	EMIT, SBG*, Carbon-i*, CarbonMapper*	NASA CARAFE
Column CO2/CH4/CO	Q1, Q2, Q4-Q8, Q10, Q11, Q13, Q14, Q18, Q20, Q22, Q26	TCCON, COCCON, EM27/SUN Spectrometers	Infrared Spectroscopy	OCO-2/3, NASA GHG ESE*, Sentinel 5P/5*, FLEX*, CO2M*, GOSAT-2, GOSAT-GW*	NASA CFIS (SIF), DLR CoMet (CO2/CH4)
Aboveground Biomass	Q1, Q2, Q4-Q8, Q10, Q11, Q13, Q15, Q18, Q20, Q22	Forest inventory plot data, terrestrial laser scanning	Lidar	GEDI, Icesat-2, MOLI*, EDGE*	NASA LVIS, small-footprint lidar (drone and aircraft)
			Radar	Sentinel-1, NISAR*, BIOMASS*	NASA UAVSAR
Tree Mortality	Q9, Q11-Q13, Q15, Q17-Q22, Q25, Q27	Repeat census forest inventory plot data	Lidar, Radar, Multispectral	Landsat, Sentinel-1/2, Planet, GEDI, NISAR*, BIOMASS*, Edge*	Repeat drone RGB or Lidar
Canopy Height / Vertical Height Heterogeneity /	Q5-Q7, Q10-Q13, Q15, Q17-Q22, Q27	Terrestrial laser scanning	Lidar	GEDI, Icesat-2, MOLI*, EDGE*	NASA LVIS, small-footprint lidar (drone and aircraft)

Canopy Gap Dynamics			Radar	NISAR*, Sentinel-1, BIOMASS*	NASA UAVSAR
Spectral Diversity	Q5, Q10-Q12, Q15, Q19, Q21, Q27	Leaf-level spectra	VSWIR Imaging Spectroscopy (IS)	EMIT, PACE, PRISMA, EnMAP, Planet's Tanager, SBG*, CHIME*, FLEX*	NASA AVIRIS-NG/3, UZH ARES, GAO
Functional Diversity	Q5-Q7, Q10-Q13, Q15, Q19, Q21, Q22, Q27	Plant taxonomic diversity; plant traits; IEK, TEK, LEK			
Canopy Foliar Traits: LMA, N, P, Ca, K, pigments	Q5-Q7, Q10-Q13, Q15, Q19, Q21, Q22	Plant taxonomic diversity; plant traits			
Faunal Diversity: presence/abs., abundance, movement, species interactions	Q5, Q10-Q12, Q19, Q27	Camera traps; bioacoustic sensors; animal tracking; eDNA; IEK, TEK, LEK; plant species inventories	VSWIR Imaging Spectroscopy (IS), Lidar, Radar	EMIT, PACE, PRISMA, EnMAP, Planet's Tanager, SBG*, CHIME*, NISAR*, BIOMASS*	NASA AVIRIS-NG/3, UZH ARES, GAO, NASA UAVSAR, NASA LVIS, small-footprint lidar
Phenology	Q2, Q4, Q11-Q15, Q19, Q22, Q27	Phenocams, Long-term ground-based phenological observations; IEK, TEK, LEK	Optical Radiometers (OR) and VSWIR Imaging Spectroscopy (IS)	Landsat, Sentinel-2, Planet, OLCI, EMIT, PACE, PRISMA, EnMAP, SBG*, CHIME*, FLEX*	Repeat drone RGB
Water Stress: soil moisture	Q1-Q4, Q6-Q9, Q13-Q18, Q22, Q24, Q25	Soil moisture probes	Microwave radar/radiometry	SMAP, SMOS, Sentinel-1, NISAR*, BIOMASS*, LSTM*,	NASA UAVSAR, AirMOSS
Water Stress: leaf water content, leaf/ plant hydraulic traits	Q2-Q4, Q6-Q9, Q12-Q18, Q22	Leaf and stem water content, potentials & conductance; tower-based VOD (L-band GNSS)	GNSS-R/Signals of Opportunity, Imaging Spectroscopy	AMSR-E, EMIT, SBG VSWIR & TIR*, CHIME*, FLEX*, SNOOPI*, CYGNSS, Lemur-2	NASA AVIRIS-NG/3 + HyTES, MASTER
Thermal Stress: T50, land surface temperature, emissivity	Q2-Q4, Q6, Q7, Q9, Q12-Q15, Q18	FLIR cams	Thermal	Landsat, ECOSTRESS, SBG*, FLEX*, TRISHNA*, LSTM*, Commercial*	NASA HyTES, MASTER
Active Fire	Q3, Q4, Q6, Q7, Q9, Q12, Q13, Q18, Q20, Q23, Q27	Life fuel moisture, soil moisture, burn area, burn severity, IEK, TEK, LEK	Thermal	Landsat, VIIRS, Sentinel-3, SBG*, TRISHNA*, LSTM*, Commercial*	NASA HyTES, MASTER

Biomass Burning Aerosols	Q3, Q4, Q6, Q7, Q9, Q12, Q13, Q18, Q20, Q27	Fuel type, fuel density, aerosol measurements	UV/Infrared, Photometers, Lidar	OMPS, VIIRS, EMIT, PACE, OLCI, NISAR*, BIOMASS*, CALIPSO-CALIOP**, AOS*	
Land-Use and Land Cover	Q1, Q3, Q4, Q6, Q7, Q9, Q12-Q14, Q16, Q18-Q20, Q25, Q27	Agriculture (crop type, yield, rotation), logging severity, fire practices, IEK, TEK, LEK, conservation management practices	Optical Radiometers (OR), VSWIR IS, Lidar, Radar	Landsat, Sentinel-2, Planet, VIIRS, OLCI, EMIT, PRISMA, EnMAP, SBG*, CHIME*, FLEX*, CarbonMapper*, PACE*	NASA AVIRIS-NG/3, UZH ARES, GAO, NASA UAVSAR, NASA LVIS, small-footprint lidar
Provisioning & Cultural Ecosystem Services: food, freshwater, medicine, spiritual and ceremonial practices	Q27	Crop and NTFP harvest areas and yield, culturally and spiritually important forest type identification, water quantity and quality	Optical Radiometers (OR), VSWIR IS, Lidar, Radar	Landsat, Sentinel-1/2, Planet, VIIRS, OLCI, EMIT, PACE, PRISMA, EnMAP, SWOT, SMAP, SMOS, GRACE-FO, SBG*, CHIME*, FLEX*, CarbonMapper*	NASA AVIRIS-NG/3, UZH ARES, GAO, NASA UAVSAR, NASA LVIS, small-footprint lidar
Surface Water: quantity, flows (discharge), inundation, Q24	Q1-Q4, Q6-Q9, Q14, Q16-Q18, Q24, Q25, Q27	Water-surface height, inundation extent, discharge characterization	Altimeter, Radar, Radiometer	SWOT, Sentinel-1, NISAR*, BIOMASS*	NASA UAVSAR
Groundwater & Terrestrial Water Storage	Q1-Q4, Q6-Q9, Q14, Q16-Q18, Q24, Q25, Q27	Well measurements	Gravimetric	GRACE-FO, MC*	
Atmospheric Moisture, VPD	Q1-Q4, Q6-Q9, Q14, Q17, Q18, Q22, Q24, Q25, Q27	Weather station	Microwave, infrared sounders, imagers	ATMS, GeoXO*, AOS*	
Wind	Q1-Q4, Q6, Q7, Q9, Q14, Q17, Q18, Q22, Q24, Q25	Weather station	Doppler wind lidar	Aeolus	Radiosonde measurements
Soil nutrients and texture	Q21, Q22, Q24, Q25, Q27	Soil samples	VSWIR Imaging Spectroscopy (IS)	EMIT, PACE, SBG*, CHIME*	NASA AVIRIS-NG/3
Topography / Geomorphology	Q1, Q8, Q18, Q21, Q22, Q24, Q25, Q27		Lidar, Radar	*Note: PANGEA will explore correlative relationships with remotely sensed variables, not direct measurements.*	
Topography / Geomorphology	Q1, Q8, Q18, Q21, Q22, Q24, Q25, Q27		Lidar, Radar	SRTM, Copernicus GLO-30	NASA UAVSAR, NASA LVIS, small-footprint lidar

6.2.2 Satellite Remote Sensing Observations

There are a wealth of NASA satellite platforms that will contribute to the science and applications goals of PANGEA, as well as an ever-increasing ecosystem of sensors from other space agencies and non-governmental entities (**Table 1**). PANGEA is well poised to leverage the NASA Program of Record (POR) from the Earth Observing System (EOS) missions for understanding patterns of tropical ecosystem properties and their changes in the recent past, as well as to advance the way we use spaceborne sensors in the age of the Earth System Observatory (ESO) missions. PANGEA is also poised to not only leverage these sensors but contribute to the improvement and refinement of algorithms to better represent tropical ecosystems and address user needs in these globally important regions. The in situ work carried out by PANGEA paired with satellite remote sensing observations will allow tropical forest biomes and the people living in these regions to become part of the Earth Science to Action virtuous cycle, ensuring their representation in the process.

In **Table 2** below, we highlight a variety of operational and forthcoming spaceborne sensors, their needs for advances in the tropics that PANGEA can contribute to, and the science that the PANGEA team will be able to advance with the use of these sensors in concert with planned PANGEA activities. This table also includes some sensors that are operated by other space agencies where data are openly available. PANGEA will also explore commercial datasets available through NASAs Commercial SmallSat Data Acquisition (CSDA) program during the Science Definition and Campaign phases of the project.

Table 2. Satellite remote sensing observations and advances.

Satellite Observations	Calibration, Validation, and Algorithm Advances
Sentinel-1, NISAR*, BIOMASS*	PANGEA will contribute to efforts underway to calibrate and validate biomass mapping along gradients of carbon stocks and disturbance. This work will support our ability to fully test the limits of NISAR capabilities and support data product development from both NISAR and BIOMASS in dense, closed-canopy tropical forests.
EMIT, CHIME*, SBG-VSWIR*	Algorithms that leverage VSWIR data to understand vegetation canopy traits and chemical properties are currently trained on datasets that have poor representation of tropical forests. PANGEA collections will support improved L3 products from SBG VSWIR and could work towards community generated products for EMIT that are focused on tropical regions.
OCO-2/3, TROPOMI, MethaneSat, EMIT, CarbonMapper	Persistent cloud cover impedes space-based XCO2 and XCH4 measurements of tropical greenhouse gas fluxes (e.g., Rayner et al., 2002; Qu et al., 2021), resulting in the filtering out of over 95% of retrieved information (Qu et al., 2021). Higher spatial resolution XCO2 and XCH4 satellite sensors (e.g., MethaneSat) will greatly improve tropical flux measurements retrievals through cloud gaps, as will other point-source mapping satellite sensors (e.g., EMIT, GHGSat, Carbon Mapper, PRISMA), although these target mode observations will not provide the global coverage needed to constrain tropical greenhouse gas budgets. PANGEA measurements will support L3 product

	development, including scaling between target mode observations and sensors with broader spatial coverage.
*Carbon-i**	TBD based on selection in the Earth System Explorer program. If selected, would be valuable for GHG fluxes from wetland systems, water cycle monitoring. Mission plan has focus on resolving data drought in tropical regions due to cloud cover.
GEDI, ICESat-2, EDGE*	Retrieval of tree- and crown-level structural attributes from lidar is necessary to link organismal processes and dynamics to ecosystem responses observed at landscape scales, as is vertical variation in forest structure. Spaceborne lidar yields community scale observations that, although incredibly valuable, remain insufficient to pair with tree level in situ measurements. PANGEA collections will support improved L3 GEDI products and EDGE calibration and validation (if selected).
SMAP, SMOS	SMAP exhibits a notable bias in tropical forests (Cho et al., 2023). However, significant advancements have been achieved by employing the Maximum Entropy Algorithm on SMAP (Wang et al., 2023). The scarcity of ground-based soil moisture observations remains a critical barrier to further enhancements
Geostationary: GOES-R ABI & AHI (Americas), MTG-I (Africa)	Geostationary satellites offer opportunities for diurnal measurements of ecosystem dynamics. With imagers that now have VNIR spectral resolutions comparable to polar-orbiting sensors, important ecosystem dynamics like GPP and ecosystem respiration can be retrieved (Khan et al. 2021, Losos et al. 2024). PANGEA will support direct calibration, validation, and product development of these metrics over the Americas and Africa.
VIIRS, Sentinel-3	Fires in standing tropical forests typically burn through leaf litter and woody fuels in the understory. Although tropical forest fires can severely degrade carbon stocks, biodiversity, and forest structure, their extent and frequency are poorly understood due to limitations in satellite fire detection algorithms, which struggle to capture low-intensity fires under dense canopies, leading to misconceptions about fire activity in these regions. PANGEA will support L3 product development to improve the accuracy of fire detection, including small-scale fires.

6.2.3 Airborne Remote Sensing Observations

PANGEA airborne observations will include instrumented aircraft and drones. Based on learned experience from ABoVE, recent recommendation from the AfriSAR-2 team, numerous international airborne NASA campaigns, and information gathered during the PANGEA scoping effort, flight plans will be co-designed with local partners. All requests for country clearances and flight permissions will be coordinated by NASA and JPL airborne programs working with the NASA Office of International and Interagency Relations (OIIR) and the US Department of State (see **Box 1**). When using a NASA aircraft or NASA contracted aircraft all appropriate airworthiness processes and flight approval and releases will be coordinated at the PANGEA project level with the appropriate centers, NASA HQ and JPL. Exact sensors and aircraft will be determined during the development of the Concise Experimental Plan.

PANGEA leverages NASA's history of successful international airborne campaigns, including many in the tropics. Most recently, NASA successfully executed the 2016 AfriSAR and 2023/2024 AfriSAR-2 campaigns to Gabon, where AfriSAR-2 expanded on the initial scope and successes of AfriSAR in Gabon to additionally collect data over Cameroon, the

Democratic Republic of Congo (DRC), Ghana, the Republic of Congo, and Sao Tome and Principe. In 2023, the BioSCape (Biodiversity Survey of the CapeBiodiversity Survey of the Cape) campaign successfully flew two NASA aircraft integrated with four airborne remote sensing instruments, acquiring contemporaneous observations from the UV through the VSWIR and into the thermal range as well as full wave-form LiDAR data. This combination of instruments was accompanied by an extensive field observation campaign, executed by a diverse science team with ~50% local participation. BioSCape, through thoughtful co-development of the campaign with local partners, secured letters of support from 18 public institutions including numerous government departments. BioSCape's success and continued capacity building has served as an excellent example of science diplomacy and has positively influenced the public's perception of NASA and the United States in Africa.

Box 1. International and Other Agreements

PANGEA international partners will be engaged at the outset and continuously to ensure strong relationships that will support the success of field and airborne campaigns. For each PANGEA landscape, formal agreements and/or permissions will be obtained from relevant governments and Indigenous community leaders. As soon as PANGEA is selected, the PANGEA Science Team will begin to engage institutional partners to support the development of formal discussions on the required diplomatic agreements that will be needed to conduct field work and deploy aircraft in support of the NASA TE campaign. As pathways with each foreign government are established, the PANGEA Science Team will work with NASA SMD via the TE Program Manager to develop proper diplomatic arrangement's for conducting field work and airborne campaigns in each country. Diplomatic agreements (such as Memorandum of Understanding (MOU's), Implementing Agreements (IA), and/or flight clearances) will need to be created between the US Government and the given Foreign Nation as early as possible. When such documents are required between NASA and a Foreign Government, the PANGEA Science Team and the TE Program Manager, in collaboration with NASA's OIIR, SMD, NASA Centers including JPL, the CCE Support Office, and the US State Department, will work through the proper diplomatic channels and protocols to establish the needed documents for a successful field and airborne campaigns. The PANGEA Science Team, TE Program and CCE Support Office will work closely to guarantee that Indigenous land and sovereign territories are fully acknowledged and respected in any diplomatic approval processes. Given the current PANGEA Science Team's experience with numerous international field and airborne campaigns, these experiences will be utilized in establishing the proper international agreements for the PANGEA program.

A number of Earth Venture Suborbital (EVS) and other international NASA airborne campaigns have also demonstrated feasibility of NASA aircraft and NASA contracted aircraft deploying internationally with in-situ and remote sensing instruments in support of multi-year large scale campaigns in both Africa and Latin America. Recently NASA JPL had a successful campaign in Latin America with AVIRIS-NG collecting remote sensing data over Chile, Colombia, and Ecuador in South America for methane point source measurements in 2023 in coordination with each country with a NASA contracted aircraft. Over the last decade, NASA has flown several highly successful campaigns in India with the AVIRIS-NG sensor on an Indian Space Research Organization (ISRO) aircraft for data acquisitions over India. All of these aforementioned campaigns represent decades of experience of NASA HQ and the centers (including JPL) working together with university and international collaborators to successfully acquire airborne remote sensing and in-situ data during global field campaigns.

When PANGEA develops the Concise Experiment Plan with the Science Definition team it will (and has already begun to) leverage team members from all of the international campaigns described above.

Importantly, PANGEA airborne data collection does not necessarily require NASA assets or NASA aircraft to be deployed. Commercial data-buys and flights on foreign and commercial aircraft are also viable options for PANGEA airborne acquisitions. NASA sensors can be flown on commercial aircraft. For example, sensors from the AVIRIS program often fly both domestically and internationally on a Dynamic Aviation aircraft. The EVS Oceans Melting Greenland (OMG), Delta-X and Coral Reef Airborne Laboratory (CORAL) programs all successfully deployed NASA JPL contracted aircraft with JPL instruments and team members. Commercial data-buys will also greatly expand airborne capabilities. For example, US funded commercial lidar transects span the entire countries of Brazil and the Democratic Republic of Congo, demonstrating feasibility in important PANGEA geographies. The Airborne Research Facility for the Earth System (ARES), run by Professor Michael Schaepman and Dr. Andreas Hueni out of the University of Zürich, is another important partner supporting PANGEA airborne acquisitions. ARES has successfully acquired data for collaborative NASA and ESA campaigns. Sensors onboard ARES include the AVIRIS-4 imaging spectrometer, a full waveform LiDAR, and a high-performance photogrammetric camera.

There is strong alignment with and interest from partner space agency airborne data acquisitions. A series of Amazon 2025/26 campaigns coordinated between Brazil's National Institute for Space Research (INPE) and the European Space Agency (ESA) will collect airborne fluorescence, methane, and in-situ measurements, as well as possible carbon flux and species measurements by means of a HELIPOD carried by a helicopter, including CO_2 and CH_4. The German Aerospace Center (DLR) is planning a coordinated campaign in Brazil in 2026 with the goal of deploying a methane lidar (CHARM-F) and imaging systems for methane detection. The French Space Agency (CNES) is involved, with a similar focus on methane, using airborne and ground-based measurements. ESA is also planning airborne campaign activities over Africa focused on validating satellite greenhouse gas observations. Plans are ongoing and will be further defined following a workshop in Morocco in the spring of 2025. The timing of PANGEA is such that it stands to greatly benefit from and contribute to these types of international collaborations. Many current PANGEA team members are working closely with the INPE, ESA, DLR and CNES teams to benefit from the upcoming campaigns.

PANGEA will also leverage rapidly advancing technologies, including drone capabilities to supplement aircraft data collection. Drone data acquisitions will be particularly valuable for capturing measurements that require higher temporal frequency acquisitions (e.g., tree mortality, phenology). PANGEA will utilize TRL 9 lidar and RGB UAV instruments. Current commercial UAV-based hyperspectral offerings often present challenges and tend to extend through the VNIR rather than including the shortwave portion of the spectrum, which contains important spectral information needed for decadal survey-relevant ecosystem measurements. However, these technologies are advancing rapidly and can be harnessed for some valuable scientific insights. The PANGEA team will continue to track the availability and utility of these technologies and will build in protocols to employ them as appropriate to support science activities.

Some PANGEA measurements will require contemporaneous field observations and airborne observations. This will require advance planning of field observations and clear, reliable methods of communication between the flight and field teams. Clear lines of communication will be established at the outset between field teams and flight teams. Field teams will be oriented to the flight campaign at the beginning of each PANGEA flight campaign and will be required to develop a plan that builds in flexibility in terms of when field samples will be collected. In preparation for and during the campaign, PANGEA will rely on near real time quicklooks and flight tracking tools, which will optimize airborne data collection and facilitate better field match ups but will also increase transparency (Cardoso et al., 2024).

Flight planning to support inclusive international collaboration: When planning flights, PANGEA will prioritize transparent and accessible community from the beginning to the end of the campaign, including frequently reminding the science team and local partners that no airborne data is guaranteed, and that all proposed acquisitions are nominal until successfully executed. Transparent flight planning and decision-making processes will help build trust across the science team and preserve relationships with local partners. Borrowing from BioSCape's success in this regard, PANGEA will work to implement a transparent prioritization scheme for science team regions of interest, with this prioritization scheme being open to feedback in advance of the airborne campaign. PANGEA will also share preliminary flight plans well in advance and implement an iterative feedback process so that the science team and local partners can provide input. While all final flight decisions will ultimately be made by the PANGEA leadership, aircraft, and instrument teams in daily go/no-go calls, the lead-up to these decisions will be participatory and open and information about daily flight activities will be conveyed once daily decisions have been made.

6.2.4 Field Observations and Studies

Ground-based measurements are necessary for 1) validation of spaceborne measurements of ecosystem properties from both the NASA POR and newly launched missions; 2) uncovering mechanistic drivers of observed fluxes and patterns, which can then inform model development and the interpretation of spaceborne observations; and 3) evaluating the scale dependencies of ecological processes. Despite the importance of tropical ecosystems, they are dramatically underrepresented with respect to field observations, which can lead to poor representation in higher level data products from satellite missions, underscoring the importance of PANGEA field-based measurements and studies. Field observations broadly include the following:

- **Manual In Situ Data** includes all data that must be directly measured by individuals with boots-on-the-ground, and cannot be easily automated. Examples include leaf traits (although drone data collection of leaf samples is possible), terrestrial laser scanning, chamber flux measurements, species identification, eDNA, animal movement data, and Indigenous, Traditional, and Local Ecological Knowledge (IEK, TEK, and LEK). These data are important for understanding the mechanistic relationships between pattern and process and for the validation of drone, aircraft, and satellite measurements.
- **Automated In Situ data** includes all ground measurements that support validation and understanding of ecologic processes but does not require frequent site visits and is more easily automated. Examples include dendrometer and sap flux measurements, camera trap and bioacoustics data. Similar to biological sampling, these observations are important for developing and understanding processes and validating remote measurements.
- **Flux and Meteorological data** include all data collected at a flux-tower or weather station, including carbon, water, and energy fluxes, air temperature, soil temperature, soil volumetric water content, relative humidity, and precipitation. The eddy-covariance technique primarily uses scaffolding towers above the forest canopy and measures high-frequency wind and scalar (gas concentration, energy, momentum) data to estimate ecosystem water and carbon fluxes. The eddy-covariance technique is the presently accepted 'gold standard' for site level fluxes and provides critical ground truthing for spaceborne and modeled estimates of carbon, water, and energy fluxes. Eddy-covariance data have also dramatically improved understanding of the drivers of carbon and water fluxes and the infrastructure around flux towers will be highly beneficial for the installation of additional support data.
- **Tower-based Proximal Remote Sensing** includes all data collected at the site/stand level that can be observed optically from airborne or spaceborne platforms. These measurements will supplement drone and aircraft remote sensing measurements to more directly link ecosystem traits and fluxes with satellite observations. PANGEA tower-based proximal remote sensing measurements include visible-to-shortwave

infrared hyperspectral reflectance, solar-induced fluorescence, thermal infrared radiation, microwave backscatter, lidar, VOD (L-band GNSS), and PhenoCams.

- **Drone-based Proximal Remote Sensing** includes lidar, RGB for both structure and spectra, multispectral data, and the potential development of a drone-based hyperspectral sensor. There are two key aspects of drone-based monitoring: (1) it allows for high-frequency data collection and continuous monitoring of temporal trends in a manner that is not possible with aircraft, and (2) it provides the ability to capture trends even during cloudy conditions, which are common in tropical forests. When paired with ground validation, drone-based acquisitions are critical to quantification of phenomena like tree mortality, carbon fluxes, phenology, and changes in functional traits with seasonal variation.

At present, field observations in the tropics are limited by the following:

- **Accessibility**: Dense, difficult-to-navigate terrain and remote areas with limited infrastructure limit the ability to deploy and maintain field equipment in the tropics.
- **High Biodiversity**: Tropical ecosystems are highly biodiverse, limiting the generalizability of field studies from one location to another and requiring more detailed knowledge about a broad variety of species in a particular location.
- **Seasonality and Climate**: Extreme weather such as heavy rainfall during monsoon seasons and extreme heat and humidity, create harsh working environments which can limit the duration and extent of fieldwork.
- **Funding and Resources**: The vast majority of funding and resources for science comes from the global north, limiting resources to directly fund research, and especially fieldwork, in the tropics.
- **Political and Social Instability**: Many tropical regions are in countries that experience political instability, conflict, or land-use disputes, which can pose risks to researchers and make it unsafe or difficult to conduct long-term studies.

PANGEA will address these limitations by building lasting, mutually beneficial, collaborative partnerships with local tropical organizations to leverage, reinforce, and gap-fill existing infrastructure and efforts. Partners have been engaged in the scoping process and will be involved throughout PANGEA, including during the development of the PANGEA Concise Experimental Plan. See *Section 7.2 - Community Engagement Strategy* for more information. The following partnerships will be essential to the success of PANGEA field observations and studies:

- **Alliance for Tropical Forest Science (ATFS)**, including sub-organizations **AfriTRON**, **ForestGEO**, **GEM**, and **RAINFOR,** comprises an international network-of-networks. The goal of the 11 tropical forest research networks is to advance tropical forest science and help build a new generation of scientists to achieve a more complete understanding of how tropical forests contribute to a healthy, functioning Earth. Forest inventory plots in the ATFS network includes 11,656 plots in 56 countries, including more than 50% of the world's tree species.

- **AndesFlux:** The Western Amazon forests span a climate gradient from areas with no dry season to areas with up to a six-month dry season, however ecohydrological studies across this climatic range do not exist, limiting understanding of forest responses to climate change. To fill this gap, the AndesFlux network, led by the Catholic University of Peru (Professors Eric Cosio and Norma Salina), established six eddy flux towers and permanent plots in the western Amazon, the region predicted to face the greatest climate change impacts. The eddy flux towers are Tambopata (PE-TNR, operational since 2017), Panguana (PE-PAN, 2023), Los Amigos (PE-AMG, 2023), Breo (PE-BRE), Sucusari (2024), San Francisco (2022).
- **Congo Basin Institute:** The Congo Basin Institute (CBI) has been dedicated to promoting transdisciplinary scientific collaborations in the Congo Basin since 2015. CBI operates two biological field stations in Cameroon and maintains environmental and phenology data sets, some dating back decades. CBI brings deep networks in the region, and can facilitate getting research permits, working with local research institutions, and collaborating with local and Indigenous communities through CBI's School for Indigenous and Local Knowledge (SILK).
- **Congo Basin Science Initiative:** The Congo Basin Science Initiative (CBSI) is an independent scientist-led platform that promotes long-term investment in science in the Congo Basin. Its mission is to transform our understanding of the world's second largest extent of tropical forest, build scientific capacity in the region, and use this knowledge to support sustainable development.
- **CongoFlux:** CongoFlux is a tropical research station centered around an eddy covariance flux tower at INERA research center in Yangambi, in the heart of the Democratic Republic of Congo. Since 2019, the tower has measured the long-term exchange of greenhouse gasses (e.g., CO_2, N_2O, CH_4, H_2O) between the forests and the atmosphere using the eddy covariance method. The CongoFlux research team also continuously collects meteorological data, phenological observations, atmospheric O_3 concentrations, and ancillary data such as tree species composition, net primary productivity, leaf area index, and GHG emissions from the soil using chambers.
- **FLUXNET**, including sub-organizations **AmeriFlux** and **ICOS**, is another international network of networks. FLUXNET connects regional networks of primarily field-based earth system scientists and research sites. FLUXNET has produced consolidated data across sites processed following a standardized pipeline. Flux sites typically have sufficient infrastructure and power supply to host additional support measurements such as proximal remote sensing instruments. Because of this PANGEA will prioritize

field observations that are partnered with FLUXNET sites to make use of existing infrastructure and build collaborations with existing sites.

- **GEO-TREES:** Building on decades of work from the global research community with a strong representation of partners from the Global South, the foundation funded GEO-TREES initiative aims to fund high-quality ground and airborne measurements from a global network of long-term forest inventories, and to make these data open access in support of efforts to estimate forest carbon stocks from space.
- **LBA:** The Large-Scale Biosphere Atmosphere Experiment in Amazonia is a permanent program of the Brazilian Ministry of Science, Technology, and Innovation. LBA works to foment cooperation in research and maintenance of infrastructure to answer questions related to the function of Amazonia in the Earth System.
- **NGEE-Tropics** is a 10-year, multi-institutional project funded by the U.S. Department of Energy (DOE). NGEE-Tropics primarily goal is to develop a predictive understanding of how tropical forest carbon balance and climate system feedbacks will respond to changing environmental drivers in the 21st Century. NGEE-Tropics has focused on data collection in the tropical Americas and Asia (Brazil, Panama, Puerto Rico, Malaysia, and Australia). NGEE-Tropics will be sunsetting by the time PANGEA enters its most active phase. PANGEA will build directly on NGEE-Tropics data collection efforts, by extending similar measurements to Africa and collecting collocated remote sensing data, in addition to building on NGEE-Tropics modeling efforts (see *Section 6.4*).

6.3 Candidate Landscapes

PANGEA will collaborate closely with in-country partner institutions to ensure the smooth execution of field and airborne activities across selected Landscapes. **PANGEA's nested sampling design supports a sampling-to-scale approach, with a nested sampling design.** Ground measurements span gradients within a landscape, and landscapes span climatic and biodiversity gradients within a continent (**Figure forthcoming**). PANGEA will prioritize countries that encompass landscapes where there is a confluence of intact, disturbed, and degraded forest, peatland, wetland, and mangrove ecosystems, with adjacent agro-ecosystems within roughly 100 km^2 area. Coordinated, coincident ground data collection will be collected across these gradients within each landscape. **Table 3** summarizes candidate landscapes based on information provided by partners.

Table 3: Candidate PANGEA Landscapes. X-NASA indicates past NASA airborne campaign.

Landscape	Country	Data Type				
		Ground	Tower	Socioeconomic	Drone	Aircraft
Potential African Tropical Forest Landscapes						
Dja Reserve	Cameroon	X		X	X	X-NASA
Mbalmayo	Cameroon	X			X	X-NASA
Korup	Cameroon	X				
Campo Ma'an	Cameroon	X				
Mai Ndombe	Democratic Republic of Congo	X		X	X	X-NASA
Yangambi	Democratic Republic of Congo	X	X		X	
Yoko Reserve	Democratic Republic of Congo	X		X		
Bia Tano	Ghana	X	X			
Lopé	Gabon	X				X-NASA
Mondah	Gabon	X				X-NASA
Mabounié	Gabon	X				X-NASA
Rabi	Gabon	X				X-NASA
Bokatola	Republic of Congo	X				
Kolongomba	Republic of Congo	X				
Lac Tele	Republic of Congo	X				
Odzala-Kokoua	Republic of Congo	X			X	X-NASA
Makera	Rwanda	X				
Rubona	Rwanda	X				
Sigira	Rwanda	X				
Potential American Tropical Forest Landscapes						
km 34 (Manaus)	Brazil	X	X		X	X
km 67 (Santarem)	Brazil	X	X			X
Rebio Jaru	Brazil	X	X			
Tanguro	Brazil	X	X			X
Caxiuana	Brazil	X	X			
Amacayacu	Colombia	X				
Amazonas	Colombia	X				
La Planada	Colombia	X				
Guancaste	Costa Rica	X	X	X	X	X-NASA
Santa Rosa	Costa Rica	X	X	X	X	X-NASA
Turrialba	Costa Rica	X			X	
Tiputini	Ecuador	X				X-NASA
Yasuní	Ecuador	X				X-NASA
Paracou	French Guiana	X	X		X	X-NASA
Agua Salud	Panama	X				
BCI	Panama	X			X	X-NASA*
Darien	Panama	X		X		
Iquitos	Peru	X				
Huánuco	Peru	X	X			
Los Amigos	Peru	X	X			
Madre de Dios	Peru	X				
San Martin	Peru	X	X			
Tambopata	Peru	X	X			
Ucayali	Peru	X				
Guanica	Puerto Rico	X	X			X
Luquillo	Puerto Rico	X				X-NASA

** indicates planned activities*

PANGEA landscapes will prioritize locations where the following already exist or have strong potential to be established:

- Existing eddy covariance flux tower data. CO_2 and CH_4 measurements can be extended with chambers.
- Long-term forest inventory plots, enabling re-censusing to support new measurements (e.g., canopy traits, bioacoustics, camera traps) that build on rich forest demographic rates information (mortality, growth and recruitment rates).
- Camera traps, bioacoustic sensors, weather station data, and eDNA data.
- Ground and/or drone-based phenology datasets.
- Partnerships with Indigenous and/or Local Communities.

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, 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 and site selection process will be formalized during the Concise Experimental Plan to ensure transparent selection and approval of landscapes and sites within landscapes for ground and airborne data collection. 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 (see Section 7.2 for more information).

6.4 Modeling, Data Synthesis, and Integrative Analyses

6.4.1 Modeling and Data Integration Approach

Modeling and data syntheses are fundamental components of PANGEA. The goals are to:

- Identify key processes that are poorly represented and regions within the PANGEA domain that drive uncertainty of key variables and processes in existing models.
- Develop Observing System Simulation Experiments (OSSEs) that will help inform the optimal location and gradients needed to maximize the representativeness of the intensive sites within the PANGEA domain.
- Synthesize and scale measurements from Landscapes to the Core and Extended PANGEA domains.
- Implement new processes and techniques, as well as improve existing ones in models and apply them to answer PANGEA's scientific questions.

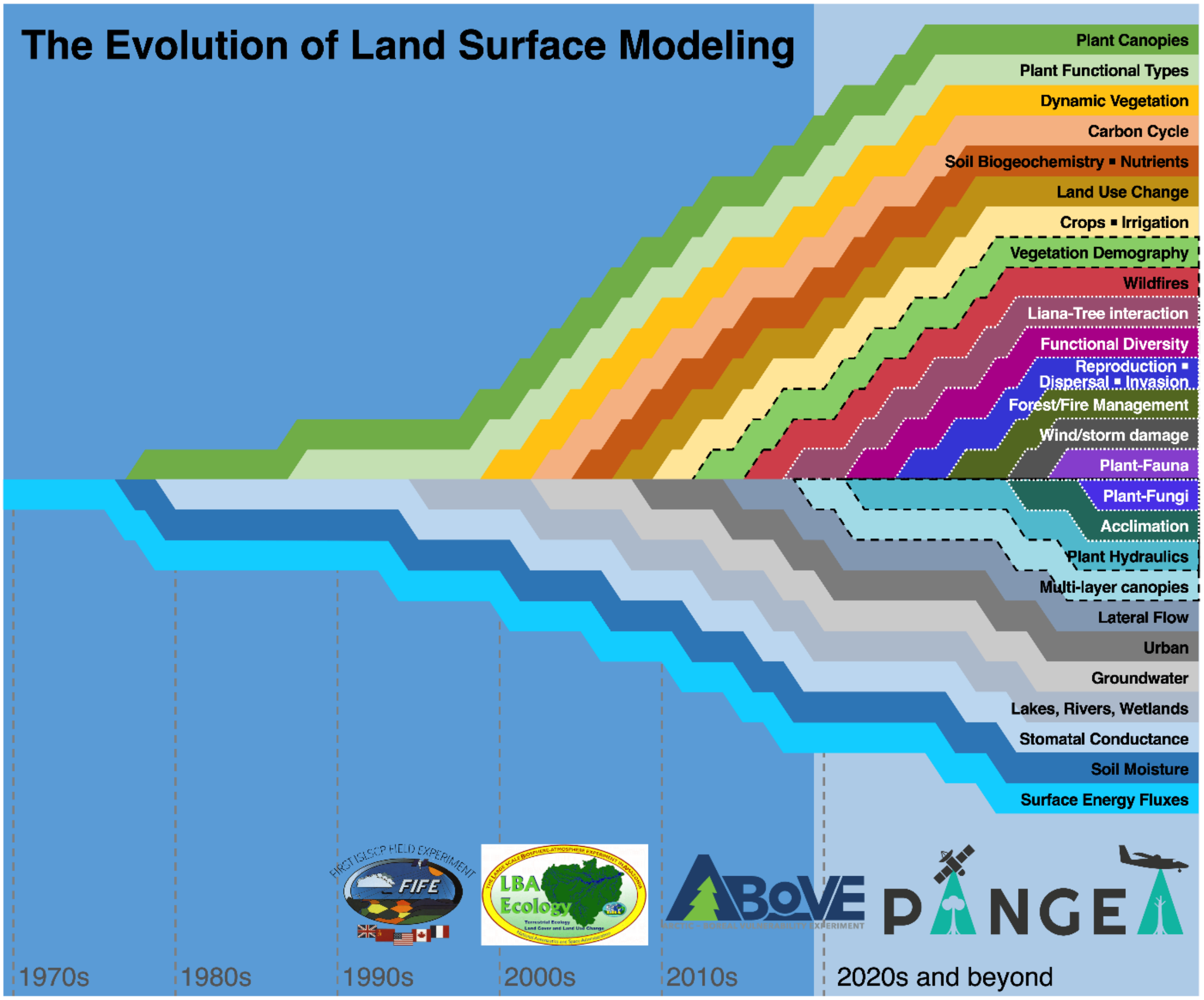


Figure 10. Change in processes solved by terrestrial biosphere models over the decades, along with prior NASA Terrestrial Ecology campaigns. Black dashed lines: implemented processes, still under significant development. White dotted lines: processes that are starting to emerge and are expected to emerge in the upcoming years. Source for original figure: Fisher and Koven (2020)

Projecting the future trajectory of tropical ecosystems presents a significant challenge to Earth system models (ESMs), as these models must accurately represent complex physical, biogeochemical, and ecosystem dynamics. Model intercomparison projects such as CMIPs (Taylor et al., 2012; Eyring et al., 2016) and TRENDY (Friedlingstein et al., 2023; Sitch et al., 2024) are crucial for tracking the development of process-based models and identifying areas that need to be improved (Arora et al., 2020). While the benchmarking and validation of ESMs have become more common in recent years (Fisher et al., 2018), it is still rare to systematically evaluate the performance of carbon cycle models after they have been updated (Fer et al., 2021). However, such comparisons with observational datasets are essential for testing hypotheses and evaluating predictive accuracy (Fisher et al., 2018). The International Land Model Benchmarking (ILAMB) project (Hoffman et al., 2017; Collier et al., 2018) provides tools to track and compare model performance using a comprehensive skill score method and incorporates multiple observational datasets to account for model uncertainty (Braghiere et al., 2023). Improved agreement between historical simulations and observations may indicate that model components can be refined to better represent processes, thereby increasing confidence in future projections. Nonetheless, as models evolve, addressing future challenges such as acclimation, nutrient limitation, shifts in functional composition, accounting for methane emissions, and carbon allocation partitioning between above and belowground biomass will be increasingly important for maintaining model accuracy. Data collected through PANGEA will be used to expand benchmarking tools, improve model comparison exercises, and identify modeling areas that need to be improved or are not yet represented.

Over the past decades, terrestrial biosphere models have expanded scope and incorporated many new processes that could not be addressed during LBA (**Figure 10**). For example, processed-based models now resolve structural and functional diversity, a broad variety of natural and anthropogenic disturbance dynamics, and strong coupling with biogeochemical cycles (Fisher et al., 2018; Fisher and Koven 2020; Negron-Juarez et al., 2020). We are now in a time in which ecological processes in diverse ecosystems driving energy, water, carbon and nutrient cycling on Earth must be accounted for (Bonan et al., 2024). Likewise, several classes of models have been increasingly leveraging the broad range of remote sensing observations, and throughout PANGEA we will have participation of a broad range of models that can use remote sensing for initialization, uncertainty quantification, and data assimilation. Examples of such models include, but are not limited to:

- **Process-based vegetation demography models** such as ED2 (Antonarakis et al., 2014; Longo et al., 2020; Schneider et al., 2023), ED (Hurtt et al., 2004; Ma et al., 2023) and FATES (Negrón-Juárez et al., 2020);
- **Data-driven hybrid models** that solve processes with a strong data assimilation approach such as CARDAMOM (Bloom et al., 2016; 2020) and CliMA (Braghiere et al., 2023; Wang et al., 2023);
- **Top-down inverse modeling approaches** that link column measurements with fluxes through atmospheric transport models such as CarbonTracker (Peters et al., 2007) and CMS-Flux (Liu et al., 2020);
- **Artificial Intelligence and machine learning models** (Schneider et al., 2017; Reichstein et al., 2019; Eyring et al., 2024); and
- **Agent-based models** that incorporate social and ecological components in tropical forest systems (Andersen et al., 2017; Chaplin-Kramer et al., 2024; von Essen and Lambin 2023).

Table 4 provides more information on several opportunities for which models can be used to investigate processes and answer PANGEA Science Questions. PANGEA measurements will also further advance both the representation of processes relevant to tropical forests under a changing Earth (**Figure 10**) and methods for remote sensing data and model integration.

Table 4. Classes of models, along with a non-exhaustive list of model examples, that can (1) produce spatial and temporal estimates of variables of interest across the PANGEA domain, (2) leverage remote-sensing and in-situ observations for initialization, assessment and benchmarking and (3) help answer science questions and test PANGEA hypotheses. Classes of model: PBM, Process-based terrestrial biosphere models; HM, Data-driven hybrid models; TDM, top-down models; AIML, Models based on Artificial Intelligence Machine Learning; and AB, Agent-Based Models. Sub-classes of PB models: IBM, Individual-Based Models; CBM, Cohort-Based Models; DGVM, Dynamic Global Vegetation Models (excluding IBMs and CBMs). Science questions marked with * mean that models could be used if coupled with other models, and science questions marked with ** mean that models have the potential to answer, although implementing new processes is required.

<table>
<tr><th colspan="4">Model</th><th colspan="3">Data-Model integration opportunities</th><th rowspan="2">Science Q's</th></tr>
<tr><th>Class</th><th>Sub-class</th><th>Examples</th><th>Variables of interest</th><th colspan="2">Remote sensing</th><th>Other data</th></tr>
<tr><td rowspan="3">PBM</td><td>IBM</td><td>FORMIND
TROLL</td><td>Carbon stocks
Vertical structure of canopies
Structural and functional diversity
Recruitment, growth, mortality (by size class and functional group)
Gross Primary Productivity
Autotrophic/heterotrophic respiration
Disturbance rates</td><td rowspan="3">Airborne:
Lidar
Radar
Hyperspectral
Drone
RGB/Lidar</td><td rowspan="3">Satellite
BIOMASS
CHIME
ECOSTRESS
EDGE
EMIT
GEDI
Landsat
MODIS
NISAR
OCO-2/3
SBG
Sentinel-1
Sentinel-2
SMAP
SWOT
Tanager
TROPOMI
VIIRS</td><td rowspan="3">Forest inventory plots
Tree-level mortality, growth and recruitment
Plant functional traits
Eddy covariance fluxes
Meteorological data
Soil flux chambers
TLS data (structural heterogeneity)
Tower-based GNSS data for vegetation optical depth
In-situ fire information
Phenocams
Isotope data for flux partitioning
FACE</td><td rowspan="3">Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8*
Q9
Q10
Q11**
Q12**
Q13
Q14*
Q15
Q16*
Q17
Q18
Q19
Q20**
Q21
Q22
Q23
Q24
Q25*
Q26</td></tr>
<tr><td>VDM</td><td>ED
ED2
Ent TBM
FATES
LPJ-GUESS</td><td>Carbon stocks
Vertical structure of canopies
Structural and functional diversity
Recruitment, growth, mortality (by size class and functional group)
Disturbance rates
Logging and crop yields
Gross Primary Productivity
Autotrophic/heterotrophic respiration
Burned area and fire emissions
Sensible and latent heat fluxes
Outgoing SW and LW radiation
Surface and subsurface runoff
Nutrient Cycles (Nitrogen, Phosphorus)</td></tr>
<tr><td>DGVM</td><td>CLM
ELM
JULES
JSBACH
ORCHIDEE
LPJ</td><td>Carbon stocks
Recruitment, growth, mortality (total)
Disturbance rates
Logging and crop yields
Gross Primary Productivity
Autotrophic/heterotrophic respiration
Burned area and fire emissions
Sensible and latent heat fluxes
Outgoing SW and LW radiation
Surface and subsurface runoff
Nutrient Cycles (Nitrogen, Phosphorus)</td></tr>
</table>

HM	CARDAMOM CliMA	Carbon stocks Gross Primary Productivity Autotrophic/heterotrophic respiration Burned area and fire emissions Sensible and latent heat fluxes Outgoing SW and LW radiation Surface and subsurface runoff	**Airborne:** Lidar Radar Airborne flux Hyperspectral Drone RGB/Lidar	**Satellite** BIOMASS CHIME ECOSTRESS EMIT GEDI GOES-R GRACE Landsat, MODIS NISAR OCO-2/3 SBG Sentinel-1/2/3 SMAP SWOT Tanager TROPOMI VIIRS	Plant functional traits Eddy covariance fluxes Meteorological data Soil flux chambers Tower-based GNSS data for vegetation optical depth In-situ fire information Phenocams Isotope data for flux partitioning	**Q1** **Q2** **Q3**** **Q4** **Q6**** **Q8*** Q9 Q14* Q15 Q16* Q18 Q21 Q22* Q23 Q24 Q25* Q26*
TDM	CarbonTracker HYSPLIT STILT-VPRM	Gross Primary Productivity Autotrophic/heterotrophic respiration Burned area and fire emissions Sensible and latent heat fluxes	**Airborne:** Airborne flux Hyperspectral	**Satellite** BIOMASS ECOSTRESS EMIT GOES-R OCO-2/3 SBG SMAP SWOT TROPOMI VIIRS	Eddy covariance fluxes Meteorological data Soil flux chambers Tower-based GNSS data for vegetation optical depth In-situ fire information Phenocams Isotope data for flux partitioning	**Q1** **Q2** **Q4** **Q6** Q9 Q14* Q17
AIML	MetaFlux	Gross Primary Productivity Autotrophic/heterotrophic respiration Burned area and fire emissions Sensible and latent heat fluxes	**Airborne:** Airborne flux Hyperspectral	**Satellite** BIOMASS ECOSTRESS EMIT GOES-R OCO-2/3 SBG SMAP SWOT TROPOMI VIIRS	Eddy covariance fluxes Meteorological data Soil flux chambers Tower-based GNSS data for vegetation optical depth In-situ fire information Phenocams Isotope data for flux partitioning	**Q1** **Q2** **Q4** **Q6** Q9 Q14* Q17
ABM	ABSOLUG Sim-Pachamama Repast EAABM	Land cover and land use state Land cover and land use transition rates Net present value of cultivations Cattle reproduction rate Household characteristics (wealth, size) Rural wages Household migration and demographics Remittances	**Airborne:** Lidar Hyperspectral Drone lidar Radar	**Satellite** BIOMASS ECOSTRESS EMIT SBG Sentinel-1, -2 Landsat	Plot-scale management data Territory boundaries Crop yields Survey data Census data Choice experiments data	**Q20** **Q27**

PANGEA modeling activities will cut across all Science Themes. Modeling efforts early in PANGEA will help inform which key areas, variables, and mechanisms drive uncertainty in patterns, processes and predictions of relevant quantities in tropical moist forests. During PANGEA ground and airborne campaigns, measurements will be prioritized that can be directly used by models either for initialization, boundary conditions, or assessment. This approach has been successfully implemented in previous model and data-integration projects (e.g., ABoVE and NGEE-Tropics), and we plan to build on these projects.

Box 2. PANGEA Modeling and Integration Example

Using PANGEA's Question 6 (cross-continent functional trait variability and effects on the tropical carbon cycle) and the ED2 model as one example, we will use parameter uncertainty approaches (e.g., through simulation ensembles using PEcAn) to identify which measurable foliar and hydraulic traits drive the model sensitivity of CO_2 and H_2O fluxes in FATES (henceforth key traits). We will then prioritize measurements of the key traits in field sites and by remote sensing across disturbance and climate gradients in both continents and use the collected data to constrain parameter distributions across the gradients of interest, by using measurements of fluxes and emergent relationships between trait gradients and fluxes across the same gradients as references. The constrained model will then be used to investigate how ecosystems at different precipitation regimes and disturbance severities respond to extreme droughts, and which processes (e.g., soil moisture limitation or vapor pressure deficit) drive the responses to extreme droughts. By using an integrated approach between models and data acquisition, PANGEA will enable significant advancement of the model's predictive ability to quantify the vulnerability of tropical forests to global change.

PANGEA data synthesis activities are integral to PANGEA's scientific approach, facilitating the upscaling of landscape ground and airborne measurements to regional and pan-tropical scales. By measuring key variables using airborne remote sensing paired with ground measurements (e.g. soil moisture, plant functional traits, fluxes), we can establish robust empirical relationships using statistical models to interpolate wall-to-wall variations in critical variables. As an example, ground measurements on biomass carbon losses due to droughts across multiple sites, can be used to develop statistical models that predict biomass changes in response to varying soil moisture, VPD, drought frequency, plant functional groups, etc. This model can then be used to map pan-tropical impacts on forest biomass following specific drought scenarios, enhancing our understanding of ecosystem responses to environmental stressors across diverse tropical landscapes.

PANGEA will leverage multiple data synthesis approaches to enhance our understanding of tropical forest dynamics. For example, there is great potential to use artificial intelligence and machine learning (AI/ML) models for data synthesis due to their robustness in handling non-linearities and interactions among predictors, which are particularly critical in the complex ecosystems of tropical forests dominated by multi-factorial processes. AI/ML can be further used to emulate process-based models (Swaminathan et al., 2024) and more efficiently explore models' parametric space or run short/long-term forecasting (Li et al., 2023; Meunier et al., 2024). To improve the interpretability of these AI/ML models, PANGEA will implement several known techniques, such as Feature Importance Analysis, which quantifies and highlights the most influential factors driving the model's predictions, and Partial Dependence Plots, which can be employed to visualize how changes in specific variables impact predicted outcomes, providing insights into the underlying ecological processes. Additionally, incorporating non-AI techniques like Causal Inference can help us understand cause-and-effect relationships within PANGEA data, offering a complementary perspective that enhances our mechanistic understanding. These strategies will not only improve our grasp of tropical forest dynamics but also provide valuable insights that can be integrated into process-based models for more accurate predictions.

Another powerful data synthesis technique is the space-for-time substitution approach, which, despite its limitations, can be particularly useful for understanding long-term dynamics in the absence of extensive temporal data series, whether remote-sensing or field-based, and used for constraining models as well (Ma et al., 2017). One significant challenge in understanding tropical forest dynamics is the limitation of current satellite biomass products. For example, while recent products like GEDI offer high spatial resolution, they only cover the past few years, restricting our ability to monitor long-term biomass changes. To overcome this challenge and obtain long-term, high-resolution forest biomass regrowth data, previous work used a space-for-time substitution approach, which calculates biomass carbon recovery from a single snapshot of current biomass data in areas that experience disturbance in different years (Heinrich et al., 2021; Rappaport et al., 2018). This approach, coupled with AI/ML models and traditional data synthesis techniques, ensures that PANGEA can robustly assess and predict tropical forest dynamics across various scales and timeframes, supporting use of long-term satellite records as a result of PANGEA data acquisitions and methodological advances.

6.4.2 Coordination with other modeling and data integration communities

Coordination with established modeling and data integration communities is crucial to extend the impact of PANGEA beyond field and satellite observations. An important PANGEA partnership is with the **International Land Model Benchmarking (ILAMB)** project (Collier at al., 2018). Data collected through PANGEA can become new benchmarking datasets, critical for model development. These datasets will be highly valuable for evaluating and improving models used in global efforts, including the land components of the **Coupled Model Intercomparison Project (CMIP)**. This partnership will enhance the representation of tropical ecosystems in Earth system models by providing benchmarks specifically tailored to tropical forests, helping global models achieve higher accuracy in their predictions. Another key partner is NGEE-Tropics, which, while scheduled to sunset around the time PANGEA enters its most active phase, provides a rich foundation of knowledge, tools, and data. Leveraging the outputs from **NGEE-Tropics** during the transition phase will align methodologies and objectives, ensuring continuity in tropical forest research.

Collaboration with the **Global Modeling and Assimilation Office (GMAO)** can provide PANGEA with advanced data assimilation techniques, facilitating the integration of PANGEA acquisitions and satellite data into predictive models of tropical forest dynamics. GMAO's established frameworks for atmospheric and land data assimilation could significantly enhance PANGEA's capacity to model tropical forests under current and future climate scenarios. The **TRENDY** project, which coordinates global carbon cycle simulations, represents another important partnership. PANGEA's detailed site-specific data for tropical forests will be critical for improving the parameterization and performance of TRENDY models, particularly for regional carbon dynamics and fluxes in tropical biomes (Sitch et al., 2024). Lastly, the CMIP initiative, a global leader in climate modeling, will benefit from PANGEA's observations, especially in the context of improving the representation of tropical ecosystems. By coordinating with CMIP, PANGEA can ensure that its data and findings contribute to ongoing efforts to enhance land model performance and reduce uncertainties in global projections as a result of tropical forest responses to climate and land-use change.

In addition to these well-established communities, PANGEA aims to collaborate with newer initiatives. For example, **Inverse modeling** will play a critical role in PANGEA's coordination strategy, offering a framework for reconciling discrepancies between observed and simulated ecosystem fluxes. This technique will help assimilate large-scale satellite-derived datasets with field measurements, allowing for refined predictions of carbon and water dynamics in tropical biomes (Liu et al., 2016). PANGEA also aims to collaborate with innovative modeling efforts such as **CARDAMOM**, which combines satellite and ground-based observations for carbon cycle data assimilation and modeling (Bloom et al., 2020), and **PEcAn** (the Parameterization and Calibration using Networks), which focuses on leveraging field and satellite datasets to optimize model parameters and improve carbon and water flux predictions (Dokoohaki et al., 2022; Meunier et al., 2021). Finally, collaboration with **CliMA**, which is developing a cutting-edge Earth system model that integrates machine learning and data assimilation techniques, will enhance PANGEA's ability to scale tropical forest observations and better represent their role in the Earth system (Schneider et al., 2017). These collaborations will help bridge the gap between field data collection and predictive modeling, driving new insights into the functioning of tropical ecosystems and their role in the Earth system.

6.4.3 Scaling Strategy

The NASA Terrestrial Ecology (NASA TE) Program has been instrumental in the development of scaling strategies for Earth system science research. The first NASA TE field campaign, the First International Satellite Land Surface Climatology Project (ISLSCP) Field

Experiment (FIFE) explicitly aimed to upscale soil-plant-atmosphere models designed for the cell and leaf level and apply them at the larger scales (kilometers) appropriate to atmospheric models and satellite remote sensing (Sellers et al., 1992). Scaling approaches were similarly central to following field campaigns such as BOREAS, LBA, and ABoVE. The development and diversification of sensors over the past decades allow us to characterize relevant properties from leaf organs (LiCOR) and individuals (terrestrial laser scanners) to forest stands (UAV-borne sensors), regions (aircraft measurements) and continents (satellite measurements) (Bustamante et al., 2016). Likewise, several terrestrial biosphere models now include processes with time scales of minutes (photosynthesis, energy cycles) to days (phenology), months (growth, mortality) and years (disturbances) that also span spatial scales from plant tissues to continents (Fisher et al., 2018; Longo et al., 2019; Koven et al., 2020). In such models, the ecosystem-scale state and fluxes emerge directly from competition between individuals happening at fine spatial scales.

PANGEA's nested sampling design, with a sampling-to-scale approach, provides opportunities for advancing satellite monitoring, product development, and assimilating data and benchmarking various processes in next-generation ecosystem models, which can significantly advance the ability of applying these models for process understanding and long-term prediction.

To ensure processes are captured across a broad diversity of environmental conditions and multiple data sources—ground, tower, drone, and aircraft sensors, PANGEA field and airborne campaigns will include sampling across gradients in nutrient availability, ecosystem structure and function, climate, and disturbance regimes. Incorporating this variability is critical for regional and pan-tropical scaling and for informing models and ensuring that they can be assessed and benchmarked under different limitations, and thus reducing the risk of equifinality (right answers due to compensating wrong reasons). The choice of priority gradients will consider the current uncertainties in models, and novel processes that have not been assessed with remote sensing data at scale to date (e.g., temporal changes in canopy structure and composition and their impacts on energy, water and carbon fluxes; plant hydraulic responses to climate variability).

PANGEA will also coordinate with existing scaling frameworks, facilitating the standardization of data collection methods. For example, the NASA EMIT team is actively working with NEON to develop scaling workflows between NEON and satellite data in preparation for NASA's upcoming Surface Biology and Geology (SBG) mission. PANGEA ground and airborne acquisitions will extend these workflows to the tropics. PANGEA will also coordinate with existing NASA funded efforts like CMS4D, a multi-scale data-fusion prototype system for carbon dynamics monitoring from space. CMS4D is a case study in the Brazilian Cerrado focused on fire dynamics led by Carlos Alberto Silva, which has many workflow parallels with PANGEA. Coordinating with these efforts to standardize and harmonize data collection and scaling workflows will help ensure consistent and high-quality data, enabling broader collaboration and cross-validation of results. An excellent example of this type of collaborative work is the High-Latitude Drone Ecology Network (HiLDEN) (https://arcticdrones.org/), which PANGEA aims to emulate in tropical biomes. In addition to drone lidar, PANGEA will draw upon other field-based collaborative efforts, such as the SPUN (Society for the Protection of Underground Networks) initiative, which has focused on mycorrhizal fungi sampling in historically under-sampled areas (https://www.spun.earth/). These networks demonstrate the power of coordination and ground-level engagement to bridge gaps in ecosystem data, an approach that PANGEA will adopt across its multiple scales of study. This multi-layered approach to field, airborne, and satellite measurements will advance satellite monitoring and the capacity of next-generation models to simulate key processes and improve long-term ecosystem predictions.

6.4.4 Modeling and data integration timeline

Modeling and data synthesis activities will occur throughout the entire duration of PANGEA. However, such tasks will shift focus as the campaign progresses. To reflect the changes in the role of modeling and data synthesis within PANGEA, we describe the activities in three phases.

Phase 1 (Y1–Y2): A Modeling and Data Synthesis Working Group (MDSWG) will be established. This group will identify key areas and processes that currently drive uncertainty in process-based models related to carbon, water, energy, and nutrient cycles, as well as biodiversity and human interactions in tropical moist forests. To this end, the group will combine synthesis studies on the 5 Science Themes at the pan-tropical scale and develop model intercomparison efforts using established benchmarking (e.g., TRENDY, FLUXCOM) and tools (e.g., ILAMB). This effort will inform the campaign design, including which environmental gradients and processes drive the uncertainty and therefore could benefit the most from PANGEA measurements. These efforts may take a non-trivial amount of time, therefore the MDSWG will also seek rapid responses through the use of Observing System Simulation Experiments (OSSEs) based on existing models and drivers to provide a first assessment of key areas of uncertainty and areas that lack representativeness in existing observations.

Phase 2 (Y3–Y6): MDSWG efforts will focus on multiple, complementary goals. Activities linked to process-based models will focus on implementing key missing mechanisms identified during Phase 1, which will advance understanding of the drivers of observed patterns on carbon, water, energy, and nutrient cycles in the field campaign. Activities linked to synthesis will enable the upscaling of findings from local and regional to the global scales. Data synthesis research will focus on using PANGEA datasets to generate products at scale that can be assimilated by inverse and hybrid models, as well as used for benchmarking of process-based models. Projects and datasets collected within the peak data acquisition period, primarily located in tropical Africa and the Americas will be reviewed and synthesized. This process will integrate individual site-level measurements with regional-scale airborne and spaceborne remote sensing imagery to upscale key variables to a pan-tropical level and create wall to wall maps. Additionally, novel inter-comparisons across basins will be conducted. Synthesis approaches will include, but not be limited to, artificial intelligence, machine learning, and space-for-time substitution. Group members working with inverse and hybrid models will use PANGEA data sets and derived synthesis products for quantifying uncertainty in scaled quantification of state variables and fluxes. Importantly, the efforts in this phase will not focus on a single set of models and techniques, but rather bring together methods that allow for scaling of space- and time-limited measurements to the entire pan-tropical region along with robust estimates of uncertainty.

Phase 3 (Y7–Y9) will focus on studies that use the constrained and improved models and data products developed during Phase 2 to directly address PANGEA Science questions and test the key hypotheses. Research using process-based models in Phase 3 should identify and attribute the causes and drivers of changes in forest functioning by leveraging PANGEA datasets for initialization and uncertainty quantification. Data synthesis and inverse modeling efforts will focus on describing how the major axes of variability in tropical moist forests drive the heterogeneity of carbon, energy, water and nutrient fluxes as well as biodiversity within and across continents. Together, these activities will advance understanding of the resilience of tropical forests under global change and provide integrative answers across all Science Themes.

7. Technical and Logistical Feasibility

PANGEA will leverage NASA's history of successful international field and airborne campaigns, including recent campaigns in the Americas, Africa, and Asia. Specifically, NASA has done extensive research in Africa very successfully, including AfriSAR-1, AfriSAR-2, BioSCape, as well as many R&A projects. In addition, there are immense investment in Africa currently that will support important feasibility elements of PANGEA, including the Congo Basin Science Initiative (CBSI), CongoFlux, One Forest Vision, the Science Panel for the Congo, Africa Master's of Machine Intelligence (AMMI) via the African Institute for Mathematical Sciences (AIMS), existing NASA collaboration with the Gabonese Space Agency (AGEOS) and Central Africa Satellite Observatory (OSFAC), and GEO-TREES.

The research being proposed as part of PANGEA will not involve the deployment of new remote sensing technologies or development of new sensors. Rather, PANGEA research will utilize existing airborne and spaceborne remote sensing systems and datasets. While much of the research for PANGEA will be conducted in locations with existing field-based studies, some of the research will be conducted in remote regions that will require more complex logistical arrangements. In addition, because PANGEA is an international deployment taking place in several countries, there are a number of challenges that need to be considered and planned for.

Anticipated challenges include deploying and maintaining in situ instrumentation, obtaining international flight permission for airborne data acquisition, visas and research permits for US and international investigators, access to field sites, human-animal interactions/conflict, political or other unrest, health and safety of scientists and participants (see *Section 7.6 for Risk and Risk Mitigation*). Building necessary relationships to obtain flight clearances for the selected countries and field sites that are part of the PANGEA domain will be an early priority (see *Section 6.2.3 Airborne Remote Sensing*). To obtain flight clearances, PANGEA will work with NASA OIIR to develop the diplomatic clearance packages needed for international airborne deployments. Prior to requesting flight clearances, PANGEA will build relationships with in-country partners such as government agencies, US Embassies, NGOs, and leaders of Indigenous territories to develop agreements that will ensure proper flight clearances and field permits. PANGEA will ensure that we follow the rules and customs of each country where we are deployed, through the co-produced design of flight plans and site selection.

In cases where NASA aircraft cannot obtain overflight permission or acquire data using its own instrumentation, PANGEA will deploy commercial or other assets, such as commercial ALS, commercial UAV-based instrumentation, or local instruments and aircraft to acquire the required airborne datasets. This is particularly important in Brazil, where NASA has historically encountered challenges for ground observations using non-Brazilian instruments and aircraft. PANGEA will build on precedents employed by NASA and the US government of using commercial airborne data providers to collect the required datasets (see *Section 6.2.3 Airborne Remote Sensing*).

7.1 Organization and Management

The organization and coordination of PANGEA will be determined by NASA Program Management. We present a concept for organization and management that reflects a successful model used in the ABoVE and LBA-ECO campaigns (**Figure 11**). This structure will enable the organization and management of a long-term project with significant investment from interdisciplinary partnerships and collaborations at the national and international scale.

7.1.1 Program Management

The NASA Terrestrial Ecology Program uses surface, airborne, and space-based observations to understand how Earth's carbon cycle and terrestrial ecosystems respond to environmental change and human interventions. Improved understanding is gained by combining observations with advanced data analysis techniques and ecosystem process modeling. Terrestrial Ecology *Program Management* will organize and oversee PANGEA with the support of the PANGEA *Project Office*. They will work within the NASA Earth Science Division to select and fund research projects conducted by the PANGEA *Science Team* for participation in PANGEA and to allocate resources to the PANGEA *Project Office* including the PANGEA *Project Scientist and Deputy Project Scientist* (jointly the *Scientific Leadership (SL))* who are also selected by Program Management. Program management will be responsible for representing PANGEA activities within NASA including to other NASA Programs that may support PANGEA activities. Program management will coordinate PANGEA activities with other research partners from domestic and foreign agencies.

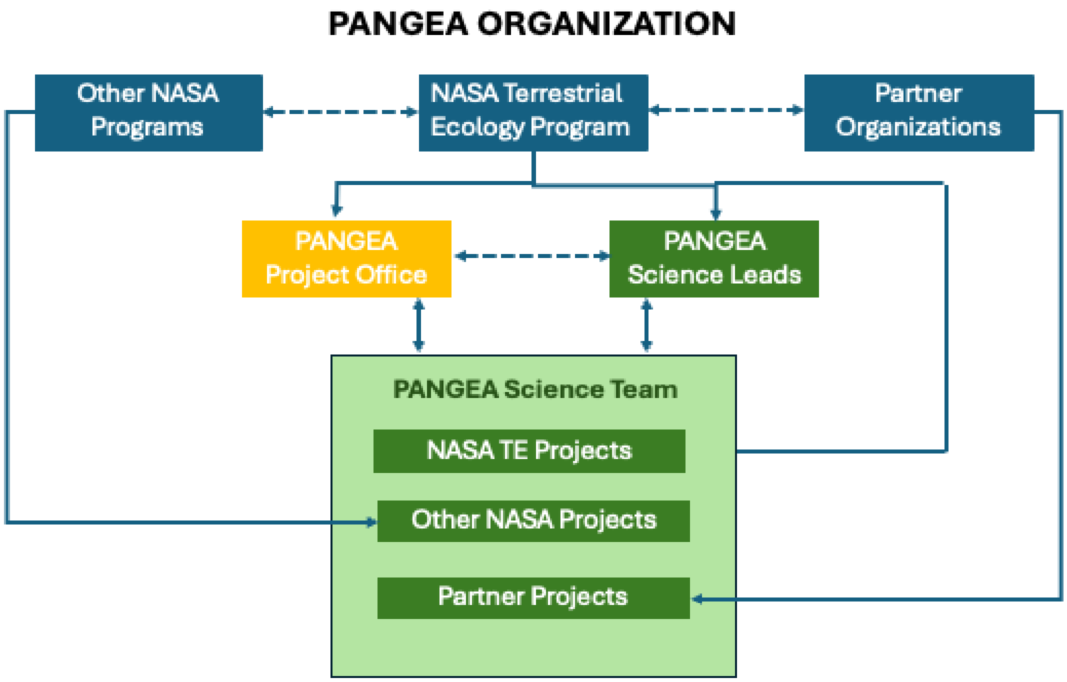


Figure 11. PANGEA organizational chart.

7.1.2 Project Office

Implementation of PANGEA will be supported by a *Project Office* led by the *Project Manager* appointed by Program Management and supported by a project staff member. The PANGEA *Project Scientist* and *Deputy Project Scientist* will serve as *ex-officio* members of the Project Office. The Project Office will (a) oversee and manage PANGEA field and airborne research activities and projects sponsored by NASA's Terrestrial Ecology Program and other NASA program offices; (b) coordinate and provide logistical support for NASA-sponsored field research and airborne remote sensing campaigns including oversight of safety and risk management; (c) provide logistical support to the PANGEA working and coordinating groups, including support of meetings and workshops; and (d) develop and maintain the PANGEA Information System. The Project Office will have important interactions with local and regional stakeholders and will share responsibility for those interactions with the Scientific Leadership. The Project Office will assist Science Team members with permit applications to appropriate authorities. Depending on the needs of the Science Team, the Project Office may also arrange for the collection of core variable data and installation of infrastructure at field sites. The Project Office will be responsible for managing the airborne science campaigns. Science Team Members will work closely with the Project Office and rely upon guidance from its staff for field activities, communications with local and regional stakeholders and authorities, and utilization of PANGEA cyberinfrastructure. The Project Office will be led by a *Project Manager* appointed by Program Management. The leaders of the PANGEA *Science Team*, the *Project Scientist* and *Deputy Project Scientist* will be ex officio members of the Project Office and will participate in Project Office activities and coordinate closely with the Project Office to enhance communication with and support of the Science Team.

PANGEA will prioritize close coordination between the PANGEA Science Team and Earth Science to Action activities. The Project Manager will designate a point of contact (POC) in the Project Office for science applications of PANGEA. This POC will monitor expectations that applications partners have of the PANGEA science team. Regular and transparent communication with potential application partners will continue at all stages of PANGEA, and updates on decisions to pursue or not pursue potential applications will be communicated promptly. NASA's international reputation depends on carefully matching user needs with NASA investment and capabilities, as well as managing expectations of all partners.

7.1.3 Science Definition

Prior to the initiation of the PANGEA science investigations, a group of scientists and scientific leadership selected by the Program Office will work with the Project Office to design the PANGEA research in a *Concise Experimental Pla*n. This plan will present a refinement of the ideas presented in this scoping document. The desired content of the Concise Science Plan will be determined by the Program Office. The purpose of the refined plan is to match scientific scope with available resources. Specific recommendations regarding research sites, field scientific infrastructure needs (including instrumentation), and requirements for airborne remote sensing will be defined in the concise plane. The Concise Experimental Plan will serve Program Management's needs to solicit science investigations and will serve the selected Science Team as a guide for their integrated investigations to answer PANGEA science questions.

7.1.3 Project Implementation

The PANGEA project will be implemented by the selected PANGEA Science Team supported by the Project Office over a nominal period of six to nine years as called for in the NASA announcement A.4 of 2022. A Project *Implementation Plan* will be elaborated based on the Concise Experimental Plan. The Project Office shall be responsible for the Implementation Plan including regular updates the frequency of which will be determined in consultation with the Science Team and Program Management. The implementation plan shall detail the research activities to be conducted and specify roles and responsibilities for investigators involved in those activities during the execution of PANGEA. A notional timetable for project implementation is presented in *Section 7.5* (**Table 8**). At the outset of the project, roughly one year will be spent preparing for field and airborne data collection activities. The main period of data collection will extend from three to six years depending upon the overall project duration and scope. Analysis of the data collected will be continuous throughout the project. We expect data collection to draw gradually to a close one to three years prior to the conclusion of the project to allow time for data analysis, integration, and synthesis. PANGEA will leave a legacy of data and open science that will support future scientific investigations that will respond to the PANGEA science questions and to new science themes.

7.1.4 Science Team and Science Leadership

NASA Program Management working within the NASA Earth Science Division will select and fund research projects conducted by the PANGEA *Science Team* for participation in the PANGEA Project. The *Science Team* led by a Project Scientist and a Deputy Project Scientist will be composed of PIs and Co-Is of selected investigations, as well as scientists recruited by those PIs and Co-Is including post-doctoral scientists and students. In close coordination with the PANGEA Science Team, the Project Office, and Program Management the Project Scientist and Deputy will call and organize the program for regular PANGEA Science Team meetings. The Project Scientist and Deputy will meet with Program Management and the Project Office management, at a minimum, quarterly, to review progress, resolve issues, and discuss implementation next steps.

Communication is a critical role of the PANGEA scientific leadership. Experience with past campaigns informs us that timely communication is important to manage the expectations of the PANGEA Science Team and researchers from partner projects and organizations. The PANGEA Project Scientist and a Deputy Project Scientist (Science Leadership, SL) will communicate the research objectives and outputs of the NASA-funded science team to diverse audiences. The SL will work with local partners to set expectations of PANGEA. The SL will accurately and promptly communicate project updates to local research partners. Presentations, webinars, and town halls will employ interpretation services and project materials will be made available in the languages of participating countries. Throughout the lifecycle of PANGEA, conversations with partners should be recorded and expectations clearly tracked as guidance for actions. After PANGEA data has been collected and as science data products become available, the SL will be responsible for ensuring that local partners continue to receive regular updates. The SL will set the tone of PANGEA, and will be mindful about setting an example to the rest of the Science Team about inclusive and respectful collaboration and the value of co-producing research. The SL and all members of the PANGEA Science Team will adhere to the PANGEA Community Guidelines[1].

[1] The PANGEA Community Guidelines is a living document found at https://tropicalforestscoping.com/community-guidelines/. The guidelines derived from existing institutional guides can be vetted by NASA and modified according to the needs of program management.

PANGEA science investigations will be executed by the Science Team. As noted, membership in the Science Team will include investigators selected by NASA and investigators who are recruited by Science Team PIs and Co-Is. PANGEA investigations will concern a number of countries throughout the humid tropics. Based on NASA experience in the Large-Scale Biosphere-Atmosphere Experiment in Amazonia, we recommend that *all* investigations have counter-part investigators humid tropical forest countries and endeavor to train early career scientists and technicians from countries where PANGEA research is active and other countries of the humid tropics. This should apply even to investigations that have no field component. During LBA, NASA learned that this approach had many benefits. Practically, it offered an incentive for host countries to support the work of NASA in-country, because of the capacity being built by the researchers. Researchers found that host countries often provided significant leverage for their research projects through in-kind and funded contributions, especially student fellowships. Decades after the NASA presence in South America for LBA concluded, NASA still has a large network of friendly collaborators in the South American scientific community. The impact of those investigators on science in their home countries has been vast. See *Section 9 - Capacity Building, Training, and Education* for more information.

The organization of the PANGEA Science Team will grow out of the Concise Experimental Plan and the selected team. We expect that the main themes represented in this scoping document will be the basis of scientific working groups, although it is too early to define a detailed structure for those groups. Other working groups may coalesce around specific sites or campaigns. Guided by the Scientific Leadership, the Science Team will coordinate their activity so that results can be synthesized and knowledge gaps can be identified. We anticipate that PANGEA will hold annual in-person team meetings supplemented by more frequent virtual meetings for the full team and sub-teams. The venue and timing of the annual meeting will be the responsibility of the Project Office, taking into account team needs, logistics, costs, and other important constraints such as visas for participants regardless of where the meeting is held. The Project Office will also provide support for virtual meetings.

PANGEA will emphasize and prioritize diversity, equity, and inclusion in all aspects of the campaign, including diverse representation in its leadership.

As such, PANGEA's Science Team will prioritize diverse representation in terms of scientific expertise, technical specialties, national origin, race, gender, native language, different career stages, and more. Early career researchers will be included from the beginning, as will representatives from participating countries where field research will take place. Team members must commit to cultural sensitivity, with respect for local collaborators and extra care taken to uphold NASA's reputation internationally.

Leadership and engagement in the PANGEA scoping process demonstrates diverse support for the campaign and diversity of candidates who have the capacity to and interest in contributing to PANGEA.

The scoping effort also exemplified PANGEA's ability to implement scientific diplomacy internationally. The Science Team will meet regularly, and for virtual meetings will endeavor to arrange meetings considerate to the time zones of persons represented.

7.1.5 Disciplinary Skills Required

PANGEA is conceived as an interdisciplinary campaign. Scientists involved in PANGEA research may identify themselves with one discipline or with several. We expect participation from scientists connected with physical, biological, and social sciences. The skills and knowledge associated with an array of disciplines will be represented in the PANGEA Science Team. As part of the Terrestrial Ecology program we expect that ecology at various levels of organization (ecosystem, community, population) will be strongly represented. Biogeochemistry and atmospheric chemistry have long been associated with NASA TE campaigns as are plant physiology and ecophysiology. The science team will include the skills and knowledge of other related disciplines including land systems, meteorology, hydrology, and social sciences. Remote sensing specialists will be well represented in the science team.

7.2 Community Engagement Strategy

PANGEA will engage with diverse communities to address PANGEA's science questions, 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, which engaged with over 500 individuals and 150 organizations from 42 countries across five continents through (a) consultative workshops, (b) outreach events, (c) working group discussions, (d) bilateral meetings, and (e) web surveys. Here, we present a list of the communities prioritized for engagement in PANGEA, the principles that underpin PANGEA's engagement efforts, and PANGEA's strategy for engaging local communities and cultivating a long-term, positive legacy during and beyond the campaign.

7.2.1. PANGEA Partners

PANGEA research on tropical forests will complement and expand upon many existing efforts. Some of these efforts are limited to small geographical domains or represent networks of individual sites. Others, such as One Forest Vision and GEO-TREES, have pan-tropical ambitions like PANGEA. The range of partnership opportunities is illustrated with examples in **Table 5**.

PANGEA interprets the word "community" broadly to encompass a wide variety of formal and informal groups of people who perceive themselves as members of a certain group, which may share interests, experiences, resources, activities, professions, livelihoods, culture, geography, origins, language, or any combination of the above. The scoping campaign identified ten types of communities with which PANGEA will prioritize engagement: (1) NASA; (2) other US government agencies; (3) international space agencies and support facilities; (3) foreign government agencies and national research institutes; (4) scientific institutions; (5) coordinated international research initiatives; (6) civil society organizations; (7) Indigenous peoples and local community alliances and organizations; (8) the donor community; (9) the private sector; and (10) intergovernmental agencies.

One key aspect of PANGEA's engagement strategy, which reflects countless recommendations from scoping events throughout the tropics, is a commitment to engage with the communities identified above in an inclusive and non-hierarchical way. Each community will play a critical role in PANGEA's planning, implementation, and its long-term legacy. Engagement with Indigenous Peoples and CSOs, for example, is essential for accessing research sites, empowering long-term, ground-based data collection, and connecting PANGEA's research to local land management decision-making. PANGEA must engage with local and international scientific institutions to build upon their work, identify synergies, and leverage co-funding and resources to collaboratively accomplish more, and invest in formal training and curricula so that current and future generations of scientists may benefit from the PANGEA Program. The support of government agencies will be critical to PANGEA's airborne data collection efforts and Earth Action strategies. National and sub-national government agencies are also well positioned to immediately apply the key findings of PANGEA's research to improve country-wide, climate and biodiversity monitoring and reporting, and to develop more informed climate change mitigation and adaptation strategies. Collaboration with climate-concerned intergovernmental organizations and donors may enable PANGEA to support activities that would not be possible using NASA funding alone, including engaging with local institutions in a more financially inclusive and equitable manner. Many private companies and industry associations are eager to learn more about their changing environments and collect ground, air- and space-borne data to understand their impact and ensure the sustainability of their supply chains. Although the interests, objectives, and potential points of engagement and collaboration vary widely, all of these communities will be instrumental to the success and positive long-term legacy of PANGEA.

Table 5. Overview of engagement strategies and example partners for each target group. Govts: governments; Int'l: International; Orgs: Organizations

Community	Description	PANGEA Relevance	Engagement Strategy & Goals	Example Partners
NASA	Research & Analysis and Earth Action Programs, Capacity Building Program	NASA is the driving force behind PANGEA	Advance scientific understanding, calibration and validation, algorithm and product development, partnerships, and capacity building across the NASA enterprise through an integrative approach.	· Terrestrial Ecology, Biological Diversity & Ecological Conservation, LCLUC, Hydrology · Carbon Monitoring System, Climate & Resilience, Disasters, Wildland Fires, NASA Harvest, Water Resources · SERVIR, ARSET, DEVELOP, GLOBE, Indigenous Peoples Initiative
Other US Government Agencies	Non-NASA US federal research and development agencies	Many US government agencies support research and training efforts that directly align with PANGEA	Coordinate with NSF program managers to identify opportunities for interagency solicitations where research and applications activities are mutually beneficial.	· DOE NGEE Tropics* · NSF BIO, GEO, SBE, GOLD-EN, RISE · USAID CARPE, USAID-PEER** · USFS-International Program · USGS SilvaCarbon
International Space Agencies and Support Facilities	Non-NASA space agencies and federal institutes that support satellite monitoring and technical capacity.	These partners collaborate with NASA on missions and campaigns. PANGEA is an opportunity to strengthen and expand these partnerships.	Support international collaboration on existing joint missions and airborne campaigns; build capacity to support greater engagement between NASA and space agencies in the tropics.	· Central African Satellite Observatory (OSFAC) · Gabonese Space Agency (AGEOS) · European Space Agency (ESA) · French National Space Agency (CNES) · The German Aerospace Center (DLR) · Indian Space Research Organisation (ISRO) · Brazil's National Institute for Space Research (INPE) · Japan Aerospace Exploration Agency (JAXA)
Foreign Government Agencies and National Research Institutes	National & local sectoral ministries; geospatial specialized institutions; govt.-led multi-stakeholder platforms	These partners take large-scale action (environmental planning, law enforcement, investment in research, etc.), and support long-term data and analysis (e.g. weather).	Inform PANGEA science questions and activities via research institutions; set enabling conditions (institutional, financial, and programmatic) for the ownership of PANGEA's research outputs; capacity-building for staff at national and local levels.	· Brazil National Institute of Amazonian Research (INPA) · Congo Basin Forest Partnership (CBFP) · Gabon National Center for Scientific and Technological Research (CENAREST) · Governors' Climate and Forests Task Force (GCF-TF) · Peruvian Mancomunidad Regional Amazónica · Relevant ministries · São Paulo Research Foundation (FAPESP)
Scientific Institutions	Universities and colleges; national labs; research institutes	These partners facilitate knowledge and tech transfer to generate capacity in the local and regional institutions to train the next generation of scientists	Co-develop research, analysis, and applications with these partners, and will strengthen local research capacity by supporting data management, infrastructure development, and early-career researcher training at local and regional institutions.	· Alexander von Humboldt Research Institute · Alliance Bioversity International & CIAT · Amazon Institute of Technology (AmIT) · Congo Basin Institute (CBI) · International Institute for Tropical Agriculture (IITA) · LBA · Woodwell Climate Research Center

Coordinated international research initiatives	Research consortiums; networks; networks of networks	These partners are working at large scales that align with PANGEA's transdisciplinary and pan-tropical objectives.	Align efforts with these partners to ensure that PANGEA activities strategically fill needed gaps rather than duplicate efforts.	· Alliance for Tropical Forest Science (ATFS) · AndesFlux · Congo Basin Science Initiative (CBSI) · FLUXNET Regional Networks (e.g., AmeriFlux, ICOS, AsiaFlux) · GEO-TREES · One Forest Vision
Civil society organizations	National and int'l non-governmental orgs (NGOs) and non-governmental research initiatives present in the target countries	These partners facilitate knowledge consolidation and translate research outputs into ongoing CSO-led campaigns and actions	Co-produce applications that leverage PANGEA scientific and technical advancements.	· Conservation International · CTrees · World Resources Institute (including Global Forest Watch & Land and Carbon Lab) · MapBiomas · Small Mammal Conservation Organization
Indigenous Peoples and Local Community Alliances	Indigenous people-, local community-, women- led orgs and alliances active in the target countries	These partners are connected with most relevant communities, leaders, and partners in targeted countries	Co-design science and applications that affect IPLCs, and campaign activities in territories and local communities, and training to empower IPLCs in data collection, research, and communication	· Global Alliance of Territorial Communities · Rights and Resources Initiative · CBI School for Indigenous and Local Knowledge (SILK) · Dynamique des Groupes des Peuples Autochtones (DGPA-DRC)
Donor community	Bilaterals, family foundations, philanthropic orgs, and specialized (geospatial) agencies from donor countries	These partners raise complementary funding that offer targeted support to extend PANGEA beyond NASA funding support.	Target investment in PANGEA applications and product development, support for international collaborators, joint workshops, and the development of IPLC data collection and management tools	· Bezos Earth Fund · Ford Foundation · Individual donors · Moore Foundation · Norwegian Agency for Development Cooperation (Norad) · Norway's International Climate and Forest Initiative (NICFI)
Private sector	Agribusinesses, extractive industries, energy companies, big data firms, investment institutions	These partners are important action takers and decision-makers with far reaching impact.	Work closely with NASA and applications partners to determine the most appropriate strategies for engaging with the private sector on various applications output.	· Sustainability Roundtable (e.g., Palm Oil, Cocoa, Soy) · Unilever · Olam · Green Resources · Cnaught; Carbon Equity; Carbon Credit Capital
Inter-governmental agencies	Orgs. composed of multiple govts. that collaborate to address common issues, develop policies, and coordinate actions on a regional or global scale	These partners provide authoritative, science-based assessments that inform global policy and guide international efforts to combat climate change and biodiversity loss.	Stay up-to-date on assessment reports and activities to ensure PANGEA science and applications outputs can be effectively utilized.	· Committee on Earth Observation Satellites (CEOS) · Group on Earth Observations (GEO) · Inter-governmental Panel on Climate Change (IPCC) · Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) · International Union for Conservation of Nature (IUCN) · United Nations Framework Convention on Climate Change (UNFCCC)

**DOE NGEE-Tropics is entering Phase 3 and will sunset as PANGEA begins, enabling important continuity to constrain model uncertainty and data-model integration efforts.*
***USAID PEER is going to be replaced by a new program called SPARK.*

7.2.2. Principles

PANGEA will prioritize diversity, equity, and inclusion (DEI) across all its activities, including community engagement, by ensuring accessibility, promoting DEI training, and establishing feedback mechanisms. PANGEA developed Community Guidelines and a Code of Conduct for the scoping study which can serve as foundational material for the campaign Code of Conduct. Organizations like the Association for Tropical Biology and Conservation (ATBC) have established similar standards specifically for the tropical research community, which spans many languages, cultures, customs, and norms. Upon selection, PANGEA will initiative a review of its Code of Conduct, learning from these and other precedents. PANGEA is also committed to gender balance and will implement targeted efforts to ensure inclusivity, such as promoting female leadership roles and providing mentorship opportunities. PANGEA aims to make significant strides by fostering gender-responsive practices and tracking key performance indicators like gender representation in leadership and participation over time. PANGEA will also engage Indigenous peoples and local Communities. In doing so, PANGEA will implement and build on principles adapted from the CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) Principles for Indigenous Data Governance' to ecology and biodiversity research based on work by (Jennings et al., 2023) and (Carroll et al., 2020). **Table 6** outlines PANGEA's principles of engagement based on CARE. See *Section 7.4* for integration of these principles with PANGEA's Open Science strategy.

Table 6. PANGEA Principles of Engagement based on CARE. Adapted from (Jennings et al. 2023; Carroll et al. 2020). IPLCs: Indigenous Peoples and Local Communities

Principles	Priorities	PANGEA Strategy
Collective benefit	Research that benefits communities	Prior to research, explain and demonstrate how research and potential results are relevant and are of value to the interests of the community and individual members; PANGEA research will work to support community-led initiatives and help secure funding for long-term investments in community.
	Data grounded in community values, aspirations, well-being	PANGEA will co-develop and/or link to Indigenous Peoples and Local Communities (IPLC) data classification and analysis frameworks that reflect community values, needs and aspirations; local community experts will be included in research teams.
	Data for self-determined development	PANGEA will collect and code data using categories that identify information and individuals using community norms; Where possible, data will be disaggregated, especially from global or large geospatial datasets, to increase relevance for IPLCs
	Compensate local experts	PANGEA will work hard to locate funding sources to be able to compensate community experts throughout the research process, including research proposal development, data collection, manuscript writing and community review of prepublication manuscripts.

Authority to control	Recognize IPLC's rights to and interests in their knowledges & data	Principles and protocols for research development, data management and publication that support IPLC's Data Sovereignty will be co-developed, including metadata fields for disclosure of Indigenous rights and interests.
	Recognize right of IPLCs to free, prior and informed consent	PANGEA will ensure data use is consistent with individual and community consent provisions and ensure ongoing consent processes, including the ability to refuse, withdraw and reconsent.
	Data available for IPLC governance	PANGEA will ensure IPLCs, and the appropriate tribal authorities, have access to data, metadata about their people, communities and non-human relations in a usable format.
	Develop and enact IPLC Data Governance protocols	IPLC partners will co-develop data and data protocols, and will use and/or incorporate IPLC frameworks and principles to inform data management protocols and processes; IPLC guidance will influence how, what, who and where research is conducted and data is managed, as well as publication standards, which will document community support, participation and approval for publishing data and authorship.
Responsibility	Enable capability and capacity sharing for research design and digital infrastructure	PANGEA will create and expand opportunities for community capacity through (1) participatory methodologies including planning and design, knowledge management and data workforce capacity building, and (2) initiatives to enable the design, collection, management, storage, security, governance, collective privacy and application of data.
	Respect reciprocity, trust and mutual understanding with those to whom data relate	PANGEA will record Traditional Knowledge and biocultural labels in metadata and will establish a system to ensure local review of draft publications before dissemination; PANGEA will also identify and address sensitive data, including privacy issues for individuals and communities.
	Data-generating resources for languages and worldviews	PANGEA will use local and Indigenous languages, link research to community worldviews, and upload data with appropriate metadata labels in culturally accessible formats (e.g., digital storytelling, seasonal calendars, visual art).
	Community-defined benefit sharing	PANGEA will conduct mutually benefit, consent driven, inclusive research relevant to the needs of IPLCs.
Ethics	Align with Indigenous and local ethical frameworks	Indigenous ethical frameworks will be used in the co-development process and community-defined review process will be developed for activities delineated in data management plans.
	Maximize benefits from the perspectives of IPLCs	PANGEA researchers will include IPLCs and PANGEA researchers will explain benefits to IPLCs, including identifying and contributing to community-defined benefits. Potential financial gain will be disclosed and benefits will be shared with communities from research outputs and/or economic value of data.
	Minimize harms from the perspectives of IPLCs	PANGEA's community-defined code of conduct will be accessible and incorporate IPLC ethical frameworks; Data-access protocols will consider the potential for community harm, which will be remedied through data sharing and ongoing consent.
	Data governance accounts for potential future use	Community protocols will be applied for infrastructure, metadata and secondary use; Traditional Knowledge and biocultural labels will be included in metadata fields, as will community and/or tribal affiliation; Community guidelines will be established for the use and reuse of data; Provenance will be recorded and recognized.

7.2.3 Engagement Strategy

PANGEA activities will coordinate with existing and future projects from other agencies and other nations. Building on lessons learned from the Brazil-led LBA program, PANGEA will implement a formal international scientific steering committee (SSC), which will be invaluable for the progress of the overall program. PANGEA's SSC will focus on co-developing strategies to ensure that scientists, local institutions, and communities can work together throughout the PANGEA campaign to develop engagement methods for effective collaboration in diverse geographic and cultural contexts. In addition, the SSC will work hard to reinforce and coordinate with existing organizations, alliances, and activities to ensure that PANGEA supports the development of a long-term a network of networks that will enhance and sustain the accessibility, usability, transferability and benefits of the data, methods, models, and knowledge about tropical ecosystems.

During LBA, the SSC met twice annually and served as a clearinghouse for information across national projects. This committee had a number of attributions including the recommendation of projects for inclusion in LBA based on criteria such as subject matter, adequacy of counterpart arrangements, and capacity building plans. The SSC shouldered much of the burden that may have otherwise fallen to agency managers. Existing organizations such as the Congo Basin Science Initiative and the still extant Brazilian LBA are primed to serve as partners for coordination of PANGEA scientific studies. Similarly, relationships established with the Global Alliance of Territorial Communities (GATC) during the scoping process will support PANGEA's ability to engage Indigenous communities in a meaningful and mutually beneficial way. The GATC is built upon 10 years of collective work by Indigenous communities across the tropics and represents 24 countries, over 35 million people, and over 958 million hectares of land.

During ABoVE's the NASA Carbon Cycle and Ecosystems Office began consultations with Canadian First Nations and Alaskan Indigenous groups before the science definition team was brought together. ABoVE proactively engaged with first nations members to finalize the experimental design in Phase 1, before field activities began. The ABoVE team continued engagement with first nations members to update them on activities, particularly related to relevant disturbances (e.g., fires). For example, ABoVE prioritized revisiting burned areas and providing information to help communities understand, adapt to, and overcome disasters. PANGEA will build on important lessons learned from the ABoVE campaign.

The process of co-production began during the scoping of PANGEA and the writing of this white paper, which has been carried out in collaboration with Indigenous leaders from the Global Alliance of Territorial Communities (GATC). If PANGEA is selected, co-production with Indigenous Peoples and Local Communities will begin immediately and will be sustained throughout.

PANGEA will also partner with many scientific institutions located in or with research expertise in tropical forests. PANGEA will establish a trailblazing network of research experts, early career scientists, and scientific institutions collaborating on PANGEA Science and Applications activities. A particular interest of this partnership is to facilitate the co-development of knowledge and support technology transfer to generate capacity in local and regional institutions. A particular focus of the PANGEA network will be to include, engage, and train the next generation of scientists and technical workforce. PANGEA will engage partner scientific institutions in the following ways:

- Co-develop research, analysis, and potential applications.
- Identify field sites, research infrastructure, and capabilities critical to PANGEA's research goals.
- Co-produce, share, and manage data; support the development of data infrastructure, equipment, and management expertise at local and regional institutions; support the creation of regional or national data banks to curate field and remote sensing data and numerical model outputs so that emerging knowledge can be integrated with and applied to regional and national demands for the socioeconomic development and policy development.
- Strengthen and broaden research infrastructure and instrumentation for local and regional scientific institutions to be able to develop and carry out long-term research.
- Design and implement strategies to support faculty and early career researcher capacity building at local and regional universities and research institutes.

PANGEA's applications also have strong potential to engage the private sector. Private sector entities relevant to PANGEA include, but are not limited to: (a) agribusinesses cultivating and/or harvesting agricultural, timber and forest non-timber products; (b) extractive industries; (c) energy companies; (d) big data companies; (e) conglomerates and financing institutions that invest in, buy, and/or sell any of the aforementioned types of companies; and (f) companies involved in ecotourism. Although the scope of companies deemed relevant may be vast, the profile of companies present in each landscape where PANGEA is implemented will vary ranging from corporations to small and medium-size enterprises, cooperatives, and associations. PANGEA will work closely with NASA and applications partners to determine the most appropriate strategies for engaging with the private sector on various applications output.

7.3 Co-funding Opportunities

PANGEA leverages Terrestrial Ecology investment for its core resources. The Optimal, Baseline, and Threshold measurements defined in *Section 6.2.1* represent stand-alone NASA campaigns with no dependencies. However, given the urgency and importance of the topic, and such widespread interest from the community, there is strong potential to augment or even exceed NASA's contributions. During the scoping effort, the PANGEA leadership team has already made significant strides towards securing diverse sources of funding to build on a NASA investment. Multiple U.S. government agencies, private foundations, international governments, and philanthropies have expressed interest in supporting PANGEA-related activities that are outside of NASA's scope, including direct support for international partners and taking NASA Earth Science to Action efforts to implementation. Opportunities to leverage additional support from partners interested in teaming up with NASA include example partners listed in **Table 7**.

The PANGEA team will work with non-NASA sponsors to detail their contributions while developing the PANGEA Concise Experimental Plan. This process will include 1) defining activities and funders to ensure support is complementary and not duplicative; 2) streamlining management, communication, and oversight between donors; and 3) addressing any data security concerns. PANGEA will demonstrate how to successfully blend NASA and non-NASA resources to address critical Earth science knowledge gaps and serve as a prototype for NASA to advance such partnerships in the future. To accomplish this, PANGEA will answer the following questions:

- *How can diverse sponsors work synergistically to advance remote sensing and terrestrial ecological research?*
- *How can complementary funding enhance NASA's work?*
- *What data sharing and security approaches work when there are multiple sponsors?*
- *How can reporting and communications to diverse sponsors be streamlined?*

Table 7. PANGEA co-funding opportunities

Project Area	NASA Programs	Other US Government	International Governments	Other
Remote Sensing	TE		AGEOS, ESA, INPE	
Data Hosting	TE	DAACs, AmeriFlux (DOE)	ICOS	MoveBank
Research	TE, Related Programs	NSF, DOE	UK NERC, EU, CNPq, FAPESP, Belmont Forum	Schmidt Sciences, Moore Foundation
Capacity Building	ARSET, DEVELOP, SERVIR, Harvest	USAID, USFS-IP	FCDO (UK)	Philanthropies, Donors, CBSI, R2FAC
Applications	SERVIR, Earth Action	USAID, USFS-IP, USGS		Bezos Earth Fund, NICFI, WRI, Moore Foundation

7.4 Open Science - Data Management and Sharing

The PANGEA data management and sharing strategy aims to facilitate open source science, promote collaboration, and maximize the value of PANGEA data more broadly and longer into the future, in alignment with NASA's Strategy for Open Science (Strategy for Data Management and Computing for Groundbreaking Science 2019-2024). This strategy will follow NASA Scientific Information Policy requirements and guidelines, adhere to community principles and practices, and keep ethical guidelines and cultural sensitivity in mind. In doing so, PANGEA will also coordinate closely with Indigenous partners to ensure data sovereignty, specifically including Indigenous data sovereignty (IDS). PANGEA will build on the success from past field campaigns and leverage new advances in open science and data management concepts and technologies.

PANGEA will integrate data streams from multiple measurement systems, partners, countries, and science paradigms (e.g., western science paradigm, Indigenous ecological knowledge, Traditional ecological knowledge). The PANGEA data management will adhere to the FAIR (Findable, Accessible, Interoperable and Reusable) guiding principles to improve data discoverability and accessibility, promote data interoperability and integration, and enhance data reusability and reproducibility. PANGEA data collection, management, and use will also align with the CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles, which emphasize the importance of considering the rights and interests of Indigenous peoples when managing data related to their communities, lands, and resources. The CARE principles for Indigenous Data Governance complement the FAIR principles by focusing on the ethical, cultural, and social dimensions of data management, and reflecting the crucial role of data in advancing Indigenous innovation and self-determination (Caroll et al., 2020).

PANGEA data collection, management, and use also acknowledges the importance of data sovereignty, which requires active partnerships with Indigenous Peoples and Local Communities. Data sovereignty is the management of information in a way that is consistent with the laws, practices, and customs of the nation-state in which it is located. Indigenous data sovereignty is the "right of Indigenous Peoples and Nations to govern the collection, ownership, and application of their own data, deriving from the inherent right of Indigenous Nations to govern their peoples, lands, and resources," and is positioned as a collective right within international Indigenous rights frameworks (Cannon et al., 2024). Indigenous knowledge-holders retain culturally sensitive information and data. To ensure that PANGEA's data collection and management efforts are ethical and respect the rights of Indigenous Peoples and Local Communities, PANGEA will work with partners and Indigenous Peoples and Local Communities (IPLCs) to:

- *Engage with partners, including IPLCs, during the development of the Concise Experimental Plan, well before data collection is conducted;*

- *Determine who is responsible for granting permission for external parties to access data and/or Indigenous territories for research;*
- *Create steps or policies for researchers and/or IPLCs for data sharing and/or requesting permission to access data or IPLC territories;*
- *Establish a plan for data collection and/or monitoring;*
- *Build capacity and work with partners, including IPLCs to secure funding for storing and managing Indigenous data;*
- *Provide training to create tools for IPLCs that would support data collection, management, and dissemination.*

Participation in the PANGEA science team will require a commitment to provide free, open, and transparent access to all data that are acquired as part of the PANGEA campaign in concordance with FAIR and CARE principles. In collaboration with NASA Program Management, the PANGEA Science Team, led by a PANGEA Open Science Coordinating Group, will work with government agencies, foreign government partners, and Indigenous partners to establish data and information gathering, sharing, and handling agreements and workflows at the national, international agency, and territorial level to outline data ownership, usage rights, and storage plans compliant with Open Science, FAIR, and CARE principles. Such agreements are an important first step to align expectations around issues associated with data and information management involving multiple territories, countries, and agencies, including data sovereignty. In exchange for their contribution of data products, PANGEA partners will have access to all of the data produced by the NASA team, which will be freely and publicly available, along with access to the NASA expertise and PANGEA collaboration and training opportunities aimed at supporting research led by researchers and Indigenous partners in the tropics. This includes prioritizing publications first-authored by early- and mid-career researchers from the tropics and advancing Indigenous-led research.

PANGEA will follow guidelines from the NASA Earth Science Data Preservation Content Specification (https://www.earthdata.nasa.gov/esdis/esco/standards-and-practices/preservation-content-spec) to prepare and preserve data as well as associated information beyond the lives of a project. This will enable a new user in the future to understand how the data were used for deriving information, knowledge, and policy recommendations, and to ensure reproducibility to ascertain the validity and possible limitations of conclusions reached in the past, and to provide confidence in long-term trends that depended on data from multiple projects. The Preservation Content Implementation Guidance document (https://www.earthdata.nasa.gov/s3fs-public/2022-07/ESDS-RFC-042VERSION1.pdf) provides guidelines and checklists to address the PCS needs for different types of Earth science research projects, including airborne and field investigations.

In collaboration with partners, the PANGEA Project Office will develop a **PANGEA Information Portal (PIP)** to point to PANGEA datasets. This Information Portal will be publicly accessible and will outline PANGEA's data management and sharing strategy, provide direct links to data, as well as information on the planned and ongoing activities of PANGEA investigators and collaborators, including inventories of the location, timing, and types of data collected. The PANGEA Science Team and Project Office will advise the project office and work closely with data owners when collating and linking to existing data sources to ensure data sharing is collaborative and ethical, and respects the rights and ownership of data already collected in concordance with FAIR and CARE principles. For example, engagement with Indigenous and local community partners will prioritize early and ongoing conversations about what types of information and data are ethical to share on this portal. The PIP will provide easy discovery and access to data collected by PANGEA and also existing data useful for PANGEA research. PIP will compile inventories of the location and types of data collected by other researchers that are being used by PANGEA investigators and collaborators. As such, PIP will serve as a critical interface both campaign coordination with aligned activities. PIP will include a web-based GIS that allows for review of the data within the tool, including information on previous and ongoing investigations. PIP will be designed to be user friendly and support both researchers and the public community at large.

Visualization and GIS support will be critical to maximize the value of PANGEA data to a broader audience. PANGEA will work with action-oriented partners like Global Forest Watch and the Rights and Resources Initiative to develop applications that ensure data are accessible to non-scientists. Additional data and results reporting mechanisms will be an important part of PANGEA to ensure accessibility to Indigenous and local community partners. Specific modes of communication will be determined in collaboration with Indigenous and local community partners, and will likely be landscape specific.

Data provenance and reproducibility are important aspects of open-source science. Sampling protocols, metadata, data cleaning, codes, algorithms, and workflows associated with data creation, processing, and validation for PANGEA will be made openly available to the extent possible. Active code development will ideally be through open collaborative platforms, like GitHub, when appropriate. PANGEA will establish consistent formats and practices for data and metadata and optimization for cloud-based access and analysis, especially for emerging types of data, like drone-based datasets. These activities will work with, rather than attempt to replicate, existing data- and disciplinary-specific efforts. For example, FLUXNET is a network of networks organized on the basis of a set of Regional and Continental Networks (such AmeriFlux and NEON in the Americas, ICOS in Europe, OzFlux and TERN in Australia and SAEON in South Africa) with the aim to make available standardized eddy covariance measurements globally. FLUXNET invested in the definition of standards in the processing and data distribution, and it is moving toward the FAIR implementation and for this reason PANGEA will work with FLUXNET and its Regional Networks to develop new and specific products, formats and tools. The Regional Networks have also activities in tropical areas; for example ICOS is coordinating the KADI project (Knowledge and climate services from an African observation and Data research Infrastructure, https://kadi-project.eu/) that has the aim of design and move toward a pan-African climate observation system and established a number of useful contacts also in the PANGEA framework. Similarly, PANGEA will work synergistically with the drones working group of the Alliance for Tropical Forest Science to build and share knowledge relating to the collection and analysis of drone-acquired data for investigating tropical forest structure, function, dynamics, and composition (https://www.alliancetropicalforestscience.net/working-groups.html). This working group is currently developing a database of protocols and facilitating knowledge sharing via regular videoconference presentations and meetings. It is co-led by PANGEA collaborators KC Cushman and Helene Muller-Landau.

Conversations to ensure alignment with these efforts have already begun. Coordination will deepen upon selection to ensure ground data, flux tower data, drone data, camera trap data, bioacoustics data, Indigenous and Traditional Ecological Knowledge, and more are collected, stored, and shared appropriately and according to the best available practices.

PANGEA will leverage and integrate with existing and emerging capabilities and systems offered by NASA Earth Science Data Systems as much as possible. These include the Distributed Active Archive Centers (DAACs) for airborne data, DAAC tools and services to make airborne and orbital data easier to use for terrestrial ecology research, NASA's Visualization, Exploration, and Data Analysis (VEDA) platform (https://www.earthdata.nasa.gov/esds/veda), and ongoing efforts to coordinate data standardization and protocols. PANGEA is an opportunity to harmonize protocols across research communities to support scaling. As an example, the SBG VSWIR Terrestrial Vegetation algorithm team is developing data collection protocols, airborne data extraction and processing strategies, and database structures that will allow community generated joint airborne-field data collection to be more easily integrated into the model training datasets needed to improve algorithms for underrepresented ecosystems. This work builds on the successes of other NASA campaigns, including SHIFT and BioSCape, working across agency funded efforts, including NEON, and is seeking to engage the research community more broadly. By engaging and partnering with these types of activities early, PANGEA will be positioned to both contribute to mission algorithm generation and verification activities, as well as ensuring tropical ecosystems are more accurately measured and represented in global data products.

PANGEA will also adopt an open-source approach for all modeling efforts. Models participating in PANGEA-related activities and projects will be expected to have the source code openly available through collaborative platforms (e.g., GitHub), and released with permissive licenses consistent with the SMD Open-Source Science Guidance, such as Apache 2.0, MIT License, or BSD 3-Clause Revised License. We will seek models whose governance promotes best practices for community engagement and development. Examples of such governance include the existence of code of conduct, technical notes and user's guides, active forum for discussing code issues, and pathways for contributions with model development from the broad scientific community. Models used by scientific publications will be required to tag and deposit the exact version in long-term repositories with DOI (e.g., Zenodo or one of NASA's Distributed Active Archive Centers), along with all the code, parameter and data information needed to reproduce results, and inform the location of the deposited code in the associated publications. In case participating models cannot follow the SMD Open-Source Science Guidance, the limitations will need to be clearly described as part of Open-Source Data Management Plan.

PANGEA will develop an open **cloud-based data analysis platform** for PANGEA investigators to support open and collaborative research. PANGEA's data analysis platform will be based on successful science clouds implemented by ABoVE, SHIFT, BioSCape, and NASA's Multi-Mission Algorithm and Analysis Platform (MAAP, https://www.earthdata.nasa.gov/esds/maap). These efforts demonstrate successful international data collaboration, including between NASA and ESA (MAAP), and by leveraging Amazon Web Services' Social Responsibility Program (BioSCape). PANGEA's cloud-based computing platform will lower barriers to entry, especially for international partners who are likely to be limited in bandwidth, data storage capacity, and computing power. The cloud computing platform will also allow PANGEA science team members to easily share early versions of data products (before they are ready for archiving) and troubleshoot data analysis problems communally (e.g. via Slack). Additionally, capacity building materials, especially coding notebooks, can be developed specifically for the cloud computing environment, allowing anyone anywhere in the world to run them and apply similar approaches. The importance of a cloud computing environment was demonstrated during BioSCape, whose South African science team members would otherwise have been severely limited in their ability to access, analyze, and apply the campaign's data. Based on BioSCape's success, PANGEA will deploy a cloud computing platform that will allow users to access and analyze the data without them needing high performance computing resources and eliminating the issue of transferring large data files over long distances on unreliable internet connections.

PANGEA will provide open-source science and data management capacity building throughout the campaign, including through trainings and workshops on data management in collaboration with the DAACs, FLUXNET, LBA, Indigenous and local community partner organizations like the Global Alliance of Territorial Communities, ATFS, and more. Many of these partners have existing training programs that will be leveraged. This will include developing campaign specific versions of NASA's Open Science 101 curriculum: https://nasa.github.io/Transform-to-Open-Science/os101-modules/ PANGEA will prioritize trainings and workshops with partners to support independent and coordinated data management efforts, which: 1) enhances the capacity of Indigenous peoples, local communities, and tropical institutions; and 2) ensures international alignment that will serve as a foundation for datasets and collaboration to continue beyond the PANGEA campaign.

7.5 Timetable

The PANGEA team has worked to utilize virtual and hybrid meetings for early engagement of a diverse science scoping team. We have time saving approaches and believe we can greatly reduce the timeline needed to develop the Concise Experiment Plan and move on to the Implementation phase. **Table 8** outlines the proposed timeline, assuming PANGEA's next activities begin in Fiscal Year 2025.

Table 8. Proposed PANGA timetable. SDT: Science Definition Team; TE: Terrestrial Ecology; CEP: Concise Experimental Plan; PAC: PANGEA Airborne Campaign.

					Phase I			Phase II			Phase III	
Study Year					1	2	3	4	5	6	7	8
Project Office Activities (Fiscal Year)	22	23	24	25	26	27	28	29	30	31	32	33
NASA's TE Program solicited ROSES proposals for scoping studies.												
Two scoping studies were selected: PANGEA and ARID scoped for 1 year.												
PANGEA Scoping activities carried out (workshops in DC, Cameroon, Peru, Brazil, Thailand, and more.)												
PANGEA selected for TE Field Campaign												
Selection of Science Definition Team for the PANGEA Field Campaign. Concise experimental plan drafted. Concise experimental plan community review. Final PANGEA Concise Experimental Plan completed.												
The PANGEA announcement of opportunity (NRA) released by NASA. Project Office for PANGEA initiates preparations based on CEP. PANGEA Phase 1 Proposals awarded. 1st Science Team and Stakeholder Meeting.												
2nd Science Team Meeting & Airborne Campaign Planning Workshop. PANGEA Airborne Campaign I (PACI)												
3rd PANGEA Science Team and Stakeholder Meeting and Airborne Planning. PANGEA Airborne Campaign II (PACII). NASA NRA PANGEA Phase 2 proposals and selection.												
4th PANGEA Science Team and Stakeholder Meeting and Airborne Planning. PANGEA Airborne Campaign III (PACIII).												
5th PANGEA Science Team and Stakeholder Meeting. PANGEA Airborne Campaign IV (PANIV).												
6th PANGEA Science Team Meeting. PANGEA Backup Airborne Campaign V (PANV). NASA NRA PANGEA Phase 3 Proposals and selection												
7th PANGEA Science Team Meeting.												
8th PANGEA Science Team Meeting.												

7.6 Risk and Risk Mitigation / Risk Assessment

PANGEA will conduct research in regions that are highly sensitive to climate change in collaboration with many agencies, making the work particularly valuable to our understanding of the globe and to our ability to respond to climate change. PANGEA will use proactive risk management to mitigate the risk of operating airborne and field measurements across the wide tropical study range required to deliver this high-impact science.

During the study phase, PANGEA will compile a comprehensive list of project risks and assess them with a standard Risk Assessment Matrix. For high and medium risk cases, the project will develop and implement a mitigation plan, which will be reviewed with the NASA Program Office. PANGEA expects most risks will fall into the following categories:

1. Risks to health and safety
2. Risks to meeting science objectives
3. Risks to meeting community engagement and applications objectives

Health and Safety: The project will keep apprised of health and travel safety guidelines issued by the US Department of State Bureau of Consular Affairs for the study areas and will consider changes in risk level under that guidance. PANGEA will also engage with the US Embassy and its Regional Security Offices in-country to receive any health and safety guidance for field and airborne campaign participants. Given the remote nature of many of the study sites, the project will develop plans for safe transportation to the field study sites, whether by off-road vehicle, boat, or other methods. The project will also develop plans for the safety of the airborne crew and instrument operators during the campaign, following NASA guidelines for aircraft operations and on the ground. Given that many of the proposed study regions are tropical forests which include a risk for malaria, yellow fever, and related diseases, the project will ensure participants are advised on relevant vaccines and medical treatments prior to participation in the campaign.

Meeting Science Objectives: Given that the study areas are located in various countries, the project will work proactively to officially engage institutional partners and develop formal MOU's, with the help of NASA's OIIR office, ESPO, and the US State Department. International airborne campaigns have been repeatedly plagued by slow landing clearances and associated bureaucracy, and much of this can be avoided by beginning the formal MOU process early. While using NASA aircraft for the airborne measurements have certain benefits, use of these aircraft require diplomatic clearance in both the country with the study area and during transit, and there is a risk of not getting diplomatic clearance for the NASA aircraft at the last minute, as the diplomatic clearance can sometimes only be obtained near its need-by date. In addition, as NASA aircraft are operated by US civil servants, there is a demonstrated risk of a US government shutdown delaying or canceling science flights, especially in the October-December timeframe. PANGEA will consider these and other risks and may consider using commercial aircraft to mitigate these risks.

Weather is also an important consideration in successful field and airborne measurements for PANGEA, especially for optical measurements that require cloud-free conditions for optimal measurements. During the study phase, PANGEA will run a climate analysis to determine the best time of year to do airborne measurements under these considerations. During the airborne campaign periods, PANGEA will hire local weather forecasters who understand the local climate to facilitate successful airborne and field measurements.

Meeting Community Engagement and Applications Objectives: PANGEA aims to engage stakeholders from across the study areas, work with local communities, and develop science and applications outcomes that will be useful to a wide variety of people. This requires a lot of coordination and genuine effort to be good partners in these efforts. PANGEA will embrace inclusivity and will actively work to develop and promote inclusive practices throughout the campaign phases. Co-developing projects and working equitably with IP&LC can take a long time and ideally builds on long-standing relationships; it should also involve a plan for how to continue supporting communities beyond the duration of the project. However, given the limited duration for PANGEA field work in each location, there is a risk that the project will not meet these goals. PANGEA will work to maintain relationships with community partners throughout the campaign and will work with international and industrial partners to secure additional funding to support these efforts in order to increase the depth and meaningfulness of these relationships.

8. Enabling Earth Science to Action

There are two main requirements for effective application of NASA research: (1) substantive overlap between NASA science and user needs; and (2) a process that brings potential users and scientists together. By meeting science and measurement objectives, PANGEA is well positioned to advance monitoring capabilities in the tropics, a region where data gaps and limited process understanding will otherwise limit the utility of new and forthcoming satellite sensors. This section presents the ways PANGEA will enable Earth Science to Action (ES2A) in critical fields like climate change and carbon monitoring, biodiversity conservation, and sustainable agriculture and livelihoods (**Figure 12**). It also details the current and future processes that the project employs to ensure uptake of research outputs by users. PANGEA's early, intensive, and diverse engagement of partners during the scoping phase for co-design is foundational to ensure the uptake and use of data products. Based on feedback from the scoping phase, PANGEA data products will be highly accessible and user friendly, and will include information on scaling approaches, offer educational materials, and continue a bidirectional dialog that raises awareness about PANGEA and its products while collecting feedback on user needs. PANGEA plans to advance methodologies to weave local, traditional, and ecological knowledge with remote sensing data, which offers both opportunities for improved scientific understanding, and unearths novel routes to put PANGEA products in the hands of decision makers and action takers.

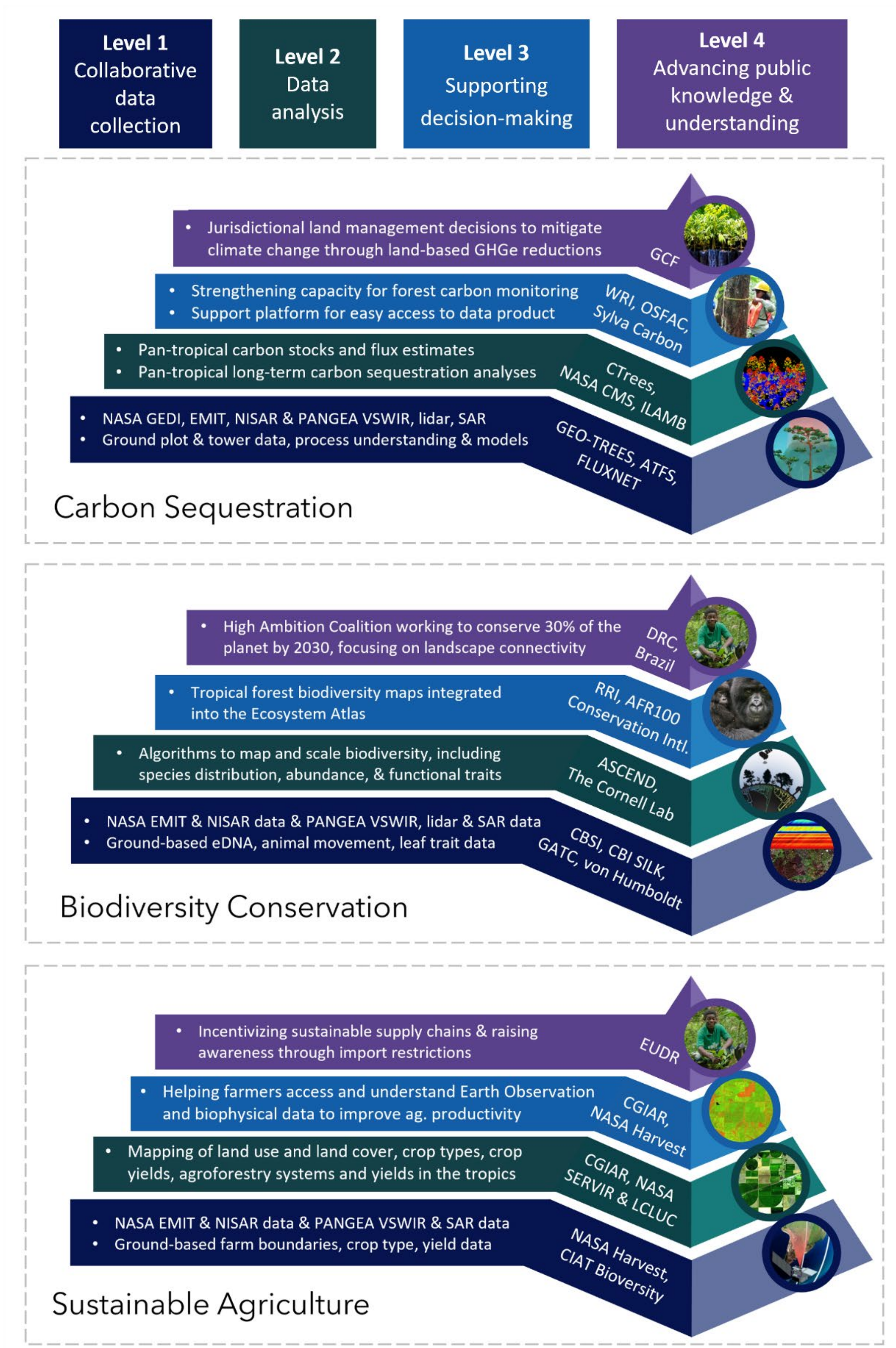


Figure 12. Example PANGEA Earth Science to Action strategy implementation, with a focus on carbon sequestration, biodiversity conservation, and sustainable agriculture.

PANGEA will engage a global network of pan-tropical scientists, including many who have spent their entire careers collecting the valuable data that go into global maps. PANGEA will prioritize strategic NASA Earth Science to Action efforts that close the gap between rapidly advancing technology and the needs of society to access science-informed decision-making platforms. PANGEA emphasizes a historically understudied tropical biome to empower one of the planet's most vulnerable regions to the consequences of climate and land use change while also acknowledging the global contributions of tropical biodiversity to resilience in the interconnected Earth System.

8.1 Applications of PANGEA research outputs

8.1.1 Carbon Sequestration Stability and Methane Fluxes

Science question	Research application	Potential partners and/or outlets for impact
Q1, Q2, Q8, Q15, Q18, Q19, Q26	Mapping and quantifying **carbon sequestration long-term stability** (i.e., permanence in carbon markets)	US GHG Center, GEO-TREES, CTrees, Land and Carbon Lab (WRI), OSFAC, GCF-TF, Woodwell, SylvaCarbon
Q1, Q2, Q4, Q15, Q26	Mapping and quantifying tropical **methane flux predictions**	US GHG Center, SERVIR, WRI

To effectively manage a problem, consistent and accurate measurement and monitoring is essential. Mapping and monitoring tropical carbon stocks and fluxes is critical for closing the global carbon budget, constraining future climate change projections, and for improving measurement, reporting, and validation (MRV) of carbon credits, offering clear applications for PANGEA data, analysis, and methodological improvements. Improving climate change projections, especially decreasing uncertainty around carbon fluxes of tropical forests, tropical land use change, and tropical forest responses to climate change are critical. While PANGEA will not focus on carbon accounting, results from PANGEA can improve our understanding of the changing carbon content of tropical forests, specifically related to the long-term stability of tropical carbon sequestration and CH_4 emissions, currently significant sources of uncertainty in the global carbon budget. PANGEA will stay up-to-date on U.S. Greenhouse Gas Center activity to determine areas of alignment, specifically relating to opportunities for PANGEA to provide data that meet stakeholder needs as emphasized in the National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring, and Information System (National GHG MMIS Strategy 2023).

Carbon sequestration long-term stability: Tropical forests, which store roughly half of the world's terrestrial carbon, are key to global carbon sequestration but face threats from climate stressors and anthropogenic impacts. Carbon financing approaches have gained popularity across tropical communities and involve polluting entities transferring payments to local governments and communities for various carbon emission remediation initiatives, including forest protection, reforestation, enhanced forest management, and the establishment of forest plantations (Anderegg et al., 2020; Morita & Matsumoto, 2023).

However, the long-term viability and success of efforts relying on tropical forests as natural climate solutions remain uncertain in the face of direct and indirect climate-driven risks (Anderegg et al., 2020). PANGEA's advancements of process-based understanding, tropical carbon stocks and flux mapping, and constrained spatially explicit model predictions of the future tropical land sink can directly support tools for mapping and quantifying the long-term stability of tropical forest carbon sequestration capacity. PANGEA will coordinate with and build on existing efforts like GEO-TREES, which is focused on carbon stocks calibration and validation, to improve carbon flux and stocks monitoring capabilities in the tropics using satellite remote sensing. PANGEA will work closely with the Governors' Climate and Forests Task Force, a network of high-level government officials, network partners, private sector companies, civil society organizations, researchers, and Indigenous Peoples, to ensure appropriate and effective tool development.

Mapping and quantifying methane flux predictions: Constraining future tropical methane flux predictions is globally important because methane is 25 times more potent as a GHG compared to CO_2 and contributes to roughly 30% of the increase in radiative forcing from anthropogenic emissions (Masson-Delmotte et al., 2021). Tropical CH_4 sources make up roughly 20% of the total global CH_4 budget of ~575 Tg CH_4 yr^{-1} and are the most uncertain component of the global carbon budget (Saunois et al., 2020; Peng et al., 2022).

Uncertainty in predicting future methane emissions from the tropics could lead to inaccurate global climate predictions, making it difficult to assess the full scope of climate change impacts. By improving our understanding of tropical methane fluxes, we can refine global carbon budgets, better anticipate future climate shifts, and inform more effective mitigation strategies to curb greenhouse gas emissions. This is crucial for achieving international climate goals and stabilizing the Earth's climate system. PANGEA's science activities will advance our ability to constrain tropical methane flux uncertainty. PANGEA will align with needs and activities emerging from the U.S. Greenhouse Gas Center in collaboration with partners like SERVIR regional hubs to advance local technical expertise in and with partners like the World Resources Institute to advance mapping and monitoring tools.

8.1.2 Biodiversity Conservation

Science questions	Research application	Potential partners and/or outlets for impact
Q5, Q6, Q7, Q10, Q11, Q12, Q19	Biodiversity mapping to support **landscape connectivity** and **corridor implementation** and **tropical forest restoration** (in alignment with Ecosystem Atlas)	Alexander von Humboldt Biological Resources Research Institute, Central African Satellite Observatory (OSFAC), Conservation International, European Space Agency, IUCN Regional Offices, AFR100
Q5, Q10, Q11, Q12	Empowering and elevating Indigenous, local, and traditional communities via **IEK, LEK, TEK and remote sensing integration**	NASA Indigenous Peoples Initiative, Global Alliance of Territorial Communities, Rights & Resources Initiative, CBI School for Indigenous and Local Knowledge, MapBiomas, Woodwell

The rate of global biodiversity loss is intensified by a poor understanding of the emergent contributions of biological assembly to the structure and function of ecosystems. Throughout the evolutionary history of life on Earth, the tropical biosphere has served as an "engine" for generating biodiversity (Antonelli et al., 2015) and remains the most diverse biome on the planet. Biodiversity conservation in the tropics has the potential to reveal reciprocal social-ecological benefits and inform strategies for local-scale adaptation and climate resilience. The first Global Biodiversity Framework 2030 target is to "Plan and Manage all Areas to Reduce Biodiversity Loss" while respecting the rights of Indigenous peoples and local communities (CBD 2030). Doing so requires a campaign on the scale of PANGEA. Targets 2 and 3 are to restore 30% of all degraded ecosystems, and conserve 30% of all land, water, and sea.

To assist in the ability to meet these targets, the Group on Earth Observations (GEO) **Global Ecosystems Atlas** effort, supported by the Convention on Biological Diversity and UNFCCC, is working to unite high-quality global, regional, and national ecosystem maps into a single, open, online resource, with the goal of developing an Atlas that will enable everyone—from governments to individual citizens—to take action to protect nature. The Global Ecosystem Atlas is prioritizing mapping "structure and function of the world's ecosystems in unprecedented detail." **PANGEA will fill major calibration and validation data gaps in Earth's most diverse biome and will directly support this effort** in collaboration with the USGS, European Space Agency, IUCN, ESRI, and others.

Biodiversity conservation can make considerable progress with large-scale observations across disturbance gradients. Participatory land-use planning with NASA Earth Observation monitoring capabilities that will result from PANGEA are needed to support collaborative decision-making between land-users and governments to design corridors and improve landscape connectivity. Similarly, forest restoration efforts require improved understanding of plant-animal interactions, and what species can effectively support restoration efforts, and where. Understanding of the complex processes that sustain regrowing tropical forest landscapes will be advanced through PANGEA, with science activities directly guided by these applications. PANGEA will enable the mapping of biodiversity and diverse processes in the tropics where methods and approaches are currently insufficient. This work is critical for efforts like AFR100, the African Forest Landscape Restoration Initiative to restore Africa's degraded and deforested land, and 30x30. NASA remote sensing of Essential Biodiversity Variables (EBVs) like the biological effects of fire and irregular inundation are among the highest priority identified by the Group on Earth Observations Biodiversity Observation Network (GEO BON; Skidmore *et al.*, 2021).

In addition, partnerships with key collaborators identified in the scoping campaign will accelerate the development of user platforms for protecting biodiversity and its contributions to people. In June 2024, a joint PANGEA workshop with the Governor's Climate and Forests Task Force included a presentation from MapBiomas proposing science-informed biodiversity management and conservation strategies with mapping and monitoring of land cover, land use, surface water, and fire scars. Partners like MapBiomas, the Alexander von Humboldt Biological Resources Research Institute, Conservation International, and other tropical and international organizations will support the development of user-friendly platforms that are accessible from local to global scales. PANGEA will specifically prioritize engagement with Indigenous Peoples and Local Community Alliances and Organizations to empower and elevate Indigenous, local, and traditional communities through the **integration of Indigenous, local, and traditional knowledge (IEK, LEK, TEK) with remote sensing.** PANGEA will support efforts initiated and led by the Global Alliance of Tropical Communities, whose women's movement is already conducting drone data collection training, and the Rights and Resources Initiative, who has partnered with Woodwell in the past to quantify and estimate the carbon stored in Indigenous, Afro-descendent, and local community lands (Research Report, Policy Brief). There is strong interest in similar initiatives emphasizing biodiversity.

8.1.3 Sustainable Agriculture and Livelihoods

Science questions	**Research application**	Potential partners and/or outlets for impact
Q6, Q9, Q14, Q17	**Intensifying agricultural** production and improving yields	SERVIR, IITA, NASA Harvest, Land and Carbon Lab (WRI)
Q14, Q16, Q17, Q19	Advancing **sustainable agricultural production**, including under climate change	SERVIR, IITA, Alliance Bioversity & CIAT
Q3, Q16, Q19	Improving **supply chain traceability** of agricultural commodities	Alliance Bioversity & CIAT, WRI, private sector, certification bodies, regulators
Q3, Q8, Q14, Q15, Q16, Q27	Improving **disaster alerts & response** (e.g., fire, flooding, drought)	SERVIR, IITA, Alliance Biodiversity & CIAT, MapBiomas, Cameroon National Observatory for Climate Change

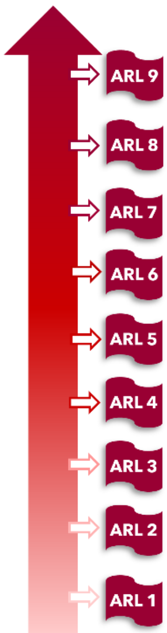
Tropical ecosystems are home to 3 billion people and produce agricultural commodities that are exported and consumed globally. Intensifying agriculture in tropical regions, making it more sustainable and resilient to climate change, and enhancing abilities to trace agricultural commodities to their origin are all critical to reduce deforestation pressure on tropical forests while meeting growing global demands. PANGEA will support these efforts in the following ways:

***Improved intensification*:** Satellite monitoring of crops offers the possibility to assess production levels in near-real time, comparing intervention and control areas across significant distances to provide critical data on the efficacy of intensification efforts and support farmer decision-making. In the Congo Basin, where most farms are small, interspersed in a mosaic with forest, and difficult to reach, remote sensing can help understand the penetration of new methods and technologies remotely. PANGEA will advance the capacity to use satellite remote sensing for precision agriculture in the tropics, including improved crop type mapping, nutrient- and water-use efficiency mapping, and yield estimation. This work will be done in collaboration with key partners working in this area, including working with the World Resources Institute (WRI) to support the Land and Carbon Lab.

Increased sustainability and capacity for adaptation: Agriculture under climate change will require farmers to grow more food under increasingly unpredictable circumstances, including shifting precipitation regimes and periods of intense heat. As a major contributor to climate change, there is also a movement to make agriculture more sustainable, through decreased use of fertilizers and pesticides, curtailed water use, and increased efforts to control erosion. Colleagues from IITA, Alliance Bioversity-CIAT, and the International Water Management Institute (IWMI) have already shared input into how PANGEA products advance these efforts, informing science questions that directly underpin opportunities for action. These include improved capabilities to support spatially explicit farm-scale crop health monitoring.

***Improved traceability*:** There is globally increasing demand to link agricultural commodities with the exact farm where they were grown, driven by both consumer demand and regulatory pressure from new policy regimes like the European Union Deforestation Free Commodities Regulations and a similar bill under consideration in the U.S. PANGEA's advancement of the use of new sensors like NISAR, BIOMASS, and SBG to detect multiple forms of agricultural expansion into tropical forests will provide necessary monitoring tools for ensuring deforestation free supply chains. Methodological improvements from PANGEA's data acquisition may also improve our ability to use remote sensing tools to distinguish between complex agroforestry and secondary forests, currently a major gap that undermines the ability to recognize and map coffee and cocoa farms that use more sustainable shading methods, allowing them to prove compliance with deforestation-free commodities requirements. These activities also position PANGEA to impact other livelihood sectors, like payments for ecosystem services and non-timber forest products.

Improving disaster alerts and response: Droughts, floods, pests, and extreme heat all threaten agricultural production in the tropics. In places where agricultural sector adaptation to climate change is insufficient, policies and practices like early warning systems, disaster alerts, and improved insurance products for smallholder farmers are critical. PANGEA's efforts to map land-use activities and land-use change, understand climate impacts on phenology, estimate plant chemical traits remotely will all support these policy solutions. For example, enhanced remote sensing of boundaries, crops, and yields in farm fields will lower monitoring costs for climate-driven insurance products for smallholder farmers.



NASA Application Readiness Level		PANGEA Application Example	PANGEA ES2A Processes
ARL 9	**Sustained Use**	**ARL 9**: Application becomes a commonly used tool to demonstrate EUDR regulatory compliance and is accepted by private sector actors and regulators.	*Engage potential community members in PANGEA scoping activities to assess needs and build working relationships*
ARL 8	**Functionality Proven**	**ARL 8**: Agricultural commodities importers rely on EUDR reference map to demonstrate regulatory compliance; EU accepts compliance documents based on application for regulatory review and approval.	*Engage a broader community of potential end users, including local and indigenous people, and treat information flow as bidirectional*
ARL 7	**Functionality Demonstrated**	**ARL 7**: Application improving the distinction between secondary forest and complex agroforestry integrated into EUDR reference map and publicly accessible.	Engage users in development of Concise Science Plan to position PANGEA research and products for application
ARL 6	**Potential Demonstrated**	**ARL 6**: Prototype tested in relevant environment (e.g., in EUDR 2020 Forest Reference Map).	
ARL 5	**Potential Determined**	**ARL 5**: Develop prototype application to distinguish between land use types at specific locations; collect feedback from end users.	Conduct environmental scans in key sectors to better position PANGEA work for application
ARL 4	**Prototype/Plan**	**ARL 4**: Integrate PANGEA data products to improve prediction of land use type using satellite datasets; connect with users about platform requirements (target environment, interface priorities, etc.).	Engage in co-design with end users (e.g. land management agencies tasked with providing climate and land use change projections) to align with program missions
ARL 3	**Viability Established**	**ARL 3**: Characterize current remote sensing capabilities; test ability to distinguish land use types remotely based on PANGEA ground and airborne acquisitions.	Develop the Integrated Modeling Framework to develop unique information products based on integrated assessments
ARL 2	**Invention**	**ARL 2**: Distinguishing between complex agroforestry and secondary forests as of 30 Dec 2020 is a priority; results would be applicable for mandatory EUDR compliance, but also for voluntary schemes.	
ARL 1	**Baseline Ideas**	**ARL 1**: *Tracing of tropical agricultural commodities and deforestation and degradation identified as a high priority for private sector and regulators. Relevant PANGEA data products identified.*	Develop PANGEA Information System (PIS) to share PANGEA results, collect feedback from potential end users, and connect researchers, end users, and the general public.

Figure 13. Example Application Readiness Level strategy for PANGEA focused on support for the European Union Deforestation Regulation (EUDR). Similar regulation is under consideration in the U.S.

To deliver on potential gains for food security and livelihoods, PANGEA has engaged agricultural research partners like NASA Harvest, NASA SERVIR, the Consultative Group for International Agricultural Research (CGIAR), including the International Institute for Tropical Agriculture (IITA), and partners working at the nexus of forests and agriculture, including the Alliance Bioversity and the International Center for Tropical Agriculture (CIAT), World Resources Institute and Center for International Forestry Research and World Agroforestry Center (CIFOR-ICRAF). Information shared by these partners during the PANGEA scoping process directly informed PANGEA's science requirements and questions to ensure Earth Action outcomes. As an example, **Figure 13** lays out the application readiness level stages for *Improving Traceability*. PANGEA partners like IITA and CIAT specialize in translation of findings from their research into practice, and builds on decades of experience with private sector and government partners to guarantee the translation of research into practice.

8.2: Process to enable Earth Science to Action

8.2.1 Partner Engagement

Substantive interest alone is insufficient to guarantee that NASA products will be used. Effective research application requires that end user communities be identified and engaged early, and must be partners in research design and tool development. This requires advanced planning, intent, and resources. That is why PANGEA has invested since the inception of the scoping phase in laying the groundwork for research translation.

Specifically, PANGEA addresses the following Guiding Principles from NASA's ES2A Strategy (2024-2034):

- **Amplify impact through partnerships:** PANGEA's investment in community engagement has attracted a diverse array of partners, including international governments, donors, and local communities (see *Section 7.2* for details about community engagement). These partners include potential users, data contributors, and potential funders for applications–the last of which will help make PANGEA's work cost effective by supplementing NASA's Earth Science resources with funds to support capacity building, community engagement, and research translation (see *Section 7.3*: *Co-funding Opportunities* for additional information). PANGEA also brings extensive international partnerships, ranging from national space agencies that could provide complementary data to tropical communities who will participate in data collection and potentially in use and action. PANGEA engaged these partners early in the process to increase their investment and their input in co-development of potential end products.
- **Engage a diverse workforce and broader Earth Science community:** PANGEA's inter- and transdisciplinary goals are supported by a diverse team that ranges from data scientists to economists and hail from NASA, academia, non-profit organizations, other federal agencies, and governments from around the world. PANGEA's extensive international engagement also offers opportunities to work with and recruit the best minds globally to NASA's Earth Science efforts, while the capacity building and training efforts (see *Section 9*) help ready the next generation of scientists.
- **Use a balanced approach:** PANGEA builds on prior decadal campaigns both for science questions and data (e.g. LBA), and for process improvement (e.g. LBA, ABoVE). By asking bold and critical science questions that were formulated based on prior campaigns and today's needs, PANGEA maximizes value.

During the Scoping Phase, PANGEA led extensive outreach to potential users, and engaged with potential users about what questions and data are most valuable to them. As a result, PANGEA has worked since its inception to bridge the sometimes-difficult gap between what science questions are being asked and what end users need for decision making. Community engagement is central to PANGEA's ES2A strategy (see *Section 7.2* for details on how PANGEA will engage the community). PANGEA is aware that with community engagement comes with the risk of creating expectations that cannot be met by the project, largely because the airborne data being collected is spatiotemporally limited in scope and will be more episodic than is needed to meet many user applications and decision-making needs. PANGEA will make every effort to repeatedly and clearly convey the impact limitations of the airborne data. PANGEA will also endeavor to leverage the momentum created by an airborne campaign to create, grow, and strengthen a new and more diverse user community for NASA Earth data beyond the airborne campaign.

Specifically, PANGEA will ensure that all community engagement activities emphasize the links between PANGEA's field and airborne data and NASA's Earth Observatory satellite sensors (both current and planned). Because users will benefit from products derived from spaceborne observations, as opposed to ground and airborne measurements, PANGEA ES2A priorities focus on advancing specific monitoring needs and capabilities that utilize ongoing services, i.e., satellite missions. Airborne campaign data will support partner training focused on operational data before, alongside, and after PANGEA scaling advances can be used to retrieve satellite-derived products. Examples include SAR and hyperspectral training and readiness in collaboration with SERVIR. In doing so, PANGEA will build NISAR and SBG early adopter communities in the tropics.

PANGEA has also prioritized seeking a diverse range of funding partners, recognizing that NASA is well-suited to support data collection, analysis, and tool/platform development, while other sponsors are better positioned to support conservation projects that apply data and application-specific forms of training and capacity building. The Scoping Phase also included a visioning exercise, where diverse teams collaborated to draw translational pathways that included data acquisition, potential uses cases, the co-development of products, and identification of partners.

8.2.2 Supporting Application of PANGEA research

PANGEA will harness its existing and planned partner engagement to integrate ES2A holistically into the campaign. This includes conducting a user needs assessment as part of the Concise Experimental Plan, and conducting an environmental scan to identify existing tools that could integrate data. This is particularly important because integration into existing tools usually increases the likelihood of uptake, use, and maintenance in the long term. **Figure 13** demonstrates PANGEA's approach to advancing campaign results through NASA's Application Readiness Levels (ARL), which will hinge on combining strong subject matter alignment with thoughtful, early, and inclusive partner engagement. While the example is displayed as a linear process using NASA's ARL framework, PANGEA expects our ES2A activities to be iterative, and at times non-linear, which is representative of the complexities that define real-world policy and decision making. In particular, we expect extensive collaborations to continue at and even before the ARL 1 stage to match PANGEA products with real-world needs.

NASA, along with other domestic and international agencies, are increasingly playing a leading role in the development and implementation of decision support systems. These systems are designed to incorporate the results from research activities within a modeling framework in order to provide information to land managers, regional governments, among others who require information in a specific context. The PANGEA Information Portal (PIP) will provide a platform to conduct further research on the use of satellite information products to support decision making. It will be a critical platform for PANGEA researchers to interact at multiple levels with scientists and managers at agencies who are responsible for assessing the impacts of climate change in tropical regions, as well as the media and general public. PANGEA's Integrated Modeling Framework will provide another scaffold for ES2A activities by creating unique information products based upon integrated assessments.

There is increasing recognition by NASA and other U.S. and international agencies of the need to co-develop decision support systems to exchange information and analysis with land managers, regional governments, and other policy and decision makers. PANGEA will co-develop products with these partners who are responsible for the provision of data required for climate and land cover change monitoring. The process-driven models that will be the focus of research in PANGEA align well with the program missions of these offices. Researchers from these offices were involved in the PANGEA scoping process, and their input has informed research questions and seeded ideas for research application of PANGEA's results. PANGEA also offers the opportunity to engage in transdisciplinary work and application, particularly given the inter-related nature of climate change, biodiversity conservation, and agricultural production, which are some of the main applications for PANGEA products.

9. Capacity Building, Training, and Education

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 change, 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 change 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 (NASA Earth Science to Action Strategy 2024-2034). 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 not only US-based research and workforce communities, but also 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. Training, Capacity Building, and Education will focus on educating a cohort of graduate students, workforce development trainings, and Indigenous peoples and local community specific training and capacity building.

The scope of each PANGEA capacity building, training, or education activity will depend on which individuals from which institutions are targeted for training. During the development of the Concise Experimental Plan, and then intermittently throughout PANGEA, a brief needs assessment will be carried out to assess what different members of the PANGEA community require and desire in terms of capacity building, training, and education activities. The intention of this assessment will be to identify who will benefit from what kind of activities, and align that with resources that are available, while also determining what additional resources are needed to support planned activities. Complementary funding will be sought to support capacity-building activities (see *Section 7.3* Co-funding Opportunities). Needs assessment results will also help PANGEA identify which complementary funding opportunities are most appropriate to pursue.

Educating a Cohort of Graduate Students: During the Large-Scale Biosphere Experiment in Amazonia (LBA), capacity building was mutually beneficial to the NASA LBA-ECO efforts and to NASA's South American hosts. Brazil required that every LBA project include a training and education component. These were tailored to the resources of each project and often linked to academic programs within Brazil. The largest group of students trained within LBA were Brazilians engaged in scientific initiation programs. These are positions for undergraduates who earned minimum wage to work 20 hours per week for a science project. These students often did technical work, but many reached the level of co-authorship on papers, and some were even primary authors. About 500 students participated in LBA in this way in the first decade of the program. These students often went on to complete masters and doctoral degrees. An additional 500 students earned MS and Ph.D. degrees associated with LBA projects. Only a small portion of the funded students were paid by NASA research projects (mainly for students who did their degrees in the US). The largest number of scholarships came through traditional Brazilian mechanisms from their national education and science ministries and through state level research foundations. While the total investment in dollar terms was probably less than 5% of the NASA investment in LBA-ECO and other foreign research activities, the immediate payoff was enormous owing to the low cost of Brazilian student stipends. In Brazil, many LBA graduates went on to do important work in the environmental field in universities, in municipal, state, and national government agencies, and in non-governmental organizations, exceeding Brazilian expectations for the impact of the LBA training and education program.

PANGEA's biggest opportunity for capacity building and training is within the science team. PANGEA will encourage NASA to explicitly indicate within ROSES funding calls that proposals co-developed with local researchers are more likely to be funded. This was done in the BioSCape funding call and was a significant contributor to roughly 50% of BioSCape's science team being local to South Africa. PANGEA will strongly encourage projects include local collaborators in Co-I roles, in addition to local graduate student and/or postdoctoral researchers. This co-development of research will enable skills and knowledge transfer within each project team and create opportunities for the Science Team to learn from researchers who span more diverse experiences and expertise. Additionally, PANGEA will strongly encourage that the ROSES solicitations require proposers to commit time to co-mentor and co-supervise students and postdocs from PANGEA countries, further building capacity. Once formed, PANGEA's Science Team will abide by a PANGEA Code of Conduct that has both advice for ethical and equitable collaboration as well as clear authorship guidelines. These guidelines will be based on the Contributor Role Taxonomy (CRediT, credit.niso.org), which values the diversity of roles that make research possible.

PANGEA's approach to equitable science, capacity building, and training will directly confront the issue of flyover campaigns and parachute science. We strongly believe that PANGEA can achieve an estimated 100 first-author papers from scientists in Africa, substantially contributing to closing the Parachute Index gap in Central Africa as described in (Culotta et al., 2024). These African scientists will continue the legacy of the PANGEA campaign, in collaboration with international peers across the tropics, well after the end of the campaign.

Another important goal of PANGEA's capacity building strategy is to strengthen and grow the NASA Earth data user community in the tropics, including Indigenous peoples and local communities. PANGEA's airborne activities will generate a lot of excitement around the potential of remote sensing for many applications, including applications focused on climate change mitigation and carbon monitoring, biodiversity conservation, sustainable agriculture and disaster risk prevention and monitoring. The diverse user group will benefit greatly from PANGEA's methodological advances for using NASA's satellite assets. PANGEA will use the momentum created by the airborne campaign to catalyze and promote broader application of NASA spaceborne datasets, particularly those that are well suited for examination alongside the airborne data products, e.g. NISAR, EMIT, PACE, ECOSTRESS, GEDI, and in the future SBG. Trainings will include an emphasis on data fusion and scaling workflows. PANGEA's approach to capacity building intends to build NASA Early Adopter user groups in the tropics - particularly for NISAR and SBG, as well as for ESA missions like BIOMASS, CHIME, and FLEX.

PANGEA will draw upon NASA Earth Science's strategy to "build capacity through an extensive and diverse set of partnerships, both traditional and new… [including with] national and international governmental agencies, academia, non-governmental and international organizations, the private sector, and philanthropies." PANGEA will partner with existing NASA programs and training efforts led by partners. Some examples are included below (**Note:** A Table with more details will be included in an appendix in the final white paper).

ARSET: PANGEA would work with ARSET and the PANGEA Science Team to deliver a multi-part training webinar series, building on the in-person training model trialed during BioSCape, in which ARSET and the ORNL DAAC worked together for the first time to deliver a 5-day in-person training in South Africa to conservation decision makers, university lecturers, and diverse researchers.

Distributed Active Archiving Centers (DAACs): PANGEA will build on the success of EMIT/LP DAAC and BioSCape/ORNL DAAC collaborations to produce capacity building materials (e.g., training notebooks) and conduct workshops at conferences. Delivering these materials at conference workshops, such as the American Geophysical Union (AGU), Ecological Society of America (ESA), European Geophysical Union (EGU), and Association for Tropical Biology (ATBC) annual meetings, will engage diverse researchers at a variety of career stages and with various levels of prior engagement with NASA Earth data.

DEVELOP: DEVELOP partners with decision makers who are interested in using NASA Earth data to support their work. Each partner would have a DEVELOP team of 4-5 people work with them over 10 weeks to assess how NASA Earth data can help address their needs. The 10-week period can be renewed for up to 3 terms. DEVELOP proposals submitted by non-US PANGEA partner organizations can help develop capacity within partner organizations and may lead to the generation of applied data products. For example, during BioSCape, the South African National Botanical Institute partnered with DEVELOP to help create data products to map ecologically important riparian vegetation.

Global Learning and Observations to benefit the Environment Program (GLOBE): GLOBE delivers educational activities to K-12 students, teachers, and citizens. During BioSCape, GLOBE traveled to South Africa to deliver an educational program to 170 high-school students from 10 under-resourced schools and delivered a "train the trainer" program to high school teachers. The South African iteration of this program was a success, due largely to the tailoring of the program to the South African context, and with the train-the-trainer program likely leading to larger impact in the future. PANGEA intends to emulate this success, capitalizing on the excitement surrounding an airborne campaign to engage the next generation of scientists in STEM.

NASA/USAID SERVIR: SERVIR works through regional hubs across the tropics to support sustainable development through capacity building and incorporating perspectives from women, Indigenous Peoples and their communities. PANGEA will work with SERVIR's regional hubs to develop custom services and data pipelines to serve the specific decision-making needs of local partner organizations. The PANGEA Science Team will work with SERVIR to build on their excellent Planning Toolkit, which provides regionally targeted instruction on how to assess and deliver impactful interventions related to agriculture, forest restoration, and more.

Indigenous Peoples Initiative: NASA's Indigenous Peoples Initiative fosters collaboration with Indigenous communities to enhance the use of Earth Observations for informed decision-making and actions. Through the co-development of trainings, support for Indigenous-led projects, and respectful engagement, the Indigenous Peoples Initiative strengthens relationships and creates opportunities for Indigenous voices within NASA's Earth Science Division. PANGEA has developed partnerships with Indigenous alliance organizations in the tropics, including the Global Alliance of Territorial Communities (GATC) and the Rights and Resources Initiative (RRI).

PANGEA will coordinate with NASA's Indigenous Peoples Initiative to extend efforts to engage Indigenous communities in the tropics.

Association for Biology and Tropical Conservation (ATBC): The ATBC, founded in 1963, is a global scientific society and professional organization promoting research, education, and communication on tropical biology and conservation. With around 1,000 members from 70 countries, ATBC supports capacity building, publishes the journal Biotropica, and hosts international meetings. Beyond workshops at ATBC's annual meeting, PANGEA will seek out opportunities to engage ATBC members more broadly in PANGEA science training.

FLUXNET: FLUXNET is a network of networks organized on the basis of a set of Regional and Continental Networks (such AmeriFlux and NEON in the Americas, ICOS in Europe, OzFlux and TERN in Australia and SAEON in South Africa) with the aim to make available standardized eddy covariance measurements globally. FLUXNET connects regional networks of primarily field-based earth system scientists and research sites. PANGEA will coordinate training and tools that are aligned with shared goals between the efforts. This includes expanding training on how to use and analyze eddy covariance flux tower data in the tropics, deepening engagement with tropical flux towers outside the FLUXNET community, and making existing trainings more accessible, for example translating AmeriFLUX materials into Portuguese and French, beyond the recent work to translate materials into Spanish.

AIMS African Master's in Machine Intelligence (AMMI): The African Institute for Mathematical Sciences (AIMS), founded in 2003, is a Pan-African network of centers of excellence for post-graduate training, research and public engagement in mathematical sciences. The AIMS network has five centers of excellence teaching a Masters in Machine Intelligence (AMMI), including in Cameroon, Ghana, and Rwanda. Currently, the AIMS network has over 2,400 alumni from 44 African countries of which 33% are women. AIMS also established an initiative that is highly relevant to PANGEA: the Next Einstein Forum to propel Africa on to the global scientific stage.

NSF Research, Innovation, Synergies, and Education (RISE): The NSF's new RISE program aims to foster transdisciplinary collaborations that engage the broader geosciences community to drive transformative discoveries, innovations in workforce development, and use-inspired solutions for urgent Earth system challenges. The program will specifically focus on supporting work that will build a resilient planet, and therefore may offer opportunities for PANGEA to engage with NSF around certain capacity building and training activities.

Ultimately, PANGEA is an opportunity to improve understanding, leave legacy datasets, and support direct action now. Perhaps its longest-lived legacy will be the foundational core of experts trained and supported who will contribute to leading the next generation in scientific and technological advances and solutions-oriented action to tackle Earth's most pressing challenges.

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11. Glossary

Anthropocene - A proposed new geological epoch resulting from significant human-driven changes to the structure and functioning of the Earth system, including the climate system. Originally proposed in the Earth system science community in 2000, the proposed new epoch is undergoing a formalisation process within the geological community based on the stratigraphic evidence that human activities have changed the Earth system to the extent of forming geological deposits with a signature that is distinct from those of the Holocene, and which will remain in the geological record. Both the stratigraphic and Earth system approaches to defining the Anthropocene consider the mid-20th century to be the most appropriate starting date (Steffen et al., 2016), although others have been proposed and continue to be discussed. The Anthropocene concept has already been informally adopted by diverse disciplines and the public to denote the substantive influence of humans on the Earth system. (IPCC AR6 WGI & WGII)

Biodiversity - The variety of life on Earth, including its variation at the level of genes, species, functional traits, and ecosystems. In tropical forests, biodiversity is exceptionally high within and across forests, supporting complex interactions and ecosystem function, and causing heterogeneity in climate responses and resilience.

Community - Formal and informal groups of people who perceive themselves as members which may share interests, experiences, resources, activities, professions, livelihoods, culture, geography, origins, language, or any combination of the above.

Carbon stocks and fluxes - Carbon stocks refer to the total amount of carbon stored in a system (e.g., in vegetation, soils, or oceans), while carbon fluxes represent the movement of carbon into and out of these stocks through processes such as photosynthesis, respiration, and decomposition, and includes fluxes of carbon dioxide (CO2), methane (CH4), and lateral flows of carbon.

Co-benefits - Joint positive contributions of biodiversity and cultural diversity for humans and other species. These contributions are associated with the concepts of nature's contributions to people and people's contributions to nature. → From: Levis et al, 2024, "Contributions of human cultures to biodiversity and ecosystem conservation", Nature Ecology & Evolution, https://doi.org/10.1038/s41559-024-02356-1

Ecosystem - PANGEA uses the IPCC working definition of ecosystion, which includes people as key organisms, thus including agro-ecosystems and more broadly social-ecological systems. A functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases, they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms or are influenced by the effects of human activities in their environment. → directly from IPCC AR6 WGI, WGII, WGII)

Ecosystem Services - Ecosystem services are the benefits that humans derive from natural ecosystems, including provisioning (e.g., food, water), regulating (e.g., climate regulation, flood control), supporting (e.g., nutrient cycling, soil formation), and cultural services (e.g., recreation, spiritual value).

Forest degradation – a forest is degraded when the rate of exogenous disturbance greatly exceeds the long-term average rate of exogenous disturbance for the ecosystem and the effects of that disturbance can be distinguished from old-growth forest structure and/or composition. Logging, fire, mining, and fragmentation are common causes of forest degradation.

Forest-friendly activities - Economic activities that utilize forest resources in a way that preserves the forest's ecological integrity and supports the sustainable livelihoods of local communities → From: IUCN. (2021). *"Forest Conservation and Sustainable Use"*

Forest function - Forest function refers to the ecological roles of forests, such as regulating climate, supporting biodiversity, cycling nutrients, and providing habitat, which contribute to the overall health and stability of ecosystems. Forest functions include gross primary productivity (GPP), woody productivity, ecosystem respiration, and evapotranspiration.

Forest structure - Biomass, canopy height, stem density, vertical height heterogeneity, and vertical plant area density distributions

Human activities - Formal, informal, legal, illegal and traditional economic, subsistence, cultural, and development practices and behaviors by humans that lead to the exploitation, alteration, and degradation of forest ecosystems, including logging, infrastructure development, agriculture, livestock rearing, fire, mining, hunting and wildlife exploitation, and charcoal production.

Land-use change - Land use and land cover change refers to the alteration of the Earth's surface, including changes in how land is utilized (e.g., agriculture, urbanization) and shifts in its physical cover (e.g., deforestation, reforestation, urban expansion).

Resilience - The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation (Arctic Council, 2016). → directly from IPCC AR6 WGI, WGII, WGII)

Vulnerable communities - Communities that are most likely to experience the adverse effects of climate change and environmental degradation, including Indigenous peoples, low-income communities, and those reliant on natural resources for their livelihoods. → From: United Nations Framework Convention on Climate Change (UNFCCC). (2020). *"Vulnerable communities".*

Vulnerability - The propensity of social and ecological systems and their practices to be adversely affected by changes, encompassing their sensitivity to such changes and their ability to adapt. → Adapted From: FAO. (2013). *"Community-Based Forest Management and Vulnerability to Climate Change"*

12. List of Acronyms

ABoVE - Arctic Boreal Vulnerability Experiment

AGEOS - Gabonese Space Agency

AI/ML - Artificial Intelligence and Machine Learning

AmIT - Amazon Institute of Technology

AMSR-E - Advanced Microwave Scanning Radiometer for EOS Mission

ATBC - Association for Tropical Biology and Conservation

ATFS - Alliance for Tropical Forest Science

BioSCape - Biodiversity Survey of the Cape

BRDF - Bidirectional Reflectance Distribution Function

CARE - Collective Benefit, Authority to Control, Responsibility, and Ethics

CBI - Congo Basin Institute

CBFP - Congo Basin Forest Partnership

CBSI - Congo Basin Science Initiative

CC&E - NASA Carbon Cycle and Ecosystems Office

CENAREST - Gabon National Center for Scientific and Technological Research

CEOS - Committee on Earth Observation Satellites

CH_4 - Methane

CGIAR - Consultative Group for International Agricultural Research

CHIME - Copernicus Hyperspectral Imaging Mission for the Environment

CIAT - International Center for Tropical Agriculture

CIFOR/ICRAF - Center for International Tropical Forestry Research-World Agroforestry Center

CMIP - Coupled Model Intercomparison Project

CNES - French National Space Agency

CO_2 - Carbon dioxide

CSDA - NASAs Commercial SmallSat Data Acquisition

DEI - Diversity, Equity, and Inclusion

DLR - The German Aerospace Center

DGPA-DRC - Dynamique des Groupes des Peuples Autochtones

EMIT - Earth Surface Mineral Dust Source Investigation

ENSO - El Niño Southern Oscillation

ESA - European Space Agency

ES2A - NASA's Earth Science to Action Strategy

ESMs - Earth System Models

FAIR - Findable, Accessible, Interoperable and Reusable

FAPESP - São Paulo Research Foundation

FLEX - Fluorescence Explorer Mission

GATC - Global Alliance of Territorial Communities

GCF-TF - Governors' Climate and Forests Task Force

GEDI - Global Ecosystem Dynamics Investigation

GEO - Group on Earth Observations

GHG - Greenhouse gas

GPP - Gross Primary Productivity

IEK - Indigenous ecological knowledge

IITA - International Institute for Tropical Agriculture

ILAMB - International Land Model Benchmarking

IPLCs - Indigenous Peoples and Local Communities

INPA - Brazil National Institute of Amazonian Research

INPE - Brazil's National Institute for Space Research

IPCC - Inter-governmental Panel on Climate Change

IPBES - Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IRD - French National Research Institute for Sustainable Development

ISRO - Indian Space Research Organisation

ITCZ - Intertropical Convergence Zone

IUCN - International Union for Conservation of Nature

JAXA - Japan Aerospace Exploration Agency

LCLUC - Land Cover and Land-Use Change

LBA - Large Scale Biosphere-Atmosphere Experiment in Amazonia

LEK - Local ecological knowledge

MOU - Memorandum of Understanding

NEE - Net Ecosystem Exchange

NISAR - NASA-ISRO SAR Mission

NSF - National Science Foundation

OFVi - One Forest Vision

OIIR - NASA Office of International and Interagency Relations

ONACC - Cameroon National Climate Change Observatory

OSFAC - Central African Satellite Observatory

PACE - Plankton, Aerosol, Cloud, ocean Ecosystem Mission

PANGEA - PAN tropical investigation of bioGeochemistry and Ecological Adaptation

RRI - Rights and Resources Initiative

SBG - Surface Biology and Geology Mission

SMAP - Soil Moisture Active Passive Mission

SIF - Solar Induced Fluorescence

SPUN - Society for the Protection of Underground Networks

SSC - Scientific Steering Committee

SST - Sea surface temperature

SWOT - Surface Water and Ocean Topography Mission

TBD - To Be Determined

TEK - Traditional ecological knowledge

TRL - Technology Readiness Level

TIR - Thermal Infrared

UAV - Uncrewed Air Vehicle

UNFCCC - United Nations Framework Convention on Climate Change

USAID - U.S. Agency for International Development

USFS - U.S. Forest Service

USGS - U.S. Geological Survey

VSWIR - Visible to Shortwave Infrared

WRI - World Resources Institute