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

Final Report—December 2024

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Foreword

NASA’s Research Opportunities in Space and Earth Sciences released in 2022 called for proposals to conduct scoping studies to identify the scientific questions and develop the initial study design and implementation concept for a new NASA Terrestrial Ecology field campaign. In the spring of 2023, NASA selected two projects for funding, including a project entitled: “A Scoping Study for the NASA Tropical Terrestrial Ecology Campaign” (NASA Grant 80NSSC23K1019 to the University of California, Los Angeles). This report contains the recommendations from this scoping study, which presents the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). NASA outlined ten expectations to be identified for each scoping study:

1. The science questions and issues.
2. The current state-of-the-science.
3. The potential for a major, significant scientific advancement.
4. The central, critical role of NASA remote sensing.
5. The essential scientific components of the study and why coordinated teamwork is required in their implementation.
6. An overall study design identifying the required observational (e.g., spaceborne, airborne, and/or supporting in situ observations) and analytical (e.g., models, data, and information system) infrastructure.
7. The feasibility of the proposed project, both technical and logistical.
8. The engagement of the broader research community to seek feedback on the ideas, to assess interest, and to foster diversity and inclusion.
9. The disciplinary skills needed to conduct the study and engage potential partners in their planning activities.
10. Potential use of results for applications and decision support.

This white paper provides 1) the scientific rationale; 2) an initial study design concept; 3) a presentation of science questions, goals, and objectives; 4) the rationale in terms of state-of-the-art, relevance, and expected advances; 5) implementation concepts; and 6) other information to enable NASA to fully evaluate the project. We outline the PANGEA concept, including the PANGEA Science Themes (*Section 2*), Science Questions (*Section 3*), the scientific and technical advancement arising from PANGEA (*Section 4*), the critical role of NASA remote sensing (*Section 5*), PANGEA’s research strategy and study design (*Section 6*), PANGEA’s capacity-building and training priorities (*Section 7*), community engagement strategy (*Section* 8), ability to enable Earth Action (*Section 9*), and technical and logistical feasibility (*Section 10*).

PANGEA offers a modular approach: We have selected a Core Domain to prioritize ground and airborne measurements in the African tropics, which have major data and knowledge gaps, and comparisons with the tropical Americas. Candidate landscapes in the Core Domain are identified in *Section 6.2.2*. We have also selected an Extended Domain, encompassing pantropical forests elsewhere, including in Asia and Australia. The Extended Domain will be the focus of satellite remote-sensing and modeling analyses. Extended Domain boundaries are identified in *Section 1.4*. During the scoping process, the PANGEA team engaged with a broad community of potential partners in both domains to ensure that, if PANGEA is selected, we will be able to collaborate and coordinate effectively in ongoing and forthcoming efforts.

The PANGEA concept reflects the voices of many and was developed in collaboration with approximately 500 individuals representing around 150 organizations from 42 countries across 5 continents. Workshops were held in Washington DC, Cameroon, Peru, Brazil, and Thailand, with approximately 275 in-person participants. Participants in the scoping process represented many communities, including the academic community in the tropics, as well as in the US and Europe, Indigenous and local communities from the tropics, the NASA community and other US federal agencies, international space agencies, foreign government agencies, civil society organizations, and private industry. The scoping effort underscored the overwhelming need for PANGEA and the timely opportunity it presents to collaborate and coordinate with many existing and forthcoming activities described in this white paper.

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# Introduction and Motivation

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| **PANGEA is a globally collaborative and globally transformative project that will determine whether tropical forests on different continents respond differently to climate and land-use change.** |

PANGEA is urgently needed to (1) ensure the utility of current and forthcoming satellite missions, (2) bridge critical knowledge gaps needed to support global climate and biodiversity goals, and (3) address the risk of collapse of critical tropical forest systems and their functions.

**Tropical forests have far-reaching impacts, encompassing globally significant quantities of carbon, nutrients and water, fluxes of carbon and energy, and the largest proportion of Earth’s biodiversity.** Over 75% of flowering plants, amphibians, terrestrial mammals, freshwater and marine fish, and 91% of Earth’s terrestrial birds have ranges that intersect tropical latitudes (Barlow et al. 2018). Tropical forests store vast amounts of carbon in soils and biomass, with moist tropical forests comprising about 40% of global plant biomass (Xu et al., 2021). As the largest carbon sink among all the forests globally (Pan et al., 2024), they play a critical role in mitigating rising atmospheric carbon dioxide (CO₂), acting as essential buffers against climate change. Tropical forests also mitigate rising global temperatures through evaporative cooling (Bonan 2008; Artaxo et al., 2022). Moreover, tropical forests interact with the atmosphere through complex feedbacks that regulate local weather and regional and global climate. Tropical forests ultimately influence the entire Earth system. For example, Amazon deforestation threatens rainfall patterns in the U.S., potentially reducing precipitation in the Midwest and Northwest (Lawrence & Vandecar, 2015) and causing a 50% decrease in California’s Sierra Nevada snowpack, which supports agriculture and urban water needs (Medvigy et al., 2013). Such changes could alter water availability, reduce crop yields, and destabilize ecosystems, posing risks to food security and societal stability. Additionally, many globally significant commodities such as coffee, palm oil, cocoa and timber originate from the tropics, underpinning global markets and supply chains while contributing to U.S. household basic needs.

**Tropical forests are undergoing rapid change.** Equatorial forest regions will soon experience the highest known temperatures since the Eocene, which, when combined with land-use change, will lead to increasing atmospheric dryness and water stress (Barkhordarian et al., 2019; Ukkola et al., 2020). Tree mortality rates are rising across the tropics due to increases in drought duration and severity, and storm intensity (Allen et al., 2010, Choat et al., 2012, McDowell et al., 2018, Urquiza-Munoz et al 2024). Rising temperatures are approaching hypothesized thermal limits for leaf function, although these limits remain much debated (Smith et al., 2020, Doughty et al., 2023, Winter 2024). In recent decades rapidly changing social-ecological systems have caused unprecedented rates of anthropogenic land-use change (DeFries et al., 2004, Hosonuma et al., 2012, Hansen et al. 2013, Pendrill et al. 2022), which have directly fed into climate changes across the tropics (Smith et al. 2023). As a result he southeastern Amazon is becoming a net source of carbon to the atmosphere (Gatti et al., 2021).

**Tropical deforestation and degradation accounted for 22% of annual anthropogenic CO2 emissions from 1990-2020** (Pan et al., 2024), although these emissions are partially offset by regrowing secondary tropical forests (Aragão et al., 2014; Rosan et al., 2024). 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 have drastically altered tropical forests disturbance dynamics and now threaten many tropical species with extinction (Feeley et al., 2012; Barlow et al., 2016; Benitze-Lopez et al., 2017; Alroy 2017; Dirzo et al., 2014). This biodiversity loss could in turn compromise the resilience of tropical forest structure and function, biogeochemical cycles, and socio-ecological systems (Bunker et al., 2005; Peres et al., 2016). Even after factoring in the greater species diversity, tropical regions are experiencing defaunation at the highest rate globally (Dirzo et al. 2017).

**Studies over the past 10 years have revealed that the trends and interannual variability of net biome carbon exchange of tropical forests varies markedly across continents** (Brienen et al., 2015; Liu et al., 2017; Hubau et al., 2020). From 1985 to 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 CO2 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 on different continents that will require regionally specific understanding and management to mitigate. The sources of atmospheric CO2 concentrations, as measured by the Orbiting Carbon Observatory-2 (OCO-2), Greenhouse Gases Observing SATellite (GOSAT), and Measurements Of Pollution In The Troposphere (MOPPIT), suggest that in the tropical Americas, lower photosynthetic rates led to reduced carbon uptake that changed the CO2 balance to net emissions. In Africa, increased temperatures led to increased respiration, which outweighed the sequestration benefits of Central African tropical forests (Liu et al. 2017). In Asia, a hotter and drier land surface resulted in more CO2 emissions from fires (Liu et al., 2017).

**Many tropical forests have floodplains and are interspersed with wetland and aquatic ecosystems, which play a critical role in global methane (CH4) budgets as well as the CO2 cycle** (Sjögersten et al., 2014; Peng et al., 2022). Tropical wetland and inland freshwater systems contribute the vast majority of natural global aquatic CH4 emissions and make up roughly 20% of the total global CH4 budget of ~575 Tg CH4 yr-1 (Saunois et al., 2020; Peng et al., 2022). Tropical CH4 sources are also the most uncertain component of the global carbon budget (Saunois et al., 2020, 2024). The expansion of deforestation and forest degradation, combined with changes in climate, significantly impacts overland water flows, river discharge and water quality. These in turn affect biogeochemical cycles; habitat suitability for freshwater plant, animal, algal, and microorganism communities; water resources for humans; and hydropower production (Castello and Macedo, 2016; Guimberteau et al., 2017; Taniwaki et al., 2017; Arias et al., 2020).

Data from NASA satellite missions and airborne campaigns, validated by ground-based measurements, play a critical role in advancing understanding of how forest ecosystems and biodiversity are responding to environmental changes. **However, before satellite data can be useful for scientific analysis or operational use, ground-based measurements are critical to calibrate and validate satellite observations. The scarcity of ground-based observations and airborne measurements 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 Soil Moisture Active Passive (SMAP) satellite retrievals exhibit 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 retrievals in tropical forests (Wang et al., 2024). Another example of measurement scarcity in the tropics is the lack of ground-based validation data for space-based CO2 retrievals over the tropics, especially tropical Africa, which has led to an ongoing debate about the magnitude of net biosphere exchanges over tropical Africa (Palmer et al., 2019; Gaubert et al.,2023). Similarly, in spite of the urgent need to assess global biodiversity at scale to evaluate the effectiveness of biodiversity conservation efforts, the biodiversity monitoring capabilities using satellite remote sensing are in their infancy.

Reducing biases in retrievals of soil moisture and atmospheric column CO2 and advancing new measurement capabilities directly related to biodiversity (e.g., canopy tree beta diversity) and proxies (e.g., diversity networks) is critical to advance understanding of the water cycle, carbon fluxes, biodiversity, and ecosystem dynamics. Validating satellite and airborne observations with ground-based measurements is essential to the success of NASA’s Earth observation missions, particularly with the advent of an exciting fleet of new and forthcoming sensors that have the potential to capture the multidimensionality of these systems (e.g., the NASA-Indian Space Research Organisation SAR [NISAR] and Surface Biology and Geology [SBG] missions). 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.

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| **Tropical forests are the least investigated of all the Earth’s major terrestrial biomes.** |

**Methods to validate satellite and airborne observations used in PANGEA include forest inventory plots, eddy-flux tower sites, other ground measurements, and Indigenous, Traditional, and Local Ecological Knowledge (IEK, TEK, LEK) that provide valuable insights into biodiversity, forest dynamics and ecosystem functions** (e.g., ForestPlots.net et al., 2021; Anderson‐Teixeira et al., 2014, Davies et al., 2021, https://fluxnet.org/). However, because of accessibility and funding challenges, the current coverage and distribution of these measurements across the tropics, particularly in Africa, is sparse and seldom follows a pattern of random or systematic sampling required for statistical power and lower bias (Goetz et al., 2015; Bustamante et al., 2016). Consequently, extrapolation from limited plot locations may lead to significant uncertainties and biases (Saatchi et al., 2015; Tejada et al., 2020). The latitudinal distribution of both forest inventory plots and eddy covariance flux towers demonstrates the underrepresentation of tropical forests in global research efforts, revealing that the fewest towers and plots are found in tropical forest regions, despite having the highest gross primary productivity and methane emissions from natural sources (Baldocchi, 2020, Schimel et al., 2015) (Figure X). In addition, the glaring data, methods, and knowledge gaps in the tropics currently limit efforts to develop global maps of diversity using hyperspectral retrievals (e.g., functional trait maps) (Dechant et al., 2024). Expanding observations of structural and functional traits and ecosystem function metrics in tropical forest regions will provide calibration data and enable a significant improvement in characterizing patterns and processes that drive the dynamics of highly diverse tropical forests. In addition to statistical and process-based models, artificial intelligence and machine learning techniques have grown considerably over the last decade and can now be used to rigorously scale ground measurements to airborne and satellite observations regionally and globally (Aguirre-Gutiérrez et al., 2021; Dalagnol et al., 2022; Lines et al., 2022).

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| **Scarce data on tropical forest structural and functional diversity impacts on carbon, water and energy cycles limits our ability to understand the role of tropical forests in the Earth’s system.** |

**Earth System Model (ESM) predictions of carbon flux have three times greater uncertainty in the tropics than at other latitudes** (Cavaleri et al., 2015). Robust remote-sensing based products describing the carbon, water, and energy cycles of tropical forests, as well as improved process characterization, are critical for understanding tropical forest-climate interactions and feedbacks and constraining predictions of ESMs. Predictions from ESMs participating in the Coupled Model Intercomparison Project (CMIP) diverge markedly in magnitude and in conclusions as to whether the land is a carbon sink or source (Arora et al., 2020; Friedlingstein et al., 2006; Friedlingstein et al., 2014; Negron-Juarez et al., 2015). While model development between CMIP - Phase 5 (CMIP5) and CMIP - Phase 6 (CMIP6) 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, ESMs ignore most biodiversity and represent tropical vegetation in simple, aggregated ways that do not capture tropical forest responses to climate variation and disturbance and contribute to model failure (Levine et al., 2016; Yang et al., 2023; Sakchewski et al., 2016; Schmitt et al., 2020).

**Constraining this uncertainty requires improved representation of ecological processes of diverse ecosystems** (Bonan et al., 2024). Newer generations of terrestrial biosphere models and vegetation demography models, such as Ecosystem Demography Model version 2 (ED2), Functionally Assembled Terrestrial Ecosystem Simulator (FATES) and BiomeE, include more structurally and functionally diverse forest canopies (Fisher et al., 2018; Longo et al., 2019; Koven et al., 2020; Weng et al., 2022). 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 currently be derived only for small areas of interest from forest plots (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 lidar, radar, and hyperspectral remote sensing provide a unique opportunity to collect data on the structure, composition, and biodiversity of tropical ecosystems at landscape scales and thereby improve model parameterization, initializing, benchmarking, and process development (Schimel et al., 2019; Schimel and Carroll, 2024).

To address these needs and in response to a call from the NASA Terrestrial Ecology Program, we present below the scope of a terrestrial ecology field project, the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA), that will advance understanding of the processes controlling changes across pantropical forest biomes and their integrated feedbacks with Earth’s climate.

FIGURE PLACEHOLDER

**PANGEA employs a science-to-scale strategy, taking an integrated systems approach that encompasses complex landscape mosaics spanning forests to wetlands and peatlands, and intact to disturbed agricultural social-ecological systems.** Transdisciplinarity and collaborative co-production are at the heart of PANGEA. PANGEA will ensure the equitable and transdisciplinary collaboration among researchers, governments, institutions, and Indigenous Peoples and Local Communities (IPLCs) to integrate diverse expertise and knowledge. This approach will enable a more comprehensive understanding of the role of tropical forests in the Earth system and will empower locally guided solutions to climate change and biodiversity loss. PANGEA’s nested design, with a science-to-scale approach described in more detail in *Section 6.1.1*, will advance satellite monitoring, remote sensing product development, and the assimilation of data and benchmarking of various processes in next-generation ecosystem models, which can significantly advance long-term prediction capabilities. To ensure coordinated measurements and analyses, PANGEA has been designed in collaboration with many aligned current and forthcoming activities including European Space Agency (ESA) campaigns and missions, Group on Earth Observations-Trees (GEO-TREES), and the One Forest Vision Initiative (OFVi). Suborbital remote sensing retrievals (e.g., drone and aircraft) are critical elements of PANGEA, which are needed to scale between ground measurements and coarser resolution satellite retrievals. In this regard, PANGEA stands on the shoulders of highly successful NASA field and airborne projects to Africa and the Americas, including SAFARI 2000, AfriSAR-1 and -2, Biodiversity Survey of the Cape (BioSCape), and several Earth Venture Suborbital (EVS) missions.

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| **PANGEA will go beyond LBA (Large-Scale Biosphere-Atmosphere Experiment in Amazonia) and beyond the Amazon, employing novel satellite technologies and observations unavailable during LBA, to advance science and monitoring capabilities pantropically.** |

**Earth Action Relevance: Implementation of PANGEA will empower and enable decision-makers to benefit fully from current and future Earth observing satellite missions to take effective, regionally tailored action to mitigate the impacts of climate and land use change and conserve and regenerate globally important tropical forest biomes.** PANGEA’s objectives (*Section 1.1*) are directly aligned with NASA’s Earth Action programs, including Climate & Resilience, Water Resources, Ecological Conservation, and Agriculture. In order to mitigate climate and land-use change impacts to tropical ecosystem function and biodiversity, and to conserve these globally important biomes, action must be taken. This action requires improved understanding of the diverse ways in which tropical forests on different continents are responding to change and requires cutting-edge methods and technologies to deploy solutions.

**PANGEA will develop the science needed to scale ground measurements to satellite monitoring capabilities and to scale local knowledge and action to global solutions.** PANGEA will map and quantify the long-term stability of carbon sequestration and methane fluxes to improve future predictions, and support climate change mitigation and adaptation efforts. PANGEA will also advance methods for mapping biodiversity and ecosystem processes to develop enhanced understanding of tropical forests, to support biodiversity conservation spans biodiversity variation at levels of genes, species, communities, and ecosystems. These efforts will be carried out through equitable, collaborative, co-developed activities with Indigenous and local communities that will weave Indigenous, Traditional, and Local Ecological Knowledge (IEK, TEK, and LEK) with remote sensing data and other forms of data and knowledge (see *Sections 6.2.4, 7.2, and 8* for more details). In addition, PANGEA’s scientific and technical advances, guided by action-taking partners, will support the regionally tailored development of farmers' climate change adaptation strategies, the development of socio-bioeconomies, improved traceability of agricultural commodities to their origin, and the creation of disaster alerts to guide rapid response. These elements cut across PANGEA’s Science Questions (*Section 3*) and Earth Science to Action Strategy (*Section 9*).

PANGEA will

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

**PANGEA was developed based on the input of approximately 500 individuals representing over 150 organizations from 42 countries across 5 continents during the scoping effort** through working group activities, 5 workshops, 10 town halls, 18 conference presentations and symposia, and over 150 bilateral meetings. Workshops were held in Washington DC, Cameroon, Peru, Brazil, and Thailand, with over 275 in-person participants and X virtual attendees. Participants in the scoping process represented many communities, including the academic community in the tropics, as well as in the U.S. and Europe, Indigenous and local communities from the tropics, the NASA community and other U.S. federal agencies, international space agencies, foreign government agencies, civil society organizations, and private industry. This scoping effort underscored the overwhelming need for PANGEA and the timely opportunity it presents to coordinate with many current and forthcoming activities as laid out in this white paper.

This white paper provides 1) the scientific rationale; 2) an initial study design concept; 3) a presentation of science questions, goals, and objectives; 4) the rationale in terms of state-of-the-art, relevance, and expected advances; 5) implementation concepts; and 6) other information to enable NASA to fully evaluate the project. In the remainder of *Section 1*,we provide an overview of PANGEA. We then detail the PANGEA concept, including the PANGEA Science Themes (*Section 2*), Science Questions (*Section 3*), the scientific and technical advancement arising from PANGEA (*Section 4*), the critical role of NASA remote sensing (*Section 5*), PANGEA’s research strategy and study design (*Section 6*), PANGEA’s capacity-building, training, and education priorities (*Section 7*), community engagement strategy (*Section*8), ability to enable Earth Action (*Section 9*), and technical and logistical feasibility (*Section 10*).

## Overview of Science Themes, Questions, and Objectives

**Knowledge of tropical forest biogeochemical cycles, biodiversity, climate feedbacks and interactions, socio-ecological systems, and disturbance dynamics are critical for predicting the response of tropical forests to climate and land use change.** Understanding these factors is also crucial for predicting the future of the Earth system and for developing forest and biodiversity conservation and change mitigation strategies. PANGEA’s research themes and questions were developed through an inclusive consultative process with contributions from hundreds of scientists on five continents (See *Section 8.1*). The resulting themes and questions emphasize resolving uncertainties related to multidecadal trends and responses to extreme events across five thematic areas:

* Biogeochemical Cyclesencompass 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 and biomass turnover; nonetheless tropical forests play a significant role in global carbon storage.
* Biodiversityis the variety of life on Earth, including its variation within and between species and ecosystems (genetic, phylogenetic, taxonomic, and functional diversity). 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 Feedbacksare the bidirectional interactions between climate systems and ecosystems. Tropical forests directly 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 Systemsare 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- to global-communities, while ecological changes impact social well-being, creating complex feedbacks between human activities and ecosystem stability.
* Disturbance Dynamicsvary 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 biogeochemical cycling, biodiversity, and feedbacks to climate and to social-ecological systems.

Using these themes PANGEA will answer the overarching question: **How vulnerable or resilient are tropical forest landscapes to climate and land-use change and what are the feedbacks from forest change on the global carbon cycle and climate?**

Addressing this broad question of tropical forest vulnerability and feedbacks, and informing forest and biodiversity conservation, and climate mitigation and adaptation strategies requires PANGEA to answer three transdisciplinary sub-questions:

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

To address the above questions, PANGEA’s objectivesare to

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

Ideally, PANGEA would be carried out across the entire tropics. In reality, PANGEA will need to be more limited in scope due to budget constraints and prioritization of what is achievable within a 6-to-9-year time frame. Limiting PANGEA to one tropical continent, however, prevents PANGEA from attaining within and between continent comparisons. For these reasons, PANGEA research and activities will prioritize the investigation of differences between the Earth’s two largest extents of tropical forests in the **Americas** and **Central Africa**. Both depend strongly on recycled rainfall (Baker and Spracklen, 2022) but have responded differently to decadal drying trends (Asefi-Najafabady & Saatchi 2013; Saatchi et al. 2013) and have been subject to contrasting land-use regimes (Malhi et al., 2013; Berenguer et al., 2021). These continents also show contrasting, albeit uncertain, projections in precipitation trends (Cook et al., 2020; Dobler et al., 2024). The focus on these two continents, while integrating datasets and research from existing and complementary activities across the tropics, will illuminate the importance of current states and processes more than a focus on a single region.

## The Urgent Need for PANGEA

Implementing PANGEA is urgently needed for three reasons. First, studies suggest the potential collapse of tropical forest ecosystems within decades, which could drastically impact the global carbon and water cycles, exacerbating climate change (Lovejoy and Nobre 2018, Malhi et al., 2009; Boulton et al., 2022; Wunderling et al., 2022). Given the critical role 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). Second, ground based research remains scarce, and there remains a lack of knowledge to adequately understand science data from satellite missions from both current —e.g. **GEDI** (Global Ecosystem Dynamics Investigation), **EMIT** (Earth Surface Mineral dust source Investigation), **OCO-2/3** , and **ECOSTRESS** (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station), and future missions e.g., **NISAR\***, **BIOMASS\***, **EDGE\***, and **SBG\***. PANGEA will provide a unique opportunity to obtain ground and airborne data with coordinated, well-timed international efforts, to understand the signals from these missions, and to develop and calibrate data synthesis and data assimilation methods, and also drive and benchmark terrestrial biosphere and social-ecological system models. Failing to capitalize on these missions to coordinate them with ground-based measurements will miss a unique opportunity for reducing uncertainties in regions with the highest carbon stocks and major contribution to carbon, water, energy, and nutrient cycling amongst land ecosystems (Schimel et al., 2015; Schimel et al., 2019). Third, the risk of critical transitions in tropical forests differs across tropical forest biomes (Liu et al. 2017), with recent examples showing pronounced differences between Africa and the Americas (Hubau et al., 2020; Bennett et al. 2021, 2023). We are just beginning to understand the mechanisms behind these differences, along with the underlying structural and functional diversity of tropical forests. PANGEA will bridge critical knowledge gaps, enabling timely advances 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, the utility of missions including NISAR and SBG, as well as tools to implement and evaluate global climate and biodiversity commitments.

Figure X. PANGEA evolution figure placeholder.

## Role of Remote-Sensing Observations

**PANGEA will fill critical data and methods gaps to advance scaling between a multitude of ground measurements and satellite and airborne observations.** We are in an unprecedented data-rich, model-rich, and computationally advanced moment. In recent years, spaceborne lidar, microwave radar, hyperspectral, altimeter, and other remote sensing capabilities have become operational at multiple scales. The satellite and airborne sensors allow more direct retrievals of atmospheric CO2 and CH4 concentrations, groundwater and surface water flows that can reveal lateral flows of carbon and nutrients, as well as structural, functional, and in some cases taxonomic diversity of forests. However, in tropical forest regions, ground observations are scarce, limiting the global utility of satellite sensors. Few tropical forest countries have regularly repeated, systematic forest and wildlife inventories, flux towers, or meteorological data, especially in tropical Africa. The limited number of research sites and ground measurements will, however, provide critical information on biogeochemical, ecological, and hydrological processes. The scarcity of these data makes it challenging to scale up measurements and analyses to regional, continental, or pantropical regions. PANGEA will conduct coordinated data collection and advance methods to scale between ground and tower measurements and airborne and spaceborne observations more accurately.

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| **To fully leverage new satellite observations from new sensors, we require coordinated calibration and validation data. Major data gaps and process uncertainties in tropical forests currently limit algorithm and product development, preventing the global utility of these satellite sensors from being fully realized.** |

**The constellation of international Earth Observing satellites in service today, those nearing launch, and those in the early stages of planning and implementation offer many dimensions of information not previously available nor widely used in tropical forest studies.** The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) (Avissar et al. 2002, Davidson et al., 2012, Keller et al. 2009), NASA’s previous tropical forest project, began in 1998 before the launch of EOS Terra and Aqua satellites. Landsat was then the primary tool for monitoring deforestation (Skole and Tucker 1993) and through the first decade of LBA research it was applied to estimate logging (Asner et al., 2005) and understory forest fires (Morton et al., 2011). Remote sensing information in early ecological models, such as the Carnegie-Ames-Stanford (CASA) biosphere model (Potter et al., 1993), originally incorporated normalized difference vegetation index (NDVI) data from polar-orbiting weather satellites (AVHRR) calibrated to net primary productivity. Understanding these data matching challenges 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). LBA filled a void in knowledge, developing baseline understanding of the vulnerability of the Amazon to climate change. Moreover, LBA created a self-sustaining, vibrant research community that has thrived in Brazil and still influences all of South America. LBA was limited by the Amazon focal area, and the type and availability of both field observations and remote sensing data. The ongoing Next Generation Ecosystem Experiment in the Tropics project (NGEE-Tropics, https://ngee-tropics.lbl.gov) focuses on the predictability of tropical ecosystem processes at site-specific scales and increasing the ability to upscale these insights to continental and pantropical levels remains a critical challenge. PANGEA will address the limitations of previous efforts by harnessing more recent and future remote sensing data to scale ecosystem states and processes. This approach paves the way for a more comprehensive and predictive understanding of tropical ecosystems from local to pantropical scales. **New satellite sensor technologies are moving beyond assessing greenness,** (see *Section 5*) **and are providing much deeper insights into the function of tropical forests to enable more direct measurements of ecosystem fluxes, biodiversity, and responses to change.**

**Understanding tropical forests at scale requires satellite remote sensing linked with ground-based measurements.** The knowledge gaps (see Section 3) that PANGEA will address cannot be answered without pan-tropical satellite observations, integrative analyses, and models. Effectively advancing the use of satellite remote sensing requires thoughtful, creative, and rigorous integration of different forms of data across spatial and temporal scales. The abundance of new satellite data, paired with advances in cloud computing, machine learning, and AI will enable more robust data analysis than in previous NASA TE projects, such as LBA. Currently, there are challenges from scarce ground observations and scale mismatches with tropical satellite data that prevent the validation of remotely sensed metrics and AI model development. PANGEA addresses these issues by integrating ground, tower, drone, aircraft, and satellite measurements with scaling approaches refined in prior projects such as the Arctic-Boreal Vulnerability Experiment (ABoVE).

## The PANGEA Terrestrial Ecology Field Campaign and Study Domain

**PANGEA is a multi-phase, multi-year project consisting of satellite and airborne remote sensing, ground measurements, and landscpe-scale campaigns.** PANGEA’s activities will measure a suite of variables to characterize the structure, function, dynamics, fluxes, and social-ecological systems of diverse forest landscapes across the tropics. Using a modular and flexible campaign design, PANGEA will advance satellite remote sensing capabilities over the tropics to understand the heterogeneous responses of tropical forests to climate and land-use change. PANGEA will acquire collocated ground-based measurements with airborne remote sensing data (e.g., hyperspectral, lidar, SAR, carbon fluxes) that have hitherto only been collected in a few locations across the tropics at different points in time, by different organizations, and with differing methods.

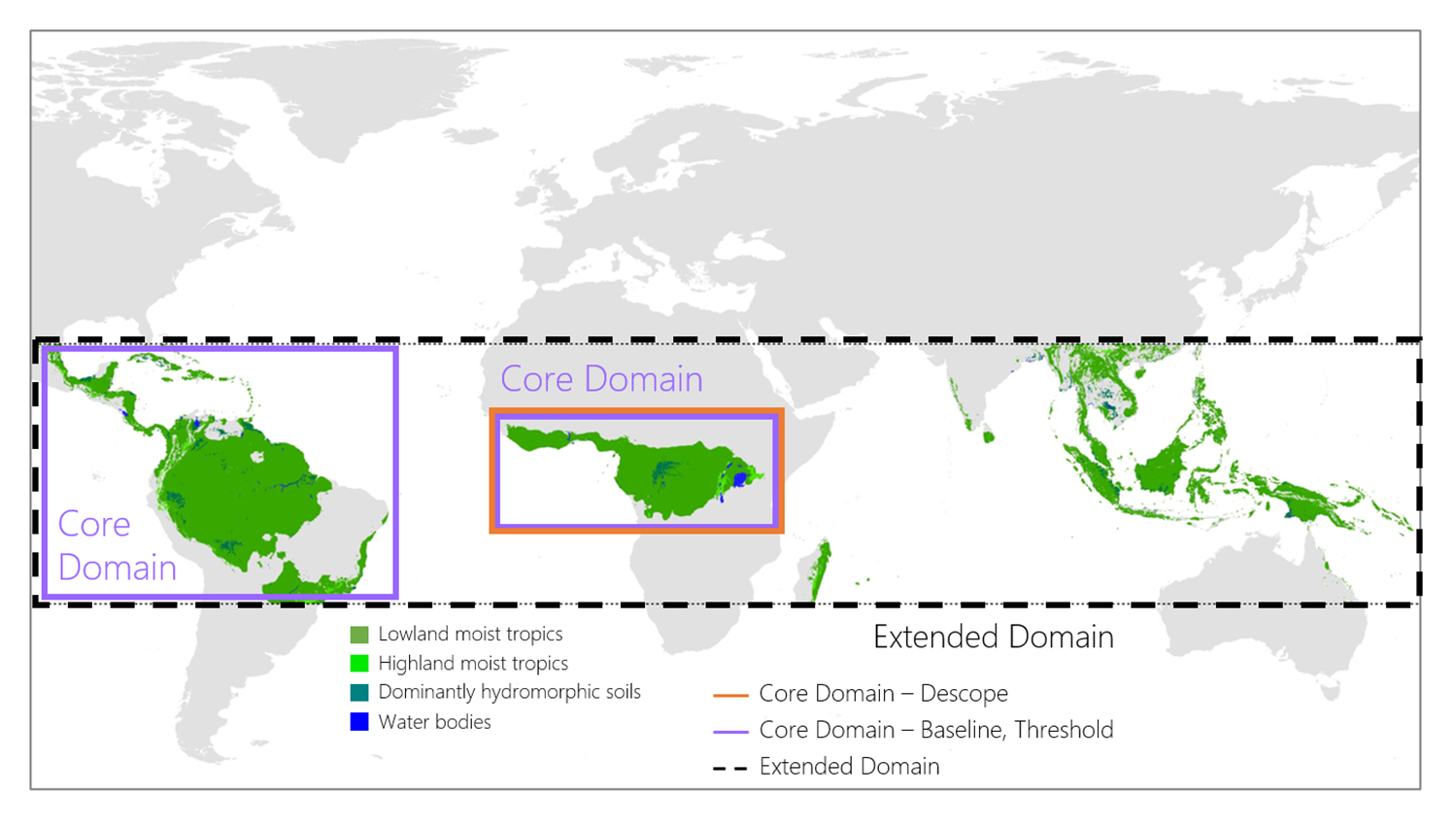


Figure X. PANGEA’s **core** domain, under the **Baseline** and **Threshold** (solid purple lines) and **Descope** (solid orange line) levels of **Essential Scientific Measurements**, and **extended** domain (dotted black line). Boundaries were sourced from the following GAEZv4 agroecological zones: lowland humid tropics, highland humid tropics, dominantly hydromorphic soils, and land with severe soil/terrain limitations.

PANGEA will include a **core** and an **extended** domain. The core domain is where the NASA-funded component of coordinated ground, tower, drone, and aircraft field campaigns will take place within multiple large (approximately 10,000 km2) landscapes. *Section 6.2.2* outlines the Candidate Landscapes assessed during the scoping process that would be evaluated during the PANGEA Science Definition phase, prior to final selection. The extended domain will encompass pantropical moist forests and is the broader area of scientific interest, where additional projects can take place through partnerships, and where satellite and modeling analyses will be emphasized. Box 1 describes a preliminary assessment of heterogeneity within key geographic landscapes in PANGEA’s extended domain. The PANGEA domain (core + extended) covers tropical forest social-ecological systems and associated landscapes found in the humid tropics and the spatial scale required to address the primary questions (*Section 3*). Both the core and extended domains will encompass moist tropical forests, including flooded forests, wetlands, and peatlands.

PANGEA will leverage NASA’s Terrestrial Ecology investment for its core resources. To account for a range of NASA funding scenarios to PANGEA, we have derived the **Baseline**, **Threshold**, and **Descope** levels of **Essential Scientific Measurements** from the PANGEA Science Objectives (see *Section 6.2.1* for details). The Essential Scientific Measurements will enable PANGEA 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. As noted above, PANGEA’s core domain covers tropical moist forests in Africa and, depending on the Essential Scientific Measurement level, tropical moist forests in the Americas (Figure X).

Here we present an overview of the Strategy and Study Design, described in detail in *Section 6*. We will focus PANGEA landscape campaigns and measurement activities at the start and end of the dry seasons. At the start of the dry season, measurements will capture system dynamics at a period of less stress, immediately following the heavy wet season. This time period enables coordinated multi-scale measurements that are unachievable during peak wet season, when cloud cover limits optical remote sensing over the tropics. Measurement campaigns at the end of the dry season will capture times when tropical social-ecological systems are at their most stressed in terms of water and temperature. While we recognize that data collected only during the dry season risks biasing understanding of tropical forests given the strong seasonal differences in dynamics and processes, including carbon cycling, hydrodynamics, species interactions, and land-use activities (e.g., fire and clearing), the need to obtain concurrent terrestrial, airborne, and satellite measurements makes this a pragmatic decision. At the end of the wet season, most processes operating during peak wet season will still be present. For this reason, PANGEA will still be able to capture seasonal differences by focusing on the start and end of the dry season. To meet PANGEA’s science and applications objectives, three potential strategies are presented:

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

The Baseline, Threshold, and Descope measurements detailed in *Section 6.2.1* represent stand-alone NASA funded projects, without any dependency on non-NASA funds or synergistic efforts (Table X). Intensive campaigns within these strategies are conceived to be implemented as stand-alone modules with limited dependencies so that the overall schedule and budget profile can be flexible. 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 10.3* for more details). Unless otherwise noted, the core domain in the white paper refers to the one defined for the Baseline level of Essential Scientific Measurements.

Table X. PANGEA achievables across the Baseline, Threshold, and Descope versions.

|  |  |  |  |
| --- | --- | --- | --- |
| Achievable | Baseline | Threshold | Descope |
| Variability across continents | Yes | Yes | No |
| Variability within continents | Yes | Limited | Limited |
| Tropical forest functioning along environmental gradients | Multiple gradients and intercontinental comparisons. | Single gradient. Indirect effects through intercontinental gradients. | Single gradient or co-linear. |
| Ability to provide calibration data in critical regions | Very strong | Strong | Moderate |
| Success contingent on external partnerships and funding | Not contingent | Somewhat contingent | Very contingent |
| Ability to answer PANGEA’s key scientific questions | Fully | Mostly | Partially |

The location of these primary research areas within the core domain will be based on (1) opportunities to conduct integrated research across science themes (*Section 2*); (2) the occurrence of key variability with respect to biotic, abiotic, and disturbance dynamics (Figure X); and (3) the existence of ongoing or planned research funded by NASA, as well as relationships with and ongoing activities conducted by local and international collaborators and institutions. During the scoping study, an initial variability analysis across the extended domain was conducted to evaluate spatial heterogeneity (see Box 1).

**Map

Description automatically generated**

**Figure X.** Results from the initial variability analysis described in Box 1. For each continent, we defined 15 clusters describing the forest heterogeneity across landscapes, using climate, forest structure, composition and function, biodiversity, land-use, land cover, and disturbance history datasets. Clusters of each continent were defined independently and shown in different random colors. The same color in different continents does not indicate correspondence of environmental conditions across continents.

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| --- |
| Box 1. Assessment of heterogeneity within PANGEA’s Extended Domain.  Tropical forest ecosystems are heterogeneous, and the patterns of forest structure, species composition, and function emerge from interactions between climate, geological history, soils, topography, biogeography, natural disturbance, biotic interactions, and land-cover and land-use change. PANGEA’s field campaigns will be designed to capture and sample forests that span multiple heterogeneous landscapes. To guide the selection of landscapes, the PANGEA team performed a cluster analysis of tropical forest ecosystems that accounted for multiple drivers of heterogeneity (Figure X). This analysis was based on (1) forest structure from live biomass and net carbon fluxes (Harris et al., 2021) and canopy height (Lang et al, 2023); (2) biodiversity metrics from the species richness for non-plant taxa (e.g., IUCN, 2024); (3) solar-induced chlorophyll fluorescence (SIF) (Li and Xiao, 2019) as a proxy of gross primary productivity (GPP); (4) mean annual temperature and total precipitation from ERA5 (Hersbach et al., 2020) and long-term climatic water deficit (Chave et al 2014); (5) soil nitrogen and clay content from SoilGrids2.0 (Poggio et al., 2021); (6) topographic information from the height above nearest drainage (Donchyts et al 2016); and (7) a global human modification dataset (settlements, agriculture, transportation, mining, energy, and infrastructure) (Kennedy et al 2019). To ensure the landscapes were consistent with evolutionary history, each continent was analyzed separately, leading to 15 unique clusters for each region (tropical Americas, Africa, and Australasia). This initial assessment did not account for the uncertainty in the datasets, and did not seek to identify the most parsimonious number of clusters. PANGEA will refine this approach during the Science Definition phase, and combine these results with the list of candidate landscapes (*Section 6.2.2*), regions dominating model and data synthesis uncertainty (*Section 6.3.1*), and the assessment of technical feasibility (*Section 10*) to define the priority landscapes in the Concise Experiment Plan (*Section 10.5*). |

Airborne campaigns will be a major component of the landscape-scale baseline, threshold, or descope data acquisitions. These will include airborne flux observations data to measure CO2, CH4, sensible heat, and latent heat fluxes at high spatial resolution, hyperspectral reflectance and small footprint lidar to measure canopy leaf traits, vegetation structure, synthetic aperture radar (SAR) data to measure wetlands, seasonally flooded systems, and disturbance dynamics, and small-footprint lidar to measure high fidelity vertical and horizontal heterogeneity in ecosystem structure and plant area index. Ground-based measurements and knowledge are crucial to (1) validate both airborne and satellite observations, (2) uncover ecological mechanisms, and (3) evaluate scale dependencies in tropical ecosystems. PANGEA addresses all three of these gaps in tropical forests through partnerships with local organizations and existing infrastructure to expand field observations and advance data and knowledge integration, including manual in situ data and TEK (e.g., floristic, faunal, and phylogenetic diversity, species interactions, disturbance dynamics, land-use activities); automated in situ data (e.g., sap flux measurements, camera traps, and bioacoustics sensors); eddy covariance flux and meteorological data; tower-based proximal remote sensing (e.g., SIF, thermal infrared radiation, VOD, and phenological cameras [PhenoCams]); and drone-based proximal remote sensing. A suite of models will be developed from the data and information collected, as well as synthesis products derived from the acquired datasets, which will be used to initialize, provide boundary conditions, and benchmark process-based models (*Section 6.3*). PANGEA’s remote sensing and ground measurements for data-model integration will help generalize mapping capabilities across the tropics, and model carbon, water, and energy fluxes and their relationships with biodiversity to examine the stability of tropical forests under future climate projections.

## The Need for Coordinated Data Collection and Teamwork

**Recognizing the deep imprint that colonialism has left on tropical forest research, along with parachute and flyover science** (Culotta et al., 2024), **PANGEA takes an interactive and interwoven approach to ensure equitable and ethical engagement with scientists, institutions and partners from governments, and Indigenous Peoples and Local Communities (IPLCs).** Several sections describe PANGEA’s approach to community engagement (*Section 8*), an inclusive organizational structure (*Section 10.1*), Earth Science to Action (*Section 9*), training and education (*Section 7*), open science and data management (*Section 10.3*), and international agreements when conducting airborne campaigns (*Section 6.2.4*). PANGEA’s approach is built upon the recognition that Earth system science is inherently multifaceted and complex. The NASA Terrestrial Ecology Program has promoted the multi-investigator model for decades of field campaigns that span the First ISLSCCP Field Experiment (FIFE), the Boreal Ecosystem-Atmosphere Study (BOREAS), the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), and ABoVE. PANGEA will also foster close collaboration with key U.S. institutions, including **USDA**, **USFS**, **DOE**, **USGS**, the **Smithsonian**, leading universities, including **Penn State**, the **University of Oklahoma**, **UCLA**, and the **University of Maryland**, and Indigenous communities, including the **Global Alliance of Territorial Communities** **(GATC)**. These partnerships span diverse research efforts, integrating expertise across disciplines to address critical knowledge gaps and the multiple drivers and interacting processes for understanding of tropical forests. Many variables require expert knowledge, ranging from the acquisition and use of satellite observations, and instruments such as a high-performance imaging spectrometer to the botanical identification of tree species or traditional knowledge of species interactions. 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 requires a large team of specialists working together. **PANGEA requires strong collaboration to ensure that measurements are coordinated in time and space to maximize their value in interpretation and modeling. This can be achieved only through a cooperative, coordinated, interdisciplinary team. To include, empower, and advance groups historically underrepresented in science, technology, engineering, and mathematics (STEM)–for example, people who identify as Black, Indigenous, Hispanic, women, or with disabilities–PANGEA will prioritize ethical and equitable engagement throughout.**

## Earth Science to Action

The Earth System with its interconnected geophysical, biological, and social systems is experiencing a particularly unique moment in its history. We must take the opportunity to benefit from the incredible advancements in modern tools, computing power (including AI), and research infrastructures. These advances will help people to take decisive action to conserve forests and biodiversity, mitigate and adapt to climate and land-use change, and improve food and water security and human health. Accelerating rates of change in the tropics drives the urgency to apply insights from the frontiers of NASA Earth Science. 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](https://assets.science.nasa.gov/content/dam/science/esd/earth-science-division/earth-science-to-action/ES2A_Booklet_web.pdf)), 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, 2017).

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| **PANGEA will build upon the strategic investments and 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’s Earth Science to Action (ES2A) contributions to advance and integrate Earth science knowledge to empower humanity to create a more resilient world are described in Section 9 in detail. In short, PANGEA supports NASA’s ES2A strategy by

* *Investigating the risks of crossing critical thresholds and the potential for cascading environmental and societal impacts.*
* *Supporting efforts to enhance Earth’s resilience through the assessment of risks and contingencies and the development of mitigation and adaptation strategies to respond to global changes.*
* *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, policymakers, and action-takers.*

# 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 introduced in *Section 1.1*: Biogeochemical Cycles, Biodiversity, Climate Interactions and Feedbacks, Social-Ecological Systems, and Disturbance Dynamics. Understanding patterns and processes and constraining the uncertainty of future projections 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 across the science themes. *Section 4* describes how addressing these questions will yield major scientific advancements.

## 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, providing information that will improve future projections.

**Tropical Net Biosphere Exchange of carbon dioxide:** Atmospheric carbon dioxide (CO2) is a greenhouse gas (GHG) that has a major impact on the global climate system. The terrestrial biosphere is a large sink of atmospheric CO2with a present-day global net biosphere exchange (NBE) estimated at 3.3 Pg yr-1, offsetting ~30% of the CO2 emitted by fossil fuels annually (Friedlingstein et al., 2023). NBE refers to the total balance of CO₂ exchanged between an ecosystem and the atmosphere. Tropical terrestrial ecosystems contribute up to 0.6±0.4 PgC yr-1 of this sink (Friedlingstein et al., 2023) and contribute strongly to atmospheric global CO2interannual variability (Friedlingstein et al., 2023). Over the past three decades tropical deforestation has negated about two-thirds of the benefits derived from the global forest sink (2.2±0.5 Pg C yr−1, 1990-2019; Pan et al., 2024). Differences in the effectiveness of the tropical forest carbon sink within and between continents are evident. Previous research indicated that, from 2001 and 2019, the Amazon region (5.14 million km2) was a weak net carbon sink (−0.03 Pg C yr−1), with gross uptake (−0.4 Pg C yr−1) and gross emissions (0.3 Pg C yr−1). This is nearly one order of magnitude larger than the net sink. Brazilian Amazon live biomass alone was a net source of carbon (0.06 Pg C yr−1; Harris et al., 2021). In contrast, the smaller African Congo Basin (2.98 million km2) was a considerably stronger carbon sink (−0.17 Pg C yr−1) than Amazon forests despite having similar gross uptake rates (−0.3 Pg C yr−1). The magnitude of gross emissions in the Congo Basin (0.14 Pg C yr−1) was about half that of the emissions in the Amazon (Harris et al. 2021). Understanding the mechanisms that drive the differences in carbon fluxes across tropical forest regions to quantify the spatial temporal distribution of carbon fluxes and their role in global carbon cycles, is a research priority.

**Methane:** Atmospheric methane (CH4) is 25 times more potent as a GHG than CO2and contributes an estimated 30% of the increase in radiative forcing from anthropogenic emissions (Masson-Delmotte et al., 2021). The tropics contribute roughly 65% of total (anthropogenic + natural) global CH4emissions to the atmosphere (364 Tg CH4yr-1) (Saunois et al., 2024). Around 40% of total CH4emissions from the tropics are from wetland, floodplains, and inland freshwater ecosystems sources (151 Tg CH4 yr-1), representing roughly 20% of the total global CH4budget and are responsible for interannual variability in the global atmospheric CH4growth rate (Feng et al., 2022; Saunois et al., 2024). Recent growth rates of CH4in the atmosphere have increased in ways inconsistent with our current understanding of global CH4sources and sinks (Turner et al., 2019). PANGEA will explore the CH4cycle across the tropics to develop improved models and understanding to contribute to management options.

**Satellite-derived CO2 and CH4 measurements:** The net biosphere exchange (NBE) over tropical South America demonstrated slower than expected carbon recovery following the 2015/2016 El Niño, possibly owing to increased heightened aridity and water deficits (Liu et al., 2024). Signals from 2009 onwards indicate a persistent carbon sink in the Congo basin that contrasts with large sources of emissions in the western and eastern parts of tropical Africa (Palmer et al. 2019). Given the global impact of increasing GHG’s and the uncertainties of recent measurements, PANGEA will use advanced sensors and the improved satellite derived column integrated CO2(XCO2) and CH4(XCH4) measurements used in inverse atmospheric models to constrain the tropical CO2and CH4budgets (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., 2024). These studies revealed the data gaps that limit our full understanding of the tropical carbon cycle. The recent OCO-2 model intercomparison project (MIP), based on 14 models, showed 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). Tropical wetland emissions of CH4estimated using satellite retrievals of XCH4 from GOSAT and TROPOMI (e.g., Parker et al., 2018; Ma et al., 2021; Feng et al., 2022; Yu et al., 2023) suggest that tropical wetland and aquatic emissions have been underestimated compared to ground based CH4inventories (Yu et al., 2023), although cloud cover prevalence inhibits satellite retrievals (Ganesan et al., 2019; Melack et al., 2022). With rapidly advancing methane point source emissions detection capabilities using hyperspectral data now available (Hulley et al., 2016; Růžička et al. 2023), PANGEA will investigate the capacity to detect natural methane emissions using these or other higher fidelity sensors.

**Validation Needs:** Satellite-based CO2inversion results are inconsistent in the tropics. For instance, GOSAT and OCO-2 atmospheric inversion results consistently showed a significant carbon source in northern tropical Africa (Palmer et al., 2019), driven by carbon releases during the dry season, when these satellites have more consistent cloud free coverage of the region. On the other hand, a recent study combining four instances of aircraft CO2measurements with satellite-based inversions suggested that northern tropical Africa is close to carbon neutral (Gaubert et al., 2023). These conflicting findings underscore the urgent need for additional research to resolve such discrepancies.

**New Insights from Satellites:** The OCO-2/3 and GOSAT 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 NBE over the tropics, as inferred from OCO-2, exhibits a much larger amplitude than that simulated by state-of-the-art biogeochemical models. This result suggests 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 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 variability in total water storage drove the spatial heterogeneity of the Amazon's carbon cycle response to the 2015-2016 drought, while temperature played a more important role in influencing carbon flux variability across the entire tropical region. A recently published study (Stinecipher et al., 2022) showed that satellite observations of carbonyl sulfide (COS) provide a constraint on Amazon regional GPP consistent with other measures, suggesting that refined quantification of the fluxes of this gas at both local and regional scales may improve estimates of GPP (Berry et al., 2013).

**Carbon in Live Plant Biomass:** Much of the carbon in the carbon cycle is in live plant biomass (ref). The amount and processing of carbon in biomass is determined by net primary productivity, which balances the uptake of CO2 and its emission from plants and some microorganisms (Bonan 2008). To understand the impact of climate and land use change in tropical forests it is essential to quantify the structure and function of tropical forests and interactions between plants and carbon in the atmosphere. Live biomass and productivity vary enormously in space and time across tropical forests (Sullivan et al., 2020; Xu et al., 2021; Muller-Landau et al., 2021; Wang et al., 2023, Sagang et al., 2024). Regions with high rainfall typically support dense, evergreen forests with large carbon stocks and high productivity stocks, while areas with seasonal or lower rainfall harbor partially or fully deciduous forests with lower carbon stocks and productivity, and more seasonal variation in carbon fluxes (Malhi et al., 2002; Bonan 2008; Muller-Landau et al., 2021). Temperature also affects forest carbon cycling, both directly and through interactions with water availability (Taylor et al., 2017; Muller-Landau et al., 2021). Differences across the tropics and within tropical regions in geomorphology, climate, species composition, and phenology drive variations in rates of photosynthesis, woody productivity, respiration, tree mortality, and carbon flux across tropical forests (Sullivan et al., 2020; Muller-Landau et al., 2021; Wang et al., 2023; Townsend et al., 2008; Quesada et al., 2010). Net primary productivity typically increases with soil fertility (Quesada et al., 2012), although there are no consistent relationships between soil fertility and live biomass, likely because turnover increases and woody residence time decreases with soil fertility (Muller Landau et al., 2021). Unfortunately, biomass and carbon dynamics studies based on ground measurements represent a miniscule fraction of tropical forest area a small and biased subset of tropical landscapes, prompting questions regarding the generalizability of these findings (Malhi et al., 2014; Marvin et al., 2014; Schimel et al., 2019; Hughes et al., 2021; Chapman et al., 2024). Disturbance regimes also play a crucial role in shaping tropical forest dynamics, influencing tree mortality, biomass turnover, and carbon cycling, detailed further in *Section 2.5*.

**Tropical Wetlands:** A major contributor to the global carbon cycle are the large areas of tropical forests that are permanently or seasonally flooded wetlands, which include forested peatlands, swamps, and floodplains (Aselmann and Crutzen 1989). For instance, Amazon River floodplain forests cover up to 250,000 km2 with most areas flooded six months of the year (Richey et al., 2002; Goulding et al., 2003). The Amazon floodplain represents the greatest natural CH4emission source in the tropics and rivals CH4sources from the Arctic (Pangala et al., 2017). In addition to the significant ebullitive CH4source from inundated soil, Amazon floodplain tree stems contribute CH4emissions which are estimated to be 200 times larger than from temperate wet forests (Pangala et al., 2017). The number of measurements and extent of coverage of CH4fluxes 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 wetland CH4emissions are controlled by climate, hydrology, vegetation cover, disturbance dynamics, and land-use practices (Parker et al., 2018; Ma et al., 2021). The lack of carbon flux measurements in wetlands has led to poorly quantified tropical wetland and inland water system CH4emissions (Ganesan et al., 2019; Rosentreter et al., 2021). Existing mechanistic models have produced large differences in tropical CH4emissions (Melton et al., 2013; Bloom et al., 2017) and do not capture the observed CH4seasonality 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 cover and inundation extents applied in individual models (Peng et al., 2022).

**Tropical Peatlands:** Organic-rich tropical peatlands store the largest and highest-density carbon reserves that are irrecoverable on human decision-making timescales (Noon et al., 2021). Tropical peatlands store approximately 100 Pg C but there are large uncertainties in the spatial extent and associated carbon stocks of these peatlands. For example, the extensive peatland carbon stocks of the central Congo Basin and Pastaza-Marañón Foreland Basin in the Peruvian Amazon were recently mapped and account for more than a third of the carbon stored in tropical peat soils (Dargie et al., 2017; Crezee et al., 2022; Lahteenoja et al, 2012). Substantial undocumented peatland areas likely remain to be assessed (Hastie et al, 2024). 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). In Southeast Asia extensive peatland drainage has turned peatlands of this region into a CO2 source on par with regional fossil fuel emissions (Hoyt et al., 2020). Increasingly extensive and intense fires in peatlands, particularly in equatorial Asia and during El Niño years, have also become a major source of carbon, other trace gas emissions and particulate matter to the atmosphere (Page et al. 2009; Yokelson et al. 2022). As anthropogenic disturbances continue to threaten tropical peatlands (Hastie et al., 2022; Page et al, 2022), a better understanding of the distribution, carbon stock density, and emissions of tropical peatlands is needed (Roucoux et al, 2017; Deshmukh et al, 2021).

**Nutrient Cycling:** Projecting the future productivity of tropical forests relies on understanding the interactions of nutrient availability from soils, plant functional composition and the impact of increasing temperature, CO2 concentrations and extreme events. The typically low soil nutrient availability from highly weathered tropical soils is expected to constrain CO2 fertilization as more nutrients are bound up in plant tissues (Fleischer and Terrer, 2022). Phosphorus will likely constrain the potential for higher forest growth rate responses to increased CO2 by about half (Fleischer et al., 2019; Braghiere et al., 2022). While phosphorus is largely assumed to be the most limiting nutrient across lowland tropical forests (e.g. Cunha et al., 2022), recent observations reveal the heterogeneity of nutrient limitation across tropical forests, including limitation and co-limitation by nitrogen, phosphorus, potassium, and calcium (Davidson et al., 2004, Wright et al., 2011, Manu et al., 2022). Potassium plays a critical role in regulating plant responses to drought (Manu et al., 2024). 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 redistribution and losses. Remote sensing offers opportunities to capture the impact of available nutrient supplies and nutrient losses from disturbance events through observations of variations in foliar chemistry, functional traits, and canopy structure across large scales (Townsend et al., 2008, Chadwick and Asner 2016; 2018, Martins et al., 2018).

## Biodiversity

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

**Tropical Biodiversity:** 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 the most biodiverse biomes on Earth by all of these measures and are home to more than half of Earth’s described species (Lewis et al., 2015; Barlow et al., 2018; Dinerstein et al., 2017; Pillay et al., 2022). The high total number of species found in tropical forests (high gamma diversity) reflects both extraordinary 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 in plant biodiversity 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 2018). The divergent evolutionary histories of different tropical continents have resulted in very different species assemblages and phylogenetic compositions (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; Rüger et al., 2018; Homeier et al., 2021; Bialic-Murphy et al., 2024).

**Functional, Structural, and Species Diversity:** 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., 2014; 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 ecosystem 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 their complex interactions (Muller-Landau et al., 2021). The species and functional composition of woody plants, which comprise the most aboveground biomass, is particularly important in shaping forest structure and function, which in turn affects microclimates, habitat, and food resources for animals and microbes. Understanding interactions among functional, structural, species diversity, and carbon cycle dynamics is critical given uncertainties surrounding whether or not tropical forests will survive and remain a carbon sink throughout the 21st century (Arora et al., 2020; Brienen et al., 2015; Hubau et al., 2020; Sabatini et al., 2019). High functional biodiversity creates greater ecosystem stability and resilience that may help mitigate negative effects of climate change (Sakschewski et al., 2016; Longo et al. 2018; Schmitt et al., 2020). Changing climate regimes could reduce biodiversity that might feedback on climate through lower carbon sequestration (Thomas et al. 2004; Cavanaugh et al., 2014). 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. Although the tropics host immense botanical species diversity, the abundance of most species is low. Forest inventory plot data reveal that just 2% of species in the Americas (174 species), Africa (77 species), and Southeast Asia (172 species) account for 50% of the tropical trees on those continents (Cooper et al., 2024). Characterizing the functional diversity of these hyperdominant species and their interactions with other taxa is tractable and within the scope of PANGEA.

**Woody Plant Trait Variability and Trade-Offs:** Woody plant functional trait distributions are an important manifestation of tropical biodiversity that affect forest structure and function. Important co-variations among traits include adult stature, the fast-slow axes of plant life history, and self-supporting versus climbing strategies to reach the canopy. Adult stature ranges from small shrubs to giant emergent trees above the main canopy (Rüger et al., 2018; Maynard et al. 2022). Vertical forest structure varies with ecosystem function even when vertically integrated metrics like leaf area index (LAI) do not (Figure X) (Ordway et al., 2022). The fast-slow axis refers to plant species with fast resource acquisition and processing (particularly in terms of nutrient-use efficiency), fast growth, high resource needs, high mortality rates, and low shade-tolerance contrasted to species with slow resource acquisition and processing, slow growth, low resource needs, low mortality rates, and high shade-tolerance (Reich 2014; Rüger et al., 2018). Variation in functional composition among ecosystems thus relates to forest successional status, woody productivity, and woody residence time. Previous research has shown that trait distributions associated with wood, leaves and reproduction can be nearly orthogonal across tropical forest species (Baraloto et al., 2010; Fortunel et al., 2012). Nevertheless, the fast-slow axis still 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 remote sensing, enabling quantification of this dimension of plant functional composition from remote sensing (Figure X) (Asner et al., 2016; Chadwick and Asner 2016). Recent work has also explored functional diversity and redundancy trends across tropical forests using multispectral imagery (Aguirre‐Gutiérrez et al., 2022).

**Lianas, Palms, and Bamboos:** Though much of the research in tropical forests is focused on trees, other plant life forms such as lianas, palms, and bamboos have a significant impact on ecosystem functioning, succession, and response to disturbances. For example, lianas (woody vines) are structural parasites that reduce tree growth and increase tree mortality via competition, and thereby alter forest structure and function and carbon stocks (van der Heijden et al. 2015; Muller-Landau and Pacala 2020; Estrada-Villegas et al., 2022). Liana abundance varies widely among tropical forests in relation to climate, disturbance history, and other factors (Dewalt et al., 2015), and is increasing on average (Phillips et al., 2002; Schnitzer and Bongers 2011, Rueda-Trujillo et al., 2024). Rising CO2 concentrations have been linked to increasing tree growth (Phillips et al., 2009, Brienen et al., 2015), whereas increasing disturbance rates favor lianas (Schnitzer and Bongers 2011, Schnitzer et al., 2021), although, previous research suggests that lianas may be vulnerable to droughts (Nepstad et al., 2007; Meunier et al., 2021). Palms are an abundant clade in tropical moist forests (ter Steege et al., 2013), and several species are culturally and economically relevant (Laureto and Cianciaruso 2017). The distribution of palms across tropical forests is highly dependent on climate and edaphic conditions (Emilio et al., 2014; Muscarella et al., 2020). The high resistance of palms to wind damage in tropical-storm affects the post-disturbance recovery of forests (Uriarte et al., 2019; Zhang et al., 2022). Intercontinental differences in palm abundance are marked, with tree-like palms being ubiquitous in the Americas, while being rare compared to understory and tree-climbing palms in Africa (Muscarella et al., 2020). Bamboos are tall grasses that occur in a broad range of habitats across the tropics (Fadrique et al., 2020). Their fast growth rates, combined with clonal reproduction allow bamboos to dominate large extents of land, which can arrest forest succession and significantly decrease forest carbon accumulation (Griscom and Ashton 2003; Lima et al., 2012), and to become invasive where it is introduced (Montti et al., 2014). Bamboos are also extensively harvested in tropical forests for economic reasons, which can impact local fauna dependent on bamboo forests for food (Sheil et al., 2012). Lianas, palms and bamboos differ from trees in their leaf traits and plant architecture, making it possible to quantify their abundance with multispectral, hyperspectral, and lidar remote sensing (de Carvalho et al., 2013; Dalagnol et al., 2022; van der Heijden et al., 2022).

**Leaf Phenology:** Tropical plants display diverse 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). The high carbon demand needed for flushing new leaves means that most drought-deciduous species in the tropics often have thinner leaves to reduce construction costs, and high nutrient demand to increase photosynthetic capacity in shorter growing seasons (Eamus and Prior, 2001; Oliveira et al., 2021). Leaf lifespan and the seasonal timing of leaf production are also important factors across evergreen and brevi-deciduous species, 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 (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). 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 when more light is accompanied by drier conditions (Wright and van Schaik 1994; Lopes et al., 2016; Wagner et al., 2017; Li et al., 2021). Long-term changes in climate, especially in areas where dry seasons are lengthening, may increase the competitive advantage and abundance of drought-deciduous species (Vico et al. 2017; Aguirre-Gutiérrez, 2019).

**Animals and Microbes:** Though studies of the importance of biodiversity for forest function have focused largely on plants, animals and microbes also drive function and are influenced by global environmental change in consequential ways. Animals and microbes contribute to essential services such as pollination, seed dispersal, and nutrient cycling, and shape plant biodiversity and forest structure and function via these mutualistic interactions, as well as through antagonistic interactions including herbivory and disease (Dirzo et al., 2014). Megafauna like forest elephants (*Loxodonta cyclotis*)—found today in Africa, but not in the Americas—have particularly important effects on forest structure and function due to browsing and physical disturbance, as well as through redistribution of nutrients and dispersal of large seeds, resulting in greater abundances of high-wood-density tree species across the landscape (Berzaghi et al., 2018; 2019; Campos-Arceiz and Blake 2011). Experimental vertebrate exclosures have been shown to result 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 directly threaten plant regeneration, and may shift plant species composition and carbon cycle dynamics (Wunderly 1997; Estrada-Villegas et al., 2023). Defaunation may ultimately lead to a shift towards lower forest carbon stocks (Brodie and Gibbs 2009; Jansen et al., 2010; Bello et al., 2015; Osturi et al., 2016; Peres et al., 2016). Among sites in Panama, for example, 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).

## 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 influence future tropical forest carbon sink/source dynamics.

Land-Atmosphere Interactions:Tropical forest land-atmosphere interactions modulate climate and weather both locally and regionally. Tropical forest plants recycle precipitation through evapotranspiration and influence the onset and timing of 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). Tropical forests also emit biogenic volatile organic compounds that affect cloud formation, albedo, and light availability for vegetation (Artaxo et al., 2022). Forest canopies regulate albedo, latent and sensible heat fluxes, and roughness, which drive biophysical climate feedbacks [(Bonan, 2008; Chen et al., 2020; Lee et al., 2011)](https://paperpile.com/c/ovIUza/J2Id+7TNp+vM0J). Furthermore, energy and water balances depend upon soil moisture, controlled by roots, soil texture, and structure [(Fan et al., 2017](https://paperpile.com/c/ovIUza/LDiS); [Seneviratne et al., 2010; Zhou et al., 2021)](https://paperpile.com/c/ovIUza/FPcy+yMq6).

Weather and Climate Effects on Tropical Forests:Mesoscale convective systems deliver much of the precipitation in Central Africa and the Amazon (Andrews et al., 2024; Rehbein et al., 2017; Negron-Juarez et al., 2024). Storms, in turn, affect forest structure and tree mortality via windthrow (e.g., Negrón-Juárez et al., 2018; Feng et al., 2023), and ecosystem functioning including including processes that influence the prevalence of storm-resistant species (Uriarte et al. 2019; Liu et al., 2017). Precipitation controls flooding cycles in lowland forests (Alsdorf et al., 2016; Hawes and Peres 2016), which adapt to submersion and waterlogging that can lower oxygen availability, reduce photosynthesis, and decrease water conductance (Parolin et al., 2004; Parolin et al., 2016; Hawes and Peres 2016), leading to production of CH4 by microorganisms. Rainfall also affects nutrient cycles via wet deposition of nutrients such as nitrogen (Bauters et al., 2018, 2021), photosynthesis via cloud cover and fog (Philippon et al., 2019; Pohl et al., 2021), and evapotranspiration via dew deposition (e.g., Gerlein-Safdi et al., 2018; Binks et al., 2019).

Drivers of Climate Interannual Variability:Tropical climate is directly impacted by variation in sea surface temperature (SST), which controls the cross-equatorial energy transport (Cook and Vizy 2015; Zhou et al., 2019) and affects precipitation 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). Phenomena like El Niño-Southern Oscillation (ENSO), the Madden-Julian Oscillation, the Indian Ocean Dipole, and Atlantic Meridional Overturning Circulation add to interannual variability in tropical convection (Raghavendra et al., 2020; Dias et al., 2017; Gu and Adler 2018). Different phases of these phenomena are strongly associated with droughts (Marengo et al., 2016; Ndehedehe et al., 2018; Jiménez-Muñoz et al., 2016), longer dry seasons (Jiang et al., 2019; Staal et al., 2020), and shifts in rainy season and storm intensification (Taylor et al., 2018; Rehbein and Ambrizzi 2023; Balaguru et al., 2018). Responses to climate shifts vary across regions. African forest appear less vulnerable to droughts than Amazon forests (Tao et al., 2022; Asefi-Najafabady and Saatchi 2013; Saatchi et al., 2012; Bennett et al., 2021), and wetter tropical forests show resilience to climatic changes (Bennett et al., 2023).

Anthropogenic Disturbance Impacts on Weather and Climate: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; Li et al., 2024). 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). Deforestation and forest degradation increase soil surface warming due to decreases in evaporative cooling [(Devaraju et al., 2018; Li et al., 2015)](https://paperpile.com/c/ovIUza/iirc+CruA), with the magnitude of this effect influenced by the amount of forest cover lost [(Alkama and Cescatti 2016)](https://paperpile.com/c/ovIUza/MoNo). Higher temperatures can subsequently increase tree respiration, which reduces NPP and changes how tropical forests cycle carbon [(Choury et al., 2022; Das et al., 2023; Liu et al., 2017; Lloyd et al., 2023)](https://paperpile.com/c/ovIUza/FoUS+HHQU+ZxJz+MUqe). Deforestation and degradation can increase streamflow and impact water quality due to sediment fluxes (Levy et al., 2018), as well as increase sensible heat flux and decrease evapotranspiration and infiltration (Costa et al., 2003; Souza-Filho et al., 2016; Longo et al. 2020, de Oliveira et al., 2021; Rangel-Pinagé et al., 2023). Land cover and land-use change can affect precipitation patterns by altering surface heterogeneity and influencing downstream moisture and heat fluxes [(Mahmood et al., 2014; Snyder, 2010)](https://paperpile.com/c/ovIUza/9zs5+pHwu) and cross-continental nutrient cycles [(Li et al., 2021](https://paperpile.com/c/ovIUza/YQKg); Barkley et al., 2019[)](https://paperpile.com/c/ovIUza/YQKg). In addition, biomass burning contributes aerosols, affecting cloud formation and dynamics (Liu et al., 2020; Zhang et al., 2008; Chaboureau et al., 2022; Tosca et al., 2015).

Climate-Induced Critical Transitions of Tropical Forests: As new climate regimes are emerging, shifts of tropical forests to alternate, open-canopy ecosystems could occur (Hirota et al., 2011; Flores et al., 2024). However, vegetation sensitivity differs among tropical continents, and complex interactions with other changes, such as increased atmospheric CO2, may alter vegetation response (Zhang et al., 2015; Bartlett et al., 2019). For example, African forests, particularly those in West Africa, are often exposed to higher temperatures compared to the relatively cooler, more humid tropical forests in Southeast Asia and therefore may be more adapted to heat stress (Malhi et al., 2013). However, this adaptation may come at the cost of West African forests operating closer to their critical temperature or hydraulic thresholds. Ultimately, exceeding historical climate thresholds in the tropics could lead to future shifts to alternative vegetation states that do not support contemporary tropical forest ecosystem services [(Aguirre-Gutiérrez et al., 2020; Flores et al., 2024; Nobre et al., 2016; Scheffer et al., 2001)](https://paperpile.com/c/ovIUza/zrGk+iDoN+6fAo+yCO2).

Climate-Biosphere Feedback Effects on Freshwater Resources: Tropical forests across the planet are also home to an extensive network of rivers and streams, which includes two of the largest river basins, the Amazon and the Congo (Dai and Trenberth, 2002). However, changes in temperature and precipitation regime, together with the expansion of deforestation and forest degradation are altering the hydrological cycles in both regions. While decreases in precipitation reduce the gross freshwater supply at the top of the canopies, deforestation and forest degradation may increase freshwater supply to rivers through the combination of higher throughfall precipitation and lower evapotranspiration (Davidson et al., 2012). In the case of the Amazon river basin, previous studies indicate that the net effect of climate change and deforestation is spatially heterogeneous, with river discharge reductions in sub-basins with strong precipitation declines or modest deforestation rates, and increases in areas heavily impacted by deforestation (Coe et al., 2011; Lima et al., 2014; Arias et al., 2018). Shifting hydrological cycles in freshwater systems also affects the extent and duration of seasonal floods across the river basins, which further impact fluxes of CO2 and CH4 (Hamilton, 2010; Alsdorf et al., 2016). Moreover, forest cover changes have significant impacts on water quality, such as changes in nitrogen and phosphorus concentration, water pH, oxygen availability and transparency (Neill et al., 2001; Ríos-Villamizar et al., 2017). These effects, combined with changes in temperature due to climate and canopy cover losses can significantly impact freshwater habitats and algal and animal riverine communities (Lorion and Kennedy, 2009; Castello and Macedo, 2016; Taniwaki et al., 2017; Zeni et al., 2019).

## Social-Ecological Systems

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

Social-Ecological Systems:To fully understand the complexity of tropical forest social-ecological systems (SES) and how they are being impacted by global change, PANGEA takes a systems approach that centers the feedbacks and interactions that exist between people, climate and the environment (Figure X). SES research has evolved over the past several decades to understand and model the relationships between and within social and ecological systems, spanning the sustainable livelihoods framework (Scoones 1998), SES subsystems and interactions (Ostrom 2009), SES resilience (Folke 2006), robustness in SES (Anderies et al., 2004), 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, including a central focus on the interactions and feedbacks that can facilitate or hinder change in SES. An SES perspective is particularly important in the tropics where land and forests are under high demand to meet food security and production needs, conservation and biodiversity goals, and support local livelihoods and development. Understanding the social and ecological impacts of these trade-offs and the feedbacks that shape them is required to develop a comprehensive understanding of the forces shaping tropical forest vulnerability and resilience and to guide effective and culturally sensitive adaptation and management strategies.

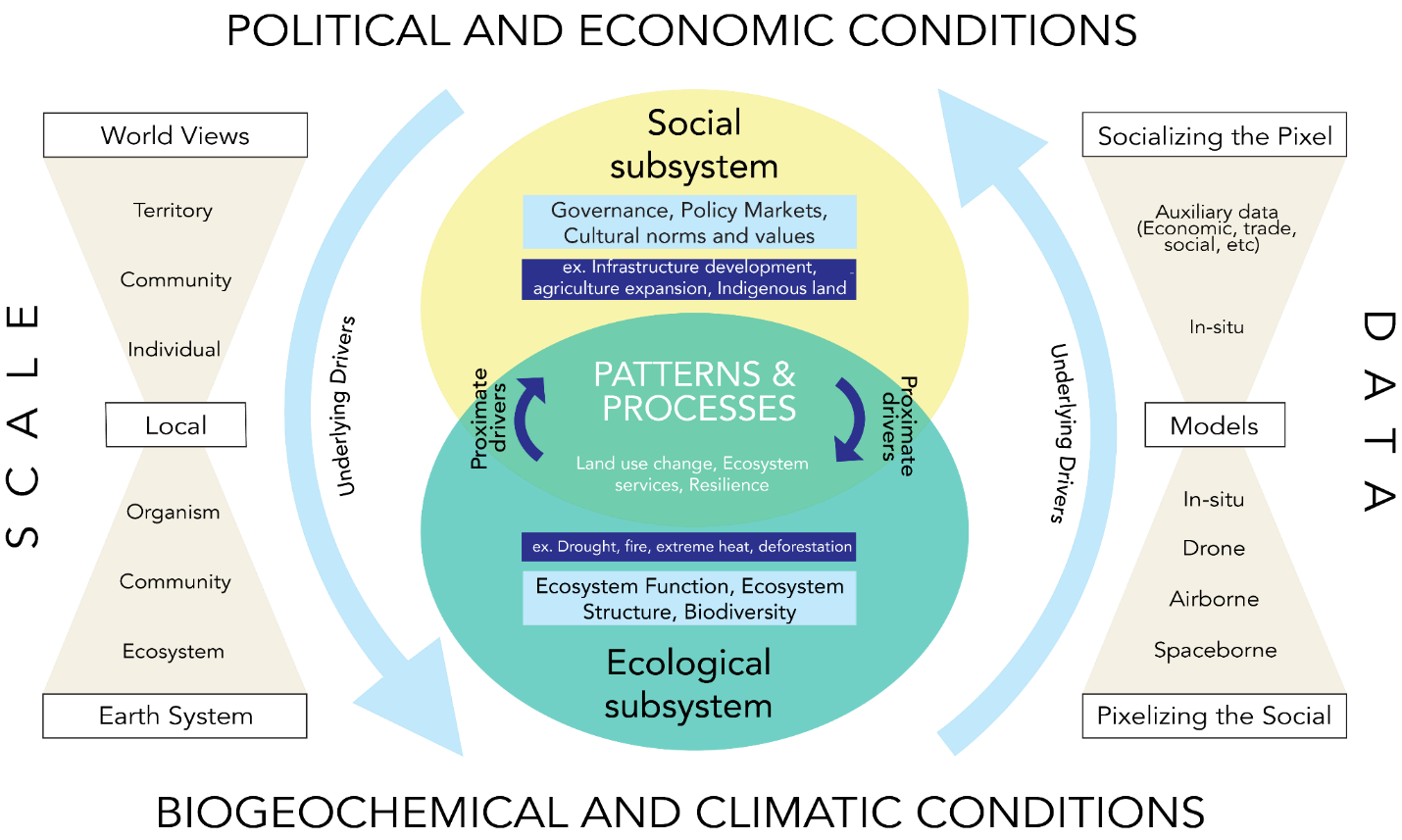


Figure X. PANGEA’s approach to SES will link proximate and underlying drivers of change in social and ecological systems across scales to understand how interactions in SES impact the vulnerability and resilience of tropical forests.

Patterns and Drivers of Land-Use Change: Across the tropics, regionally distinct drivers and patterns of land-use change, including deforestation, degradation, and forest regrowth, have the potential to impact the resilience of the tropical carbon sink (Saatchi et al., 2021; Hubau et al., 2020). In the Amazon and Southeast Asia, deforestation and degradation is primarily driven by the expansion of large-scale, commodity-based agriculture to meet demand from domestic and international markets (Curtis et al., 2018; Haddad et al., 2024). Specifically, in the Amazon land-use change is driven primarily by the expansion of pasture land for cattle and by industrial soybean production (Barlow et al., 2018; Londres et al., 2023). Soy farming and cattle ranching alter biogeochemical cycles (e.g., nitrogen and phosphorus), hydrologic and fire regimes, and are a leading cause of deforestation (Mapbiomas, 2023). In Southeast Asia, where large-scale plantations are rapidly expanding at the expense of primary forest and peatlands, land-use change is driven largely by global demand for palm oil (Koh & Wilcove 2008). In 2020, oil palm expansion was estimated to contribute 20% of the region’s carbon emissions (Carlson 2013). Improved smallholder livelihoods from oil palm expansion in Indonesia has been shown to yield direct tradeoffs with ecosystem function (Clough et al. 2016). Unlike the Amazon and Southeast Asia, the majority of land-use change in the Congo Basin is small-scale and driven by the expansion of subsistence and hyper local commodity crop agriculture (Tyukavina et al., 2018). Persistent demand for cocoa and timber continues to shape land-use change in tropical Africa, although small-scale and subsistence-based land-use change still plays an outsized role in driving land-use change (Hosonuma et al., 2012, Kamath et al., 2024; Fuller et al., 2018). For example, while commodity crops like oil palm have been expanding across tropical Africa since the 1990s, the expansion is linked to domestic demand and fulfilled by smallholders and informal market systems (Ordway et al., 2017a; Ordway et al. 2017b). The degree to which these different scales, intensity, and forms of land-use change among tropical continents impact distinct biodiversity and carbon cycle trajectories, however, remains poorly understood.

Feedback Interactions:In tropical social-ecological systems, feedbacks between people and the Earth system plays a critical role in maintaining resilience and guiding the trajectory of these integrated systems (Dearing et al., 2010). Social-ecological systems dynamics in tropical forests involve feedbacks with a combination of proximate and underlying forces, including policy and/or market-based incentives, regulatory frameworks, access or barriers to information and resources, and long-standing connections between local communities and Indigenous peoples and forest ecosystems (Lambin & Geist 2002, Lambin et al. 2003). These drivers not only shape dynamics within the ecological subsystem, including the carbon and water cycles, plant-animal interactions and weather and climate systems, but also in the social subsystem, including food security and local livelihoods (Sonwa et al., 2012; Flores et al., 2024). Moreover, they shape the feedbacks and interactions between the social and ecological subsystems, through changes, for example, in land use and cover, ecosystem resilience, and fire regimes (Whitfield et al. 2019; Gatti et al. 2023). The feedbacks between humans and tropical forests are tightly linked through the provisioning of ecosystem services and conservation and management activities, where, for example, the collection of non-timber forest products such as seeds, leaves, fruits, and roots can play an important role in supporting the livelihoods and cultures of tropical forest communities. While these interactions play out across the tropics, locally-specific political, economic, cultural, and management conditions influence the response, resilience, and adaptations of tropical forests and local communities to global change dynamics (Saatchi et al., 2021; Geist and Lambin, 2002; Turner, 2014).

Impacts on Vulnerability and Resilience: 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 not only the feedbacks that amplify vulnerability, but also those that heighten the resilience of tropical forests is essential for developing place-based and culturally sensitive management plans that support both ecosystem resilience and community livelihoods. An example includes recent research focused on social-ecological ‘hope spots’—defined as areas that can meaningfully impact social-ecological resilience, where local communities and public engagement can be strategically combined with science, engineering, and technology, including remote sensing, to provide the greatest impact for the conservation of vulnerable biodiversity (Levis, et al., 2024). The authors highlight the example of the Upper Xingu, located in the Brazilian Amazon’s arc of deforestation, where 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, demonstrating cultural and management practices that promote forest resilience (Levis, et al., 2024). PANGEA offers an opportunity to expand similar research elsewhere in the tropics through equitable collaboration and co-production with Indigenous and local communities to identify practices that promote resilient systems that benefit both nature and people, including those that have the potential to be scaled. Far more work is needed to identify culturally appropriate methods and practices for integrating remote sensing and Indigenous science.

Social-Ecological System Implications: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 feedback cycles between human activities and ecosystem function, people at local to global scales can make more informed decisions about land-use, resource management, and conservation efforts that align with both ecological resilience and their socio-economic needs (Aguiar et al., 2020). Subnational and national-level decision-makers 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). 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 or continuation of trends in land use and management could lead to irreversible regime shifts, and to design interventions that might prevent or mitigate such outcomes (Staal et al., 2020; Liu et al., 2024; Flores et al. 2024). Advances in understanding, methods, and monitoring capabilities from PANGEA have the potential to empower Indigenous Peoples, local communities, and decision-makers with the information they need to govern and engage with these ecosystems more sustainably. Ultimately, the ability to predict and manage complex feedbacks in tropical ecosystems is key to fostering both environmental and social resilience in these critical regions.

Global Impacts of Tropical Forests:The impacts of tropical forests also extend far beyond the pantropics. People in the US and globally are impacted by and are agents of change in tropical ecosystems, for example through consumption patterns and the lived reality of climate impacts at high latitudes that are influenced by tropical land-atmosphere interactions. For example, the Amazon plays a critical role in stabilizing climate systems across the Americas, and its continued deforestation threatens rainfall patterns in the U.S. The loss of Amazon forests could disrupt rainfall patterns in the U.S. midwest, northwest, and parts of the south, posing serious risks for U.S. agriculture and water resources (Lawrence & Vandecar, 2015). For example, Amazon deforestation could lead to a 20% reduction in rainfall across the northwestern U.S. and a 50% decrease in the Sierra Nevada snowpack in California, which is the water source agriculture and urban areas that the entire U.S. depend upon (Medvigy et al., 2013). Such changes in precipitation, combined with shifts in atmospheric circulation, would strain water availability, diminish crop yields, and destabilize ecosystems from the U.S. Central Plains to the West Coast, with potential food security concerns. Amazon forest loss and degradation poses direct and serious threats to U.S. agriculture, water resources, and societal stability. In addition to the role tropical forests play in regulating global climate, many key commodity crops are grown primarily or entirely in the tropics, including cocoa for chocolate, coffee, palm oil, and rubber. Numerous timber species are also only found in the tropics (Romero et al. 2017). While the contribution of these crops and the harvesting of timber to tropical deforestation and degradation is not insignificant, their production plays an important role in global markets and supply chains, and in meeting household food security in the US, where many items found in the grocery store rely at least in part on crops grown in the tropics (Meyfroidt et al. 2013).

## Disturbance Dynamics

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

Disturbance Dynamics in the Tropics: There are two primary modes of forest disturbance: (1) direct and indirect human disturbance resulting from land cover and land-use change, such as deforestation, degradation, and human-ignited fire, and (2) natural disturbances that are largely associated with water stress, storms, biotic agents, and natural fire ignition, all of which are 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 (McDowell et al 2020, Qin et al., 2021), but they have distinct spatial distributions, intensities, frequencies, and consequences for tropical forests. In a study in Brazil’s Arc of Deforestation, forest degradation through logging and fires caused more carbon loss than forest clearing from 2016-2018 and surprisingly, the effect of windstorms was almost as great as fires and larger than logging (Csillik et al. 2024). The effects of changing drought and storm frequency and severity, rising temperatures, and deforestation and degradation are highly variable among ecosystems and can impact tree mortality, evapotranspiration, ecosystem respiration, species composition, and much more. Critically, interactions among disturbances can be 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 biodiversity, climate, and edaphic gradients is needed to understand these interactions and their consequences.

Direct Human Disturbance: Over the past several decades, direct human disturbance has posed the primary risk to tropical forest persistence and function. 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, defaunation, and conversion of land to non-forest ecosystems (Lewis 2005; Gibson et al., 2011, Wearn et al., 2012; Brodie et al., 2014; Silva Junior et al., 2020, Brando et al., 2014, Flores et al., 2024). Satellite remote sensing has revolutionized the rapid detection and quantification of direct human disturbance and enabled deeper understanding of the drivers (see *Section 2.4*). Deforestation and land cover change is now actively being mapped in high spatial resolution across the tropics and in association with specific sectors and practices driving these trends (Curtis et al., 2018; Maxwell et al., 2019; Qin et al., 2021; Harris et al., 2021; Lapola et al., 2023; McGregor et al., 2024; Csillik et al., 2024). With the advent of small-satellite arrays (e.g., PlanetScope), it is now also possible to quantify both deforestation and degradation in some systems 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. Still, interactions between deforestation and degradation and things like hydrological cycling, micrometeorological conditions, species interactions, and biogeochemical cycling remain poorly understood, particularly in tropical Africa.

Fire:Fire dynamics often interact with deforestation and degradation in moist tropical forests, where naturally ignited fires remain rare, and human-ignited fires are common (Uhl and Kaufmann, 1990; Cochrane, 2003; Brando et al., 2019). From 2003-2018, an estimated 41 ±14% of all forest loss in humid tropical forests was fire-related, although this varied considerably between continents (van Wees et al., 2021). 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 (van Wees et al., 2021). Fires transfer ecosystem nitrogen to the atmosphere through pyrodenitrification with the consequent effect of nitrogen impoverishment, leading to reduced rates of vegetation regeneration (Davidson et al. 2007). Although fires are associated with deforestation, the impacts of deforestation decline in the Amazon since 2005 on fire activity remains uncertain, with studies showing either declines in fire activity (e.g., Andela et al., 2017; Libonati et al., 2021) or decoupling between fires and deforestation (Aragão et al., 2018). While there has been an increase in fire-related forest loss in tropical forests in Africa, the majority of fires in the region are likely going undetected (Wimberly et al., 2024). Satellite and ground measurements have revealed the widespread effects of fires and their major contributions to pantropical carbon cycling (Cochrane, 2001; Berenguer et al., 2021). Human-ignited fires commonly spread into the understory of intact tropical forests where they cause tree mortality and make forests more susceptible to subsequent wind-driven disturbance (Barlow et al., 2003; Brando et al., 2014; Silvério et al., 2019; Berenguer et al., 2021). Changes in forest structure associated with fires and forest fragmentation may increase the risk of subsequent fires both through the increased abundance of fuel loads like grasses and understory plants (Silvério et al., 2013, Sagang et al., 2024b) and higher solar radiation reaching the ground, which favors hotter and drier conditions near the surface (Brando et al., 2014; Longo et al., 2020; Nunes et al., 2022). 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., 2006; Brando et al., 2014, 2019; Barbosa, 2024; Burton et al., 2024a,b; da Veiga, 2024; Jones, 2024).

Natural Disturbance Dynamics:Natural disturbances - primarily drought, storms, and biotic agents - present distinct challenges for detection, quantification, and attribution compared to direct human disturbances like deforestation and forest degradation–although defaunation remains essentially impossible to detect using remote sensing. Most natural disturbances occur at small spatiotemporal scales, with over 98% of biomass mortality from treefalls in the Amazon attributable to events less than 0.1 ha in area (Espírito-Santo et al., 2014). However, small disturbance events can 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). Natural disturbances can also 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, Negron-Juarez et al. 2023), 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., 2020; Sullivan et al., 2020; Gora and Esquivel-Muelbert 2021; Fang et al., 2022). Given their tremendous contributions to tropical forest carbon cycle dynamics–for example in the Brazilian Amazon, natural disturbances accounted for over 50% of total biomass carbon losses (Csilik et al. 2024)–even small changes in natural disturbance regimes will impact tropical forest function, biodiversity, and the global carbon budget.

Drought:Drought events are major drivers of natural disturbance in tropical forests. Atmospheric water stress associated with high temperatures and vapor pressure deficits has increased in recent decades (Fang et al., 2022), and episodic droughts are occurring with greater 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 by 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.

Storms:Tropical storms (hurricanes, cyclones, and typhoons depending on their geographical location) are increasing in intensity and are a dominant form of disturbance in coastal 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 thunderstorms are a dominant drivers of tree mortality and forest biomass dynamics (Chambers et al., 2013; Negrón-Juárez et al., 2018; Negron-Juarez et al. 2017, Negron-Juarez et al. 2023, Gora et al., 2020; 2021). Furthermore, tree mortality from storms in the Amazon have quadrupled since the 1980s (Urquiza-Muñoz et al. 2024), yet these events remain overlooked as drivers of forest dynamics and composition. 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., 2020; 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).

Rising Temperatures:Most lowland tropical forests experience high average temperatures throughout the year, with relatively low seasonal and inter-annual variability, which may make tropical forests uniquely vulnerable to shifts in temperature (Cunningham and Read, 2002). Climate projections indicate that tropical forests will increasingly experience no-analog high temperatures and extreme temperatures throughout the 21st century (Seneviratne et al., 2021). High temperatures can rapidly and non-linearly increase vapor pressure deficit (VPD) (Barkhordarian et al., 2019), which in turn negatively impacts primary productivity due to stomatal closure (Lloyd and Farquhar, 2008). Previous research experiments indicated that without increases in VPD, tropical tree species are able to sustain productivity up to 38°C (Smith et al., 2020). However, if average temperatures increase more than 4°C, tropical forest ecosystems may experience frequent periods of temperatures near 50°C, which could cause irreversible tissue damage and persistent loss of photosynthetic capacity (Doughty et al., 2023). However, the exact threshold in which permanent and extensive damage would occur remains highly uncertain (Slot and Winter, 2016; Winter, 2024).

# Knowledge Gaps and 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. Importantly, most of the current knowledge gaps are inherently interdisciplinary, and require advancing process understanding of the interactions between climate change, shifts in natural and anthropogenic disturbance regimes, and structurally, functionally, and socially diverse and heterogeneous tropical moist forest ecosystems, and their impacts on biogeophysical and biogeochemical cycles. Therefore, PANGEA science questions cut across multiple science themes described in *Section 2*. The questionsaddressing each of the themes–Biogeochemical Cycles, Biodiversity, Climate Interactions and Feedbacks, Social-Ecological Systems, and Disturbance Dynamics–are organized according to considerations of pattern(*Section 3.1*), process(*Section 3.2*), and projected future change(*Section 3.3*). The ecological and geophysical variables required to address the science questions and the corresponding measurements, obtained through ground, satellite, and airborne, are described briefly in this section, and referenced in more detail in Table Xin *Section**6.2* and Table Xin *Appendix D.* These include ground, tower, airborne and satellite measurements on: ecosystem fluxes, atmospheric exchange, aboveground biomass and structure, biodiversity, critical thresholds, fire and aerosols, land use and land cover and ecosystem services, hydro-meteorology, and edaphic conditions (Figure X).

## Pattern

### Pattern: Carbon Stocks and Fluxes

Current estimates of both carbon stocks and fluxes diverge markedly across the tropics (Sullivan et al. 2020, Xu et al., 2021, Muller-Landau et al., 2021, Wang et al. 2023). Data in Africa, albeit sparse, suggest that disturbance regimes and forest responses to disturbances are distinct from other continents (Hubau et al., 2020; Bennett et al., 2021; 2023), although the geographic bias and overall lack of representativeness of ground datasets leave much room for debate. In addition, the spatial and temporal patterns of disturbance dynamics are poorly characterized across the tropics, which exacerbate the uncertainty for the future of the global carbon budget (Pugh et al., 2020). To address these knowledge gaps, PANGEA will address the following pattern-related questions about carbon stocks and fluxes that are related to Overarching Question 1 (see *Section 1*):

Q1.How do spatial variations in tropical forest carbon stocks, and CO2, CH4, and lateral fluxesrelate to spatial variation in climate, hydrological cycling, soils, geomorphology, and social-ecological interactions?

Q2.How do temporal variationsin tropical landscape carbon dioxide, methane, and lateral fluxes relate to temporal variation in climate change trends and extreme events?

Q3.How do carbon stocks and carbon dioxide, methane and lateral fluxes of tropical forests vary across disturbance regimegradients?

Q4.How does geographic, spatial and temporal variation in tropical forest phenology co-vary with carbon stocks and fluxes, and how is phenology changing in relation to systematic shifts in forcing processes, including climate, land-use, and disturbance regimes?

To improve the spatial characterization of biomass and changes in biomass across the Core and Extended geographical domains, PANGEA will integrate forest inventory plot data and airborne lidar with additional measurements at the landscape scale selected for intensive measurements of tropical biomass and its changes. PANGEA will partner with GEO-TREES, an effort coordinating ground measurements from forest inventories with terrestrial laser scanning, drone, and airborne lidar data collection. PANGEA will leverage information on allometry-based estimates of carbon stocks, and will prioritize collocating landscapes with GEO-TREES sites and support upscaling efforts using GEDI, NISAR, BIOMASS, and EDGE\*. To advance the temporal quantification of ecosystem fluxes, PANGEA will integrate CO2 and CH4 collected using existing eddy covariance flux measurements (Baldocchi 2020) and will also identify areas for implementing new towers to fill data and knowledge gaps across climatic, biodiversity, and disturbance gradients, and make further measurements with strategic deployment of automated and manual gas chambers. To provide regional and pantropical constraints on CO2 and CH4 fluxes, PANGEA will employ satellite sensors like the OCO-2 and -3, TROPOMI, Carbon Mapper, and new products from geostationary satellites like GOES-R (Crisp et al., 2017; Lorente et al., 2021; Khan et al., 2021; Ranjbar et al., 2023). NISAR and BIOMASS will be used for mapping tropical wetlands, and integrated with Surface Water and Ocean Topography Mission (SWOT) surface water data for constraining lateral carbon fluxes measurements.

If necessary, PANGEA will fill satellite validation gaps in the Total Carbon Column Observing Network (TCCON) and COllaborative Carbon Column Observing Network (COCCON), especially in Africa, to resolve debates on continental source and sink estimates inferred from OCO-2 observations. The TCCON and COCCON are networks of ground-based Fourier Transform Spectrometers that are used to retrieve accurate and precise column-averaged abundance of CO2, CH4, N2O, HF, CO, H2O, and HDO, providing an essential validation resource for OCO-2/3, GOSATand GOSAT-2, TROPOMI, and other missions. These validation measurements are currently extremely scarce in the tropics, limiting the interpretation of the spatiotemporal flux patterns inferred from satellite CO2 and CH4 data. These measurements will help constrain and quantify uncertainties of regional-scale estimates of CO2 and CH4 fluxes across the PANGEA domain fluxes derived from inverse modeling (Beck et al., 2013; Liu et al., 2016; Schuh et al., 2019). Lastly, PANGEA will quantify the impact of canopy disturbancefrom wind, lightning, and drought and tropical forest phenology on carbon fluxes and stocks through a combination of field observations, PhenoCams, and uncrewed aerial vehicle (UAV) and satellite data to address knowledge gaps related to the divergent leaf phenological responses from individual species and functional types to landscapes across climate and disturbance gradients. PANGEA’s datasets will complement existing efforts to expand geographic coverage of phenology using Landsat, Sentinel-2 and commercial satellite data (Guan et al., 2015; Yang et al., 2021; Wang et al., 2023).

### Pattern: Biodiversity and Functional Composition

Biodiversity is positively associated with higher net primary productivity in tropical forests (Durán et al. 2019). Understanding the mechanisms that support this relation at regional to pantropical scales is a gap that PANGEA can help fill. Moreover, biodiversity varies markedly among tropical continents, not just due to climatic differences, but also due to their evolutionary past (Corlett and Primack 2006; Slik et al., 2018; Raven et al., 2020). Yet, we still lack detailed information on the functional diversity of tropical forest ecosystems. An initial assessment on tropical forest plant trait data abundance in the American tropics, based on TRY (Kattge et al., 2020); LT-Brazil (Mariano et al., 2021) and NGEE-Tropics (<https://ngt-data.lbl.gov/dois/>), reveals that a few sites in Central Panama and coastal French Guiana account for the bulk of trait data, and most traits remain scarce (Figure X). Data from African landscapes are even less abundant. By addressing these knowledge and data gaps, PANGEA will directly link ground measurements with airborne and satellite remote sensing to understand the distribution of canopy functional traits and functional diversity across the tropical forest biomes and investigate the strength and scale-dependence of biodiversity controls on ecosystem function. Responding to the questions below, PANGEA can fill large knowledge gaps in the understanding of biodiversity and functional composition across spatial scales.

Q5. How does tropical biodiversityvary geographically, and spatially with forest structure and function?

Q6.What are the plant functional trait distributions in tropical forestson different continents, and how do these differences reflect responses to extreme events and across disturbance and climatic gradients?

Q7.To what degree are tropical carbon cycle dynamics related to plant functional composition?

To relate biodiversity metrics with structural and functional diversity, PANGEA will collect coincident ground and airborne hyperspectral measurements across functional composition and disturbance gradients, building on previous research that demonstrates how this approaches enables estimation of the functional composition and diversity of tropical forest ecosystems (Feret and Asner, 2013; Asner et al., 2014; Asner et al., 2017; Chadwick and Asner 2020; Ordway et al., 2022). In addition to airborne hyperspectral data, PANGEA will employ satellite hyperspectral data, including from the EMIT; PRISMA; DESIS; Plankton, Aerosol, Cloud, ocean Ecosystem (PACE); and Planet Tanager missions, and it will advance calibration and algorithm development supporting the SBG mission. PANGEA will also characterize forest structural diversity using terrestrial and UAV-based, airborne, and spaceborne lidar (GEDI, EDGE\*) at individual-tree to ecosystem scales (e.g., Decuyper et al., 2018; Momo et al., 2020, 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). To investigate the association between shifts in plant composition and shifts in ecosystem functioning (Coverdale and Davies 2023), PANGEA will combine measurements on structural and functional diversity with in situ and remote-sensing observations of CO2, CH4, water and energy fluxes and nutrient cycling, using time series of measurements and space-for-time sampling across the landscapes. To relate functional diversity with ecosystem responses to extreme events, PANGEA data collection will span landscapes that exhibited distinct responses to previous extreme events, for example the 2015 El Niño, to use a space for time approach in the absence of extreme events during PANGEA. The detection of responses to extreme events, as well as the emergent relationships between functional diversity and ecosystem function will be used to scale datasets across the domain and for process-based model benchmarking. *Section 3.2.1* presents additional PANGEA biodiversity-related questions that extend beyond botany to include non-plant taxa and species interactions. Based on conversations with Indigenous collaborators during the PANGEA scoping effort, addressing those questions is more likely to benefit from the integration of Indigenous, Traditional, and Local Ecological Knowledge with other forms of knowledge and data. However, IEK, TEK, and LEK have the potential to advance understanding of all PANGEA science questions in ways that remain underexplored. Doing so through PANGEA will rely upon co-developed and equitable science.

### Pattern: Land-Atmosphere Interactions and Thresholds

Despite advances in understanding the interactions and feedbacks between the biosphere and atmosphere in tropical regions from previous NASA projects and campaigns (Davidson et al., 2012), there remain substantial knowledge gaps on how these interactions vary within and across continents (Phillipon et al., 2019; Pohl et al., 2021; Martins et al., 2018; Chakraborty et al., 2019; Jonard et al., 2022). Hydroclimatic conditions in tropical forests vary significantly along disturbance gradients, from intact forests to heavily fragmented landscapes (Gutierrez-Cori et al., 2021), and there is evidence from modeling and remote-sensing studies that widespread tropical forest degradation can alter energy and water fluxes (e.g., Longo et al., 2020; Rangel Pinagé et al., 2023), yet the effects of degradation on rainfall intensity and recycling remains unknown. The impacts of deforestation on the transport pathways for recycled atmospheric moisture are an increasing focus of research in the Amazon, but to a lesser extent in 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). This knowledge gap in Africa is concerning given recent evidence that suggests Central African tropical forests actually rely more heavily on moisture recycling to provide atmospheric moisture for rainfall than the Amazon (Worden et al., 2021; Baker and Spracklen 2022). Moreover, land-use related fire activities can significantly change the aerosol concentration in the atmosphere and directly impact convective activities in tropical ecosystems (Andreae et al., 2004; Freire et al., 2020). To address knowledge gaps related to land-atmosphere interactions and hydroclimate thresholds, PANGEA will answer the following questions:

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

Q9.How do hydroclimatic thresholds, such as critical soil moisture levels or thermal boundaries, vary within and among tropical continents?

To investigate how land-atmosphere interactions vary across continents, PANGEA will build on measurements used for spatial and temporal variation of carbon stocks (*Section 3.1.1*), and structural and functional diversity (*Section 3.1.2*), complemented with ground measurements from micrometeorological stations, latent and sensible heat fluxes from eddy covariance towers, soil moisture, canopy ecophysiological measurements, and live and dead fuel moisture. PANGEA will scale ground and tower data on soil moisture, canopy water content, hydraulic traits, and thermal stress and evapotranspiration to the pantropics by combining airborne radar and hyperspectral with SMAP, Soil Moisture and Ocean Salinity mission (SMOS), NISAR\*, Advanced Microwave Scanning Radiometer for EOS Mission (AMSR-E), EMIT, ECOSTRESS, and Fluorescence Explorer Mission (FLEX). Ground-based data from PANGEA will further improve SMAP’s soil moisture estimates in tropical forests, known to be significantly biased in tropical ecosystems (Cho et al., 2024), by building on recent correction efforts (Wang et al., 2024). To identify critical hydroclimate thresholds, PANGEA will advance emerging approaches to quantify vegetation water stress from space. For example, canopy water content from airborne hyperspectral data have illustrated ecologically meaningful patterns related to water stress in Mediterranean systems (Brodrick et al., 2019; Paz-Kagan and Asner 2017), however, the transferability of this approach to the tropics remains to be tested. Vegetation optical depth estimate from microwave remote sensing is another promising technology for quantification of drought-related stress (Konings et al., 2021), but there are still uncertainties on how to scale between leaf- and individual-level response, and how to account for confounding effects, such as the signal being dominated by leaf surface water instead of interstitial water (Xu et al., 2021). PANGEA will collect canopy leaf-level ecophysiological measurements, as well as tower-based VOD retrieval methods using GNSS microwave signals (Humphrey and Frankenberg 2023) and evaluate the scalability of those measurements using airborne and spaceborne hyperspectral and microwave retrievals. Tower and airborne based SIF and thermal data will also be used to evaluate diurnal and seasonal GPP and ET (evapotranspiration) measurements to further constrain data products and metrics retrieved from satellites like ECOSTRESS(e.g., Fisher et al., 2020; Li et al., 2021) and solar induced fluorescence (SIF) retrievals from satellites like OCO-2/3 and TROPOMI(Sun et al., 2018). The constrained products will provide valuable calibration data at regional scales for process-based models.

## Process

### Process: Species Interactions and Resilience

Although tropical forests are known high biodiversity ecosystems, the science and technology for quantifying and monitoring biodiversity at large scales, as well as process understanding of how structural and functional diversity mediates carbon, water, energy, and nutrient cycling is still incipient. Moreover, most terrestrial biosphere models still represent tropical forests with fewer plant functional types than temperate forests (e.g., Lawrence et al., 2019; Schaphoff et al., 2018). Even when they represent multiple life strategies, obtaining robust coexistence remains a significant challenge (Koven et al., 2020; Li et al., 2023; Powell et al., 2018). Part of this challenge stems from the fact that plants in dense tropical forests must compete for multiple limiting resources (light, water, nutrients) and there are strong trade-offs between resource acquisition, growth and survivorship (Choat et al., 2018; Oliveira et al., 2021). These trade-offs are characterized by different traits, but most efforts to characterize trait distribution at regional and global scales have resulted in marked disagreement in estimates for tropical forests (Dechant et al., 2024). In addition, plant communities across different continents have distinct evolutionary histories (Slik et al., 2018), as well as unique contemporary plant-animal interactions on each tropical continent (Corlett & Primack 2006). For example, by selectively consuming species with lower wood density and aiding in the dispersal of large-seeded plant species that have high average wood density, herbaceous megafauna like forest elephants in Central Africa can directly and indirectly support more carbon-dense forests and aid their carbon sequestration capacity (Berzaghi et al., 2019). Research suggests that the loss of tropical forest megaherbivores reduce tropical forest carbon stocks by as much as 9% (Berzaghi et al., 2023; Berzaghi et al., 2018). These differences may have led to different relationships between biodiversity and forest function, but this is a hypothesis that still needs to be tested. Further, tropical forests are undergoing significant changes through deforestation and forest degradation. Previous research has indicated that even modest levels of degradation can significantly deplete biodiversity in tropical forests (Barlow et al., 2016). Understanding how such losses may impact the ability of forests to recover and respond to intensifying changes in climate is a critical research priority. While there is a growing body of evidence showing the role of wildlife on biogeochemical cycles, particularly carbon fluxes and sequestration (Berzaghi et al., 2023; Berzaghi et al., 2018; Schmitz et al., 2018), the extent to which wildlife affect natural carbon cycling remains an area of active research and not adequately represented in existing ESMs. Therefore, PANGEA will address the following questions:

Q10.What is the role of biodiversityin 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 to climate and land-use change are the species interactions that underpin tropical forest function , including interactions among life habits (trees, lianas, palms, herbs/grasses and bamboos)?

Q13.What plant functional traits and structural attributesconfer carbon cycle resilience, and how do they vary across forest types, environmental gradients, and vertically within forests?

In addition to the measurements described in *Section 3.1.2*, the characterization of biodiversity across scales will combine in situ measurements that include plant taxonomic diversity and abundance, animal movement data, bioacoustics sensors, camera traps, environmental DNA, Indigenous Ecological Knowledge (IEK), Traditional Ecological Knowledge (TEK), Local Ecological Knowledge (LEK), airborne hyperspectral, lidar, and radar, and satellite hyperspectral (EMIT, PRISMA, DESIS, PACE, and Planet Tanager), and lidar and radar (GEDI, EDGE\*, NISAR\*, and BIOMASS\*). These datasets, described further in *Section 6*, will enable direct and indirect estimates of biodiversity, and will provide initial conditions and benchmarks for process-based terrestrial biosphere models that can represent structural and functional diversity (e.g., BiomeE, ED/ED2, FATES; *Section 6.3*) to develop process-understanding and attribution of the role of biodiversity on carbon, water, and energy fluxes, and how these relationships vary within and across continents. To investigate how biodiversity and land-use driven biodiversity change impact the resistance and resilience of tropical forests to climate extremes, PANGEA will identify landscapes across disturbance, climate, and edaphic gradients, and use data to quantify emergent relationships between forest structure and composition and forest sensitivity to climate extremes. Indicators of water stress and ecosystem function (*Section 3.1.3*), for example, will be developed using data from SMAP, SMOS, NISAR\*, AMSR-E, EMIT, ECOSTRESS, FLEX, TROPOMI, and OCO-2/3. These relationships will be applied to constraint inverse models and process-based terrestrial biosphere models, allowing the use of these models to attribute the role of biodiversity in mitigating the impacts of global change in the tropical land carbon sink.

### Process: Disturbance-Ecosystem Function Feedbacks

Changing disturbance regimes, including drought, fires, storms, and land-use change, are reshaping tropical forests. Tropical regions across continents differ in their responses to similar disturbance events, such El Niño events (Liu et al., 2017). These continental differences may be associated with variation in forest resilience to both human action and climate change (Bennett et al., 2021; Saatchi et al., 2021), however, the mechanisms underlying differences in forest vulnerability to shifting disturbance regimes remain elusive. Likewise, we lack large-scale quantification of the drivers of tree mortality, as well as attribution of reasons for higher tree mortality on different continents (McDowell et al., 2018; Gora and Esquivel-Muelbert 2021). Part of this difficulty stems from scaling limitations. Although large blowdowns can span hundreds to thousands of hectares in the Amazon and will likely increase with climate change (Feng et al. 2023), most storm-related disturbances occur at very small scales (<0.1 ha) (Espírito-Santo et al., 2014; Negrón-Juárez et al., 2018; Negron-Juarez et al., 2023), which are too small to be detected with contemporary satellite methods (Cushman et al., 2021). In addition, these disturbances cannot be reliably attributed using traditional forest plot methods because of the typically long intervals between censuses (Arellano et al. 2021). 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). More broadly, the relative influence of carbon starvation and hydraulic failure on tree mortality in the tropics, and the drivers and mechanisms for these influences, remain major knowledge gaps (Anderegg et al., 2016; McDowell et al., 2018; Bauman et al., 2022). Understanding time-varying carbon- and water-use efficiency of tropical forest ecosystems in relation to tree mortality trends and ecosystem-scale carbon uptake and respiration, particularly in response to extreme events, is critical to reconcile tropical forest source-sink dynamics (Chambers et al. 2004; Peñuelas et al., 2010; Adams et al. 2019). Advancing understanding of distinct ecosystem responses to mortality and disturbance events 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. PANGEA will seek to answer the following questions:

Q14.How are changing disturbance regimes affecting 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? How do temporal and spatial variability of mortality influence the heterogeneity of tropical carbon stocks and fluxes across tropical forests?

To characterize the spatial and temporal distribution of canopy turnover and degradation disturbances across the tropics, PANGEA will leverage advancing efforts to quantify fine-scale forest degradation from space using deep learning (e.g., Dalagnol et al., 2023). With this approach, it may be possible to integrate multiple sources of satellite remote sensing—drone and aircraft RGB and lidar measurements, commercial high resolution optical data, Landsat, Sentinel-1, Sentinel-2, GEDI, NISAR\*, BIOMASS\*, and EDGE\*—to advance monitoring of tree mortality and natural disturbance regimes from space in ways that have been previously attempted with airborne lidar data (Dalagnol et al., 2021). To train deep-learning models, PANGEA will combine field measurements of mortality and disturbance at the key PANGEA landscapes (*Section 6.3*) with field inventory plot mortality data. To investigate the emergent relationships between disturbance regimes, CUE and WUE across the different landscapes, PANGEA will combine the mortality and degradation products with high-resolution estimates of WUE from and CUE derived from airborne and spaceborne hyperspectral, multispectral, and VOD, including Landsat, ECOSTRESS**,** EMIT**,** and AMSR‑E, and test the robustness of these relationships at sites with eddy covariance fluxes and inventories. Airborne data, especially hyperspectral, will be critical to evaluate the scalability of these metrics from the organisms with varying carbon- and water-use efficiencies to entire ecosystems. The spatial- and time-dependent degradation maps will be used to drive disturbance rates in process-based models and both mortality maps and the emergent relationships between mortality rates and WUE and CUE will be used for model benchmarking along environmental and anthropogenic-influence gradients and across continents.

### Process: Recovery Dynamics and Management

As climate change increases the recurrence of natural disturbances, the expansion of deforestation and forest degradation is further amplifying climatic disturbance regimes across tropical forests (Armenteras et al., 2006; Portela & Rademacher, 2001; Jusys, 2018; Hosonuma et al., 2012). More frequent disturbances pose a threat to the resilience of tropical forests, with the potential to influence critical transitions to alternate states (Verbesselt et al., 2016; Whitfield et al., 2019; Falk et al., 2022). To assess such risks, however, it is imperative to thoroughly quantify how frequently disturbances occur, the ecosystem resistance to disturbances, and the recovery time following disturbance impacts (Cole et al., 2014; Longo et al., 2018). While much research has focused on the impacts of disturbances (e.g., McDowell et al., 2018; Brando et al., 2014), large uncertainties remain on recovery rates. 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). Previous field-based research indicated that post-disturbance recovery time scales and rates of recovery vary considerably across the tropics and depending on disturbance intensity and disturbance type (Poorter et al., 2016; Rutishauser et al., 2015). However, how generalizable these findings are regionally and across continents remains unknown. More critically, the geographic connectivity of changes in land management across different scales remains highly uncertain. For example, shifts from intensive cropping systems to agroforestry systems and management (e.g., Indigenous stewardship), as well as interventions aimed at conservation, may result in local restoration and increased resilience of systems relative and support local livelihoods (e.g. Ebeling & Yasué, 2008; Auckland et al., 2011; Santika et al., 2017; Mills et al., 2019, Pienkowski et al., 2024). 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 playing an increasingly large role in global agriculture (Alexandratos and Bruinsma, 2012; Berenguer et al., 2021b). 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. On the other hand, intensification and efforts to improve the sustainability of agricultural practices can also lead to leakage and the displacement of disturbances to other geographies (Ewers & Rodrigues, 2008; Gan & McCarl, 2007; Henders & Ostwald, 2014; Meyfroidt et al., 2020; Hertel et al. 2019). To address knowledge gaps related to post-disturbance recovery and tropical forest resilience linked to management practices, PANGEA proposes to address the following questions:

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

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?

To quantify the post-disturbance recovery time scales, PANGEA will integrate data from field inventories in disturbance-impacted regions with disturbance age datasets derived from long-term remote sensing (Landsat) and near-present remote sensing of forest structure (airborne lidar, GEDI, EDGE\*, NISAR\*, BIOMASS\*), forest composition (airborne hyperspectral, EMIT, PRISMA, DESIS, PACE, and Planet Tanager), ecosystem function (ECOSTRESS, TROPOMI), and agricultural systems (Landsat, EMIT, NISAR\*, Planet) at landscapes across environmental and management gradients to build chronosequences. These chronosequences will be used to reduce uncertainties in process-based models that will then be used to attribute the role of environmental drivers and different disturbance characteristics on the recovery time scales across the PANGEA domain. By incorporating constraints on recovery, models could better simulate forest regrowth with the complex interactions among 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). Moreover, drawing on a variety of SES frameworks, PANGEA will adopt a systems perspective that centers the feedbacks between human systems (including governance, policy, markets, cultural norms, and values) and environmental processes to better understand how human activities and management practices influence the resilience of tropical landscapes. PANGEA will leverage ongoing efforts to detect human activities and agroecosystems, such as a set of innovations that enable detection, mapping and monitoring of natural resources needed to enable livelihoods and human well being (Meemken et al. 2024), and advances in crop type, yield, and disaster risk mapping (Jain et al., 2016; Azzari et al., 2017; Meza et al., 2020; Song et al., 2021). To address the diversity of practices across actors in tropical systems as well as different management practices, PANGEA will build on existing global categorization of management regimes (Lesiv et al. 2022) in combination with locally specific information on the diversity of implementation options for these different regimes, as well as recent approaches to extract socio-economic information from satellite data (Yeh et al., 2020). By integrating these methods and remote-sensing data with in situ and other auxiliary information and knowledge, PANGEA will advance tropical social-ecological system measurables and causal diagrams, fundamental to examine whether SES feedbacks deliver and support the resilience of the tropical carbon sink and other ecosystem processes.

### Process: Hydrological Cycle Feedbacks

Tropical forests play a fundamental role in the water cycle (van der Ent et al., 2010; Spracklen et al., 2018), and climate projections from CMIP6 indicate increases of both extreme dryness and extreme wetness in different parts of the tropics (Vogel et al., 2020). Yet, the spatial distribution of precipitation across the tropics by Earth System Models is highly uncertain, due to limited ability to represent extreme rainfall events (Negron-Juarez et al., 2024), marked divergence on how models represent rainfall recycling across continents (Baker and Spracklen 2022). Moreover, accurate representation of evapotranspiration and sensible heat flux in models is critical for quantifying precipitation recycling. Model benchmarking of evapotranspiration at regional scales relies on remote-sensing products, which also must be assessed. Previous studies indicated encouraging agreement between remote-sensing estimates and eddy covariance towers at tropical forests (Melo et al., 2021; Salazar-Martínez et al., 2022), but they rely on a very limited number of sites. In reality, there is considerable spatial variation in magnitude and seasonality of evapotranspiration at regional and continental scales (e.g., Baker et al., 2021; Weerasinghe et al., 2020). Furthermore, previous research has shown that the impacts of deforestation on tropical forest rainfall depends on the scale of deforestation (Spracklen et al., 2018). Previous research also indicated marked impacts of forest degradation on evapotranspiration and sensible heat fluxes (Brando et al., 2014; Jucker et al., 2018; Longo et al., 2020; de Oliveira et al., 2021; Rangel Pinagé et al., 2023). Widespread degradation-induced shifts in water and energy fluxes could also impact rainfall recycling across the tropics, but this hypothesis has not been tested yet. The combined effects of shifts in precipitation regimes, warmer temperatures, and expansion of deforestation and forest degradation are known to impact river discharges, freshwater habitats; and water quality (Lima et al., 2014; Castello and Macedo, 2016); however, the predicted magnitude of these impacts remains highly uncertain (Guimberteau et al., 2017; Farinosi et al., 2019). Understanding the net effects on freshwater resources is also economically important, for many countries in the tropics rely on hydropower (Arias et al., 2020). More critically, studies on tropical freshwater resources remain highly concentrated in tropical South America and are severely understudied across the Congo river basin (Fugère et al., 2016). To address these knowledge gaps, PANGEA will answer the following questions:

Q18.What are the direct and indirect hydroclimate controlson tropical forests’ carbon (including CH4 emissions), energy and water cycles?

Q19. How does precipitation recycling influence the resilience or vulnerability of forest carbon balance with shifting disturbance regimes, land cover and land-use change, and increasing atmospheric CO2?

Q20.How are climate and land-use change altering land surface biophysical properties that influence the strength of land-atmosphere interactions?

Q21.How do deforestation, degradation, and forest regrowthalter regional hydrological cyclesin tropical regions, including precipitation regimes and freshwater resources?

To investigate the hydroclimate drivers of ecosystem function across the tropics, PANGEA will integrate in situ weather and eddy covariance measurements with satellite retrievals of water vapor content and precipitation (GOES-R, GPM), land surface temperature, evapotranspiration and evaporative stress (ECOSTRESS) and SIF (FLEX\***,** TROPOMI**,** OCO‑2/3). In addition, PANGEA will employ SMAP, SMOS, NISAR, AMSR-E, and EMIT data to measure soil moisture, canopy water content, hydraulic traits, and thermal stress. To further quantify land surface biophysical properties, PANGEA will also obtain surface albedo, and other surface radiation fluxes from VIIRS and GOES-R. Surface hydrological measurements from SWOT will be used to characterize tropical terrestrial water bodies (lakes, reservoirs, wetlands) and assess fresh water resources. These datasets will be used in conjunction with forest structural and compositional changes associated with deforestation and forest degradation (*Section 3.2.3*) to assess the emergent relationships between different types of land-cover and land-use change with shifts in precipitation and water storage across the PANGEA domain. These datasets will be used to both provide initial and boundary conditions to process-based models (*Section 6.3*) on the extent of deforestation and forest degradation, and to provide benchmarks on the impacts of deforestation and degradation on water, energy and carbon cycles at different landscapes. In situ, airborne and satellite datasets obtained and/or constrained by PANGEA will also provide critical datasets to assess the ability of Earth System Models to represent precipitation recycling across the different continents.

## Projections

### Projections: Carbon, Water, Energy, and Nutrient Cycles

The future of precipitation patterns across the tropics remain highly uncertain, but Earth system model simulations suggest that tropical South America may see mean annual precipitation reductions while total precipitation in Central Africa may remain similar or even increase (Dobler et al. 2024). However, stability in mean annual precipitation does not mean stability in the hydrological cycle. For example, rainfall seasonality may become more pronounced and with stronger interannual variability (Gloor et al., 2013), and warming trends may increase atmospheric and soil dryness even if precipitation remains similar to historical averages (Cook et al., 2020; Ukkola et al., 2020). In addition, the effects of atmospheric CO2 on hydroclimate depend on multiple interacting factors and remain uncertain. For example, high CO2 may reduce leaf-level transpiration due to lower stomatal conductance (Sampaio et al., 2021), but the ecosystem-level response also depends on changes in leaf area index (Li et al., 2018). Moreover, deforestation and forest degradation have major impacts on evapotranspiration, canopy interception, runoff and water storage (Heerspink et al., 2020), which could potentially impact rainfall across the Amazon (Spracklen et al., 2018; Baudena et al., 2021), although there is great uncertainty on the magnitude of this effect in modeling studies (e.g., Pires and Costa 2013; Swann et al., 2015).

Changes in hydroclimate, atmospheric CO2, land cover and land also interact with changes in the nutrient cycling, and understanding these feedbacks is critical. Phosphorus and potassium availability influence net primary productivity during droughts (Manu et al., 2024), and nitrogen can be an important limiting factor in secondary forests (Davidson et al., 2007). Research suggests that CO2 fertilization effects can be greatly reduced when phosphorus is a limiting factor (Yang et al., 2016; Fleischer and Terrer 2022). However, our understanding of the feedbacks between nutrient cycling and other drivers (climate, CO2 fertilization, and land-cover and land-use change) come from highly localized manipulative experiments, making the scaling to highly heterogeneous landscapes and continental scales challenging (Townsend et al., 2008). By integrating coordinated measurements across multiple landscapes and scales, PANGEA will address the following questions:

Q22.How will changes in precipitation patterns (e.g., ITCZ displacement), increasing temperatures, and shifting disturbance dynamics in tropical forests alter the terrestrial water balancevia changes in seasonal precipitation timing and duration, evapotranspiration, and soil water?

Q23.How will future changes in vegetation, including deforestation, degradation, and regrowth, impact local, regional, and continental climate and hydrology?

Q24.How will increasing temperatures, atmospheric CO2, and extreme climate events impact nutrient availability and soil-vegetation interactions?

Considering that these questions will explore future scenarios of changes across the tropics, PANGEA will rely on process-based models (*Section 6.3*) that will be fully integrated with remote sensing (*Section 6.2*). For example, to initialize cohort- and individual-based mechanistic models with realistic, observed forest structure and composition across environmental gradients, PANGEA will integrate multispectral, hyperspectral, lidar, and radar data collected both through PANGEA airborne campaigns and from satellite measurements (GEDI, EMIT, VIIRS, Sentinel-3, NISAR\*, SBGvisible to shortwave infrared [**VSWIR\*** imaging). The emergent relationships based on remote sensing relating forest structure, composition and function (*Section 3.1.2*) as well as remotely sensed hydroclimate and water stress variables (*Section 3.1.3*) will be used for assessing and reducing model uncertainty. In addition, canopy nutrient concentrations estimated from hyperspectral remote-sensing retrievals guided by lidar-derived geomorphological characteristics can be used to inform patterns and drivers of nutrient distributions across heterogeneous tropical forest landscapes. The optimized models will then be applied to scenarios that are representative of a range of scenarios that allow for quantifying and attributing the role of changes in climate, atmospheric CO2, land cover and land use in driving changes in biogeophysical and biogeochemical cycles.

### Projections: Heterogeneous Forest Resilience

Climate change and the expansion of deforestation and forest degradation across the tropics will likely expose forests to more frequent anthropogenic and natural disturbances (Seidl et al., 2017; Lapola et al., 2023). Widespread shifts in disturbance regimes will 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 (Malhi et al. 2014). However, the long-term impact of novel disturbance regimes on tropical forests will ultimately depend several factors that are still poorly understood in tropical ecosystems: (1) the relative impact of intensity and frequency changes in disturbances (Williams et al., 2013); (2) the variability of resistance to disturbances and post-disturbance recovery across species and landscapes (Anderson-Teixeira et al., 2013, Powell et al., 2018; Liu et al., 2022); (3) the interactions between multiple disturbances impacting the same region; (4) the feedbacks between disturbance-driven shifts in forest structure and composition and additional disturbances (Silvério et al., 2019; Brando et al., 2020); and (5) the impacts of disturbances on ecosystem services and people livelihoods (Feng et al., 2013; Mamalakis et al., 2021). Advancing process-understanding and observation-based quantification of these factors is critical for improving modeling capabilities. Therefore, research in PANGEA will address the following questions:

Q25.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?

Q26.How will climate warming and shifting extreme events interact withland cover and land-use change to influence shifting fire regimes and their feedbacks with forest function and the climate?

Q27.How will these future changes in climate and extreme events impact carbon cycling within tropical forests, and at what point will this lead to a large-scale transitionin functional composition and/or the regions becoming a net carbon source?

Q28.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?

Process-based and social-ecological system models (e.g., agent-based, bioeconomic, disequilibrium, or network modeling) will be used to quantify the impacts of changes in disturbance regimes on hyper-diverse tropical forests, and the consequences for ecosystem provisions and services that may impact economic activities and the livelihood of Indigenous Peoples and Local Communities. For process-based models, PANGEA will use the same approach described in *Section 3.3.1* to generate initial and boundary conditions. Likewise, emergent relationships between functional diversity and recovery rates will be derived using data from airborne campaigns and combined with data streams from SIF (TROPOMI, OCO‑2/3, FLEX\*), thermal infrared measurements (ECOSTRESS,GOES-R, MTG-I) and the remote-sensing based chronosequences of ecosystem recovery (*Section 3.2.3*). To quantify the impacts of tropical forests on social-ecological co-benefits, 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 will integrate 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.

# Scientific and Technical Advancement from PANGEA

PANGEA will leverage decades of scientific efforts, including large projects such as LBA (Avissar et al. 2002, Davidson et al., 2012), international forest inventory plot networks (ForestPlots.net et al., 2021), and multiple model development efforts, including (but not restricted to) NASA’s Global Modeling and Assimilation Office (GMAO), NASA’s GISS BiomeE (Weng et al., 2022) and DOE-supported FATES model being developed as part of NGEE-Tropics ( Koven et al., 2020; Huang et al., 2020; Xu et al., 2023; Knox et al., 2024; Shuman et al., 2024). Despite these efforts, attempts to assess the resistance and resilience of tropical forests to disturbance have garnered inconsistent results. Field studies suggest Central African forests may be more 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. Several factors may explain these inconsistencies, including: 1) changing rates of tree mortality, 2) different sensitivity of photosynthesis, respiration rates, and other ecosystem processes, (which 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 to be determined by the PANGEA community, by adding a pan-tropical view gaining new knowledge from enhanced multidimensional remote sensing measurements and analyses. PANGEA 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 coordinated and collocated remote, ground measurements, and Indigenous, Traditional, and Local Ecological Knowledge embedded within a collaborative scientific effort that prioritizes interdisciplinarity. To advance scientific and technological capabilities and solutions, 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.
* Increaseunderstanding of processes that control heterogeneity in the vulnerability of tropical forest landscapes to structural and functional change.
* Advance remote-sensing capabilities to measure, map, and monitor biodiversity, carbon cycle dynamics, and agricultural systems.
* Provideimproved 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 enabled by technical advances:

* Integration of ground and remote-sensing measurements leading to more reliable calibrations of remotely sensed variables;
* Scaling of data and workflowsfor integrated ground and remote-sensing data analysis;
* Advances in the use of AI and machine learningfor data assimilation, fusion, and scaling;
* Developmentof data-model-integration that improves the representation of the functionally important components of tropical forest diversity that are scalable with remote sensing;
* Improved accuracy and refined uncertainty estimatesfor remote-sensing-derived data products.

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 vegetation demographic rates, using existing ground data from long-term forest inventory plots, and functional and structural diversity using airborne lidar. Coincident airborne hyperspectral 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 other biotic 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.

The integration of field and remote sensing data with model development and assessment will be an integral part of PANGEA (*Section 6.3*). In situ and airborne remote sensing (e.g., hyperspectral and lidar) measurements across critical gradients will be used to reduce parameter uncertainty and provide initial and boundary conditions for process-based models. PANGEA’s teams will employ artificial intelligence and machine learning models to obtain synthesis datasets that scale measurements at intensive PANGEA sites and partner sites to the core and extended PANGEA domain using satellite remote sensing. These synthesis datasets will be used to parameterize and benchmark process-based models and social-ecological systems models at large scales, and will provide boundary conditions for inverse models. Model and data integration will be fundamental for answering PANGEA’s key questions (*Section 3*), which will serve as the basis for studies seeking to (1) understand the role of structural and functional diversity in controlling tropical forest carbon, water, energy, and nutrient cycles; (2) investigate how increased CO₂ levels and rising temperatures specifically affect carbon sequestration rates in tropical forests; (3) quantify the impacts of extreme events, such as severe droughts, on forest health and CO2 and CH4 emission; (4) advance understanding of the consequences of deforestation and forest degradation on biodiversity, biogeophysical and biogeochemical cycles, ecosystem services and hydroclimate; (5) evaluate the effectiveness of restoration strategies on tropical forest resilience and climate change mitigation; and (6) characterize the risk of tropical forests reaching critical transitions to alternative states due climate change, deforestation, and forest degradation, and determine the role of biodiversity in mitigating such vulnerabilities.

# 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 resistance to 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 X). PANGEA builds directly upon the scaling developments and successes from the NASA 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 will leverage NASA’s Airborne Science Program to obtain high-resolution data from hyperspectral, small footprint lidar, synthetic aperture radar (SAR), and other remote-sensing systems over tropical forests in Central Africa and the Americas to 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 XCO2 and XCH4 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 XCH4 (e.g., TROPOMI[3.5 km × 7.0 km]) and XCO2 (e.g., OCO-2[1.3 km × 2.2 km]) over 95% of retrieved information is filtered due to clouds in the tropics (Qu et al., 2021). Higher spatial resolution XCO2 and XCH4 satellite sensors such as the recently launched MethaneSat (100 m × 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 × 100 m). However, these target mode observations will not provide the global coverage needed to constrain tropical greenhouse gas budgets. Cloud cover will likewise affect estimates of land surface temperature and evapotranspiration from thermal remote sensing, which will require bias-correction approaches (Van Niel et al., 2012).

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-2, Landsat, GEDI), international (e.g., TROPOMI, GOSAT, GOSAT-2, CO2M, RADARSAT, Envisat, PRISMA, DESIS, BIOMASS), and commercial (e.g., GHGSat, MethaneSat, WorldView, Quickbird**/**GeoEye, Planet) satellite products. These observations will aid in validation of these satellite’s retrievals of forest structure, foliar traits, forest diversity, 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 (Copernicus Hyperspectral Imaging Mission for the Environment), 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.

# Research Strategy and Study Design

Similar to previous NASA projects, PANGEA will enable investigators to study the main scientific questions (*Section 3*) by responding to NASA calls for proposals. Co-funding will be sought; therefore we present a modular and flexible project design. Research will integrate ground, airborne, and satellite-based science investigations and models to enable effective interpretation of present and future satellite-based data. Building on former NASA projects in the tropics, PANGEA will be co-designed with local institutions and partners to facilitate collaborations and build new relationships within the scientific community, with a special emphasis on interactions among scientists from the US and tropical forest countries. Throughout the science definition and project years, PANGEA will work to engage and train early career scientists, both from the US and local tropical forest institutions. PANGEA will leave a legacy of open data, open science, capacity building, and strengthened partnerships, providing a strong basis for future research.

## Overall Study Approach

Understanding tropical forests at global, policy-relevant scales requires satellite remote sensing.

The utility of remote sensing over tropical forests depends on multi-scale data and knowledge integration. The abundance of new satellite data can now be paired with new capabilities for data analysis. There is also now a far greater ability to carry out numerically intensive analyses compared to previous NASA TE projects like LBA, with cloud computing, advanced computational resources, and rapidly evolving machine learning and AI capabilities for classification, regression, and prediction. However, the scarcity of observations and label data for training and validating data-hungry AI models, and limited process knowledge in tropical regions to date has led to significant challenges in improving satellite products and interpreting scientific findings gleaned from these products. Scale mismatches still exist for desired retrievals from nearly all satellites over the tropics. To overcome these limitations and advance the utility of satellite remote sensing over tropical forest biomes, PANGEA builds on scaling approaches developed during previous NASA TE field projects such as BOREAS, LBA, and ABoVE. PANGEA will reconcile scale mismatches through collocated ground, tower, drone, aircraft, and satellite measurements in combination with advances in understanding of processes that underpin scaling theory. The remainder of *Section 6* describes the Science to Scale Strategy (*Section 6.1.1*), Notional Timeline (*Section 6.1.2*), Essential Scientific Measurements across scales (*Section 6.2*), as well as the Modeling, Data Synthesis, and Integrative Analysis approach to tie it all together (*Section 6.3*).

### PANGEA’s Science-to-Scale Strategy

PANGEA’s nested sampling design, with its science-to-scale strategy, provides opportunities to advance satellite monitoring, product development, data assimilation, and benchmarking of processes in next-generation ecosystem models. These advances can significantly improve the ability of stakeholders to apply models to improve understanding and long-term prediction of processes.

PANGEA’s science-to-scale strategy implements an integrated systems approach that encompasses complex landscape mosaics spanning forests to wetlands and peatlands, and intact to disturbed to agricultural social-ecological systems (Figure X). 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 projects 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 conditions, thus reducing the risk of equifinality—getting the 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).

Suborbital remote-sensing retrievals (e.g., drone and aircraft) are critical to scale between ground measurements and coarser-resolution satellite retrievals. PANGEA stands on the shoulders of highly successful NASA field and airborne projects to Africa and the Americas, including SAFARI 2000, AfriSAR-1 and -2, BioSCape, and several Earth Venture Suborbital (EVS) missions.

Differences 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 require reconciliation (e.g., Li et al., 2018). Similarly, the 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 spaceborne data exceed the dimensions of a tree crown, they do not support retrieval of crown- and tree-level metrics, or fine-scale ecosystem metrics like canopy gap detection and tree mortality.

Another example is the use of hyperspectral remote-sensing data to estimate metrics of biodiversity. Hyperspectral retrievals of the top-of-the-canopy from EMIT, PACE, SBG, and CHIME have the potential to yield direct measures of plant spectral diversity (Cawse-Nicholson et al., 2021; Schimel et al., 2020), which can also be used to estimate beta diversity (Schweiger and Laliberte, 2022), plant functional diversity (Cawse-Nicholson et al., 2021; Rocchini et al., 2022; Thompson et al., 2021), and in some cases plant taxonomic diversity (Schimel et al., 2020; Rossi and Gholizadeh, 2023). The fusion of these retrievals and metrics with data and knowledge on animal movement, plant-animal interactions, multi-taxa community assembly, and ecosystem structural variation from IEK, TEK, and LEK, as well as eDNA, bioacoustics, camera traps, and other remote-sensing datasets (e.g., GEDI, NISAR, SWOT) has the potential to yield additional indirect biodiversity estimates and proxies. This integrative approach can, for instance, improve the implementation of carbon-based incentive programs (Castro-Magani et al., 2021), or improve national services, maximizing societal benefits (Schiavon et al., 2023). However, calibration and validation data in the tropics are currently lacking to test the generalizability of existing algorithms. For instance, proper spectral resolution, pixel size, and the coexistence of multiple tree species in a given pixel, or the temporal resolution to quantify characteristic diurnal processes associated with those species, need to be properly addressed (Schimel et al., 2020; Rocchini et al., 2022). Endmember diversity is an approach to address some of these challenges (Rossi and Gholizadeh, 2023). Further, functional trait maps still require estimation using models calibrated to specific sites based on in situ leaf-trait measurements (e.g., Chadwick & Asner 2016), and very limited work has been conducted to explore the fusion of disparate data types for developing process-based metrics or proxies (Schimel et al., 2020; Bastin et al., 2019; Mairota et al., 2015; Ordway et al., 2022; Portillo-Quintero et al., 2022).

PANGEA will 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](https://carlos-alberto-silva.github.io/silvalab/cms4d/cms4d_workshop.html), a multi-scale data-fusion prototype system for carbon dynamics monitoring from space. CMS4D, led by Carlos Alberto Silva, is a case study in the Brazilian Cerrado focused on fire dynamics 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 Society for the Protection of Underground Networks (SPUN) 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-scale 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.

Effectively advancing the use of satellite remote sensing requires rigorous and thoughtful data, information, and knowledge integration across spatial and temporal scales. A decade of coordinated efforts during NASA ABoVE advanced understanding of boreal biome transitions and non-linearities, revealing spatially explicit increasing and decreasing resilience trends (Zhang et al. 2024) and yielding a new biome-specific model benchmarking system (Stofferahn et al., 2019). PANGEA will build on scaling theory advanced by ABoVE and further integrate ML/AI with remote-sensing data to advance the measurement and monitoring of heterogeneous processes, dynamics, and changes across tropical forest regions, including carbon flux source/sink dynamics, land-use classification, species distribution modeling, leaf-area index estimation, and weather forecasting. PANGEA offers 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 (e.g., Rödig et al., 2019; Longo et al., 2020; Schneider et al., 2023). *Section 6.3.3* describes PANGEA’s modeling, data synthesis, and integration approach in more detail.

Finally, PANGEA will improve our ability to push the limits of what we can infer 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.

Persistent cloud cover, for example, is an important limitation for optical sensors in tropical forests (e.g., Landsat, EMIT, 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 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. Interrogating and clarifying the capabilities and limits of remote sensing of the tropics through methodological and computational advances and data fusion is urgently needed to support monitoring, guide ground-based research and implementation activities, and guide targeted long-term multi-scale monitoring efforts.

### Notional Project Timeline

The PANGEA Project Office will develop the definitive project schedule. Here, we provide a notional outline of the main events of the PANGEA project that will be executed over 6 to 9 years (see *Section 9.4*). Prior to project implementation, PANGEA will develop a Concise Experiment Plan during the Science Definition phase lasting between one to two years. This phase involves selecting priority landscapes, refining ground, airborne, and satellite measurement plans, defining analyses to address the project’s science questions, and determining a preliminary budget. This strategy will form the basis for a NASA announcement of an opportunity to recruit the PANGEA Phase 1 science team. Nominally, we expect NASA will solicit proposals for science team participation every three years. Following the Science Definition phase and the selection of a Phase 1 science team, we consider a PANGEA project to be executed over about 8 years although longer or shorter implementations periods are possible using a flexible and modular approach. A wide range of budget and schedule profiles are possible under a modular approach because individual campaigns have limited dependencies. The initial focus will be to establish and augment field sites with new instrumentation, as well as satellite-based data analyses and models to optimize future measurements. Early model development and analyses of existing data will reveal the greatest sensitivities that will guide the implementation details and campaign measurements. Peak data acquisition would occur during years 2-6, ensuring that resources are spent on measurements with the highest scientific return. In a final synthesis during years 7 and 8, field activity will be limited and PANGEA will concentrate on synthesis and modeling studies that extensively use the data previously acquired.

## Essential Scientific Components

Addressing data and knowledge gaps in the tropics requires a coordinated ground and airborne project 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, revealing functional differences (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. Yet there remains a critical need for collocated and coincident measurements across the highly variable tropical landscapes, particularly in Africa, where data gaps are the greatest, and process-based understanding is poorest. In addition, heavy cloud cover limits remote sensing over the tropics during the wet season. Measurements limited to the dry season risk biasing understanding of tropical forests, given strong seasonal differences in dynamics and processes (Cleveland et al., 2015), including carbon cycling, species interactions, land-use activities (e.g., fire and clearing), hydrological cycling, and more. PANGEA will fill important temporal gaps in remote sensing by acquiring suborbital measurements timed during the onset and end of the dry season coordinated with continuous and/or more frequent measurements from flux towers, drones, and other sensors. 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 will link high resolution process measurements (forest plots, chamber measurements, flux towers, eDNA, animal movement data, TEK, IEK, and LEK) with extensive airborne and satellite remote-sensing data providing a baseline for ongoing field and spaceborne measurements, and allowing comparison with past studies.

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.

PANGEA will establish a network of coordinated field and airborne campaigns 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. 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 influence tropical forest stability in the face of climate and land-use change impacts.

### Baseline, Threshold, and Descope Strategy

We derive three alternative levels of Essential Scientific Measurements, namely the Baseline, Threshold, and Descope, 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 Baseline Investigationfulfills all Science Objectives (*Section 1.1*) and all Science Questions (*Section 3*) at 3–6 American and 3–6 African tropical forest landscapes. To meet these Baseline Investigation Objectives, we establish the following requirements:

1. Collect aircraft measurements via wall-to-wall flightline mosaics and sampling transects over a minimum of three priority landscapes in Africa and three priority landscapes in the Americas, where landscapes cover hundreds of kilometers encompassing a variety of socio-ecological systems—the ecosystems and the people who depend upon them (see *Sections 6.2.3* and *6.2.4* for details on landscape measurements).
   1. Airborne measurements will include one successful capture at the beginning of the dry season and one successful capture at the end of the dry season at each landscape. Beginning of the dry season (wet-to-dry) and end of the dry season (dry-to-wet) captures occur in different months on different continents. Tropical forests can have unimodal seasonality (one dry and one wet season), or bimodal seasonality (two dry and two wet seasons). For this reason, measurement schedules will be defined based on landscape-specific seasonality.
   2. Landscapes will be selected from candidate sites during the development of the Concise Experiment Plan.
   3. A variability analysis building on Figure X and an analysis of model uncertainty will be used to inform important endmembers to capture, and will contribute to landscape selection during the development of the Concise Experiment Plan.
2. Collect coincident and collocated ground measurements during airborne acquisitions for required measurements (e.g., chemical leaf traits, chamber flux measurements).
3. Collect ongoing ground measurements at required temporal frequencies throughout the project (e.g., monthly drone- and ground-based tree mortality and phenology acquisitions, sub-hourly flux measurements).
4. Develop and apply data synthesis approaches to scale field and airborne observations to PANGEA’s Core Domain, using satellite data to obtain constrained estimates (and uncertainties) of variables of interest.
5. Evaluate the transferability of data synthesis products across the Core Domain through cross-validation.
6. Model carbon, water, and energy fluxes, as well as vegetation dynamics, using terrestrial biosphere models initialized, parameterized, and benchmarked with the remote-sensing based data synthesis products.
7. Apply optimized models to test tropical forest stability within and among all investigation landscapes and regionally based on terrestrial biosphere and social-ecological systems model results.
8. Model the relative role of climate, soils, and divergent evolutionary histories in determining variation in tropical forests’ stability in the face of climate impacts.

The Threshold Investigationfulfills all Science Objectives (*Section 1.1*) at exactly two American and two African tropical forest landscapes. The Threshold Investigation requires one successful airborne capture at the end of the wet season and one successful airborne capture at the end of the dry season at each landscape.

Our Descoped Investigation fulfills all Science Objectives (*Section 1.1*) at two landscapes in Africa only. Our Descoped Investigation relies on existing data, planned campaigns in the American tropics (see *Section 6.2.4*), commercial data-buys, and deployable drones, to use satellite data over the Americas for comparisons.

Temporal revisit requirements:Two focused airborne campaigns with wall-to-wall mosaics and transects across multiple landscapes are necessary to capture seasonal variations and account for both within- and between-continental heterogeneity in a standardized way. The timing for surveys will account for the precipitation seasonality of each landscape. For landscapes where two dry seasons exist, PANGEA’s campaigns will focus on the longest dry season. Airborne campaigns 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, allowing for a modular design and building in valuable airborne campaign flexibility. Within landscape-level subsections of these airborne acquisitions (e.g., 10–20 km2), 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, over a 6- to 9-year project, it is highly likely that extreme events, such as a major fire, drought, or an El Niño event, will occur, providing further opportunities for analysis.

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 X). PANGEA data collection will be conducted at landscapes that encompass intact, disturbed, and degraded conditions across forests, peatland, and wetland ecosystems, 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. For more information, see *Section 6.2.2, Candidate Landscapes,* and *Section 6.2.5, Field Observations and Studies*.

Flexible and modular approach: PANGEA will be executed with a combination of multiyear ground, tower, and drone measurements at specific landscapes and seasonal campaigns of intensive measurements that may include ground and airborne components. Each landscape and each campaign can be implemented and funded separately. PANGEA will require multi-year measurements at landscape to overlap spatially with ground and airborne campaign measurements. However, we emphasize that there will be no requirements for campaigns in separate seasons or on separate continents to be conducted in the same year or in a particular order (e.g. wet before dry). The number of continents and landscapes within continents can vary according to the strategy followed (Baseline, Threshold, or Descope). The combination of strategies and campaign timing yields multiple options for schedules and budget profiles that offer flexibility to NASA management and to potential co-funders of PANGEA activities.

Table X. Description of ecological and geophysical variables relevant to this project, 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. See Table AX for additional detail.

| Variable(s) | Science Questions | Ground Measurements | Observing Technologies | Earth Observation Assets | |
| --- | --- | --- | --- | --- | --- |
| Satellite  (Planned/Proposed) | Airborne  (Drone/Aircraft) |
| Ecosystem Fluxes  (GPP, ET, Ecosystem Respiration) | Q1–Q8, Q10, Q11, Q13-Q15, Q17, Q20–Q24 | Flux towers, leaf-level spectra | Infrared Spectroscopy, Thermal | OCO-2/3, TROPOMI, GOES-R ABI, AHI, MTG-I, NASA GHG ESE\*, Sentinel 5P/5\*, FLEX\*, CO2M\*, GOSAT-2, GOSAT-GW\*, Landsat, ECOSTRESS, SBG\*, CHIME\*, TRISHNA\*, LSTM\*, VIIRS, Sentinel-3, Commercial\*, GEO weather satellites | NASA AVIRIS-NG/3 + HyTES, MASTER |
| Atmospheric Exchange  (CO2 & CH4 Fluxes, Column CO2/CH4/CO) | Q1, Q2, Q4–Q8, Q10, Q11, Q13, Q14, Q20, Q21, Q24, Q27 | Flux towers, chamber measurements, TCCON, COCCON, EM27/SUN Spectrometers | Hyperspectral, Airborne Eddy Covariance (AEC), Infrared Spectroscopy | EMIT, MethaneSat, SBG\*, Carbon-i\*, CarbonMapper\*, OCO-2/3, NASA GHG ESE\*, Sentinel 5P/5\*, FLEX\*, CO2M\*, GOSAT-2, GOSAT-GW\* | NASA AVIRIS-NG/3, CARAFE, CFIS (SIF), DLR CoMet (CO2/CH4), UZH ARES, NEON AOP, GAO |
| Aboveground Biomass & Structure  (Canopy Height, Vertical Height Heterogeneity, Gap Dynamics, Tree Mortality) | Q1, Q2, Q4–Q13, Q15, Q17–Q21, Q23, Q25, Q28 | Forest inventory plot data, terrestrial laser scanning, repeat census forest inventory plot data | Lidar, Radar, Multispectral | GEDI, Icesat-2, MOLI\*, EDGE\*, Sentinel-1, NISAR\*, BIOMASS\*, Landsat, Sentinel-1/2, Planet | NASA LVIS, UAVSAR, small-footprint lidar (aircraft), repeat drone RGB or Lidar |
| Diversity  (Spectral, Functional, Canopy Foliar Traits, Faunal, Phenology) | Q2, Q4–Q7, Q10–Q15, Q20, Q24, Q25, Q28 | Leaf-level spectra, taxonomic diversity; plant traits; IEK, TEK, LEK; camera traps; bioacoustics sensors; animal movement; eDNA; PhenoCams; long-term phenological observations | Hyperspectral, Lidar, Radar, Optical Radiometers (OR) | EMIT, PACE, PRISMA, EnMAP, Planet & Planet Tanager, SBG\*, CHIME\*, FLEX\*, NISAR\*, BIOMASS\*, Landsat, Sentinel-2, OLCI | NASA AVIRIS-NG/3, UAVSAR, LVIS, UZH ARES, GAO, small-footprint lidar, repeat drone RGB |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable(s) | Science Questions | Ground Measurements | Observing Technologies | Earth Observation Assets | |
| Satellite  (Planned/Proposed) | Airborne  (Drone/Aircraft) |
| Critical Thresholds  (Water Stress, Thermal Stress) | Q1–Q4, Q6–Q9, Q12–Q20, Q22, Q23, Q25 | Soil moisture probes, Leaf water content, leaf/stem water potentials & conductance, tower-based VOD (L-band GNSS), FLIR cameras | Microwave radar/radiometry, GNSS-R/Signals of Opportunity, Hyperspectral | SMAP, SMOS, Sentinel-1, NISAR\*, BIOMASS\*, LSTM\*, AMSR-E, EMIT, SBG VSWIR & TIR\*, CHIME\*, FLEX\*, SNOOPI\*, CYGNSS, Lemur-2, Landsat, ECOSTRESS, TRISHNA\*, Commercial\* | NASA UAVSAR, AVIRIS-NG/3 + HyTES, MASTER, AirMOSS |
| Fire & Aerosols  (Active Fire, Biomass Burning Aerosols) | Q3, Q4, Q6, Q7, Q9, Q12, Q13, Q19, Q21, Q26, Q28 | Life fuel moisture, soil moisture, burn area, burn severity, IEK, TEK, LEK, Fuel type, fuel density, aerosol measurements | Thermal, UV/Infrared, Photometers, Lidar | Landsat, VIIRS, Sentinel-3, SBG\*, TRISHNA\*, LSTM\*, Commercial\*, OMPS, EMIT, PACE, OLCI, NISAR\*, BIOMASS\*, CALIPSO-CALIOP\*\*, AOS\* | NASA HyTES, MASTER |
| Land-Use & Land Cover & Ecosystem Services:  (Food, Freshwater, Medicine, Spiritual and Ceremonial Practices) | Q1, Q3, Q4, Q6, Q7, Q9, Q12–Q14, Q16, Q19, Q21, Q23, Q28 | Agricultural activity, logging severity, fire practices, IEK, TEK, LEK, conservation management practices, cultural identifications, water quantity and quality | Optical Radiometers (OR), Hyperspectral, 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, UAVSAR, LVIS, UZH ARES, GAO, small-footprint lidar |
| Hydro-Meteorology  (Surface Water, Groundwater, Atmospheric Moisture, VPD, Wind) | Q1–Q4, Q6–Q9, Q14, Q16–Q19, Q22, Q23, Q25, Q28 | Water-surface height, inundation extent, discharge characterization, well measurements, weather stations | Altimeter, Radar, Radiometer, Gravimetric, Microwave, Infrared Sounders, Imagers, Doppler wind lidar | SWOT, Sentinel-1, NISAR\*, BIOMASS\*, GRACE-FO, ATMS, GeoXO\*, AOS\*, Aeolus | NASA UAVSAR, Radiosonde measurements |
| Edaphic  (Soil Nutrients and Texture, Topography, Geomorphology) | Q1, Q8, Q18, Q19, Q22–Q25, Q28 | Soil samples | Hyperspectral, Lidar, Radar | EMIT, PACE, SBG\*, CHIME\*, SRTM, Copernicus GLO-30 | NASA AVIRIS-NG/3, UAVSAR, LVIS, small-footprint lidar |
| **Note:** PANGEA will explore correlative relationships with remotely sensed variables, not direct measurements | |

[Table Note PANGEA style: The note in the bottom-right corner could go here—or in the caption with the other notes—if it applies to the whole table.]

### Candidate Landscapes

PANGEA will collaborate closely with in-country partner institutions to ensure the smooth execution of field and airborne activities across selected landscapes that are about 10,000 km2. 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 X). PANGEA will prioritize countries that encompass landscapes where there is a confluence of intact, disturbed, and degraded forest, peatland, and wetland ecosystems, with adjacent agro-ecosystems. Coordinated, coincident ground data collection will be collected across these gradients within each landscape. Table Xsummarizes candidate landscapes based on information provided by partners. PANGEA landscapes will prioritize locations where the measurements described at the top of *Section 6.2.4* are already being collected or where additional measurements can be extended under PANGEA.

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, the One Forest Vision Initiative, Moore Foundation and National Science Foundation (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 in the Concise Experiment 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 8* for more information).

**Table X.** Candidate PANGEA landscapes. Colored circles indicate existing available data, by type.

A purple circle with white letter n in it

Description automatically generated🟡= Ground data; 🟠= Socioeconomic data; 🟢= Tower data; 🔵= Drone data; 🟣= Aircraft data.   
 = NASA aircraft data. \* Indicates planned activities. ATTO: Amazon Tall Tower Observatory.

| Landscape | Country | Available Data |  | Landscape | Country | Available Data |
| --- | --- | --- | --- | --- | --- | --- |
| Potential American Forest Landscapes | | |  | Potential African Tropical Forest Landscapes | | |
| KM 34 & ATTO (Manaus) | Brazil | 🟡🟢🔵🟣 |  | Dja | Cameroon | A purple circle with white letter n in it  Description automatically generated🟡🟠🔵 |
| KM 67 (Santarem) | 🟡🟢🟣 |  | Mbalmayo | A purple circle with white letter n in it  Description automatically generated🟡🔵 |
| Rebio Jaru | 🟡🟢 |  | Korup | 🟡 |
| Tanguro | 🟡🟢🟣 |  | Campo Ma’an | 🟡 |
| Caxiuana | 🟡🟢 |  | Luki | Democratic Republic of Congo | 🟡🔵 |
| Amacayacu | Colombia | 🟡 |  | Mai Ndombe | A purple circle with white letter n in it  Description automatically generated🟡🟠🔵 |
| Amazonas | 🟡 |  | Yangambi | 🟡🟢🔵 |
| La Planada | A purple circle with white letter n in it  Description automatically generated🟡 |  | Yoko Reserve | 🟡🟠 |
| Santa Rosa | Costa Rica | A purple circle with white letter n in it  Description automatically generated🟡🟠🟢🔵 |  | Ankasa | Ghana | 🟡🔵 |
| Turrialba | A purple circle with white letter n in it  Description automatically generated🟡🔵 |  | Bia Tano | 🟡🟢 |
| Tiputini | Ecuador | A purple circle with white letter n in it  Description automatically generated🟡 |  | Bobiri | 🟡🔵 |
| Yasuní | A purple circle with white letter n in it  Description automatically generated🟡 |  | Kogyae | 🟡🔵 |
| Paracou | French Guiana | A purple circle with white letter n in it  Description automatically generated🟡🟢🔵 |  | Lopé | Gabon | A purple circle with white letter n in it  Description automatically generated🟡 |
| Agua Salud | Panama | 🟡 |  | Ipassa |  |
| BCI | A purple circle with white letter n in it  Description automatically generated🟡🔵 \* |  | Mondah | A purple circle with white letter n in it  Description automatically generated🟡 |
| Darien | 🟡🟠 |  | Mabounié | A purple circle with white letter n in it  Description automatically generated🟡 |
| Iquitos | Peru | 🟡 |  | Rabi | A purple circle with white letter n in it  Description automatically generated🟡 |
| Huánuco | 🟡🟢 |  | Bokatola | Republic of Congo | 🟡 |
| Los Amigos | 🟡🟢 |  | Kolongomba | 🟡 |
| Madre de Dios | 🟡 |  | Lac Tele | 🟡 |
| San Martin | 🟡🟢 |  | Loundoungou |  |
| Tambopata | 🟡🟢 |  | Odzala-Kokoua | A purple circle with white letter n in it  Description automatically generated🟡🔵 |
| Ucayali | 🟡 |  | Makera | Rwanda | 🟡 |
| Guanica | Puerto Rico | 🟡🟢🟣 |  | Rubona | 🟡 |
| Luquillo | 🟡 |  | Sigira | 🟡 |
|  |  |  |  | Sebitoli | Uganda |  |
|  |  |  |  | Nalohou | Benin | 🟡🟢 |
|  |  |  |  | Bellefoungou | 🟡🟢 |
|  |  |  |  | La Lama Forest | 🟡🟢 |

### 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 nongovernmental organizations (NGOs) (Table X). PANGEA is well-poised to leverage 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 contribute to the improvement and refinement of ESO 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 inclusion in the process.

In Table Xbelow, we highlight a variety of operational and forthcoming NASA spaceborne sensors, their needs for advances in the tropics which PANGEA can address, 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 non-NASA space agencies where data are openly available. PANGEA will also explore commercial datasets available through NASA’s Commercial SmallSat Data Acquisition (CSDA) program during the Science Definition and Implementation phases of the project.

Table X. Examples of satellite remote-sensing observations and advances.

Purple text indicates satellites from non-US federal agencies.  
\* Indicates missions that have not yet launched and/or may still be under competitive consideration.

| Satellite Observations | Calibration, Validation, and Algorithm Advances from PANGEA |
| --- | --- |
| Sentinel-1, NISAR\*, BIOMASS\* | * Expand calibration/validation of biomass mapping along disturbance and climate gradients. * Support data product development from NISAR and BIOMASS in dense forests. |
| EMIT, CHIME\*, SBG-VSWIR\* | * Expand validation data for EMIT-derived product in tropical forests. * Support for improved L3 vegetation products from SBG VSWIR. |
| OCO-2/3, TROPOMI, MethaneSat, EMIT, CarbonMapper | * Obtain XCO2 and XCH4 cloud-free calibration samples in tropical regions. * Support data for L3 products, scaling between target-mode and broad spatial coverage data. |
| Carbon-I\* | * Validation data of greenhouse gas fluxes from wetlands. |
| GEDI, ICESat-2, EDGE\* | * High-accuracy forest structure data for improved L3 spaceborne lidar products. * Opportunities for calibration data for L4 biomass quantification products. |
| SMAP, SMOS | * Calibration data for soil moisture products in dense forests. |
| Geostationary: GOES-R ABI & AHI (Americas), MTG-I (Africa) | * Calibration data for ecosystem function estimates at sub-daily time scales. |
| VIIRS, Sentinel-3 | * Support development of L3 products of fire dynamics. * Calibration data for detection of small-scale fires. |
| ECOSTRESS, SBG-TIR, FLEX\* | * Support data for deriving all-weather L3 and L4 ecosystem function estimates. * Calibration data for emergent relationships between forest structure and composition and ecosystem function. |

### Airborne Remote-Sensing Observations

PANGEA airborne observations, including instrumented aircraft and drones, 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 2). When using NASA 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 Experiment Plan.

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| Box 2. 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 arrangements for conducting field work and airborne campaigns in each country. Diplomatic agreements (such as memoranda of understanding [MOUs], implementing agreements [IAs], and/or flight clearances) will need to be created between the U.S. 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 will also consult with NASA, the State Department, U.S. Forest Service (USFS) and U.S. Agency for International Development (USAID) to identify and pursue synergies between PANGEA activities and U.S. diplomatic objectives, including scientific cooperation and country-to-country ties. The PANGEA Science Team, TE Program, and CCE Support Office will work closely to guarantee that Indigenous land and sovereign territories are co-developers in any diplomatic approval processes. The current PANGEA Science Team’s experience with numerous international field and airborne campaigns will be used in establishing the proper international agreements for the PANGEA project. |

PANGEA leverages and builds on NASA’s history of successful international airborne campaigns, including many in Africa. Most recently, NASA executed the 2016 AfriSAR and 2023/2024 AfriSAR-2 campaigns, 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 campaign flew two NASA aircraft integrated with four airborne remote-sensing instruments, acquiring contemporaneous observations from the UV through the VSWIR and thermal range as well as full waveform LiDAR data. This combination of instruments was accompanied by an extensive field observation campaign, executed by a diverse science team with ~50% local participation. AfriSAR and 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.

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 the American tropics. In 2023, NASA JPL had a successful campaign with AVIRIS-NG collecting remote-sensing data with a NASA contracted aircraft over Chile, Colombia, and Ecuador for methane point source measurements in coordination with each country. This built on previous successful campaigns in the region, including for example UAVSAR flights in Colombia, Ecuador, Peru, and French Guiana; AVIRIS flights in Colombia, Ecuador, and Chile, and planned AVIRIS flights in Panama and Costa Rica; and LVIS in French Guiana. All these campaigns represent decades of experience of NASA HQ and the centers (including JPL) working together with universities and international collaborators to successfully acquire airborne remote-sensing and in-situ data during global field campaigns.

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| **When PANGEA develops its Concise Experiment Plan, we will continue to leverage the experience of team members from past international campaigns.** |

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, AVIRIS sensors 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) missions 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 acquired with USAID support through Sustainable Landscapes Brazil span large areas of Brazil (dos Santos et al., 2019), and similar efforts allowed sampling over forests in the Democratic Republic of Congo (Xu et al., 2017), demonstrating feasibility in important PANGEA geographies. The Airborne Research Facility for the Earth System (ARES) from 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) plan to collect airborne fluorescence, methane, and in-situ measurements, as well as possible carbon flux and species measurements, including CO2 and CH4 by means of a HELIPOD carried by a helicopter. 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. ESA plans are ongoing and will be further defined following an ESA-led workshop in the spring of 2025. Many current PANGEA team members are working closely with the INPE, ESA, DLR and CNES teams. PANGEA stands to greatly benefit from and contribute to these types of international collaborations.

PANGEA will also leverage drone capabilities, to supplement aircraft data collection and to acquire measurements that require higher temporal frequency acquisitions (e.g., tree mortality, phenology). PANGEA will use Technology Readiness Level (TRL) 9 lidar and RGB UAV instruments. Current commercial UAV-based hyperspectral offerings often present challenges and tend to cover the VNIR range only, losing the shortwave portion of the spectrum which is important for relevant ecosystem measurements. 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 nearly simultaneous field observations and airborne observations enabled by advance planning of field observations and clear, reliable methods of communication between the flight and field teams, and plans that incorporate timing flexibility. In preparation for and during the campaigns, PANGEA will rely on near-real time quick looks and flight tracking tools, which will optimize airborne data collection and facilitate better field match-ups and will also increase transparency, as used in BioSCape (Cardoso et al., 2024).

PANGEA also supports inclusive international collaboration. Borrowing from BioSCape’s success in this regard, PANGEA will implement a transparent prioritization scheme for science team regions of interest and will solicit feedback on the prioritization scheme in advance of the airborne campaign through town halls, workshops, bilateral meetings, and surveys. PANGEA will share preliminary flight plans and implement an iterative process so that the science team and local partners can contribute to refining the data acquisition design, while making clear to the science team and local partners that no airborne data is guaranteed, and that all proposed acquisitions are tentative until successfully executed. Information about daily flight activities, including go/no-go calls, will be conveyed promptly once daily decisions have been made.

### Field Observations and Studies

Ground-based measurements are necessary for (1) validating spaceborne measurements of ecosystem properties from both the NASA program-of-record 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 (see Table X), underscoring the importance of PANGEA field-based measurements and studies. Field observations broadly include the following:

* Manual in situ data and knowledgeinclude all data that must be directly measured and/or gathered by individuals on-the-ground and cannot be easily automated. Examples include forest inventory plots, leaf and wood traits, 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 and knowledge bases are important for understanding the mechanistic relationships between pattern and process and for the validation of drone, aircraft, and satellite measurements.
* Automated in situ datainclude 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 datainclude 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 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–where carbon refers to CO2, CH4, and lateral fluxes.
* Tower-based proximal remote sensingincludes all data that can be observed from platforms mounted on towers. 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 hyperspectral reflectance, solar-induced fluorescence (SIF), thermal infrared radiation (TIR), microwave backscatter, lidar, VOD (L-band GNSS), and PhenoCams.
* Drone-based proximal remote sensing includes lidar, RGB images 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, (2) it provides the ability to capture trends even during cloudy conditions, which are common in tropical forests, and (3) it can complement ground-based observations that may miss the top of the canopy due to occlusion. 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.

Several factors may restrict or limit field observations in tropical forests. First, access to dense, difficult-to-navigate terrain and remote areas may limit the ability to deploy and maintain field equipment in multiple sites. Likewise, extreme weather, such as heavy rainfall during monsoon seasons and extreme heat and humidity, creates harsh working environments which can limit the duration and extent of fieldwork. Moreover, many tropical regions are in regions that experience political instability, conflict, or land-use disputes, which can pose risks to researchers and make it difficult to conduct long-term studies. Furthermore, funding and resources for science comes mostly from the global north, limiting resources to directly fund fieldwork in the tropics. These limitations have historically resulted in the implementation of only a few sites across tropical forests with intensive measurements. These measurements cannot be easily generalized, because tropical ecosystems are highly biodiverse and data may be representative of only the local conditions.

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 (Table X). Partners have been engaged in the scoping process and will be involved throughout PANGEA, including during the development of the PANGEA Concise Experiment Plan. See *Section 8, Community Engagement Strategy*,for more information. PANGEA plans to build upon relationships with all of these partners to address the project’s Science Objectives. We note in particular that flux sites, such as those in the Global eddy covariance flux tower network (FLUXNET), 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. We also note 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 6.3*).

**Table X.** Partner organizations with ongoing field-based research and activities that are synergistic to PANGEA. AMMA-CATCH: African Monsoon Multidisciplinary Analysis Couplage de l’Atmosphère Tropicale et du Cycle Hydrologique. ForestGEO: Forest Global Earth Observatory. GEM: Global Ecosystems Monitoring network. RAINFOR: Amazon Forest Inventory Network.

| Organizations | Potential Contributions |
| --- | --- |
| Alliance for Tropical Forest Science (ATFS) | * 11 research networks (e.g., AfriTRON, ForestGEO, GEM, RAINFOR). * 11,656 forest inventory plots in 56 countries. * Strong leadership in capacity building. |
| Amazon Tall Tower Observatory (ATTO) | * Joint German-Brazilian project. * Three flux towers (including a 325-m one). * Ancillary data (biogeophysical/biogeochemical cycles and weather). |
| AndesFlux | * 6 eddy flux towers and permanent plots in western Amazon. * Sites spanning a dry-season length gradient (0–6 months). |
| Congo Basin Institute (CBI) | * 2 biological field stations in Cameroon. * Organizational networks across the Congo Basin. * CBI School for Indigenous and Local Knowledge (SILK). |
| Congo Basin Science Initiative | * Scientist-led platform for long-term scientific investment. * Efforts on building local scientific capacity. * Sustainable development initiatives. |
| CongoFlux | * Tropical research station in Yangambi (Democratic Republic of Congo). * Eddy covariance fluxes (CO2, N2O, CH4, H2O, sensible heat). * Additional data to characterize carbon cycling. |
| FLUXNET | * International network of networks (e.g., Americas' eddy-covariance Flux tower network [AmeriFlux], ICOS). * Consolidated and standardized eddy covariance flux data. |
| GEO-TREES | * Network of networks (e.g, AfriTRON, ForestGEO, GEM, RAINFOR). * Coordinated forest inventory plots and airborne remote sensing. * Data for calibrating carbon stock estimates from space. |
| Global Alliance of Territorial Communities (GATC) | * Network of Indigenous Peoples and Local Communities. * Represent 35 million people in 24 countries (Africa, Americas, Asia). * Capacity building for sustainable management and cultural protection. |
| Guyafor and Guyaflux | * Guyafor: Network of 54 long-term plots across 17 sites in French Guiana. * Guyaflux: Long-term (21 years) eddy covariance tower at the Paracou. |
| LBA | * Permanent Program of the Brazilian government. * Platform for infrastructure and research collaboration support in the Amazon. |
| NGEE-Tropics | * Decadal, multi-institutional project by the U.S. Department of Energy (DOE). * Intensive sites in Australia, Brazil, Malaysia, Panama, and Puerto Rico. * Data collection aimed at improving modeling of diverse forests. |
| NAME TBD - Benin | * 3 eddy flux towers: 2 forest (Bellefoungou and La Lama), 1 mixed crop (Nalohou) * Bellefoungou and Nalohou: Long-term (16 years) eddy covariance and weather measurements, surface water (AMMA-CATCH network), and soil samples that span topography and geomorphology gradients. * La Lama: Species survey available in GBIF |

## Modeling, Data Synthesis, and Integrative Analyses

### Modeling and Data Integration Approach

Modeling and data syntheses are fundamental components of PANGEA. Modeling and data synthesis activities will cut across all Science Themes (*Section 2*) and be instrumental for answering PANGEA’s key scientific questions (*Section 3*). Throughout the project, PANGEA will prioritize ground and airborne measurements that can be synthesized across multiple scales and integrated 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. The modeling and data synthesis 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 activities akin to Observing System Simulation Experiments (OSSEs) that will help inform the best locations 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 using remote sensing and modeling.
* Implement new processes and techniques, as well as improve existing ones that leverage remote-sensing data-model integration and apply them to answer PANGEA’s scientific questions.

Over the past decades, terrestrial biosphere models have expanded scope and incorporated many new processes that could not be addressed during LBA (Figure X). 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 (Table X). Moreover, new technologies such as artificial intelligence can advance both model calibration (Li et al., 2023) and become integral parts of predictive modeling (Schneider et al., 2017; Reichstein et al., 2019; Eyring et al., 2024). 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.

Projecting the future trajectory of tropical ecosystems presents a significant challenge to 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 (Negron-Juarez et al 2015, Fisher et al., 2018). The ILAMB project provides tools to track and compare model performance using a comprehensive skill score method and incorporates multiple observational datasets to account for model uncertainty (Hoffman et al., 2017; Collier et al., 2018; 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. In addition to representing processes accurately, the model performance can be significantly influenced by the quality and representativeness of the initial and boundary conditions (Antonarakis, 2014; De Frenne et al., 2021). Data collected through PANGEA will be used to expand benchmarking tools using integration of ground-based observation and remote-sensing data, and to provide initial and boundary conditions that are representative of the actual state of tropical forest ecosystems.

**Table X.** Non-exhaustive list of models that can integrate PANGEA data and 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 ABM, agent-based models. Subclasses of PBM models: IBM, individual-based models; CBM, cohort-based models; DGVM, dynamic global vegetation models (excluding IBMs and CBMs).

| Models | | | | | Examples of Data-Model Integration Opportunities | | Science Questions Addressed |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Class | Subclass | Examples | References | Examples of  Processes of Interest | Airborne/Spaceborne  Remote Sensing | Field Measurements |
| **PBM** | **IBM** | FORMIND  TROLL | Fischer et al. (2016)  Maréchaux & Chave (2017) | Carbon stocks and fluxes  Structural/Functional diversity  Demographic rates  Disturbance rates | Forest structure/carbon stocks:  Airborne lidar  GEDI, EDGE\*, NISAR\*, BIOMASS\*  Landsat, Sentinel‑1, Sentinel‑2  Forest composition:  Airborne hyperspectral  DESIS, EMIT, PACE, PRISMA, SBG\*  Other:  **Water/energy fluxes:** ECOSTRESS  **C fluxes:** FLEX, OCO-2/3, TROPOMI  **Soil water:** SMAP, SMOS, SWOT  **Canopy water content:** AMSR-E, EMIT  **Phenology:** Landsat; Sentinel-2; drone RGB  **Cloud/precipitation:** GOES-R, GPM  **Land cover:** Landsat; Sentinel-2  **Burned area:** Landsat, Sentinel-2, VIIRS | Forest inventory plots  Litter/coarse woody debris  Terrestrial laser scanning  Plant functional traits  Meteorological data  Eddy covariance fluxes  COS/Isotopes  Sapflow  Soil moisture/temperature  Soil flux chambers  Tower-based GNSS data  PhenoCams | Q1–Q27 |
| **VDM** | BiomeE  ED/ED3  ED2  Ent TBM  FATES  LPJ-GUESS | Weng et al. (2022)  Ma et al. (2023)  Longo et al. (2019)  Kim et al. (2015)  Koven et al. (2020)  Hickler et al. (2012) | Carbon stocks and fluxes  Structural/Functional diversity  Demographic rates  Disturbance rates  Water/energy cycling  Nutrient cycling  Land-cover/land-use change  Burned area/fire emissions |
| **DGVM** | CLM ELM JSBACH  JULES  LPJ  ORCHIDEE | Lawrence et al. (2019)  Ricciuto et al. (2018)  Reick et al. (2021)  Harper et al. (2018)  Sitch et al. (2008)  Krinner et al. (2005) | Carbon stocks and fluxes  Disturbance rates  Water/energy cycling  Nutrient cycling  Land-cover/land-use change  Burned area/fire emissions |
| **HM** | | CARDAMOM  CliMA | Bloom et al. (2016)  Braghiere et al. (2023) | Carbon stocks and fluxes  Water/energy cycling  Land-cover/land-use change  Burned area/fire emissions | Q1–Q4; Q6; Q8; Q9; Q14–Q16; Q18; Q22–Q27 |
| **TDM** | | CarbonTracker  CMS-Flux  HYSPLIT  STILT-VPRM | Peters et al. (2007)  Liu et al. (2020)  Stein et al. (2015)  Dayalu et al. (2024) | Carbon fluxes  Water/energy cycling  Burned area/fire emissions | **C fluxes:** FLEX, OCO-2/3, TROPOMI  **Water/energy fluxes:** ECOSTRESS  **Burned area:** Landsat, Sentinel-2, VIIRS | Eddy covariance fluxes  Meteorological data  COS/isotopes  Soil flux chambers  PhenoCams | Q1–Q2; Q4; Q6; Q9; Q14; Q17 |
| **AIML** | | MapBiomas Fire  MetaFlux | Alencar et al. (2022)  Nathaniel et al. (2023) | Carbon stocks and fluxes  Water/energy cycling  Burned area/fire emissions | Carbon stocks:  Airborne lidar/hyperspectral  GEDI, EDGE\*, NISAR\*, BIOMASS\*  Landsat, Sentinel-1 and -2  Other:  **Water/energy fluxes:** ECOSTRESS  **C fluxes:** FLEX, OCO-2/3, TROPOMI  **Burned area:** Landsat, Sentinel-2, VIIRS | Plant functional traits  Meteorological data  Eddy covariance fluxes  COS/isotopes  Soil flux chambers  Tower-based GNSS data  PhenoCams | Q1–Q2; Q4; Q6; Q9; Q14; Q17 |
| **ABM** | | ABSOLUG  SimPachamama  RepastSimphony | von Essen & Lambin (2023)  Andersen et al. (2017)  North et al. (2013) | Land cover/land-use change  Household state/dynamics  Bioeconomics metrics  Cattle reproduction rate | Carbon stocks:  Airborne lidar/ hyperspectral  GEDI, EDGE\*, NISAR\*, BIOMASS\*  DESIS, EMIT, PACE, PRISMA, SBG\*  Landsat, Sentinel‑1 and -2  Other:  **Land Cover:** Landsat; Sentinel‑2  **Burned Area:** Landsat, Sentinel‑2, VIIRS | Forest inventory plots  Forest management data  Crop/timber yields  Cattle dynamics data  Territory boundaries  Human census data  Survey data  Choice experiment data | Q21; Q28 |

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| Box 3. Example of PANGEA Modeling and Remote-Sensing  Data Integration Approach  Using PANGEA’s Question 6 (cross-continent functional trait variability and effects on the tropical carbon cycle) and the FATES model as one example, PANGEA’s team 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 CO2 and H2O fluxes in FATES (henceforth key traits). The team 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 from towers and remote sensing, and emergent relationships between trait gradients and remote-sensing derived 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 will facilitate the upscaling of landscape ground and airborne measurements described in *Sections 6.2.4* and *6.2.5* to regional and pan-tropical scales. By synthesizing key variables using airborne remote-sensing datasets 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, and plant functional groups. The derived product 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. Moreover, the combination of multiple data synthesis products can be used for exploring the emergent relationships of the tropical forest ecosystems. For example, canopy height maps before droughts can be contrasted with evaporative stress indices during drought conditions. These datasets can be then applied as additional constraints and benchmarks for process-based models.

PANGEA will leverage artificial intelligence and machine learning (AI/ML) models for data synthesis due to their robustness in handling non-linearities and interactions among multi-factorial processes and predictors. 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 and insights into the underlying ecological processes of AI/ML models, PANGEA will implement techniques such as (1) Feature Importance Analysis, which quantifies and highlights the most influential factors driving the model's predictions; and (2) Partial Dependence Plots, which can be employed to visualize how changes in specific variables impact predicted outcomes. Additionally, PANGEA will employ non-AI techniques including causal inference (Venelli Pyles et al., 2022), time series analysis (Bullock et al., 2020) including Breaks For Additive Season and Trend Monitor (BFAST; DeVries et al., 2015; Verbesselt et al., 2012), and Bayesian statistics (Goulamoussène et al., 2017), which yield insights into cause-and-effect relationships, uncover temporal patterns, and quantify uncertainty in predictions and analyses. These strategies will also provide valuable insights and effective workflows that can be integrated into process-based models for reducing parameter uncertainty and increasing prediction accuracy (Dietze et al., 2013; Meunier et al., 2021).

One significant challenge in understanding tropical forest dynamics across large scales is the relatively short time series of most data products related to forest structure, composition, carbon stocks, and function. 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 recovery rates of variables of interest (e.g., biomass, canopy height) from a reference time in areas that experienced disturbance in different (and known) 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. Chronosequences have been used to constrain process-based models that characterize distributions of age since last disturbance (Ma et al., 2017).

### Coordination with Other Modeling and Data Integration Communities

Coordination with established modeling, data synthesis, and data integration communities will be crucial to extend the impact of PANGEA beyond providing field and satellite observations. For example, the TRENDYproject (Sitch et al., 2024), which coordinates global carbon cycle simulations, represents another potentially 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. Likewise, the CMIP (Eyring et al., 2016), a global leader in climate modeling, will benefit from PANGEA’s observations, especially in the context of improving the representation of tropical ecosystems. These datasets will be highly valuable for evaluating and improving models used in global efforts, including the CMIP land components. 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.

PANGEA will 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. For instance, one important partner of PANGEA is the ILAMB project (Collier at al., 2018). Data collected through PANGEA and derived products developed through data synthesis can become new benchmarks on processes that currently show high uncertainty among datasets (e.g., gross primary productivity) or are absent in ILAMB (e.g., vegetation demography, plant hydraulics). Similarly, PANGEA will pursue collaborations with PEcAn(Predictive Ecosystem Analyzer; LeBauer et al., 2013), 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). Another key partner is NGEE-Tropics, which, while scheduled to end around the time PANGEA enters its most active phase, provides a rich foundation of modeling tools including the FATES model (Functionally Assembled Terrestrial Ecosystem Simulator; Koven et al., 2020), and extensive experience in designing and executing field campaigns to collect data aiming at reducing model uncertainty. Finally, the Global Modeling and Assimilation Office (GMAO)can complement PANGEA’s efforts with advanced data assimilation techniques that can be used for benchmarks and boundary conditions for predictive models of tropical forest dynamics. Examples of products include the SMAP Level-4 products on soil temperature and soil moisture in the rooting zone (Reichle et al., 2019) and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2, Gelaro et al., 2017).

In addition to the communities developing process-based models, data synthesis products, and benchmarking workflows, PANGEA aims to collaborate with initiatives that directly assimilate remote-sensing data into model predictions. 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(CARbon DAta-MOdel fraMework; Bloom et al., 2020), which combines satellite and ground-based observations for carbon cycle data assimilation and modeling, Finally, collaboration with CliMA(Climate Modeling Alliance; Schneider et al., 2017), 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. 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.

### Modeling and Data Integration Activities

Modeling and data synthesis activities will occur throughout PANGEA. However, such tasks will shift focus as the project progresses. Once a science team is selected for PANGEA, a Modeling and Data Synthesis Working Group (SWG) 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. The group will develop model intercomparison efforts using established benchmarking (e.g., TRENDY, FLUXCOM) and tools (e.g., ILAMB) to inform the project design. The SWG will also seek rapid responses through the use of approaches based on Observing System Simulation Experiments (OSSEs) using existing models and drivers to provide a first assessment of key areas of uncertainty and areas that lack representativeness in existing observations.

After initial evaluations and OSSE efforts, SWG focus will shift to 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 campaigns. 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 scales that can be assimilated by inverse and hybrid models, as well as used for benchmarking of process-based models. Synthesis approaches will include, but will not be limited to, artificial intelligence, machine learning, and space-for-time substitution. Group members working with inverse and hybrid models will use PANGEA datasets and derived synthesis products for quantifying uncertainty in scaled quantification of state variables and fluxes. Efforts 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.

During a final synthesis, PANGEAwill focus on studies that use the constrained and improved models and data products developed earlier to directly address PANGEA Science questions and test key hypotheses. Research using process-based models at this stage 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 Science Themes (*Section 3*).

# Capacity Building, Training, and Education

Strengthening capacity and investing in training and education are fundamental for the successful implementation of PANGEA, and critical for preparing the next generation of researchers with the necessary expertise and tools to fully leverage NASA’s Earth Observing System (EOS). 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. Experience gained during prior TE field projects, especially LBA, demonstrated that capacity building built in longevity to the projects and justified the projects in our host countries. PANGEA will partner with existing NASA programs, as well as with local and international collaborating institutions, to plan and execute capacity building, training, and educational activities that are appropriate for a range of potential trainees, including students, early career scientists, the broader workforce, and Indigenous Peoples and Local Communities (IPLCs). Capacity building, training, and education will focus on IPLC-specific training and capacity building, workforce development training, and educating a cohort of undergraduate and graduate students.

PANGEA capacity building, training, and educational activities will be designed according to each specific audience. During the development of the Concise Experiment Plan, and then intermittently throughout PANGEA, assessments will be carried out to appraise what different members of the PANGEA community require and desire in terms of capacity building, training, and educational activities. The assessment will identify potential beneficiaries, and align them with available resources. Training is a preferred target for many co-funding opportunities (see *Section 10.2, Co-Funding Opportunities*).

## Workforce Development

PANGEA will advance goals outlined in the National Science Board (NSB) Vision 2030 by fostering workforce development in STEM fields. Through advanced remote sensing technologies, Earth system model development and applications, and extensive international fieldwork, PANGEA will cultivate a STEM-educated workforce equipped with expertise in fundamental science and engineering research and ML/AI, including deep learning, large language models, computer vision, and data assimilation, to address critical ecological and social challenges in regions pantropically and skills that are applicable globally. PANGEA provides hands-on training opportunities for students and early-career scientists, bridging fundamental science with applied tools and solutions-oriented decision-making, and ensuring inclusivity by engaging minority serving institutions (MSIs). In addition to support existing NASA training and workforce development efforts through ARSET, DEVELOP, and NASA’s Indigenous Peoples Initiative, PANGEA’s training programs align well with DOE Artificial Intelligence for Earth System Predictability (AI4ESP) and the NSF Research, Innovation, Synergies, and Education (RISE) and Geoscience Opportunities for Leadership in Diversity (GOLD-EN) programs (Table 1). By integrating partners across academia, government, and international institutions, PANGEA will advance fundamental research and workforce readiness in alignment with the NSB’s Vision 2030.

## Educating a Cohort of Graduate Students

PANGEA will provide a unique opportunity for a generation of undergraduate and graduate students across the United States to develop highly integrative and interdisciplinary research. PANGEA’s scientific goals will allow students to carry out data-intensive research goals using both field observations and remote-sensing datasets, and to develop critical skills on data synthesis (including artificial intelligence, machine learning and data assimilation) as well as process-based modeling. Equipping students with the skills to use big data, artificial intelligence, and computationally intensive modeling will prepare students for multiple career opportunities in academia, government, and industry. In addition, the implementation of the PANGEA project will be inherently collaborative, and will bring together scientists from multiple institutions and universities, both within the US and internationally. By participating in field work activities and scientific events, undergraduate and graduate students will directly interact and collaborate with researchers based at NASA and other US agencies (e.g., DOE, USFS, USGS). This will open possibilities for students to pursue long-term careers at these agencies and pursue private sector and entrepreneurial activities in related sectors. PANGEA will enable students to develop the collaborative critical thinking skills required for multi-institutional and international partnerships.

PANGEA will also continue the critical role of NASA promoting strong capacity building internationally. During LBA, capacity building was mutually beneficial to the NASA Terrestrial Ecology Program contribution to the first phase of LBA (LBA-ECO) efforts and to NASA’s South American hosts. Brazil required a training and education component for every LBA investigation, defined by available resources and generally linked to academic programs within Brazil. The largest group of students trained within LBA were Brazilian undergraduate students who were paid to engage in science projects. While these students mainly did technical work, many became co-authors on papers, and some were even primary authors. This program helped identify students engaged in pursuing masters and doctoral degrees. About 500 Brazilian students earned MS and Ph.D. degrees associated with LBA investigations. While a small portion of the funded students were paid by NASA research projects (mainly for students who obtained their degrees in the US), most scholarships were awarded through existing Brazilian mechanisms from their national education and science ministries and through state level research foundations. While the total investment in dollar terms was less than 5% of the NASA investment in LBA-ECO and other foreign research activities, the immediate and long-term payoff was enormous. 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 NGOs, exceeding Brazilian expectations for the impact of the LBA training and education.

PANGEA’s biggest opportunity for capacity building and training is within the science team. Following LBA and BioSCape models, NASA can encourage or require that proposals be co-developed with local researchers. These requirements ensured that about 50% of the BioSCape science team was from South African institutions. Likewise, PANGEA funding announcements can require or strongly encourage training, education, and capacity building as part of the proposed activities, similar to what was achieved during LBA.

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| **PANGEA’s approach to equitable science, capacity building, and training will directly confront the issue of flyover campaigns and parachute science. Based on successes from LBA, we believe that PANGEA can publish 100 first-author papers from scientists in Africa, contributing to closing the Parachute Index gap in Central Africa (Culotta et al., 2024). These African scientists will continue the legacy of PANGEA, in collaboration with international peers across the tropics, well after the end of the project.** |

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 campaigns 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., EMIT, PACE, ECOSTRESS, GEDI, and in the future NISAR and SBG. Working with regional partners, PANGEA will collaborate with host countries on the development of national data banks so that the emerging knowledge from PANGEA can be integrated with and applied to regional and national demands for socio-economic promotion and policy development. 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” (REF). PANGEA’s partners will include “national and international governmental agencies, academia, nongovernmental and international organizations, the private sector, and philanthropies,” consistent with that strategy. PANGEA will partner with existing NASA programs and training efforts led by partners, in line with the goal of “leveraging existing value-amplifying initiatives” that “could be national or international” to “achieve both depth and wide breadth in our impact and support to humanity while being cost effective” (REF). Examples are included in **Table X** below.

**Table X.** Potential partners and providers that could collaborate with PANGEA for training and capacity building activities.

| Partner/ Provider | Activity | Target Audience |
| --- | --- | --- |
| AI4ESP |  |  |
| AIMS | Postgraduate training, research, and public engagement in math, science, and machine learning. The AIMS network has 5 centers of excellence teaching African Masters in Machine Intelligence (AMMI), including in Cameroon, Ghana, and Rwanda. The AIMS network has over 2,400 alumni from 44 African countries of which 33% are women. | African students |
| ARSET | Multipart training webinar series, building on the in-person training model trialed during BioSCape. | Decision-makers, academics, scientists |
| ATBC | Trainings, workshops, and networking among researchers pantropically with the Association for Tropical Biology and Conservation (ATBC) who promotes research, education, and communication on tropical biology and conservation. ATBC has ~1,000 members from 70 countries and supports capacity building and hosts international meetings. | ATBC members from over 70 countries |
| DAACs | Training notebooks and workshops modeled on those already presented at conferences (e.g., AGU, ESA, ATBC) facilitating access to NASA EOS. | Researchers at all career stages |
| 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 (renewable) to develop capacity to use NASA Earth data to address their needs. | Decision makers and the broader workforce |
| FLUXNET | Training and tools to use and analyze eddy covariance flux tower data, including in multiple languages (extensive FLUXNET training materials already available in Spanish & English). PANGEA will work with FLUXNET to extend translation to French and Portuguese and develop new training materials that integrate NASA remote-sensing data and flux-tower data. | Researchers and students |
| GLOBE | Locally tailored educational activities for K-12 students, teachers, and citizens including train-the-trainer elements allowing multiplication. Opportunity to channel excitement of airborne campaigns and Earth Observation data. | K-12 students, teachers, and citizens |
| Indigenous Peoples Initiative | Collaboration with Indigenous communities to enhance the use of Earth Observations for informed decision-making. PANGEA has developed partnerships with Indigenous alliance organizations in the tropics, including the GATC and the Rights and Resources Initiative (RRI), and will coordinate with NASA’s Indigenous Peoples Initiative to extend efforts to co-develop trainings, support Indigenous-led projects, strengthen relationships, and create opportunities for Indigenous voices in NASA’s Earth Science Division. | Indigenous communities |
| NSF RISE | Foster transdisciplinary collaborations that engage the broader geosciences community to drive discoveries and innovations in workforce development. | Researchers and students |
| SELPER | Identify partnership opportunities with SELPER, the Latin American Society for Remote Sensing and Space Information Systems to develop remote sensing training and research activities across Latin American countries. SELPER promotes these activities at workshops, symposia, and short courses, often with partnership with the broader international community. | SELPER members and participants of scientific meetings |
| SERVIR | Coordinate with SERVIR regional hubs to develop custom services to serve the specific decision-making needs of local partner organizations, including building on SERVIR’s Planning Toolkit, which provides regionally targeted instruction on how to assess and deliver impactful interventions related to agriculture, forest restoration, and more. | SERVIR hubs, implementing partners (local and national governments, NGOs) |

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| **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.** |

# Community Engagement Strategy

PANGEA will engage with diverse communities to address 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, and that establishes and strengthens long-term partnerships between US-based and international institutions. The strategy draws upon the knowledge, expertise, and experiences shared throughout PANGEA’s scoping study, which engaged with over 500 individuals and 150 organizations from 42 countries across 5 continents through (a) consultative workshops, (b) outreach events, (c) working group discussions, (d) bilateral meetings, and (e) web surveys. Within the U.S., PANGEA has engaged with more than 20 federal agencies and U.S. institutions across 9 states and Washington, DC. A more detailed description of engagement methods used during the scoping study is provided in **Appendix C**. 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 project.

## PANGEA Co-Development and Partners

PANGEA research on tropical forests will complement and expand upon many existing efforts. Data acquired during the PANGEA field campaigns will be used for initializing, assessing, and constraining predictions of multiple process-based terrestrial ecosystem models and Earth System Models across tropical forests. Examples of models include FATES, a model whose development is supported by DOE through NGEE-Tropics, as well as multiple models with current and previous support by NASA, such as BiomeE (NASA-GISS), ED2 (led by Harvard University), ED3 (University of Maryland), CliMA’s land component (California Institute of Technology and JPL), and CARDAMOM (JPL) (*Section 6.3*). PANGEA will enhance SilvaCarbon’s efforts by incorporating a broader range of field sites and remote-sensing data, offering deeper insights into carbon dynamics and forest processes at regional and global scales while strengthening its MRV analyses. Improved understanding and analyses of carbon dynamics and ecosystem functions will be key elements to inform USDA USFS International Program to develop forest management and conservation strategies with international organizations. Some of these efforts are limited to small geographical areas or represent networks of individual sites. Others, such as One Forest Vision and GEO-TREES, have pantropical ambitions like PANGEA. The range of partnership opportunities is illustrated with examples in Table X. *Appendix B* describes in greater detail the communities with which PANGEA will engage, lists all PANGEA partners according to community type, and discusses more specific engagement considerations for each.

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 group, which may share interests, experiences, resources, activities, professions, livelihoods, culture, geography, origins, language, or any combination of the above. The scoping study 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) the academic community, scientific institutions and scientific societies; (5) coordinated international research initiatives; (6) civil society organizations (CSOs); (7) Indigenous peoples and local community alliances and organizations; (8) the donor community; (9) the private sector; and (10) intergovernmental agencies.

PANGEA will commit to engage communities in an inclusive and non-hierarchical way. Each community will play a 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 PANGEA. The support of government agencies will be critical to PANGEA’s airborne data collection efforts and Earth Action strategies. National and subnational 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 and biodiversity-loss 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 can contribute to the success and positive long-term legacy of PANGEA.

## Diversity, Equity, and Inclusion 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 serves as foundational material for a project 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 implement a Code of Conduct considering existing precedents, make it publicly available, and ensure that research groups are aware of and agree to the code upon joining the project. The Code of Conduct will include clear mechanisms for reporting violations and will establish the consequences for confirmed violation of the code. PANGEA is also committed to gender balance and will implement targeted efforts to ensure inclusivity, such as promoting leadership roles for females and historically underrepresented groups 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 Collective Benefit, Authority to Control, Responsibility, and Ethics (CARE) Principles for Indigenous Data Governance’ to ecology and biodiversity research based on work by Jennings et al. (2023) and Carroll et al. (2020). Table Xoutlines PANGEA’s principles of engagement based on CARE. See *Section 10.3* for the integration of these principles with PANGEA’s Open Science strategy.

**Table X.** PANGEA principles of engagement based on CARE. Adapted from Jennings et al. (2023) and Carroll et al. (2020). IPLCs: Indigenous Peoples and Local Communities.

| CARE Principles | Issues | 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 the community. |
| Data grounded in community values, aspirations and 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 and data | Principles and protocols for research development, data management and publication that support IPLC’s Data Sovereignty will be co-developed; These will include metadata fields available for disclosure of Indigenous rights and interests. |
| Recognize the rights 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, worldviews and lived experiences | PANGEA will work hard to use the local and Indigenous languages, link research to community worldviews, and upload data with appropriate metadata labels in culturally accessible formats (digital storytelling, seasonal calendars, visual art forms, etc.). |
| Community-defined benefit sharing | PANGEA will conduct research that is of mutual benefit, consent driven, inclusive and relevant to the needs of IPLCs and individuals. |
| 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 sharing data; ensuring 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. |

## 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 promote an international scientific steering committee (SSC). The SSC will reinforce and coordinate with existing organizations, alliances, and activities to ensure that PANGEA supports the development of a long-term network of networks that will enhance and sustain the accessibility, usability, transferability and benefits of the data, methods, models, and knowledge about tropical ecosystems. PANGEA’s SSC will co-develop strategies to ensure that scientists, local institutions, and communities work together throughout the PANGEA project to effectively collaborate in diverse geographic and cultural contexts. 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 national agency managers. Existing organizations such as the Congo Basin Science Initiative and the extant Brazilian LBA are primed to serve as partners for coordination of PANGEA scientific studies. Similarly, PANGEA established relationships with the GATC during the scoping process. The GATC, built over 10 years by tropical Indigenous communities, represents 24 countries and over 35 million people who occupy over 958 million hectares of land. The partnership with GATC will support PANGEA’s ability to engage Indigenous communities in a meaningful and mutually beneficial way.

During ABoVE, 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 ABoVE.

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| **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. 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 universities and research institutes.

PANGEA’s applications also have strong potential to engage the private sector, including, but not limited to: (a) agribusinesses and cooperatives 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. 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. Currently, several PANGEA partners, including AndesFlux, have collaborated with Starlink to facilitate data transfer from the AndesFlux eddy flux towers located in different areas of the western Amazon to the AndesFlux headquarters in Lima, Peru.

# Enabling Earth Science to Action

**PANGEA emphasizes historically understudied tropical biomes and empowers one of the planet’s most vulnerable regions to address the consequences of climate and land use change, while also acknowledging and documenting the global contributions of tropical biodiversity to resilience in the interconnected Earth system.** PANGEA will prioritize strategic NASA Earth Science to Action (ES2A) efforts that close the gap between rapidly advancing technology and the needs of society to access science-informed decision-making platforms.

Achieving PANGEA’s science and measurement objectives will advance monitoring capabilities in the tropical forest biomes in ways that address direct end-user needs, where data and knowledge gaps 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. Uptake of research products requires meaningful end user engagement, so this section 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. Engagement of potential end users at a diverse range of fora like Biodiversity COP 16 in Colombia have demonstrated interest in PANGEA’s products from a wide variety of potential end users, including private sector, government, NGO, and academic actors. 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.

## Applications of PANGEA Research Outputs

ELSA NOTES TO SELF

* Add info from:
  + Alliance Biodiversity & International Center for Tropical Agriculture (CIAT) meeting
  + CARPE meeting
  + USAID meeting
  + ICCN
  + Congo Basin Forest Partnership (CBFP) meeting
  + NICFI
  + MapBiomas
  + Convo w Brian O’Donnell
  + Alison
  + Emphasize fires
  + Integrate NASA harvest RS capabilities and science above in *Sections 1, 2*, and *3*

### Carbon Sequestration Stability and Methane Fluxes

**Table X.** PANGEA research applications for carbon sequestration stability and methane fluxes. GCF-TF: Governors’ Climate and Forests Task Force. OSFAC: Central African Satellite Observatory.

| Science questions | Research Application | Potential Partners and/or Outlets for Impact |
| --- | --- | --- |
| Q1, Q2, Q3, Q8, Q15, Q16, Q18–Q20, Q25, Q27 | 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, SilvaCarbon, IPCC |
| Q1, Q2, Q3, Q18, Q27 | Mapping and quantifying tropical methane flux predictions | US GHG Center, SERVIR, WRI |

Mapping and monitoring tropical carbon stocks and fluxes is critical for closing the global carbon budget, constraining climate projections, and for improving measurement, reporting, and validation (MRV) of carbon credits. This requires improving climate projections by decreasing uncertainty around carbon fluxes of tropical forests, tropical land-use changes, and tropical forest responses to climate shifts. Results from PANGEA can improve our understanding of the carbon budget, support carbon markets, and improve understanding of CH4 emissions. PANGEA will coordinate with the U.S. Greenhouse Gas Center activity to determine areas of alignment and opportunities for PANGEA to contribute data and understanding that meet stakeholder needs (National GHG MMIS Strategy 2023).

**Understanding tropical forest contributions to the carbon budget:** Improving climate change projections, especially decreasing uncertainty around carbon fluxes of tropical forests, tropical land-use change, and tropical forest responses to climate change is critical per the National Science and Technology Council (NSTC) Fast Track Action Committee (FTAC) on Climate Services March 2023 report. The Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC AR6) noted the promise of remote sensing for improving the accuracy of estimates of forest carbon, but listed uncertainty in estimates from Earth Observations as a significant shortcoming (IPCC AR6). PANGEA offers an opportunity to directly address this limitation by, for example, providing IPCC Working Group III with the answers to Science Questions 2, 3, 8, 13, 14, and 25-27 during their development of the seventh and eighth assessment reports, which could decrease uncertainty and improve carbon estimates.

**Improving the carbon finance market:** Carbon financing approaches have gained popularity across tropical communities and involve polluting entities transferring payments to local governments and communities for various carbon emission remediations including forest protection, reforestation, enhanced forest management, and the establishment of forest plantations (Anderegg et al., 2020; Morita & Matsumoto, 2023). However, carbon markets are constrained by a lack of confidence in methods, high monitoring costs, and increasing concerns related to their long-term viability (Anderegg et al., 2020; Pan et al., 2024). 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 including

* Collaborating with the GATC to allow local and Indigenous communities to combine PANGEA findings on carbon fluxes in their territories with community monitoring of land change to estimate carbon sequestration for credit validation and marketing;
* Partnering with the Governors’ Climate and Forests Task Force (GCF-TF) to support implementation of their New Forest Economy Blueprint by providing carbon stocks, fluxes, and interconnected biodiversity data assessing the impact of jurisdictional decarbonization strategies; and
* Working with the Forest Stewardship Council (FSC) to leverage PANGEA findings and methods advances on forest carbon stocks and flux responses to climate change and plant-animal interactions to develop a decision support system that will help certificate holders mitigate climate impacts on forestry in the tropics and manage forests more effectively for combined carbon sequestration and biodiversity conservation outcomes.

**Mapping and quantifying methane flux predictions:** 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. PANGEA will advance natural and anthropogenic tropical methane flux monitoring capabilities using satellite remote sensing in alignment with needs and activities emerging from the U.S. Greenhouse Gas Center. These efforts will be carried out in collaboration with partners like SERVIR regional hubs and the Land and Carbon Lab led by the World Resources Institute to advance capabilities from local technical expertise to global mapping and monitoring applications.

### Biodiversity Conservation

**Table X.** PANGEA research applications for biodiversity conservation.

| **Science questions** | **Research Application** | **Potential Partners and/or Outlets for Impact** |
| --- | --- | --- |
| Q5, Q6, Q7, Q10, Q11, Q12, Q13, Q17 | 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, Alliance Bioversity CIAT, OSFAC, Conservation International, European Space Agency, IUCN Regional Offices, AFR100 |
| Q5, Q6, Q10, Q11, Q12, Q13, Q17, Q23-24, Q26, Q28, | Empowering and elevating Indigenous, local, and traditional communities through the integration of IEK, LEK, and TEK with remote sensing | NASA Indigenous Peoples Initiative, Global Alliance of Territorial Communities, Rights & Resources Initiative, Congo Basin Institute School for Indigenous and Local Knowledge, MapBiomas, Woodwell Climate Research Center |

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 project 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. However, data scarcity and quality concerns have limited the ability to even assess progress against these targets (Forest Declaration Assessment 2024). PANGEA will support biodiversity conservation in three ways:

***Improved understanding of biodiversity***: PANGEA will advance understanding of biodiversity across a range of scales. The Group on Earth Observations (GEO) Global Ecosystems Atlaseffort, supported by the Convention on Biological Diversity (CBD) and United Nations Framework Convention on Climate Change (UNFCCC), is working to unite high-quality global, regional, and national ecosystem maps into a single, open, online resource. 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 U.S. Geological Survey (USGS), European Space Agency (ESA), International Union for Conservation of Nature (IUCN), ESRI, and others.** Likewise, PANGEA will catalyze NASA remote sensing of Essential Biodiversity Variables (EBVs) like the biological effects of fire and irregular inundation to address high-priority data gaps identified by the Group on Earth Observations Biodiversity Observation Network (GEO BON; Skidmore et al., 2021). PANGEA understands that weaving diverse knowledge sources improves overall understanding and 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 Territorial Communities (GATC), whose women’s movement is already conducting drone data-collection training, and the Rights and Resources Initiative (RRI), who has partnered with Woodwell in the past to quantify and estimate the carbon stored in Indigenous, Afro-descendent, and local community lands (policy brief, research report). There is strong interest in similar initiatives emphasizing biodiversity.

**Facilitating biodiversity conservation actions:** Biodiversity conservation can make considerable progress with large-scale observations across disturbance gradients. For example, PANGEA can work with the Congo Basin’s regional environmental coordination body, the Central African Forests Commission (COMIFAC), and its regional remote sensing office, OSFAC, to provide updated maps of likely forest responses to climate change, which will allow land-use planners to identify potential high-value wildlife corridors for cross-border conservation. Similarly, forest restoration efforts require improved understanding of plant-animal interactions, including what species can effectively support restoration efforts and where. By addressing Science Questions 10-13, 18, and 27, PANGEA will delineate complex processes that sustain regrowing tropical forest landscapes. These results can be shared with the myriad tree-planting initiatives across the tropics to improve their efficacy and efficiency. This work is critical for efforts like AFR100, the African Forest Landscape Restoration Initiative to restore Africa’s degraded and deforested land, and 30x30.

***Monitoring and improving biodiversity conservation efforts***: In addition, partnerships with key collaborators identified in the scoping study will accelerate monitoring of biodiversity and the development of user platforms. For example, the advent of innovative land management efforts like Other Effective Conservation Measures (OECMs) offer promise to reach international goals like 30x30, but the impact of these new management types on biodiversity is unknown. Organizations like IUCN and the Campaign for Nature can use PANGEA data and methodologies that improve assessment and identification of land use change to assess the efficacy of OECMs as biodiversity conservation tools. Similarly, PANGEA can partner with nature financing initiatives like Fund for the Amazon and Tropical Forests Forever Fund to develop comprehensive and low-cost approaches to monitor whether their financing is impacting biodiversity.

### Sustainable Agriculture and Livelihoods

**Table X.** PANGEA research applications for 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 climate influence | 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. Identifying bioeconomy alternatives to agricultural production while simultaneously 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 crop 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 based on remote sensing of crop needs. Such “precision agriculture” is already commonplace in the U.S. but is lacking in much of the tropics because the underlying data and methods are incomplete. PANGEA will work with colleagues from the International Institute for Tropical Agriculture (IITA), Alliance Bioversity-CIAT, and the International Water Management Institute (IWMI) to develop and deploy techniques like spatially explicit farm-scale crop health monitoring that will allow these organizations to identify threats to food security quickly and respond with mitigating measures.

**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 (EUDR) and a similar bill under consideration in the U.S. PANGEA will allow for the use of new sensors like NISAR, BIOMASS, and SBG to detect multiple forms of agricultural expansion into tropical forests, which will make it easier for agricultural commodities companies to assess the land-use change impact of their value chains. Companies like Satelligence will use data from PANGEA to demonstrate EUDR compliance for some of the largest food companies in the world. 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. PANGEA will work with partners like Alliance Bioversity CIAT to apply these improvements to help farmers and farmer cooperatives demonstrate compliance and market high-value products. These activities also position PANGEA to impact other livelihood sectors, like payments for ecosystem services, bioeconomies, and non-timber forest products.

**Improved disaster alerts and response:** Droughts, floods, pests, and extreme heat all threaten agricultural production in the tropics. In places where agricultural 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 changes, understand climate impacts on phenology, and estimate plant nutrient concentrations remotely will all support these policy solutions. For example, enhanced remote sensing of farm boundaries, crop type, and crop yield at the field scale will lower monitoring costs for climate-driven insurance products for smallholder farmers.

To deliver on potential gains for food security and livelihoods, PANGEA has engaged agricultural research partners like NASA Harvest, 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 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 questions to potentiate Earth Action outcomes. Partners such as IITA and CIAT specialize in translation of findings from research into practice and build on decades of experience with private sector and government partners.

## Process to Enable Earth Science to Action

### User 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 8* 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 10.2*](#_w90m76cd6k00)*,* *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 7*](#_8t6ay0v9gizk)) help ready the next generation of scientists.

During the Scoping Phase, PANGEA led extensive outreach to potential users (see *Appendix B*), 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 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 8* for details on how PANGEA will engage the community). We are aware that 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 limitations of project data which are necessarily limited spatially and temporally. PANGEA will also endeavor to leverage the momentum created by a brief but intense project period to create, grow, and strengthen a new and more diverse user community for NASA Earth data. The depth and reach of PANGEA’s engagement will be contingent on funding and is a priority in co-funding opportunities.

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, PANGEA ES2A priorities focus on advancing specific monitoring needs and capabilities that use 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 use cases, the co-development of products, and identification of partners.

### Supporting Application of PANGEA Research

PANGEA will harness its existing and planned partner engagement to integrate ES2A holistically into the project. This includes conducting a user needs assessment as part of the Concise Experiment 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 Xdemonstrates PANGEA’s approach to advancing 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.

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, subnational and national 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, 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 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. Figure X demonstrates the potential overlap in these topics, and highlights a small selection of the partners who are already engaged in work at the intersection of the different subject matter.

# 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. 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 the American tropics. In 2023, NASA JPL had a successful campaign with AVIRIS-NG collecting remote-sensing data with a NASA contracted aircraft over Chile, Colombia, and Ecuador for methane point source measurements in coordination with each country. This built on previous successful campaigns in the region, including for example UAVSAR flights in Colombia, Ecuador, Peru, and French Guiana; AVIRIS flights in Colombia, Ecuador, and Chile, and planned AVIRIS flights in Panama and Costa Rica; and LVIS in French Guiana. In addition, NASA has done extensive research in Africa, including SAFARI, AfriSAR-1, AfriSAR-2, and BioSCape. There are also immense investments 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 African Satellite Observatory (OSFAC), and GEO-TREES. The PANGEA team has been in contact with the US State Department’s Bureau of Oceans and International Environmental and Scientific Affairs, which is enthusiastically supportive of PANGEA and the benefits it would have for environmental and scientific diplomacy.

PANGEA will require international deployments potentially taking place in several countries. Anticipated challenges include deploying and maintaining in situ instrumentation, obtaining international flight permission for airborne data acquisition, obtaining visas and research permits for US and international investigators, access to field sites, human-animal interactions/conflict, political or other unrest, and health and safety of scientists and participants (see *Section 10.5* for *Risk Assessment*). 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 6.2.4*, *Airborne Remote-Sensing Observations*). 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 work closely with NASA and the US Department of State to build relationships with in-country partners such as government agencies, NGOs, and leaders of Indigenous territories to develop agreements that will ensure proper flight clearances and field permits.

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 restrictions 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 6.2.4, Airborne Remote-Sensing Observations*).

## 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 ABoVE and LBA-ECO. 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.

### Program Management

The NASA 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.

### 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 national stakeholders and authorities, and use of PANGEA cyberinfrastructure.

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 the expectations of all partners.

### 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 *Concise Experiment Pla*n. This plan will present a refinement of the ideas presented in this scoping document. 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 plan. The Concise Experiment 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.

### 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 Experiment 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 10.4* (Table X). At the outset of the project, approximately 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.

### Science Team and Science Leadership

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 postdoctoral 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 agendas for regular PANGEA Science Team meetings. Nominally, the Science Team will meet annually. These meetings will advance science team planning, exchange of early results, and greatly facilitate interactions among project participants. The meetings are a particularly important opportunity for students and postdoctoral scientists to meet with the senior scientists from other projects. The meeting venues will be selected to facilitate travel and to minimize complications related to obtaining visas. 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.

Experience with past projects 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 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. 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]](#footnote-1).

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 LBA, we recommend that *all* investigations have counter-part investigators in 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. For more information, see *Section 7, Capacity Building, Training, and Education*.

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

PANGEA’s Science Team will prioritize diverse representation in terms of scientific expertise, technical specialties, national origin, race, gender, native language, career stages, and more. Early career researchers have been active in the development of this scoping proposal and will participate in all stages of the project, as will representatives from participating countries where field research will take place. Team members must commit to respectful interactions with local collaborators and cultural diversity and extra care taken to uphold NASA’s reputation internationally.

|  |
| --- |
| **Leadership and engagement in the PANGEA scoping process demonstrates diverse support for the project 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 diplomacyinternationally. The Science Team will meet regularly, and for virtual meetings will endeavor to arrange meetings considerate to the time zones of people represented.

### Disciplinary Skills Required

PANGEA is conceived as an interdisciplinary project. 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 have 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.

## Co-Funding Opportunities

The Baseline, Threshold, and Descope measurements defined in *Section 6.2.1* represent stand-alone NASA projects with no dependencies. However, given the urgency and importance of the topic, there is strong potential to augment or even exceed NASA’s contributions. During the scoping effort, the PANGEA leadership team has 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 both within and outside of NASA’s scope, including direct support for international partners and implementation of Earth Science to Action. Opportunities to leverage additional support from partners interested in teaming up with NASA include example partners listed in Table X. For further details, see *Appendix A*, *Letters of Support*.

As in other TE field projects such as BOREAS, LBA, and ABoVE, the PANGEA team will work with non-NASA sponsors to incorporate their contributions into the PANGEA Concise Experiment Plan. This process will include (1) defining activities and funders to ensure support is complementary and not duplicative; (2) streamlining management, communication, and oversight among sponsors; and (3) addressing data security concerns. PANGEA will build on past TE experience that successfully blended 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.

**Table X.** PANGEA potential co-funding and in-kind support opportunities.

| Project Area | NASA Programs | Other US Government | International Government | Other |
| --- | --- | --- | --- | --- |
| Remote Sensing | TE, Related Programs | NOAA, NSF, USDA, USFS, USGS | AGEOS, ESA, INPE | Land and Carbon Lab, MapBiomas |
| Data Hosting | TE | DAACs, AmeriFlux (DOE) | ESA, ICOS | Global Forest Watch, Google, MoveBank, Planet |
| Research | TE, Related Programs | DOE, NOAA, NSF | UK NERC, EU, São Paulo Research Foundation (FAPESP), CNPq, Belmont Forum | Schmidt Sciences, Moore Foundation |
| Training and Education | ARSET, DEVELOP, SERVIR, GLOBE, Indigenous Peoples Initiative | USAID, USFS-IP | FCDO (UK), One Forest Vision Initiative | CBSI, R2FAC, Philanthropies, Donors |
| Applications | Earth Action, SERVIR, Harvest | USAID, USFS-IP, USGS | EU, GCF-TF, ONACC, OSFAC | Bezos Earth Fund, NICFI, Moore Foundation, Private sector |

## Open Science—Data Management and Sharing

PANGEA will facilitate open-source science, promote collaboration, and maximize the value of PANGEA data broadly and for the long term, in alignment with NASA’s Strategy for Open Science (Strategy for Data Management and Computing for Groundbreaking Science 2019-2024). This strategy will adhere to community principles and practices and keep ethical guidelines and cultural sensitivity in mind. 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 projects 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 paradigms (e.g., Western science paradigm, Indigenous ecological knowledge, Traditional ecological knowledge). PANGEA data management will adhere to the Findable, Accessible, Interoperable and Reusable (FAIR) guiding principles to improve data discoverability and accessibility, promote data interoperability and integration, and enhance data reusability and reproducibility (Wilkinson et al. 2016). PANGEA data collection, management, and use will also align with the CARE principles, which emphasize the importance of considering the rights and interests of Indigenous Peoples and Local Communities 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 following CARE principles as described in Table X.

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 PANGEA 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. PANGEA will prioritize first-authored publications 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[[2]](#footnote-2) to prepare and preserve data as well as associated information beyond the lives of a project. This will enable future users 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[[3]](#footnote-3) 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 publicly accessible PANGEA Information Portal (PIP). This Information Portal will outline PANGEA’s data management and sharing strategy, provide direct links to data, models, and 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 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. The PIP will provide easy discovery and access to data collected by PANGEA and also existing data useful for PANGEA research.

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 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. 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. Existing networks and programs such as FLUXNET, NEON, ICOS, OzFlux, TERN, and SAEON have invested in the definition of standards in the processing and data distribution and are moving toward the FAIR implementation. 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.

**Table X.** Examples of coordinated data management and sharing activities with partners.

| Partner(s) | Data Management and Sharing Activity |
| --- | --- |
| LBA | PANGEA will X - needs to be finalized. |
| Alliance for Tropical Forest Science (ATFS) | Coordinate with ATFS tropical forest plot network partners to ensure that ground and drone data collection and management follow existing standards and protocols. |
| Indigenous and Local Community partners (e.g., GATC, RRI) | Engage with IPLC partners during the development of the Concise Experiment 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 IPLC-led storing and managing of Indigenous data. Provide training to create tools for IPLCs that would support data collection, management, and dissemination. |
| NEON, SBG & NISAR Science Teams | Harmonize protocols across research communities to support scaling. Examples of existing initiatives that PANGEA will engage with include the SBG VSWIR Terrestrial Vegetation algorithm team and the NISAR cal/val network. PANGEA will contribute to 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. |

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 will also adopt an open-source approach for models. 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 Science Mission Directorate (SMD) Open-Source Science Guidance. PANGEA will promote model governance for community engagement including a 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. To comply with PANGEA’s open science principles, projects part of PANGEA will deposit the exact version of published models in long-term repositories with a DOI along with parameter and data information needed to reproduce results.

PANGEA will develop an open cloud-based data analysis platformfor 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. 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.

PANGEA will provide open-source science and data management capacity building throughout the project, 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. 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 project. Co-funding is being sought to support the investment in infrastructure needed to ensure open-source science can be carried out equitably across PANGEA landscapes, including funding to support local electricity and internet infrastructure.

## Timetable

The PANGEA team has used virtual and hybrid meetings for early engagement of a diverse science scoping team. We have time-saving approaches that can greatly reduce the timeline needed to develop the Concise Experiment Plan and move on to the Implementation phase. Table Xoutlines the proposed timeline, assuming PANGEA’s next activities begin in Fiscal Year 2025.

**Table X.** Proposed PANGEA timetable. SDT: Science Definition Team; TE: Terrestrial Ecology; CEP: Concise Experiment Plan; PAC: PANGEA Airborne Campaign; SATSM: Science and Applications Team and Stakeholder Meeting

|  | CEP | | Phase I | | | Phase II | | | Phase III | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Study Year |  |  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Project Office Activities | FY25 | FY26 | FY27 | FY28 | FY29 | FY30 | FY31 | FY32 | FY33 | FY34 |
| PANGEA selected. Detailed planning begins: Selection of Science Definition Team. Concise Experiment Plan drafted, open for community review, and completed. |  |  |  |  |  |  |  |  |  |  |
| The PANGEA announcement of opportunity (NRA) released by NASA. Project Office initiates preparations based on CEP. PANGEA Phase 1 Proposals awarded. 1st SATSM. |  |  |  |  |  |  |  |  |  |  |
| 2nd SATSM and Airborne Campaign Planning Workshop. PANGEA Airborne Campaign I (PACI) |  |  |  |  |  |  |  |  |  |  |
| 3rd PANGEA SATSM and Airborne Planning. PANGEA Airborne Campaign II (PACII). NASA NRA PANGEA Phase 2 proposals and selection. |  |  |  |  |  |  |  |  |  |  |
| 4th PANGEA SATSM and Airborne Planning. PANGEA Airborne Campaign III (PACIII). |  |  |  |  |  |  |  |  |  |  |
| 5th PANGEA SATSM. PANGEA Airborne Campaign IV (PANIV). |  |  |  |  |  |  |  |  |  |  |
| 6th PANGEA SATSM. PANGEA Backup Airborne Campaign V (PANV). NASA NRA PANGEA Phase 3 Proposals and selection. |  |  |  |  |  |  |  |  |  |  |
| 7th PANGEA SATSM. |  |  |  |  |  |  |  |  |  |  |
| 8th PANGEA SATSM. |  |  |  |  |  |  |  |  |  |  |

## Risk Assessment

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 high-impact science. The Project Office 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 three categories: (1) health and safety; (2) meeting science objectives; and (3) meeting community engagement and applications objectives.

Health and Safety: The project will follow health and travel safety guidelines issued by the US Department of State Bureau of Consular Affairs. PANGEA will also engage with local US Embassies, Consulates and their Regional Security Offices for guidance. 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 campaigns, following NASA guidelines for aircraft operations and on the ground. Some potential study regions include risks for malaria, yellow fever, and other diseases; the project will ensure participants are advised on relevant vaccines and other prophylaxis prior to field visits.

Meeting Science Objectives: The Project Office will work proactively to 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 airborne measurements have benefits, use of these aircraft require diplomatic clearance in both the country with the study area and during transit. Diplomatic clearance can sometimes only be obtained near its need-by date so portions of campaigns or entire campaigns may be canceled on short notice. In addition, because 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. The PANGEA Project Office 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. During the Science Definition phase, PANGEA will run a climate analysis to determine the best time of year for airborne measurements. During the airborne campaigns, PANGEA will work with local weather forecasters who understand the local climate to facilitate successful airborne and field measurements.

Field work presents multiple risks. For those who do not work in tropical forests, risks such as venomous snakes and poisonous spiders come to mind. While these biological risks are real, they can be managed by establishing and enforcing safety guidelines to educate researchers on safe behavior, and the requirement of using safety gear (gaiters) and keeping stocks of anti-venoms. Surprisingly, the greatest risk to researchers is transportation to and from the field. Travel by truck and by boat was the greatest risk during LBA. This risk can be mitigated by assuring that drivers are trained and that vehicles are properly maintained. Other risks in the field include disease and loss of equipment through theft and violence. Endemic diseases, such as malaria, can be mitigated by medical prophylaxis and violence simply needs to be avoided by maintaining good community relations, situational awareness, and communications. All of these risks can be mitigated by conducting locally specific field safety and cultural awareness training, and establishing good relations with local communities.

Meeting Community Engagement and Applications Objectives:Engaging with local communities, and developing science and applications outcomes that will be useful to a wide variety of people requires coordination and genuine effort. A risk of PANGEA is that engagement efforts are not successful and/or applications are not useful. PANGEA will take several actions to mitigate these risks. PANGEA will co-produce engagement plans for each landscape during the Concise Experiment Plan development that includes milestones, objectives, and metrics to evaluate success regularly throughout the project. PANGEA will embrace inclusivity and will actively work to develop and promote inclusive and co-developed practices throughout. Co-developing projects and working equitably with all partners, including Indigenous Peoples and Local Communities, can take a long time. PANGEA will continue to work hard to build on long-standing relationships. 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 with partners to develop plans for continued support beyond the duration of the project. PANGEA will work to maintain relationships with community partners throughout the project, 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.

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# References

[References Google Doc](https://docs.google.com/document/d/1O6XpISwtJ2ere9_OnkLi6uvaFm01RWqjYj7SE8xy4ZQ/edit)

# Figure and Photograph Credits

[To be supplied.]

# Glossary

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 (Levis et al., 2024).

Ecosystem:PANGEA uses the IPCC working definition of ecosystem, 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](https://apps.ipcc.ch/glossary/)).

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 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 use forest resources in a way that preserves the forest's ecological integrity and supports the sustainable livelihoods of local communities IUCN (2021).

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 refer to the alteration of the Earth's surface, including changes in how land is used (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](https://apps.ipcc.ch/glossary/))

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. United Nations Framework Convention on Climate Change (UNFCCC) (2020).

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).

# Acronyms and Abbreviations

AboVE Arctic Boreal Vulnerability Experiment

**ABSOLUG** Agent-Based Simulator of Land Use Governance

AGEOS Gabonese Space Agency

AGU American Geophysical Union

AI Artificial intelligence

AI/ML Artificial Intelligence and Machine Learning

AI4ESP Artificial Intelligence for Earth System Predictability

AmeriFlux Americas' eddy-covariance Flux tower network

AmIT Amazon Institute of Technology

AMMA-CATCH African Monsoon Multidisciplinary Analysis Couplage de l’Atmosphère Tropicale et du Cycle Hydrologique

AMSR-E Advanced Microwave Scanning Radiometer for EOS Mission

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer

ATBC Association for Tropical Biology and Conservation

ATFS Alliance for Tropical Forest Science

ATTO Amazon Tall Tower Observatory (Presidente Figueiredo, Brazil)

BioSCape Biodiversity Survey of the Cape

BOREAS Boreal Ecosystem–Atmosphere Study

BRDF Bidirectional reflectance distribution function

CARAFE Carbon Airborne Flux Experiment

CarbonTracker Data assimilation system for CO2 tracking

CARDAMOM Carbon Data Modeling Framework

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

CBI Congo Basin Institute

CBFP Congo Basin Forest Partnership

CBSI Congo Basin Science Initiative

CCE Carbon Cycle and Ecosystems (NASA office)

CENAREST Gabon National Center for Scientific and Technological Research

CEOS Committee on Earth Observation Satellites

CFIS Chlorophyll Fluorescence Imaging Spectrometer

CGIAR Consultative Group for International Agricultural Research

CH4 Methane

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

CliMA Climate Modeling Alliance

CLM Community Land Model

CMIP Coupled Model Intercomparison Project

CMIP5 CMIP—Phase 5

CMIP6 CMIP—Phase 6

CMS-Flux Carbon Monitoring System Flux inversion system

CNES French National Space Agency

CNRS National Centre for Scientific Research (France)

CO2 Carbon dioxide

COCCONCOllaborative Carbon Column Observing Network

COMIFAC COMIFAC

COS Carbonyl sulfide

CSDACommercial SmallSat Data Acquisition

CUE Carbon use efficiency

DEIDiversity, equity, and inclusion

DGVM Dynamic Global Vegetation Model

DLRGerman Aerospace Center

DGPA-DRCDynamique des Groupes des Peuples Autochtones

DOE Department of Energy

E3SMEnergy Exascale Earth System Model

EBV Essential Biodiversity Variable

ECOSTRESSEcosystem Spaceborne Thermal Radiometer Experiment on Space Station

EDEcosystem Demography

ED2Ecosystem Demography Model version 2

ED3Ecosystem Demography Model version 3

EDGE Earth Dynamics Geodetic Explorer

eDNA Environment deoxyribonucleic acid

ELM E3SM Land Model

EMIT Earth Surface Mineral Dust Source Investigation

ENSOEl Niño Southern Oscillation

Ent TBM Ent Terrestrial Biosphere Model

EOS Earth Observing System

ESAEcological Society of America

ESAEuropean Space Agency

ES2ANASA’s Earth Science to Action Strategy

ESMEarth System Model

ETEvapotranspiration

EUDR European Union Deforestation Free Commodities Regulations

FAIR Findable, accessible, interoperable, and reusable

FAPESPSão Paulo Research Foundation

FATESFunctionally Assembled Terrestrial Ecosystem Simulator

FIFE First ISLSCP Field Experiment

FLEX Fluorescence Explorer Mission

FLUXNET Global eddy covariance flux tower network

ForestGEOForest Global Earth Observatory

FORMIND Forest Model Individual-based model

FTAC Fast Track Action Committee (on Climate Services)

GATC Global Alliance of Territorial Communities

GCF-TFGovernors’ Climate and Forests Task Force

GEDI Global Ecosystem Dynamics Investigation

GEM Global Ecosystems Monitoring network

GEOGroup on Earth Observations

GEO BON Group on Earth Observations Biodiversity Observation Network

GEO-TREES Group on Earth Observations-Trees

GHG Greenhouse gas

GIS Geographic Information System

GLOBE Global Learning and Observations to Benefit the Environment

GNSS Global Navigation Satellite System

GOES Geostationary Operational Environmental Satellites

GOSAT Greenhouse Gases Observing Satellite

GPM Global Precipitation Measurement

GPPGross primary productivity

GPS Global Positioning System

GPU Graphics processing unit

GRACE Gravity Recovery and Climate Experiment

GRACE-FO Gravity Recovery and Climate Experiment Follow-On mission

**GSFC** Goddard Space Flight Center

GuyaFlux Eddy covariance flux tower at the Paracou Field Station (Sinnamary, French Guiana)

H2O Water

HBCUs Historically Black Colleges and Universities

HQ Headquarters

HYSPLIT A NOAA atmospheric transport and dispersion model

HyTES Hyperspectral Thermal Emission Spectrometer

IA Implementing agreement

ICOS Integrated Carbon Observation System

IEKIndigenous ecological knowledge

IITA International Institute for Tropical Agriculture

ILAMBInternational Land Model Benchmarking project

IPLCsIndigenous Peoples and Local Communities

INPANational Institute of Amazonian Research (Brazil)

INPE National Institute for Space Research (Brazil)

IPCCIntergovernmental Panel on Climate Change

IPBESIntergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IRDFrench National Research Institute for Sustainable Development

ISLSCP International Satellite Land–Surface Climatology Project

ISROIndian Space Research Organisation

ITCZIntertropical Convergence Zone

IUCNInternational Union for Conservation of Nature

JAXAJapan Aerospace Exploration Agency

JSBACH Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg model

JULES Joint United Kingdom Land Environment Simulation

K34 Kilometer 34 eddy covariance tower (Manaus, Brazil)

K67 Kilometer 67 eddy covariance tower (Belterra, Brazil)

LAI Leaf Area Index

LBALarge-Scale Biosphere-Atmosphere Experiment in Amazonia

LBA-ECOThe NASA Terrestrial Ecology Program contribution to the first phase of LBA

LBNL Lawrence Berkeley National Laboratory

LCLUCLand-Cover and Land-Use Change

LEKLocal ecological knowledge

LiDAR Light detection and ranging

LPJ Lund-Potsdam-Jena dynamic global vegetation model

LPJ-GUESS LPJ General Ecosystem Simulator

LST Land surface temperature

LUH2 Land-Use Harmonization project, version 2

LVIS Land, Vegetation, and Ice Sensor

MAAP Multi-Mission Algorithm and Analysis Platform

MapBiomas Biome Mapper initiative

MASTER MODIS/ASTER Spaceborne Thermal Emission and Reflection Radiomete

MetaFlux Meta-learning framework for climate sciences

ML Machine learning

ModEX Model-Experimentation

MODIS Moderate Resolution Imaging Spectroradiometer

MOUMemorandum of understanding

**MSI** Minority Serving Institution

**N2O** Nitrous oxide

**NASA** National Aeronautics and Space Administration

**NBE** Net biosphere exchange

NDVI Normalized Difference Vegetation Index

NEENet ecosystem exchange

NEON National Ecological Observatory Network

**NGEE-Tropics** Next-Generation Ecosystem Experiments—Tropics

NGO Nongovernmental organization

NISAR NASA-ISRO SAR Mission

NOAA National Oceanic and Atmospheric Administration

NOANET Northwest Open Access Network

NPP Net primary productivity

NSB National Science Board

NSC Nonstructural carbohydrate

NSFNational Science Foundation

NSTC National Science and Technology Council

OCO-2/3 Orbiting Carbon Observatory–2 or –3

OECMs Other Effective Conservation Measures

OFViOne Forest Vision

OIIRNASA Office of International and Interagency Relations

ONACCCameroon National Climate Change Observatory

ORCHIDEE Organising Carbon and Hydrology in Dynamic Ecosystems

ORNL Oak Ridge National Laboratory

OSFACCentral African Satellite Observatory

OSSE Observing System Simulation Experiment

PACE Plankton, Aerosol, Cloud, ocean Ecosystem Mission

PANGEAPAN tropical investigation of bioGeochemistry and Ecological Adaptation

PFT Plant functional type

PhenoCam Phenological Camera

PI Principal Investigator

PIP PANGEA Information Portal

QA/QC Quality assessment and quality control

RAINFOR Amazon Forest Inventory Network

RepastSimphony Recursive Porous Agent Simulation Toolkit with Symphony Java interface

RGB Red green blue

RRIRights and Resources Initiative

RUBISCO Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation

S&E Science and Engineering

SBGSurface Biology and Geology Mission

SERVIR SERVIR is a NASA and USAID partnership that supports locally led efforts to strengthen climate resilience, food and water security, forest and carbon management, and air quality.

SES Social-ecological systems

SHIFT SBG High-Frequency Time Series

SIF Solar-induced (chlorophyll) fluorescence

SILK School for Indigenous and Local Knowledge

SimPachamama Hybrid simulation model for socio-environmental trade-offs

SL Science Leadership

SLA Specific leaf area

SMAP Soil Moisture Active Passive

SMOS Soil Moisture and Ocean Salinity

SPUNSociety for the Protection of Underground Networks

SSCScientific Steering Committee

**SSP** Shared Socioeconomic Pathways

SSTSea surface temperature

STEM Science, technology, engineering, and mathematics

STILT Stochastic Time-Inverted Lagrangian Transport model

STRI Smithsonian Tropical Research Institute

SWOT Surface Water and Ocean Topography Mission

Tallo A global tree allometry and crown architecture database

TBDTo be determined

TCCONTotal Carbon Column Observing Network

TEKTraditional ecological knowledge

TERN Terrestrial Ecosystem Research Network

TIRThermal infrared radiation

TIRS Thermal Infrared Sensor

TLS Terrestrial Laser Scanning

TmFO Tropical managed Forests Observatory

TRISHNA Thermal infraRed Imaging Satellite for High-resolution Natural Resource Assessment

TRL Technology Readiness Level

TROLL Tree Representation Of Landscape Level model

TROPOMI Tropospheric Monitoring Instrument

TRY Plant Trait Database

UAVUncrewed aerial vehicle

UCLA University of California, Los Angeles

UNFCCCUnited Nations Framework Convention on Climate Change

U.S. United States of America

USAID U.S. Agency for International Development

USDA U.S. Department of Agriculture

USFSU.S. Forest Service

USGSU.S. Geological Survey

VEDA Visualization, Exploration, and Data Analysis

VIIRS Visible Infrared Imaging Radiometer Suite

VOC Volatile organic compound

VOD Vegetation optical depth

VPD Vapor pressure deficit

VPRM Vegetation Photosynthesis and Respiration Model

VSWIRVisible to shortwave infrared

WRI World Resources Institute

WUE Water use efficiency

# Appendices

[[Appendices Google Doc here](https://docs.google.com/document/d/1EIzwIZK0uF6_y0lzz7i8TMb0EHxecDYDWX4mQEinWXY/edit)]

## Appendix A: Letters of Support

## Appendix B: PANGEA Partners

## Appendix C: Engagement during the Scoping Study

## Appendix D: Planned and Ongoing Research and Monitoring Activities

## Appendix E: PANGEA Core and Extended Domains Detailed Table

## Appendix F: Potential PANGEA Training Activities

## Appendix G: Responses to Feedback

Model Tables

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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. [↑](#footnote-ref-1)
2. <https://www.earthdata.nasa.gov/esdis/esco/standards-and-practices/preservation-content-spec> [↑](#footnote-ref-2)
3. <https://www.earthdata.nasa.gov/s3fs-public/2022-07/ESDS-RFC-042VERSION1.pdf>) [↑](#footnote-ref-3)