PANGEA Draft White Paper

[**WRITING ASSIGNMENTS HERE**](https://docs.google.com/spreadsheets/d/1USQ6QT2ePmF1G68PucHvCO_6cWeVqritkIX1cv3cOMU/edit?gid=21525332#gid=21525332)

***Questions, Hypotheses, Data Needed Table:*** [***PANGEA Questions & Hypotheses***](https://docs.google.com/spreadsheets/d/1IMawYdO6ZRRX0R5MexkIwF3_BZTi52_tHQxmHoxjtNU/edit?usp=sharing)

[NASA Tropical Ecology Scoping Solicitation](https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=860588/solicitationId=%7BEB63A640-7CE0-70F6-BE80-C12541C56B5F%7D/viewSolicitationDocument=1/A.4%20Terrestrial%20Ecology%20Amend%2036.pdf)

ABoVE White Paper: [ABoVE Final Scoping Report 2010.pdf](https://drive.google.com/file/d/1r9vFP5H4r7QVy379OSeGuPAWdINTQuRj/view?usp=sharing)

***From Solicitation:***

The main deliverable will be a scoping report that lays out the scientific issues at stake, the logistical framework, and one or more paths forward toward implementation. Scoping studies will be required to address the following elements:

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.

Scoping studies must produce a written report that **provides the scientific rationale and an initial study design concept** for a new field campaign or related team project. While this report need not be lengthy, it **must include a thorough presentation of science questions, goals, and objectives; the underlying rationale in terms of state-of-the-art, relevance, and expected advances; implementation concepts**; and other information to enable NASA to fully evaluate the project.

**[LOGO]**

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

**Draft Report**

**September 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.

In this white paper, we XXX.

**Acknowledgments**

The scoping of PANGEA is very much an international community effort. It would not be possible without the contributions of an untold number of individuals. We are deeply grateful to all have contributed their ideas, time, energy, resources, and funding to scope this urgently needed campaign. More detailed acknowledgements will be included in the final draft of this PANGEA white paper.

**Specifically acknowledge additional funding sources and co-organizers of workshops**

* **UCLA**
* **GCF**
* **USFS-IP**
* **WCS**
* **PUCP**
* **IITA**
* **University of Yaounde I**
* **…**

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## 

## 1. Introduction and Motivation

In response to a call from the NASA Terrestrial Ecology Program, we present the scope of a terrestrial ecology field campaign, *The PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA), that will focus on tropical forest biomes. PANGEA will answer globally relevant and urgent big science questions emphasizing comparison among the major tropical forest formations on our planet through effective interpretation and analysis of space-based measurements and through a combination of ground, airborne, and satellite-based science investigations. PANGEA will foster collaborations and build new relationships within the scientific community with an emphasis on interactions between US scientists and researchers from countries with tropical forests, as well as strengthening relationships with partners from international space agencies. PANGEA will also provide opportunities for training and educating the next generation of scientists and the broader workforce, including scientists and trainees from countries where field research will be based. PANGEA will leave a legacy of open data, open science, and strengthened partnerships between the US, tropical institutions, and international partners as the basis for future research and applications.

Tropical forests account for globally significant carbon and water fluxes, biomass carbon stocks, and biodiversity. Tropical forests regulate climate locally, regionally, and globally and account for a majority of terrestrial biodiversity. Tropical forests also store vast amounts of carbon; moist tropical forests in particular comprise about 40% of global biomass (Xu et al., 2021) and are currently a globally important carbon sinky. However, tropical forests are highly threatened by climate change and land-use change.Forests in the equatorial regions will soon experience the highest known temperatures since the Eocene which, combined with land-use change, will lead to increasing atmospheric dryness and water stress (Barkhordarian et al 2019). Tropical tree mortality rates are rising differentially across the tropics due to increases in drought duration and severity and storm intensity (Allen et al 2010, McDowell et al 2018, Choat et al 2012). Rising temperatures are approaching hypothesized thermal limits of leaf function, although those limits remain much debated (Smith et al. 2020, Doughty et al. 2023, Winter 2024). Unprecedented rates of anthropogenic land-use change in recent decades (DeFries et al 2004, Gibbs et al 2010a, Hosonuma et al 2012) have resulted in some tropical forests becoming net sources of carbon to the atmosphere (Gatti et al 2021). Prolonged hot and dry conditions increase forest vulnerability to fires and already burned forests in turn become hotter and drier leading to a positive feedback that has been called a “gathering firestorm” (Brando et al. 2020). Deforestation, forest degradation, direct exploitation (e.g., hunting, harvesting), and climate change threaten many tropical species with extinction (Feeley et al. 2012; Barlow et al. 2016; Benitze-Lopez et al. 2017; Alroy 2017), and this biodiversity loss could in turn compromise tropical forest function (Bunker et al. 2005; Peres et al. 2016).

Even as regrowing, secondary tropical forests continue to sequester large amounts of carbon from the atmosphere, tropical deforestation and degradation accounted for 22% of annual anthropogenic carbon dioxide (CO2) emissions, while intact tropical forest sinks weakened by an estimated 31% in the past two decades (1990-2019; [Pan et al., 2024](https://www.nature.com/articles/s41586-024-07602-x)). Tropical forests and floodplains, which are frequently interspersed with wetland and aquatic ecosystems, also play a critical role in the global methane (CH4) and CO2 budgets (Sjögersten et al., 2014; Peng et al., 2022). CH4 has experienced recent atmospheric growth rates inconsistent with our current understanding of global sources and sinks of this critical greenhouse gas (GHG) (Turner et al., 2019). CH4 contributes an estimated 30% of the increase in radiative forcing from anthropogenic emissions and is >25 times more potent as a GHG compared to CO2 (Masson-Delmotte et al., 2021). Tropical wetland and inland freshwater systems contribute the vast majority of 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). These tropical CH4 sources are the most uncertain component of the global carbon budget (Saunois et al., 2020, 2024).

Halting tropical deforestation and forest degradation and conserving regrowing tropical forests can be a cost-effective tool for mitigating climate change, with co-benefits that extend beyond carbon sequestration (e.g. [Heinrich et al., 2023](https://www.nature.com/articles/s41586-022-05679-w)). Tropical forests maintain high levels of evaporation and transpiration throughout the year, transferring energy and water to distant latitudes and maintaining high rates of regional precipitation through rainfall recycling (Salati et al. 1979; recent refs Amazon; Worden et al. 2021; Worden et al. 2024, van der Ent et al., 2010, Staal et al., 2018). Deforestation and forest degradation reduce evapotranspiration in the dry season (Sampaio et al. 2007; Longo et al. 2020; Zemp et al., 2017; recycling models refs) potentially leading to forest mortality and a positive feedback loop resulting in forest ecosystem collapse that has been called a “tipping point” (Xu et al., 2022,Lovejoy and Nobre 2018).

The biogeochemical response of tropical forests to changing climate forcing and climate extremes varies strongly across the globe in ways that urgently require improved understanding.. This knowledge gap is greater in the humid tropics than in other biomes (e.g., dryland, boreal or temperate forest ecosystems). Differences in the evolutionary history of tropical ecosystems across continents have produced major variation in species and functional composition,structure, and biogeochemical cycling, that directly affects their vulnerability and resilience, i.e., the ability to withstand and recover from changes is directly linked to the conditions under which these systems evolved. From 1985-2015, the carbon sink of intact African lowland tropical forests measured in forest inventory plots was effectively constant while the carbon sink in Amazonian lowland tropical forests declined by one-third from 2005 through 2015 compared to the 1990s (Hubau et al. 2020; Brienen at al. 2015). Under El Niño conditions during 2015-2016, tropical America, Africa, and Asia, all temporarily became net sources of 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 and will require regionally specific understanding and management to mitigate. The sources of CO2 concentrations, as measured by the Orbiting Carbon Observatory-2 (OCO-2), suggest that in the tropical Americas, reduced photosynthesis led to reduced carbon uptake reversing the balance to net emissions. In Africa, increased temperatures led to increased respiration, outweighing the sequestration benefits of Central African tropical forests (Liu et al. 2017). In Asia, a hotter and drier land surface resulted in more emissions from fires. However, **we cannot explain with confidence why different tropical forest biomes are responding differently to similar climate forcing with our current understanding of tropical forest ecology and biogeochemistry.**

**Satellite Missions require validation in tropical forests. NASA satellites play a critical role in advancing understanding of how forest ecosystems respond to environmental changes such as climate variability and land-use change. However before satellite data can be useful for scientific analysis or operational use, ground based observations are critical to validate these measurements. Yet, the scarcity of such observations in tropical regions has led to significant challenges in improving satellite products. For instance, recent ground-based observations revealed that the Soil Moisture Active Passive (SMAP) satellite exhibits strong biases in tropical ecosystems (Cho et al. 2024). Moreover, these same ground-based data have provided an opportunity to improve SMAP’s soil moisture measurements in tropical forests (Wang et al. 2024).Reducing biases in tropical soil moisture measurements enhances our understanding of the water cycle, carbon fluxes, and ecosystem dynamics in critical areas as tropcial forests.**

**Validating satellite data with ground based observations is essential to the success of NASA’s Earth observation missions. The development of more accurate satellite products, particularly in under-observed tropical regions, directly supports NASA’s mission to improve global environmental monitoring and advance predictive models.**

**Future predictions of the role of the tropical carbon land flux in the Earth system remain highly uncertain** (Arora et al. 2020; Friedlingstein et al 2014; Friedlingstein et al 2006). The current uncertainty in terrestrial carbon flux predictions across Earth System Models (ESMs) is three times greater in the tropics than at any other latitude (Cavaleri et al 2015). [*more here - reference Friedlingstein et al 2023 - CMIP5 to CMIP6 updates, but remaining uncertainties regarding processes - are we getting the right answers for the right reasons - and need for improved RS data model integration, e.g., developing ESMs that link satellite measurements more directly to land processes, such as models that simulate SIF (Braghiere et al., 2021), have a more detailed radiative transfer model, spectrally resolved (Braghiere et al. 2023), directly linking traits to spectral/physiological forest properties, etc. As well as models that learn directly from data such as CARDAMOM (Bloom et al. 2016), AI (Massoud et al. 2023) and Pierre Gentine’s papers*]

Traditionally, ESMs ignore most biodiversity and represent tropical vegetation in simple and aggregated ways that directly contribute to model failure to capture tropical forest responses to climate variation and disturbance (Levine et al. 2016; Yang et al. 2023; Sakchewski et al. 2016). The need to improve the representation of ecological processes of diverse ecosystems is increasingly recognized by the modeling community (Bonan et al. 2024). Newer generations of terrestrial biosphere models—vegetation demography models (Fisher et al. 2018)— namely XX include more structurally and functionally diverse forest canopies (Longo et al. 2019; Koven et al. 2020). Vegetation demography models represent forest dynamics processes more directly. However, the additional complexity creates two challenges for regional and global simulations. First, initial conditions require detailed forest structure and composition data that can be derived from forest plots only for small domains (Marvin et al. 2014). Second, existing model benchmarking systems, such as the International Land Model Benchmarking (ILAMB; Collier et al. 2018) are insufficient, because the newer generation of models may predict reasonable aggregated properties (e.g., total aboveground biomass) via compensating errors in process representation (e.g., overly high productivity and mortality). Recent advances in remote sensing provide a unique opportunity to collect data on the structure, composition and diversity of ecosystems over large areas and thereby better inform models(Schimel et al. 2019).

Critically, **tropical forests are also the least investigated of all of the Earth’s major terrestrial biomes**. Few tropical forest countries maintain systematic repeated forest inventories because inventories are costly and require technical and management expertise. Networks of research plots provide valuable insights into forest dynamics, but their distribution is sparse and extrapolation from potentially biased plot locations may lead to significant uncertainties and biases (Saatchi et al., 2015). The latitudinal distribution of both forest inventory plots and eddy covariance flux towers is nearly inversely proportional to gross primary productivity, demonstrating the underrepresentation of sampling in these critical ecosystems (Baldocchi et al 2022, Schimel et al. 2015) (Figure X).

*[1-2 paragraphs on the critical timing of PANGEA that emphasize the points below - many efforts trying to ameliorate this with respect to XYZ, but still critical need to fill knowledge, data, and methods gaps - PANGEA will fill these gaps while coordinating with and reinforcing existing activities and preparing the next generation to continue leading this work into the future] A hallmark of PANGEA is its commitment to community-engaged research. By engaging communities traditionally left behind in major and international projects from the beginning, PANGEA is poised to …*

* *equitable science and not extractive science*
* ***Urgency/Timeliness*** *- need to do this now - why this should be the next campaign; why we can’t wait another 5-10 years* 
  + *tropical ecosystems, and in our data-rich era of new dimensionality effectively utilize current and forthcoming satellite missions to diagnose the current state of tropical forests*
* ***Societal need*** *- lots of people depend on those forests*
  + *local, regionally, or globally*
* *state that this is feasible and necessary* 
  + *the lack of cal-val data in the tropics, XXX*
  + *we HAVE to do this to understand XYZ*
  + *we need this global context that we can only get from remote sensing*
* *we learned from LBA that by adding new components and integrating / interdisciplinarity results in the pie growing for everybody*
* ***Embed within Earth Science to Action Strategy*** 
  + *PANGEA is an opportunity to integrate!!!*
  + *CC&E umbrella logical place to start*
  + *but emphasize integration beyond CC&E*
  + *integrate across R&A and Applied*

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

### 1.1 Questions, Objectives, and Science Themes

Tropical forests have been a globally important carbon sink in recent decades, absorbing large amounts of CO₂ from the atmosphere. However, deforestation, increases in extreme weather events, frequent wildfires, and other disturbances are reversing this trend, with some regions now acting as net carbon sources. Moreover, forest regrowth following these disturbances does not fully restore the original carbon sink capacity. This reversal is not uniform: tropical forest landscapes differ in their recent carbon sink trends, sensitivity to extreme events, and interactions with climate and land-use change. Understanding controls on tropical forest carbon flux trends and the resilience of tropical forest carbon sinks to extreme events is crucial to accurately projecting the future of the earth systemand requires an improved understanding of patterns and processes. Critically, continued monitoring of these dynamics at pan-tropical and global scales urgently requires filling data and methods gaps to effectively leverage the new era of satellite remote sensing capabilities available now and in the next 1-10 years. PANGEA will study the complex interactions of the carbon cycle and social-ecological systems in the tropics to answer: **How vulnerable or resilient are tropical forest landscapes and their feedbacks to the global carbon cycle and climate?**

Addressing this knowledge gap to inform climate mitigation and adaptation strategies and biodiversity conservation requires answering three critical questions:

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

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

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

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

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

### 1.2 The urgent need for PANGEA

Implementing PANGEA is urgent for two reasons; both relate to our lack of knowledge of tropical forest ecosystems. First, PANGEA is urgent because recent scientific results find real potential for the collapse of tropical forest ecosystems in the next few decades. Because of the importance of these ecosystems in the global carbon and water cycles, the collapse of tropical forest ecosystems would have potent effects on the whole Earth System exacerbating current trends in climate change (REF). The second urgent reason for implementing PANGEA now is the lack of knowledge to adequately understand existing and near-future satellite data. The tropical forest biomes are woefully understudied compared to other biomes on Earth because of their inaccessibility and because much of the tropical forest area is in moderately poor or extremely poor nations that have limited resources to devote to the study of tropical forests. In order to maximize the gains from current (e.g., EMIT, GEDI) and future (e.g., SBG, BIOMASS) satellite missions we urgently need studies with field and airborne resources to understand the signals from those missions. Immediate implementation of a PANGEA as a Terrestrial Ecology Field Campaign will fill knowledge gaps, and coordinate with well-timed international efforts, **PANGEA will advance scientific understanding and remote sensing capabilities across thematic areas that directly address the goals of NASA’s Carbon Cycle and Ecosystems Focus Area, in alignment with the Water and Energy Cycle and Climate Variability and Change Focus Areas.**

PANGEA [KEPT THIS WORD HERE TO PRESERVE LONG COMMENTS]

### 1.3 Role of Remote Sensing Observations

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

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

The constellation of Earth observing satellites available today, those nearing launch, and those in earlier stages of implementation and planning offer many dimensions of information not previously available and not widely used in tropical forest studies. Pan-tropical forest structure and biomass can now be studied using spaceborne lidar from GEDI (Dubayah et al. 2020) and upcoming radar missions including the NASA-ISRO NISAR mission and the ESA BIOMASS mission. Detailed canopy chemistry can now be studied through high-fidelity spectroscopy from current missions including NASA’s EMIT mission (REF) and Italian Space Agency PRISMA (REF) and forthcoming SBG and CHIME missions. Canopy solar induced fluorescence, a close correlate of gross primary productivity, is now measured instruments on several satellite platforms including OCO-2 and OCO-3 (REF), and TROPOMI (REF). Land surface temperature has long been available at coarse resolution from weather satellites but is now measured at 70 m resolution from ECOSTRESS (Fisher et al. 2020) providing new insights on XYZ. Satellite observations of total column carbon dioxide (e.g. from GOSAT, OCO-2, OCO-3 and TROPOMI) and gravitational anomalies (GRACE and GRACE-FO) provide regional constraints on atmospheric carbon and water budgets. Similarly, river stages are now available from space through SWOT. High spatial and temporal resolution data on the land surface are now available from sources such as Planet and the GOES-R series of missions. Many of these sources of information have barely been employed for tropical forest studies.

The knowledge gaps that PANGEA will address cannot be answered without pan-tropical satellite observations, integrative analyses, and models. However, **we are currently unable to fully leverage these satellite datasets without coordinated calibration and validation measurements. Major data gaps and process uncertainties in tropical forests currently limit algorithm and product development, preventing the global utility of these sensors from being fully realized.** Scale mismatches exist for desired retrievals from nearly all of these satellites. For example, differences need reconciliation between the approximately 1 km footprint of tower-based eddy covariance fluxes and x-20 km satellite retrievals of gross primary productivity, methane fluxes, and ecosystem respiration. Similarly, leaf- and organismal-scale measures of biodiversity like functional traits and structural attributes scale non-linearly to 30-60 m pixels that incorporate multiple species (REFS). Reconciling these scale mismatches requires collocated ground, tower, drone, aircraft, and satellite measurements in combination with advances in understanding of processes that underpin scaling theory (REF).

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

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

### 1.4 The PANGEA Terrestrial Ecology Field Campaign

[Specifically outline what PANGEA is and is not] - section that explicitly defines what NASA PANGEA covers

* What NASA funded elements of PANGEA covers
  + Science themes
    - Data collection
    - Data curation
    - Open science
  + Training activities directly related research
  + Community engagement, including engagement w partners who are:
    - Leading on the applications development and decisions support
    - Leading on the workforce development training
* What complementary funding towards PANGEA can cover - refer to Section 7.6 - Co-funding Opportunities
  + Specify where we have commitments and where we do not - in final white paper - not needed in draft
* How PANGEA is coordinated with other activities (CBSI, GEO-TREES, …)
* Somewhere here or earlier, we should write about our positionality as authors trained in Western science. Do we have Indigenous coauthors? If not, we should mention, if yes, we should mention how this is incorporating or not Indigenous knowledge…

### 1.5 PANGEA Study Domain

PANGEA will include a core and extended domain. The extended domain for pan-tropical satellite remote sensing and modeling analyses will encompass moist tropical forests, including flooded forests, wetlands, peatlands, and mangroves (Figure X). The initial focus of PANGEA will be on tropical biomes in Africa and the Americas. The PANGEA study region covers the major ecosystems and landscapes found in the tropics and the spatial scale required to address the primary questions in the 5 science themes. The location of these Primary Research Areas will be based on opportunities to conduct integrated research across science themes as well as the existence of ongoing or planned research funded by NASA, as well as local and international partner agencies and organizations.

* Map of core and extended domains (Elsa will create based on ESA or FAO boundaries)
  + Modeling and satellite RS at pan-tropical scale
* Coordinated ground, tower, drone, and aircraft measurements will be collected in landscapes that capture variation in ….
  + See Section X for more detailed information
* Core PANGEA domain (tropical Americas & Africa) and extended PANGEA domain (pan-tropical - includes SE Asia and Australia enabling inclusion of existing datasets and opportunistic collection, but not focus of PANGEA data acquisition)

[1 brief paragraph on the variability analysis]

Include placeholder for variability analysis map here or in Overall Study Design section or in Candidate Study Sites / Regions section?

### 1.6 The need for coordinated teamwork

Individual investigator science excels in testing singular hypotheses. However, Earth system science is inherently multifaceted and complex. Recognizing this complexity, NASA scientific leadership embraced the multi-investigator team approach to Earth System Science decades ago (Asrar et al. BAMS v 82, pp.1309-1330, 2002, no DOI found). The Terrestrial Ecology Program has promoted the multi-investigator model for decades of field campaigns that span FIFE, BOREAS, LBA, and ABoVE. Multiple drivers and interacting processes that cannot be isolated in controlled experiments characterize Earth system investigations. Numerous variables require expert knowledge for acquisition and measurement whether if be through the operation of a high-performance spectrometer or botanical identification of a tree species. No single individual or small group of individuals possesses all the knowledge and tools demanded by an Earth system science investigation. Fulfilling the needs of integrative analyses of the tropical biomes for many variables and models that incorporate the complex interactions of those variables requires a large team of specialists working together. Equitable collaboration is required to assure that measurements are coordinated in time and space to maximize their value in interpretation and modeling. This can only be achieved by a cooperative, coordinated, interdisciplinary team.

It is also important to note that there is real risk that a campaign like PANGEA could perpetuate parachute and flyover science (Culotta et al. 2024). Recognizing the deep imprint of colonialism on tropical forest research, PANGEA takes an interwoven approach to equitable and ethical engagement with researchers, governments, institutions, and Indigenous Peoples and Local Communities (IPLCs). Several sections describe PANGEA’s approach to community engagement (Section 7.4), an inclusive organizational structure (Section 7.1), Earth Action (Section 8), capacity building (Section 9), data management (Section 7.7), and international agreements (Section 7.3).

### 1.7 Earth Science to Action

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

The 2017 Decadal Survey directs us to “pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observations and analysis to the nation and to the world in a way that delivers great value” (Decadal Survey). Now is the time for strategic investment in ambitious international collaborations to bridge the gap between rapid advancements in science and technology and society’s ability to harness them for a more resilient world.

PANGEA is highly relevant to NASA’s strategic goal to advance and integrate Earth science knowledge to empower humanity to create a more resilient world. Specifically, PANGEA supports NASA’s Earth Science to Action strategy by:

* *Investigating the risks of crossing tipping points and the potential for cascading environmental and societal impacts.*
* *Supporting efforts to enhance Earth’s resilience through mitigation strategies, adaptation, and the assessment of risks and contingencies from global change*
* *Developing efficient, interactive end-to-end tools, models, and assessment systems with appropriate latencies, temporal and spatial scales, and uncertainty quantification to enable science-based actions for communities, decision-makers, and policymakers.*

Text Box A. NASA Earth Science to Action “Service” in the Tropics

* SERVIR’s first hub opened in Panama at the Water Center for the Humid Tropics of Latin America and the Caribbean, or CATHALAC. This hub, SERVIR Mesoamérica, serves Central America and the Dominican Republic. CATHALAC completed its NASA funding contract in 2011 and began **self-sustaining operations**. CATHALAC continues as a SERVIR network affiliate, using Earth observations and models in providing maps and information products to the region.

## 2. PANGEA Science Themes

Owing to the inherent complexity of tropical terrestrial ecosystems and their feedbacks with the Earth system, PANGEA takes an integrated, interdisciplinary approach. Understanding patterns and processes and constraining prediction uncertainty requires diverse expertise and coordinated collaboration. PANGEA bridges disciplines and ways of knowing to co-produce science that will address specific knowledge gaps and support urgently needed applications. In the following sections we parse the current state-of-the-science by thematic area. In Section 3, we present PANGEA’s integrated science questions in response to knowledge gaps related to pattern, process, and future projections. Section 4 describes how addressing these questions will yield major, scientific advancements.

### 2.1 Biogeochemical Cycles

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

The terrestrial biosphere is a large sink of atmospheric CO2 with a present-day global net ecosystem exchange estimated at 3.3 GtC yr-1, offsetting ~30% of the CO2 emitted by fossil fuels annually (Friedlingstein et al., 2023). From 1990 to 2019, the global forest carbon sink was equivalent to nearly half of fossil-fuel emissions (7.8±0.4 Pg C yr−1) (Pan et al. 2024). Furthermore, tropical landscapes are a controlling factor of atmospheric global CO2 interannual variability (Ahlström et al., 2015). Tropical terrestrial ecosystems are estimated to contribute up to 0.6±0.4 GtC yr-1 of this sink, with large interannual variability (Friedlingstein et al., 2023). However, over the past three decades an estimated two-thirds of the benefit from the global forest sink was negated by tropical deforestation (2.2±0.5 Pg C yr−1, 1990-2019) (Pan et al. 2024). In addition, according to the most recent Global Carbon Project CH4 budget synthesis (Saunois et al., 2024), the tropics contribute roughly 65% of total (anthropogenic + natural) global methane (CH4) emissions to the atmosphere (364 Tg CH4 yr-1). A significant portion of total CH4 emissions from the tropics are from wetland, floodplains, and inland freshwater ecosystems sources (151 Tg CH4 yr-1) contributing ~20% of the total global CH4 budget.

Due to the improved observational coverage of column integrated CO2 (XCO2) and CH4 (XCH4) compared to ground-based and airborne in situ measurement networks, satellite remote-sensing retrievals have been used in inverse atmospheric models to estimate tropical GHG budgets. The tropical CO2 terrestrial budget has been constrained using satellite remote-sensing XCO2 data from GOSAT, OCO-2, and TanSat (e.g., Liu et al., 2016; Lunt et al., 2019; Crowell et al., 2019; Palmer et al., 2019; Yang et al., 2021).Tropical wetland emissions of CH4 have been estimated 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).These studies have made critical findings about how climate, hydrology, and vegetation characteristics impact the tropical carbon budget across multiple temporal scales. These major findings are a result of satellite XCH4 observations filling a critical gap in ground-based measurements in the tropics and allowing for better constraint on regional emissions. Using spaceborne XCH4 retrievals it has been determined that our current estimates of tropical wetland and aquatic emissions are largely underestimated (Yu et al., 2023) and spatiotemporal variability in these natural CH4 sources are driven by environmental characteristic such as vegetation type/amount, temperature, and inundation extent (Parker et al., 2018; Ma et al., 2021). Furthermore, using satellite XCH4 data, it was determined that tropical wetlands are a primary driver of global interannual variability in the global atmospheric CH4 growth rate (Feng et al., 2022).

* 1-2 paragraphs on the state-of-the-science of satellite remote-sensing GHG fluxes in the tropics

Tropical carbon stocks and fluxes vary enormously in space and time (REFS). [SPACE] Intact, disturbed, and regrowing forests differ dramatically in their ability to uptake carbon. From 1990-2019, regrowing tropical forests increased in area, resulting in a 29±8% increase in their ability to sequester carbon, while intact forest areas shrank, directly reducing their ability to store carbon by 31±7% (Pan et al. 2024). [TIME] As a result of climate and land-use change, the tropical carbon sink is weakening. Critically, tropical forests differ in their sensitivity to extreme events and responses to climate and land-use change (REFS). However, most studies are based on ground-based data that represent a small fraction of tropical forest area, raising key questions regarding the generalizability of these findings, especially given that monitoring plots constitute a very small and biased subset of tropical landscapes (REFS). [bring in Hubau, Liu, Bennett, others that demonstrate differences in responses to extreme events and future change]

Variation in geomorphology, climatic conditions, human activities, water and nutrient availability, and plant species composition drive wide variation in rates of photosynthesis, respiration, tree mortality, woody productivity, and carbon flux across the tropics. As a result, **tropical forests vary enormously within and among tropical continents, including over relatively small spatial scales**. This variation encompasses species composition and species interactions, land-atmosphere feedbacks, hydrological dynamics, forest productivity, and the carbon storage capacity and flux of these landscapes. Climate plays a critical role in driving the tropical carbon cycle. For example, regions with high rainfall typically support dense, evergreen forests with high productivity and large carbon stocks while areas with seasonal or lower rainfall harbor partially or fully deciduous forests with more seasonal variation in carbon fluxes and relatively lower productivity and carbon stocks (Malhi et al., 2002; Bonan et al., 2008; Muller-Landau et al. 2021). Precipitation also interacts nonlinearly with temperature: ; in cool forests high precipitation can decrease productivity, while in warmer forests precipitation typically increases productivity (Taylor et al., 2017). Productivity typically increases with temperature until water is limiting (Muller Landau et al., 2021). Elevation also drives variation in temperature, among other variables, with lower elevation associated with greater rates of productivity and biomass (Muller Landau et al., 2021). Tropical forests also exhibit enormous variation in geomorphology (Townsend et al. 2008), and often variables such as higher soil fertility and less favorable physical properties correlate, making it more difficult to tease apart their relationships with productivity and biomass. For example, across the Amazon Basin, lower soil fertility is often associated with deeper, more stable, well-aggregated, and well-drained soils (Quesada et al., 2010). Regardless, productivity typically increases with soil fertility, although there are no consistent relationships between soil fertility and biomass, likely because turnover increases and woody residence time decreases with soil fertility (Muller Landau et al., 2021).

Tropical forests are thought to be strongly influenced by nutrient availability because many tropical forests are situated on highly weathered soils depleted in rock-derived nutrients (Townsend et al. 2008). Large variation in nutrient availability leads to large uncertainties around nutrient constraints on the CO2 fertilization effect (Fleischer and Terrer 2022). For example, phosphorus is expected to constrain forest growth responses to increased CO2 by about 50% (Fleischer et al., 2019; Braghiere et al. 2022). In addition, land-use change can displace large quantities of nutrients (Bauters et al. 2022;​​ 2018; 2021, Kauffman et al., 1995), leading to local nutrient losses and redistribution of some elements. While phosphorus is largely assumed to be the most limiting nutrient across the lowland tropics (e.g. Cunha et al., 2022), recent observations reveal the heterogeneity of nutrient limitation across tropical forests, including limitation and colimitation by nitrogen, phosphorus, potassium and calcium (Davidson et al., 2004, Wright et al., 2011, Manu et al., 2022; 2024). The high biodiversity in tropical forests means that it is challenging to generalize results from manipulative experiments testing where and when nutrient limitation affects productivity. Remote sensing allows for the detection of foliar chemistry and canopy structure that can inform coordinated belowground soil processes across larger scales (Townsend et al., 2008, Chadwick and Asner 2016; 2018, Martins et al. 2018).

A large proportion of tropical forests are permanently or seasonally flooded wetlands, which include forested peatlands, swamps, and floodplains (Aselmann and Crutzen, 1989). For instance, Amazon River floodplain forests represent areas up to 250,000 km2 with most flooded six months of the year (Richey et al., 2002; Goulding et al., 2003). These tropical forest wetlands play a critical role in the global CH4 and CO2 budgets (Sjögersten et al., 2014; Peng et al., 2022). Tropical wetlands are a moderate source and sink of CO2 to the atmosphere depending on environmental characteristics (Sjögersten et al., 2014; Helfter et al., 2021); however, tropical wetland and inland water systems contribute the vast majority of global total wetland/aquatic CH4 emissions and make up ~20% of the overall global CH4 budget (Saunois et al., 2020, Peng et al., 2022). CH4 contributes ~30% of the increase in radiative forcing from anthropogenic emissions and is 25× or more effective as a GHG compared to CO2 (Masson-Delmotte et al., 2021). Methane has experienced recent atmospheric growth rates inconsistent with our current understanding of global sources and sinks of this critical greenhouse gas (GHG) (Turner et al., 2019). As CH4 concentrations soar past all-time record levels, climate scientists worry that climate change itself could be contributing to these elusive sources of CH4 (Tollefson, 2022). Tropical forest wetlands, floodplains, and inland waters like lakes, reservoirs, and rivers are significant sources of CH4 and are sensitive to changes in climate, yet remain the most uncertain contributors to the global CH4 budget (Saunois et al., 2020).

[Peatlands paragraph]

[briefly mention biodiversity as segue into Section 2.2] This environmental heterogeneity is conducive for a rich this biodiversity of tropical forests, which might introduce some variability in their response to disturbances, such as logging or fire (Phillips et al., 2004). Different species and forest communities may vary in their capacity to store carbon, recover from disturbances. The heterogeneity in climate, soils, and biotic factors lead to an non-uniform response of tropical forests to global change. Understanding and accounting for these heterogeneities is crucial for improving the accuracy of carbon monitoring efforts and for developing targeted strategies to mitigate the impacts of global change on tropical forests.

### 2.2 Biodiversity

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

* Immense biodiversity and its importance to ecosystem structure and function
  + Importance of biodiversity to ecosystem structure & function
    - Plant diversity -
    - Cite Schmitz et al 2018
  + hypotheses that greater diversity should confer greater resilience (REFS)
  + Although complex - e.g., diversity & carbon stocks not necessarily linearly correlated (Sullivan et al 2017) in spite of
* Variation in tropical diversity including in functional composition
  + Description of patterns and changes
    - Plant diversity (Chave et al; Feldpausch et al; Banin et al; Declan et al )
    - **Animals** - Meg Crofoot; Martin Wikelski; Roland Kays; Tom smith; Berzaghi;
      * **Emphasize important plant-animal interactions (e.g. seed dispersal; redistribution of nutrients on the landscapes; etc.)**
      * Emphasize impacts of defaunation (cite Rodolfo’s work)
      * Emphasize impacts of fragmentation and questions related to connectivity
    - Microbial?
    - *Genetic adaption - too slow; Migration - too slow; Acclimation - large knowledge gaps. Need PANGEA to fill these knowledge gaps at landscape scales that capture the heterogeneity of responses*
      * *Fadrique et al 2018 Nature:* [*https://www.nature.com/articles/s41586-018-0715-9*](https://www.nature.com/articles/s41586-018-0715-9)
      * *Báez et al 2022 PlosONE:* [*https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0263508*](https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0263508)
      * *Cuni-Sanchez et al 2024:* [*https://www.nature.com/articles/s41467-024-48520-w*](https://www.nature.com/articles/s41467-024-48520-w)
* Remotely sensed diversity
  + Trait-based functional composition, functional diversity and functional communities (Asner et al 2017; Chadwick & Asner; Ordway et al;
  + Spectral methods for estimating functional composition and beta diversity - Ferret & Asner 2014; Cavender-Bares et al 2022; Draper et al 2018; Draper et al 2020;
  + Structural diversity: Schneider et al; Stovall et al; Jucker;
* Quantifying diversity at large spatial scales is critical for many purposes, including ….
* New technologies and computing capabilities have resulted in large steps forward in
  + Conservation importance and mappability: Rose et al 2010; Skidmore et al 2021;

—----------------------------------------------------------------------------------------------------------------------

Tropical biomes are the most biodiverse on Earth. Biodiversity is the variability among all living organisms and ecosystems including taxonomic, phylogenetic, functional, and genetic diversity within and among species, as well as within and among sites. Tropical forests are home to more than half of Earth’s described species diversity, even though they encompass only about one-fifth of terrestrial areas and even though many tropical species remain undocumented (Lewis et al. 2015, Barlow et al. 2018, Dinerstein et al. 2017, Pillay et al. 2022; Gatti et al. 2022). The high total number of species found in tropical forests (high gamma diversity) reflects both extraordinarily high numbers of species within sites (alpha diversity) as well as high turnover of species among sites (beta diversity). The divergent evolutionary histories of different tropical continents has resulted in very different species assemblages and phylogenetic composition (Slik et al. 2018). The high taxonomic and phylogenetic diversity of tropical forests is accompanied by high functional diversity, with species displaying a wide range of life history strategies, functional traits, and environmental responses. However, there is a large knowledge gap in characterization by functional traits (Jetz et al. 2016).

Tropical biodiversity is critically important to the functioning of tropical ecosystems and their feedbacks to the earth system. 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. The wide variation in structure and function among tropical forests is closely linked to wide variation in biodiversity, reflecting not only the influences of abiotic environmental factors on biodiversity as well as on structure and function, but also feedbacks between biodiversity and structure and function (Muller-Landau et al. 2021). The species and functional composition of woody plants is particularly important in shaping forest structure and function, which in turn affects microclimates, habitat availability, and food resources for animals and microbes.

Leaf phenological strategy is an important aspect of plant functional trait variation in tropical forests, which plays a major role in stand-level productivity, responses to climate variation, and the seasonal availability of food resources for animals and microbes (Hutyra et al. 2007; Christoffersen et al. 2014; Xu et al. 2016; Wu et al. 2017; Longo et al. 2018; Manoli et al. 2018). Tropical trees and lianas display a large diversity of leaf phenological strategies, from evergreen to deciduous, with variation in the duration, timing, and completeness of deciduousness, and in whether deciduousness is obligate or facultative (Borchert 1994; Eamus 1999; Kushwaha and Singh 2005; Williams et al. 2008; Kearsley et al. 2024). Leaf lifespans and the seasonal timing of leaf production also vary widely, with implications for seasonal variation in leaf quality and photosynthetic capacity (Wu et al. 2016; Lopes et al. 2016; Wu et al. 2017; Albert et al. 2018). The relative abundance of different leaf phenological strategies varies systematically among tropical forests in relation to climate, geomorphology, soils, and other factors (e.g., Condit et al. 2000), and contributes importantly to strong stand-level variation in leaf phenology among sites (Bohlman 2010; Guan et al. 2015; Fisher et al. 2020; Fadrique et al. 2021; Yang et al. 2021). Leaf phenology also varies substantially among years within sites and thereby contributes to interannual variation in forest function (Pau et al. 2010; Detto et al. 2018; Lamjiak et al. 2021). Year-to-year variation in leaf phenology on short time scales is due mainly to responses of extant plants to climate variation, though it can also arise from temporal shifts in species composition and abundance due to disturbances, succession, or other factors, which become increasingly important at longer timescales. Climate drivers of leaf phenology include not only water availability, but also light. Many tropical trees, species, and stands “green up” at those times of year when they receive the most light, even if this higher light is accompanied by drier conditions (Wright and van Schaik 1994; Lopes et al. 2016; Wagner et al. 2017; Li et al. 2021).

Tropical forest structure and function is also strongly influenced by other dimensions of woody plant functional trait composition, including the fast-slow axes of plant life history, adult stature, and self-supporting vs. climbing strategies to reach the canopy. The fast-slow axis extends from plant species with fast resource acquisition and processing, fast growth, high resource needs, high mortality rates, and low shade-tolerance to species with slow resource acquisition and processing, slow growth, low resource needs, low mortality rates, and high shade-tolerance (Reich 2014, Ruger et al. 2018). Associated variation in functional composition among stands thus relates to forest successional status, woody productivity, and woody residence time. The fast-slow axis encompasses variation in leaf traits such as leaf mass per area (LMA) and leaf nutrient content that can be measured with hyperspectral imaging, enabling quantification of this dimension of plant functional composition from remote sensing (Asner et al. 2016, Aguirre-Gutierrez et al. 2021). Another major axis of variation among tropical trees is adult stature, which ranges from small shrubs to giant emergent (Ruger et al. 2018). Forest carbon stocks, structure and productivity are intimately related to the relative abundances of trees of different sizes, which in turn depends on functional composition with respect to this axis. Lidar can provide information on canopy height and even tree size distributions, thus providing information on this dimension of plant functional variation (Stark et al. 2012). Finally, tropical woody plants may be self-supporting like trees and shrubs, or be structural parasites like lianas (woody vines) that rely on other plants for support (Muller-Landau and Pacala 2020). Lianas reduce tree growth and increase tree mortality, and thereby alter forest structure and function (Estrada-Villegas et al. 2022). Higher liana abundance leads to slower carbon accumulation in secondary forests, lower woody productivity, lower forest stature, and lower biomass carbon stocks (van der Heijden et al. 2015). Liana abundance varies widely among tropical forests in relation to climate, disturbance history, and other factors (Dewalt et al. 2015), and is on average increasing, for reasons that remain unclear (Schnitzer and Bongers 2011). Lianas differ from trees in their leaf angles and in the distributions of their leaf traits, making it possible to quantify liana abundance with remote sensing (van der Heijden et al. 2022).

Understanding the influence of ecosystem diversity on ecosystem functioning, such as carbon sequestration and storage, is critical in the face of climate change, since it remains uncertain whether or not tropical forests will remain a carbon sink under future climate (Arora et al., 2020; Brienen et al., 2015; Hubau et al., 2020; Sabatini et al., 2019). High biodiversity could help mitigate negative effects of climate change through increased ecosystem stability and resilience (Schmitt et al. 2020), but changing climate regimes could also negatively impact levels of biodiversity that might feedback on climate through decreased carbon sequestration (Thomas et al. 2004; Cavanaugh et al. 2014). Recent research also suggests that soil biodiversity plays an important role in the association between plant diversity and multiple ecosystem functions across biomes (Delgado-Baquerizo et al. 2020; van Ruijven et al. 2020), which might be critically impacted by climate change (Jansson and Hofmockel 2020).

Tropical forests store the largest amounts of aboveground carbon globally, as tropical trees absorb carbon from the atmosphere to build large, long-lasting or slow-decaying structures such as tree bark or root systems. A forest's potential for carbon sequestration is highly linked to its biological and functional diversity. Experimental studies have found that more diverse assemblages of plants are more productive and hold higher carbon stocks, albeit there are few such studies in tropical forests. Many findings on relationships between biodiversity and ecosystem productivity and biomass so far stem from grassland experiments that have been established since the 1990s and consistently show positive effects of plant species richness on ecosystem productivity and stability (e.g. Jochum et al. 2020; Tilman, Isbell, and Cowles 2014; Craven et al. 2018). In a review of 258 studies of naturally assembled communities, van der Plas ([2019](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023JG007421#jgrg22473-bib-0124)) also found that, while most studies focused on the effects of taxonomic diversity, metrics of functional diversity were generally stronger predictors of ecosystem functioning. There are several possible mechanisms for this phenomenon that need to be tested outside of experimental set-ups and in tropical forests. Species with diverse traits and resource requirements may exhibit niche complementarity, more completely utilizing available resources under a wider array of environmental conditions (Williams et al. 2017). In parallel, more diverse species assemblages are more likely to contain the most productive species and trait combinations, which can increase overall functioning through selection (Hooper et al. 2005) (sampling effect). Larger species pools are also more likely to include plastic and adaptive species increasing resilience, also known as the ecological insurance or portfolio effect (Silva Pedro, Rammer, and Seidl 2017).

Though studies of the importance of biodiversity for forest function have focused largely on plants, animals and microbes also matter. They contribute to essential services such as pollination, seed dispersal, and nutrient cycling, and shape plant biodiversity and forest structure and function both via these mutualistic interactions as well as through antagonistic interactions including herbivory and disease (Dirzo et al. 2014). Megafauna like elephants have particularly important effects in determining forest structure due to their browsing and physical disturbance, as well as their redistribution of nutrients across the landscape (Berzaghi et al. 2018). Experimental vertebrate exclosures resulted in an increase in understory plant density and seedling abundance (Beck et al. 2013; Camargo-Sanabria et al. 2015; Kurten and Carson 2015). A large majority of tropical tree species and approximately half of liana (woody vine) species depend on vertebrates for seed dispersal, with most of the remaining species relying on wind for seed dispersal, and a few on water, ballistics, and/or invertebrates (Muller-Landau and Hardesty 2005). Defaunation of tropical forests by hunting and other human activities thus threatens plant regeneration, and has the potential to shift plant species composition, and abundances of animal seed dispersers shape tropical forest regeneration in secondary forests (Wunderly 1997, Estrada-Villegas et al. 2023). Among sites in Panama, increased defaunation was associated with compositional shifts in the seedling layer including more abiotically dispersed species and more lianas (Wright et al. 2007; Kurten et al. 2015). Because plant species dispersed by large vertebrates tend to have larger seeds and higher wood densities, some have argued that defaunation will ultimate lead to a shift towards lower forest carbon stocks, although debate continues (Brodie and Gibbs 2009; Jansen et al. 2010; Bello et al. 2015; Osturi et al. 2016; Peres et al. 2016; Bennett & Robinson 2023). In general, defaunation tends to increase the dominance of some plant species, and thus decrease plant diversity (Kurten 2013). Other changes in animal communities, whether due to anthropogenic pressures via hunting, habitat alteration and fragmentation, or changing climate, also have the potential to shift plant communities via these interactions.

### 2.3 Climate Interactions and Feedbacks

***This PANGEA science theme will investigate complex feedbacks and interactions between tropical forests and climate systems, as well as changes to these feedbacks and interactions, which influence whether tropical forests will act as a future carbon sink or source.***

Changes to water, temperature, and energy cycling can induce large variability in tropical forest carbon cycling, with large heterogeneity in this response both within and between tropical rainforests (e.g., Liu et al., 2017, Staal et al., 2023). Tropical forests alter surface properties, including land surface albedo, latent and sensible heat fluxes, and roughness, which in turn exert biophysical climate feedbacks [(Bonan, 2008; Chen et al., 2020; Lee et al., 2011)](https://paperpile.com/c/ovIUza/J2Id+7TNp+vM0J). Additionally, belowground rooting systems and soil texture regulate soil moisture [(Fan et al., 2017)](https://paperpile.com/c/ovIUza/LDiS), exerting strong impact on surface energy and water balances [(Seneviratne et al., 2010; Zhou et al., 2021)](https://paperpile.com/c/ovIUza/FPcy+yMq6). As a result of tightly coupled land-atmosphere interactions in tropical forests, anthropogenic and climate disturbances can alter key surface and atmospheric properties that determine local and regional climate conditions. For example, deforestation and degradation exert significant surface warming effects 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 constrained by the forest cover fraction [(Alkama & Cescatti, 2016)](https://paperpile.com/c/ovIUza/MoNo), and may exert asymmetry in response to forest cover gain and loss [(Su et al., 2023; Zhang et al., 2024)](https://paperpile.com/c/ovIUza/Chrq+nNbr). Higher temperatures can increase tree respiration, which may reduce net primary productivity (NPP) and change how tropical forests cycle carbon [(Choury et al., 2022; Das et al., 2023; Liu et al., 2017; Lloyd et al., 2023)](https://paperpile.com/c/ovIUza/FoUS+HHQU+ZxJz+MUqe). In addition, deforestation and degradation can increase streamflow and sediment fluxes ([Levy et al., 2018](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017GL076526)) due to reductions in evapotranspiration and infiltration ([Costa et al., 2003](http://dx.doi.org/10.1016/S0022-1694(03)00267-1), [Souza-Filho et al., 2016](https://www.sciencedirect.com/science/article/pii/S0301479715303935?via%3Dihub#bib10)), leading to changes in the surface water balance.

Land-atmosphere interactions in tropical rainforest regions play key roles in modulating water, temperature, and energy conditions both locally and regionally. Tropical forest atmospheric emissions can alter the vertical profile of the atmosphere, and in turn, feedback to tropical convection and rainfall on diurnal to decadal time scales [(](https://paperpile.com/c/ovIUza/1Ghm+fNLl+2TA9+7XOK)[Betts and Silva Dias 2010; Suni et al. 2015; Gentine et al. 2019; Weber et al. 2024](https://paperpile.com/c/gMdJbo/gTtBt+MPMLM+TnAjI+EwxMa), [Chakraborty et al., 2021](https://doi.org/10.5194/acp-21-12855-2021)). Tropical forest moisture recycling influences the onset and timing of their own rainy seasons and provides large proportions of atmospheric moisture for rainfall locally and regions downwind ([Wright et al., 2017](https://doi.org/10.1073/pnas.1621516114), [Sori et al., 2022](https://doi.org/10.1002/9781119657002.ch11), [Worden et al., 2021](https://doi.org/10.1029/2020JG006024), [van der Ent et al., 2010](https://doi.org/10.1029/2010WR009127), [Staal et al., 201](https://doi.org/10.1038/s41558-018-0177-y)8, Dirmeyer et al., 2009, Zemp et al., 2017, Nyasulu et al., 2024). Additionally, emitted biogenic volatile organic compounds influence cloud formation and albedo, which influences the amount and quality of light available for vegetation ([Artaxo et al., 2022](https://doi.org/10.1371/journal.pclm.0000054)).

Tropical rainfall magnitude and patterns are tightly linked to LCLUC activities ([Xu et al., 2022](https://iopscience.iop.org/article/10.1088/1748-9326/ac4c1d/meta), [Bell et al., 2015](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JD022586), [Smith et al., 2023](https://www.nature.com/articles/s41586-022-05690-1)) that change land surface heterogeneity at various spatial scales [(](https://paperpile.com/c/ovIUza/XlMK+2OlF+Ykxm)[Khanna et al., 2017](https://paperpile.com/c/ovIUza/qpFq); [Lawrence & Vandecar, 2014; Leite-Filho et al., 2021; Smith et al., 2023)](https://paperpile.com/c/ovIUza/XlMK+2OlF+Ykxm). Along with atmospheric circulation, local and regional moisture and heat anomalies will be transferred to generate teleconnection on downstream circulation patterns [(Mahmood et al., 2014; Snyder, 2010)](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://doi.org/10.1073/pnas.1906091116)[)](https://paperpile.com/c/ovIUza/YQKg). Additionally, extensive biomass burning releases large amounts of aerosols into the atmosphere. Subsequent aerosol-cloud and aerosol-radiation interactions can alter cloud formation and life time ([Liu et al., 2020](https://doi.org/10.5194/acp-20-13283-2020)), induce subsidence ([Zhang et al., 2008](https://doi.org/10.1029/2007JD009449)), and change temperature gradients controlling regional dynamic systems ([Chaboureau et al., 2022](https://doi.org/10.5194/acp-22-8639-2022)), ultimately limiting convection and rainfall ([Tosca et al., 2015](https://doi.org/10.1002/2015GL065063)).

Climate systems, in turn, strongly influence vegetation structure and function. For example, mesoscale convective systems provide large proportions of rainfall within central Africa and the Amazon ([Andrews et al., 2024](https://doi.org/10.1007/s00382-023-06903-7), [Rehbein et al., 2017](https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/joc.5171)), while also influencing tree mortality via windthrow (e.g., [Negrón-Juárez et al., 2018](https://iopscience.iop.org/article/10.1088/1748-9326/aabe9f/meta), [Feng et al., 2023](https://doi.org/10.1038/s41467-022-35570-1)). Precipitation controls flooding cycles within the African and Amazon rainforests ([Alsdorf et al., 2016](https://doi.org/10.1002/2016RG000517), [Hawes and Peres 2016](https://doi.org/10.1111/btp.12315)), which in turn, affects lowland floodplain forests as they adapt to long periods of submersion and water-logging that can affect oxygen availability, reduce photosynthesis, and decrease water conductance ([Parolin et al., 2004a,](https://doi.org/10.1007/BF02803209) [Parolin et al., 2016](https://doi.org/10.1007/978-3-319-27422-5_6), Hawes and Peres 2016) and support conditions for microorganisms to produce CH4. Indirectly, rainfall can also significantly influence local nutrient cycles via wet nutrient deposition onto forest canopies (Bauters et al., [2018](https://doi.org/10.1073/pnas.1714597115), [2021](https://doi.org/10.1038/s41467-021-25428-3)), altering the amount and quality of light available for photosynthesis via clouds and fog (Philippon et al., 2019, [Pohl](https://doi.org/10.1016/j.rse.2021.112620) et al., 2021), and evapotranspiration and photosynthesis via dew deposition (e.g., [Gerlein-Safdi et al., 2018](https://doi.org/10.1016/j.agrformet.2018.05.015), [Binks et al., 2019](https://doi.org/10.1111/gcb.14666)).

Tropical climate systems are changing in other important ways. Large-scale deforestation, anthropogenic aerosols, greenhouse gases, and changes in sea surface temperature (SST) patterns can alter cross-equatorial ([Cook and Vizy 2015](https://doi.org/10.1175/JCLI-D-14-00230.1)) and land-ocean energy transport and temperatures ([Zhou et al., 2019](https://www.nature.com/articles/s41558-019-0603-9)). In turn, this affects tropical precipitation and moisture patterns via changes to the intertropical convergence zone (ITCZ; [Schneider et al., 2014](https://www.nature.com/articles/nature13636), [Byrne et al., 2018](https://link.springer.com/article/10.1007/s40641-018-0110-5#ref-CR26)), monsoons ([Cook and Vizy 2019](https://link.springer.com/article/10.1007/s40641-019-00130-1), and regional-scale dynamic systems ([Cook and Vizy 2019](https://link.springer.com/article/10.1007/s00382-019-05033-3), [Creese et al., 2019](https://link.springer.com/article/10.1007/s00382-019-04728-x), [Montini et al., 2019](https://doi.org/10.1029/2018JD029634)). Climate phenomena such as ENSO, the Madden-Julian Oscillation, the Indian Ocean Dipole, and Atlantic Meridional Overturning Circulation can alter tropical convection and induce climate variability ([Raghavendra et al., 2020](https://link.springer.com/article/10.1007/s00382-020-05133-5), [Dias et al., 2017](https://doi.org/10.1002/2017JD026526), Gu and Adler, 2018) by modifying dynamic systems that control rainfall ([Jiang et al., 2021](https://doi.org/10.1029/2020GL092370)), or inducing drying and droughts ([Ndehedehe et al., 2018](https://www.sciencedirect.com/science/article/pii/S0048969718336489?casa_token=oSJiFPgcdAYAAAAA:Js7DfKa7_T4JbahgzIGAPO0CZ2fPKZT1yC1hpZOG8glUpVcXpfS0ZzL4Y4_YYvqIDxrnqRdDjtk)). Due to these changes, tropical forests are experiencing significant changes in their water cycle, including increases in dry season lengths and intensity ([Jiang et al., 2019](https://www.nature.com/articles/s41558-019-0512-y), [Staal et al., 2020](https://iopscience.iop.org/article/10.1088/1748-9326/ab738e/meta)), variability in wet season onsets (Yin et al., 2014), decadal-scale declines in rainfall ([Zhou et al., 2014](https://www.nature.com/articles/nature13265)), and changes to the timing and intensity of mesoscale convective systems (Taylor et al., 2018, [Rehbein and Ambrizzi 2023](https://link.springer.com/article/10.1007/s00382-022-06657-8)). However, they are showing different responses to changes in water availability. Central African tropical forests appear less responsive to drought conditions compared to the Amazon rainforests ([Tao et al., 2022](https://www.pnas.org/doi/abs/10.1073/pnas.2116626119), [Asefi-Najafabady and Saatchi 2013](https://doi.org/10.1098/rstb.2012.0306), [Saatchi et al., 2012](https://doi.org/10.1073/pnas.1204651110), [Bennett et al., 2021](https://www.pnas.org/doi/abs/10.1073/pnas.2003169118)), and in general, intact, wetter tropical forests seem better able to withstand these changing climatic conditions ([Bennett et al., 2023](https://www.nature.com/articles/s41558-023-01776-4)).

Projected increases in the intensity and frequency of extreme weather events can alter ecosystem structure and function in many ways, including higher tree mortality rates, loss of canopy cover, and subsequent changes in species composition and ecosystem processes [(Uriarte et al. 2019; Feng et al. 2023; Negron-Juarez et al. 2023)](https://paperpile.com/c/gMdJbo/Kyl6g+xVK1H+gc1mx). Increases in precipitation can increase streamflow and induce heavy floods within primarily rainfed watersheds ([Marengo et al., 2012](https://link.springer.com/article/10.1007/s00704-011-0465-1)). With increasing temperatures and changing rainfall patterns, thresholds are being tested [(Esquivel-Muelbert et al., 2019)](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.14413). For instance, during the 2015 El Niño event, parts of the Amazon experienced temperatures that exceeded critical thresholds, leading to significant forest dieback (Liu et al., 2017, Jiménez-Muñoz et al., 2016). Variability in temperature sensitivity can be observed across tropical continents. African forests, particularly those in West Africa, are often exposed to higher temperatures and may be more adapted to heat stress compared to the relatively cooler, more humid regions of Southeast Asia ([Malhi et al., 2013](https://royalsocietypublishing.org/doi/10.1098/rstb.2012.0312)). However, this adaptation might come at the cost of reduced overall photosynthetic capacity under extreme conditions. Meanwhile, tropical forests, especially within the Congo Basin (Worden et al., 2024) are heavily reliant on moisture recycling to produce their own rainfall. Reductions in moisture recycling can exacerbate drying in both local and nonlocal regions (Zemp et al., 2017), and delay the rainy season onsets ([Leite-Filho et al., 2019](https://doi.org/10.1029/2018JD029537)), eventually leading to critical transition points and possibly even tipping points (Flores et al., 2024). Exceeding these climate thresholds could lead to subsequent shifts to alternative states, such as savannas, which are less capable of supporting globally important tropical forest ecosystem services [(Aguirre-Gutiérrez et al., 2020; Flores et al., 2024; Nobre et al., 2016; Scheffer et al., 2001)](https://paperpile.com/c/ovIUza/zrGk+iDoN+6fAo+yCO2).

### 2.4 Social-Ecological Systems

Tropical forests are important not only for biodiversity, carbon storage, and climate regulation but also for food security, cultural diversity, and the livelihoods of millions of people. Tropical forests are of particular importance to local and Indigenous communities whose lives and cultures have long shaped and been shaped by the forest. By centering on the feedback between people and the ecosystems they rely on, PANGEA has the opportunity to expand integrated social-ecological system research to better understand patterns 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, including the roles of a range of management from modern industrial systems to traditional local and Indigenous forest management and how these systems affect ecosystem resilience and the provision of ecosystem services. PANGEA research 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.

Social-ecological systems in tropical ecosystems have been shaped by complex interactions that result from a diversity of actors, each differing in their values, capacities, and goals that influence their relationships with nature (Meyfroidt et al., 2018, 2022). Despite their critical role in climate regulation, biodiversity conservation, and provision of essential benefits to human well-being, tropical ecosystems are increasingly threatened by environmental changes and overexploitation (Koellner et al. 2008), leading to shifts in species composition, declines in ecosystem health, reduced resilience, and diminished productivity across key resources and benefits (Siyum, 2020). These shifts affect the functioning of natural tropical systems from local to planetary scales, inducing changes in social-ecological feedbacks and affecting benefits that humans derive from and contribute to nature (Houghton and Castanho, 2022, Mendoza-Ponce et al., 202).

Several conceptual frameworks have been developed to understand the relationships between and within social and ecological systems. Prominent approaches include the Club of Rome report (Meadows et al, 1972), the sustainable livelihoods framework (Scoones, 1998), and various models of social-ecological systems (Anderies et al., 2004; Folke, 2006; Ostrom, 2009). Other frameworks focus on coupled human-nature systems (Liu et al., 2007), socionature (Swyngedouw 1999), ecosystem services (Costanza et al., 2017; Daily, 1997), nature’s contributions to people (Díaz et al., 2018; Pascual et al., 2017), and social-ecological co-benefits (Levis et al, 2024). While these frameworks may differ in their definitions (Colding & Barthel, 2019), they converge on key principles and variables that describe the social-ecological system, facilitating comparability and systematic operationalization, often through the use of remote sensing, field-based surveys, and auxiliary data in both ecological and social realms. Adopting a systems perspective that integrates human and environmental processes, interactions, and feedbacks is critical for assessing the sustainability of natural systems (Ostrom, 2009), in particular for the highly dynamic ecosystems of the tropics.

Analyzing processes through the lens of complex social-ecological systems puts a focus on systemic aspects, including interactions, feedback mechanisms and dynamics exhibiting path dependency and non-linear change (Dearing et al. 2010, Mueller et al. 2024), and reveals new and complex patterns and processes not evident when studied by social or natural scientists separately (Liu et al. 2007). In tropical social-ecological systems, feedbacks play a critical role in maintaining resilience and guiding the trajectory of these systems (Dearing, et al. 2010). In particular, changing social-ecological systems dynamics in tropical forests are driven by a combination of direct and indirect forces (Lambin & Geist 2002, Lambin et al. 2003) including, deforestation and degradation, restoration and reforestation, international policy initiatives, market dynamics, agriculture and commodity crop expansion, infrastructure development, local and Indigenous forest management, and various forms of environmental governance (Potapov et al. 2022, Lapola et al. 2023, Bourgoin et al. 2024, Crouzeilles et al. 2017, Jackovak et al. 2021, Getti et al. 2023; Lambin et al. 2018, Grass et al. 2020, Koh & Wilcove 2008; Bennett et al. 2018; Geist & Lambin 2002; Shapiro et al. 2023; Tyukavina et al. 2018; Garrett et al. 2018; Robbins et al. 2015, Lambin et al. 2003; Wiersum 1997, Michon et al. 2007, Sze et al. 2022, 2024; Fent et al. 2019; Bennett et al. 2018). Each of these drivers interacts with changing climate dynamics to impact carbon stocks), hydrological regimes, seasonality, phenology, ecosystem function, plant-animal interactions, species composition and biodiversity, fire regimes, food security, and local livelihoods (Liu et al. 2017; Hubau et al. 2020; Bennett et al. 2021; Staal et al. 2018; Karam et al. 2023; Wolh et al. 2012; Fu et al. 2013; Couralet et al. 2013; Koltunov et al 2009; Ordway & Asner 2020; Aguirre-Gutiérrez et al. 2022; Schmitz et al. 2018; Oliver & Moorcroft 2014; Asner et al. 2010; Tyukavina et al. 2022, Williamson et al. 2024; Flachsbarth et al. 2015; Sanchez et al. 2000; Whitfield et al. 2019; Sonwa et al. 2012). While these drivers are similar across the tropics, place-specific political, economic, cultural, and management conditions influence the response, resiliency, and adaptations of tropical forests and local communities to global change dynamics (Liu et al. 2017; Hubau et al. 2020; Saatchi et al. 2021; Geist & Lambin 2002; Bennett et al. 2018; Turner 2014).

Feedbacks, both positive and negative, occur when changes in the environment or human behavior trigger responses that either amplify or mitigate those changes, including non-linear ones (Mueller et al. 2024). For instance, in tropical forests, deforestation from agriculture can degrade ecosystem services like water regulation, leading to soil erosion and reduced agricultural yields. This negative feedback can, in turn, drive further clearance as communities seek fertile land, creating and reinforcing degradation cycles. Conversely, positive feedbacks can emerge from restoration efforts, such as diversified agricultural systems. These restoration practices can enhance biodiversity, improve ecosystem services, and provide economic benefits, fostering greater investment in conservation. Understanding and managing these feedbacks is essential for ensuring long-term sustainability, as they reveal points of leverage where interventions can stabilize or enhance system resilience in the face of disturbances (Reyers and Selig 2020).

In the Amazon, traditional management practices have recently been complemented or replaced by larger-scale management practices, including large-scale deforestation to meet global demand for commodity agriculture, such as soybeans and cattle (Barlow et al. 2018, Londres et al 2023). This has not only led to intensification of land use and informal and illegal activities that have led to large scale deforestation, changes in biogeochemical cycles, water cycling, fire frequency and intensity, and major and irreversible losses of biodiversity within the Amazon Basin, but also to changes in social processes and feedbacks that determine social and ecological co-benefits that emerge from the forest. Such unsustainable practices led to the emergence of a web of private, public, and civil governance systems that regulate the access to and use of land and its natural resources (von Essen & Lambin, 2021, Lambin et al, 2018).In contrast, in the Congo Basin, land use change and deforestation are primarily a result of small-scale rotational agriculture to meet food security and local livelihood needs (Tyukavina et al. 2018; Shapiro et al. 2023) and thus points to a different set of actors at play in regulating access to and decisions around land use in the Congo Basin.

Cattle Ranching is another significant driver of land-use change in the tropics, particularly in regions like the Amazon, where vast tracts of forest are cleared to make way for cattle pastures (Mapbiomas 2023). This not only contributes to loss of biodiversity but also alters carbon and water cycles, exacerbating climate change (Nobre et al. 2016). Illicit activities, such as unregulated mining, further degrade the environment by contaminating water sources, destroying habitats, and displacing local communities (REF). Timber harvesting, often carried out illegally or without regard for sustainable practices, leads to the depletion of forests that are critical for maintaining ecological balance and supporting the livelihoods of indigenous peoples (REF). These human activities create complex interactions and feedbacks between social and ecological systems, resulting in a cascade of environmental and social impacts (REF). For instance, the degradation of ecosystems can reduce the availability of ecosystem services, such as clean water, fertile soil, and pollination, which are vital for the well-being of local communities (REF). In turn, the loss of these services can drive further unsustainable practices as communities struggle to meet their basic needs, perpetuating a cycle of environmental degradation and social hardship (Lambin & Meyfroidt, 2011). A better understanding of the diverse social-ecological feedbacks across tropical geographies and communities can improve our understanding of tropical heterogeneity and help inform the development of place based and culturally sensitive management plans and policies while also supporting the livelihoods and cultures of the people who depend on them.

Tropical forests are regions of cultural and biological diversity, home to a vast array of ecosystems and communities that have coexisted for millennia (Nobre et al. 2021). However, this diversity is increasingly under threat due to a variety of human activities that disrupt the balance between social and ecological systems (Malhi et al. 2014). Small-scale and subsistence agriculture, which has traditionally been practiced sustainably by many indigenous, and local communities, is now often driven to unsustainable levels due to population pressures and economic needs. Additionally, the expansion of commercial agriculture, driven by global demand for commodities like palm oil, soy, and coffee, has led to widespread deforestation and habitat fragmentation, severely impacting biodiversity and ecosystem functions (Curtis et al. 2018, Haddad et al. 2024). Yet new thinking aims at promoting the emerging concept of socio-ecological hope spots (Levis, et al. 2024). Hope spots reimagine conservation as a process that integrates both ecological and cultural dimensions, recognizing that IPLCs have long influenced biodiversity through land management practices. The case of the Upper Xingu hope spot, located in the Brazilian Amazon’s arc of deforestation, demonstrates the power of such integration (REF). Indigenous groups like the Kuikuro have enriched biodiversity through millennia of landscape management, including the creation of anthropogenic soils, domestication of diverse crops, and formation of cultural forests. Rather than degrading ecosystems, these practices have created resilient systems that benefit both nature and people. By engaging Indigenous knowledge alongside remote sensing technologies, the Upper Xingu hope spot offers a model of how conservation can benefit from Two-Eyed Seeing or the integration of Indigenous knowledge and Western science.

While much understanding is being gained about tropical systems, to date as the majority of the studies to date focus on the impacts of human activities. PANGEA has therefore the unique opportunity to pioneer research in social-ecological feedbacks, fundamental to maintaining tropical systems as well as accurately predict the long-term impacts of human actions on tropical ecosystems, such as deforestation, agricultural expansion, and resource extraction (Pörtner et al. 2021), as well as the short and long term effects of loss of ecosystem functionality on local communities. This understanding is essential for forecasting potential outcomes, such as species loss, changes in ecosystem services, or the resilience of these ecosystems to external pressures (Leclère et al., 2020). Accurate predictions allow scientists to identify potential tipping points, where small changes could lead to irreversible damage, and to design interventions that might prevent or mitigate such outcomes (Staal et al., 2020, Liu et al., 2024, Flores et al. 2024).

In SES research, significant gaps remain, particularly in linking the drivers and effects of SES across regions with long histories of human management and stewardship. This is especially relevant in large systems like the Amazon, Congo, and Mekong river basins, where human interventions over millennia have altered both ecological and social outcomes (Wu, et al. 2024). Analyzing these regions through a multi–scalar lens can reveal critical insights into how these interactions have developed over time.

Further, a research frontier lies in addressing emerging areas, such as incorporating feedbacks into models, where the dynamic interplay between ecological impacts and human well-being is quantified (Brown and Rounsevell 2020). This might mean, exploring how changes in biodiversity, ecosystem health, and ecosystem services directly affect livelihoods, health, and social stability (Berrio-Giraldo et al 2021, Gonzalez-Redin et al. 2019). Moreover, new research might focus on disaggregating outcomes to address distributional equity, ensuring that SES research accounts for different social groups, stakeholders, and rights holders, and the inequities they face in managing resources. Finally, more research is needed seeking to analyze dynamic feedbacks between ecosystem services and social-economic systems, recognizing that the co-benefits of ecosystem services must be considered in terms of their contributions to both ecological integrity and economic stability (Chaplin-Kramer et al 2024).

Moreover, this knowledge is indispensable for empowering local communities and decision-makers with the information they need to govern these ecosystems effectively. Tropical regions are often home to indigenous and local populations whose livelihoods are intimately tied to the health of their surrounding environment. By understanding the feedbacks between human activities and ecosystem health, these communities can make more informed decisions about land use, resource management, and conservation efforts that align with both ecological sustainability and their socio-economic needs (Aguiar et al., 2020). Decision-makers at regional and national levels can also use this information to craft policies that balance development goals with the preservation of biodiversity and ecosystem services, ensuring that the benefits of these ecosystems are equitably shared and sustained for future generations (Pörtner et al., 2021). Ultimately, the ability to predict and manage the complex feedbacks in tropical ecosystems is key to fostering both environmental and social resilience in these critical regions.

### 2.5 Disturbance Dynamics

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

Disturbance regimes dominate trends in tree mortality and forest biomass turnover with major consequences for forest carbon storage. There are two primary modes of forest disturbance: (1) disturbance resulting from direct human action, such as deforestation, degradation, and fire, and (2) natural disturbance that is largely associated with water stress, storms, and biotic agents. These two modes of disturbance have similar contributions to total forest turnover and carbon emissions from tropical forests (1-2% per year), but they have distinct spatial distributions, intensities, frequencies, and consequences for forest ecosystems. Moreover, climate change is altering both human and natural disturbance regimes with implications for current and future forest function. We must quantify the patterns and processes underlying these disturbances to understand forest vulnerability and provide high-level decision support for management, reforestation, and policy.

The primary risk to tropical forest persistence and function is direct human action. Humans deforest huge areas of tropical forests each year and cause severe degradation through selective logging, hunting of animal taxa, and fire ignition. Direct human disturbances are characterized by their high intensity relative to natural disturbances and the persistent legacy effects of biomass removal, animal extirpation, and land conversion to non-forested ecosystem types (Lewis 2005, Gibson et al. 2011, Wearn et al. 2012, Brodie et al. 2014, Silva Junior et al. 2020, Brando et al. 2024, Flores et al. 2024).

Tremendous research effort has allowed for rapid detection and quantification of direct-human disturbance and identified social-ecological interventions that can successfully limit their effects (see 2.4 for details). Deforestation and land conversion is now actively being mapped in high spatial resolution across the tropics and in association with specific industries and practices driving these trends (Curtis et al. 2018, Maxwell et al. 2019, Longo et al. 2020, Qin et al. 2021, Harris et al. 2021, Lapola et al. 2023, McGregor et al. 2024). With the advent of small-satellite arrays (e.g., PlanetScope), it is now also possible to quantify both deforestation and degradation rapidly after they occur (Welsink et al. 2023, Dalagnol et al. 2023). These advances have shown that degradation contributes as much or more than deforestation to total disturbance regimes (Maxwell et al. 2019, Qin et al. 2021), highlighting the importance of high-resolution and high-frequency data on changes in forest structure. However, like essentially all aspects of tropical forest science, we know much more about the effects of degradation and deforestation in American tropical forests than in other regions.

Fire is also a major mechanism of direct human action. Naturally ignited fires are essentially non-existent in moist tropical forests, but human-ignited fires are common aspects of both deforestation and agriculture (Brando et al. 2019). 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). Moreover, fires provide prime evidence for the key role of interactions among various anthropogenic and natural disturbances (Cochrane 2001, 2003, Brando et al. 2019). Human-ignited fires commonly spread into the understory of intact tropical forests where they directly cause tree mortality and indirectly make intact forests more susceptible to subsequent wind-caused disturbance (Barlow et al. 2003, Brando et al. 2014, Silvério et al. 2019, Berenguer et al. 2021). Additionally, periodic droughts amplify the effects of fire by increasing fuel flammability, and climate-driven increases in severe droughts are expected to be broadly increasing the effects of fire (Alencar et al. 2009, Brando et al. 2014, 2019). It is likely that other forms of interaction exist between human and natural disturbance (Laurance and Curran 2008, Schwartz et al. 2017), but the interplay among various disturbances requires greater investigation.

Natural disturbances present distinct challenges for detection, quantification, and attribution relative to direct human disturbance. Nearly all natural disturbances occur at small spatiotemporal scale, with >98% of biomass mortality in the Amazon attributable to events <0.1ha in area (Espírito-Santo et al. 2014). Although natural disturbance events are typically small, they collectively cause about 1.5-2% of biomass turnover annually, indicating that natural disturbances release the equivalent to the entire tropical forest carbon pool every 50-75 years (Galbraith et al. 2013, Espírito-Santo et al. 2014). However, natural disturbances very tremendously over space and time (Galbraith et al. 2013, Sullivan et al. 2020, Hubau et al. 2020, Dalagnol et al. 2021, Csillik et al. 2024), with distinct drivers of disturbance in different regions and strong evidence that natural disturbance regimes are shifting with climate change (Gloor et al. 2013, McDowell et al. 2018, Gora et al. 2020a, Sullivan et al. 2020, Gora and Esquivel-Muelbert 2021, Fang et al. 2022). Given their tremendous cumulative contributions to mortality and biomass trends, even small changes in natural disturbance regimes would have a tremendous impact on tropical forest function and the global carbon budget.

Storms are major drivers of natural disturbance regimes. Cyclonic storms (hurricanes and typhoons) are increasing in intensity and are the dominant form of disturbance in some coastal tropical forests (Hoyos et al. 2006, Lugo 2008), but their effects are largely >10 latitude and they play a limited role in pantropical disturbance regimes . By contrast, there is abundant evidence that wind and lightning associated with local and mesoscale convective storms are dominant drivers of tree mortality and forest biomass dynamics (Chambers et al. 2013, Negrón-Juárez et al. 2018, Gora et al. 2020a, 2021). Specifically, temporal variation in storm activity predicts canopy disturbance rates (Araujo et al. 2021) and spatial variation in storm activity is a strong correlate of spatial variation in forest biomass, biomass mortality rates, and species composition (Gora et al. 2020a, Gorgens et al. 2021, de Lima et al. 2023, Feng et al. 2023). Accordingly, storms likely contribute to spatial variation in carbon dynamics; 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 their effects are rarely quantified and storm disturbance data from 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 into the future (Taylor et al. 2018, Raghavendra et al. 2018, Lavigne et al. 2019, Harel and Price 2020).

Despite their apparent importance, the contributions of convective storms to mortality are less studied than other major agents of forest disturbance. The paucity of data is largely logistical; large-scale blowdowns are relatively well-studied (Negrón‐Juárez et al. 2010, Feng et al. 2023), but the small-scale storm events (<0.1 ha) that represent nearly all of storm-caused disturbance (Espírito-Santo et al. 2014, Negrón-Juárez et al. 2018) are too small to be reliably detected with contemporary satellite methods (Cushman et al. 2021) and cannot be reliably attributed using traditional forest plot methods because of their long census intervals. Moreover, these disturbances are highly aggregated in space and time (Negrón‐Juárez et al. 2010, Araujo et al. 2021, Gora et al. 2021), meaning that hundreds or thousands of hectares of study are needed to precisely quantify temporal trends in storm-caused disturbance at even a single site (McMahon et al. 2019). Corresponding with the lack of data on patterns of storm-caused mortality, data describing the mechanisms underlying tree vulnerability to storm-associated winds and lightning are also limited (Gora et al. 2017, 2020b, Jackson et al. 2019, 2021a, 2021b). There is tremendous potential for knowledge gain regarding storm-caused disturbance if we can leverage recent advances in technology to perform high-resolution, high-frequency, and large-scale quantification of tree mortality across tropical forests.

Water stress, particularly periodic drought, is also a major driver of natural disturbance in tropical forests. Atmospheric water stress associated with increasing temperatures and vapor pressure deficits has been increasing the past several decades (Fang et al. 2022), and periodic droughts are occurring with increasing severity and frequency (Gloor et al. 2013, Trenberth et al. 2014). Unlike storms, natural disturbance associated with water stress causes widespread increases in tree mortality and decreases in tree growth that are readily detectable with both forest inventory plots and satellites (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). Moreover, 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 is the best studied driver of forest change, providing strong evidence of its importance, but also revealing that the effects of drought are highly variable among ecosystems. For example, the 2015-2016 El Nino had strong effects on the Amazon (Bennett et al. 2023), but only a marginal effect in African tropical forests (Bennett et al. 2021) and counterintuitively caused a substantial increase in GPP in central Panama(Detto and Pacala 2022). Moreover, 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.

Pests and pathogens are major agents of natural disturbance in extratropical forests, but their effects in tropical forests are not well documented (McDowell et al. 2018). This distinction could arise for two reasons that are not mutually exclusive. First, it is possible that pests and pathogens effects are poorly quantified because of the limited research investment in tropical forests relative to the extremely high diversity of potential pests and pathogens (Schimel et al. 2015). Second, pests and pathogens may have limited impact on tropical forests because of their high diversity, which is known to reduce exotic invasions and is expected to reduce outbreaks (Keesing and Ostfeld 2021, Delavaux et al. 2023). Large-scale quantification of the drivers of tree mortality are needed to determine the true importance of biotic pests to tropical forest disturbance regimes.

Competition among plants is also a driver of natural disturbance, particularly in tropical forests where lianas (woody vines that structurally parasitize trees) are abundant. Increasing CO2 concentrations appear to be increasing tree growth (Phillips et al. 2009, Brienen et al. 2015), which is expected to increase tree mortality rates by increasing tree competition and favoring fast-growing tree species (Bugmann and Bigler 2011, McDowell et al. 2018). Simultaneously, there is widespread evidence of increase liana abundances in tropical forests (Phillips et al. 2002, Schnitzer and Bongers 2011, Rueda-Trujillo et al. 2024), due in part to increasing disturbance rates (Schnitzer and Bongers 2011, Schnitzer et al. 2021). Lianas reduce forest carbon storage by decreasing tree growth and increasing tree mortality rates (van der Heijden et al. 2013, 2015, Visser et al. 2018), thereby producing a positive feedback loop between liana proliferation and forest disturbance rates. The effects of lianas are clear, but increased mortality associated with greater tree-on-tree competition and CO2 fertilization is uncertain and more challenging to demonstrate (Bugmann and Bigler 2011, Rozendaal et al. 2020).

Overall, direct human action and climate-associated increases in natural disturbance rates are the two primary threats to tropical forests today. Because tropical forests play at outsized role in global climate (Pan et al. 2024), the patterns and processes underlying these two distinct modes of disturbances are crucial to the function of tropical forests and among the largest sources of uncertainty for the future of the global carbon budget (Pugh et al. 2020). Information about these disturbances is primarily from American tropical forests, and this geographic bias is highly problematic because the sparse existing data suggest that disturbance regimes and forest responses to these disturbances are distinct from other continents (Hubau et al. 2020, Bennett et al. 2021, 2023). We must develop a mechanistic understanding of these disturbances, how they are regulated by social-ecological systems (section 2.4), and how their effects are modulated by local biodiversity (section 2.2) to predict the future trajectory of tropical forests and their contributions to the Earth system (sections 2.1 and 2.3).

## 3. Knowledge Gaps & Questions

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

### 3.1 Pattern

#### 3.1.1 Carbon Stocks and Fluxes

Varying geographic patterns of tropical carbon stocks and fluxes, as well as their inter-annual and intra-annual variability and responses to extreme events remain poorly understood. Satellite remote sensing now makes it possible to map annual forest-related emissions and removals from changes in biomass at a range of spatial resolutions (e.g., 4m - Xkm) (Harris et al 2021; Xu et al 2021; Csillik et al 2019). However, estimates of the biomass stocks, as well as the magnitude of fluxes, still require spatial maps of tropical forest biomass, which are generated from integrating ground inventory plots with airborne and satellite data using statistical relationships and increasingly AI. Forest plot-derived carbon stocks, which are based on allometry, can miss variation due to the lack of species-specific allometric equations, buttressed trees, and errors with missing woody biomass in branches. Terrestrial lidar offers opportunities for more accurate ground data, but is labor-intensive to process. Ground plots are also sparse relative to the amount of carbon in biomass, and much more calibration/validation is needed to scale estimates of aboveground biomass. GEO-TREES, a PANGEA partner effort, is developing a biomass reference system across forests globally, with “strong priority placed on the tropics” to improve the calibration and validation of satellite-derived biomass mapping. This will include coordinated ground measurements (forest inventory plot censuses), terrestrial laser scanning, and drone and aircraft lidar data collection.

Despite the advances with satellite remote sensing, higher temporal resolution of carbon, energy, and water fluxes are still critical for going beyond stocks to understand how fluxes respond to environmental drivers and extreme events. A critical gap, however, is fluxes from respiration, methane emissions, and lateral flows of carbon, which have been shown to be substantial in tropical forests (REFS). Current literature also stresses that the observational coverage of CH4 fluxes from wetlands and aquatic systems in the tropics is extremely limited compared to temperate and boreal regions (Johnson et al., 2022; Melack et al., 2022; Stanley et al., 2023). The lack of flux observations for use in mechanistic model development and statistical upscaling has led to poorly quantified tropical wetland and inland water system CH4 emissions (Ganesan et al., 2019; Rosentreter et al., 2021). Existing mechanistic models have large differences in tropical CH4 emissions (Melton et al., 2013; Bloom et al., 2017) and do not capture observed CH4 seasonality in tropical regions dominated by forested wetlands (Melack et al., 2022). Much of this difference is driven by the lack of fine-scale measurements detailing the drivers of wetland and aquatic emissions (Melack et al., 2022) and the threefold difference in wetland/inundation extents applied in individual models (Peng et al., 2022).

[paragraphs on knowledge gaps related to variation in **disturbance type, intensity, and frequency within and among tropical continents**] Given recent successes quantifying deforestation and degradation from space (e.g., Dalagnol et al. 2023), it is likely possible to integrate multiple sources of satellite remote sensing using artificial intelligence to begin remotely monitoring natural disturbance regimes from space. However, we still need high-quality, validated, field data at scale to produce the training datasets required for developing these methods. Regardless of the method, we need large-scale, quantified, and agent-specific data on the proximate drivers of tree biomass turnover and patterns of disturbance. Disturbances are typically studied in isolation and interactions among disturbances are poorly understood, but the reality is that tropical forests are facing multiple interacting and changing agents of disturbance. This is problematic because the few studies investigating interactions among disturbances typically find that their effects are multiplicative, rather than additive, meaning that we need to explicitly quantify their interactions to understand their effects. Examples include drought amplifying the effects of fire (Brando et al. 2014), deforestation amplifying the effects of wind (Schwartz et al. 2017), and lianas amplifying the effects of lightning (Gora et al. 2023). We need to concurrently quantify the effects of all types of disturbance across variation in forest composition, climate, and edaphic factors to understand these interactions and the consequences for forest carbon cycling.

More recently, polar-orbiting satellite sensors like the Orbiting Carbon Observatory (OCO-2, OCO-3), TROPOMI, Carbon Mapper, and geostationary satellites like GOES-R are being used to estimate CO2 and CH4 emissions, terrestrial GPP, and ecosystem respiration (OCO & TROPOMI REFS needed; Khan et al. 2021; Ranjbar et al. 2023). Sensors like SWOT, measuring surface water flows, enable direct measurements of lateral carbon fluxes from tropical systems. **Effectively and accurately using these satellite measurements to map and monitor spatial and temporal variation in carbon stocks and fluxes over the tropics, however, requires filling major data and methodological gaps.** To address knowledge gaps directly related to variation in carbon stocks and fluxes, PANGEA will answer the following questions:

* *How does spatial variation in tropical forest* ***carbon stocks and fluxes*** *relate to spatial variation in climate, hydrological cycling, soils, geomorphology, and social-ecological interactions?*
* *How does* ***temporal variation*** *in tropical landscape carbon fluxes relate to temporal variation in climate change trends and extreme events?*
* *How do tropical forests vary in their* ***disturbance regimes****?*
* *How does geographic and temporal variation in* ***tropical forest phenology*** *covary with carbon stocks and fluxes, and how is this changing in relation to systematic shifts in forcing processes, including climate, land-use, and disturbance regimes?*

Eddy covariance flux measurements are one of the few ways to measure the ecosystem-scale exchange of carbon, water, and energy across time (hours to decades) and space (leaves to communities) (Baldocchi 2020). Long-term eddy covariance flux measurements, inclusive of CO2 and CH4 fluxes, including ecosystem respiration, also enable direct monitoring of changing forcings, including warming temperatures, shifting rainfall regimes and soil moisture, rising atmospheric CO2 concentrations, changing phenology, compositional shifts resulting in changing structural and functional plant traits, and land-use change (Keenan et al., 2013; Keenan et al., 2014; Stocker et al., 2018; Fernández‐Martínez et al., 2014; Magnani et al., 2007; Balzarolo et al., 2016; Keenan et al., 2014; Chen, Dirmeyer, Guo, & Schultz, 2018; Luyssaert et al., 2007; Thornton et al., 2002).

The long-term data and ability to capture extreme events has facilitated critical findings. Under LBA, eddy covariance captured the previously unknown late dry-season increases in GPP (Doughty and Goulden 2008, Saleska et al. 2003). By capturing areas ranging from tens to hundreds of meters, eddy covariance towers also play a critical role in ground-truthing remote sensing measurements. Despite the advances and growing number of planned eddy covariance flux towers in the tropics, they are still underrepresented globally (Schimel et al., 2015) due to the high cost of installation and maintenance. For example, only a single, recent flux tower has been built in Central Africa (Sibret et al. 2022). While there have been about 21 towers across the Amazon, most flux tower data ended around 2014, and they are geographically biased towards the lower precipitation and lower soil fertility gradient in the central Amazon (REFS). This leads to discrepancies in both our understanding of environmental drivers of variation, but also our ability to predict how fluxes will respond to large perturbations. For example, models project that about half the precipitation within the Amazon Basin comes from evapotranspiration carried via trade winds to the Andes, but towers in the western Amazon to ground-truth these estimates have been lacking, making it difficult to model future precipitation (REF).

In addition, despite the advantages that eddy covariance towers provide, scaling is a must and integrative process understanding is still sorely needed. It will never be possible to have eddy covariance flux towers everywhere. PANGEA airborne observations can serve to reconcile the scale mismatch between flux tower footprint measurements and spaceborne observations. Understanding and scaling processes linked to heterogeneous flux dynamics also requires ground and airborne observations of tree mortality, species interactions, phenology, and functional traits, for example.

Tropical forested wetlands are an uncertain component of the global CH4 budget due to the: a) complexity of the meteorology, hydrology, ecology, land-use practices, and CH4 emission drivers in these regions; and b) extreme data limitations amplified by cloud cover prevalence that inhibits satellite retrievals (Ganesan et al., 2019; Melack et al., 2022). Given these complexities in the main flux drivers (e.g., meteorology, hydrology, biomass, vegetation type, soil moisture, edaphic factors, aquatic constituents/quality, etc.) and the persistent cloud coverage in the tropics inhibiting our understanding of tropical forest GHG fluxes, PANGEA will acquire vital airborne remote-sensing and in situ data coincident with ground-based observations to improve regional CH4 model capabilities and emission budget estimates.

Finally, tropical forest leaf phenology can be quantified with field observations of focal trees, litter traps, phenocams, drone-based or airborne imaging, and satellite remote sensing (e.g., Williams et al. 2008, Detto et al. 2018; Park et al. 2019; Yang et al. 2021; Albertson et al. 2023). Satellite remote sensing has greatly expanded the geographic area for which tropical forest phenology data are available, enabling mapping of stand-level phenology over large areas, and analyses of its relationship with climate (Guan et al. 2015; Yang et al. 2021; Wang et al. 2023). However, high cloud cover and sensor artifacts complicate satellite-based studies of tropical forest phenology (Chambers et al. 2007; Chirabi et al. 2021), which also mainly provide information on overstory phenology, although lidar approaches have been used to glean data on understory phenology as well (Tang and Dubayah 2017). PANGEA ground and airborne measurements will address knowledge gaps related to the divergent leaf phenological responses of individual species and functional types, which requires data linked to individual plants of known species identity, a link that is difficult to make for most satellite remote sensing (but see Bush et al. 2020 ).

#### 3.1.2 Biodiversity & Functional Composition

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

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

* *How does tropical* ***biodiversity*** *vary spatially with forest structure and function?*
* *What are the plant* ***functional trait distributions of tropical forests*** *on different continents, and how do these differences affect forest carbon cycle responses to extreme events and across disturbance and climatic gradients?*
* *To what degree are changing tropical carbon cycle dynamics caused by shifts in* ***plant functional composition****?*

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

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

#### 3.1.3 Land-Atmosphere Interactions / Tradeoffs and Thresholds

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

Variation in land-atmosphere interactions and the impacts of changes in environmental conditions on these interactions also remain highly uncertain. For example, Central African tropical forests appear to rely more heavily on moisture recycling to provide atmospheric moisture for rainfall than the Amazon (Worden et al., 2021, Baker and Spracklen 2022). However, compared to the Amazon, Central African studies investigating transport pathways for recycled atmospheric moisture, consequences of deforestation on moisture recycling, and potential thresholds for transition are either at non-regional scales or do not exist (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). In addition, aerosol emissions, clouds, and their interactions can modulate available energy for carbon fluxes such as photosynthesis and respiration. Variability in regional and cross-continental climate conditions and cloudiness (e.g., Phillipon et al., 2018, Pohl et al., 2022, Martins et al., 2018, Chakraborty et al., 2019, Jonard et al., 2022), as well as the magnitude, type, and location of anthropogenic disturbances (for example, large-scale deforestation within the southeastern Amazon versus massive biomass burning in semi-arid regions directly north and south of Central African forests) necessitates regionally-specific investigations of how changing environmental conditions affect carbon fluxes via climate feedbacks (Braghiere et al., 2020, Durand et al., 2021, Adebiyi and Zuidema 2016).

Hydroclimatic conditions in tropical forests vary significantly along disturbance gradients, from intact forests to heavily fragmented landscapes (Gutierrez-Cori et al., 2021), and are unique across tropical regions as they are heavily shaped by local climate and disturbance histories. Deforestation and degradation have been directly linked to reductions in rainfall and increased dry season lengths and intensities (Staal et al., 2020, [Fu et al., 2013](https://doi.org/10.1073/pnas.1302584110), [Spracklen and Garcia-Carreras 2015](https://doi.org/10.1002/2015GL066063)), and can result in altered microclimate conditions from edge effects, such as increases in surface temperatures (Silva Junior et al., 2020, [Zhao et al., 2021](https://doi.org/10.1038/s41561-021-00763-8), Smith et al., 2018, Butt et al., 2023). The effects of these disturbances can happen at small spatial scales or be hard to measure, such as changes in local winds (Staal et al., 2020). Additionally, they can depend on the geographic distribution and spatial extent of deforestation (Butt et al., 2023), on background climate conditions, or interact with other factors such as climate change or natural fluctuations (Staal et al., 2020). The role of these disturbances pushing tropical regions past water and temperature thresholds is thus highly uncertain. To address knowledge gaps related to hydroclimate thresholds and land-atmosphere interactions, PANGEA will answer the following questions:

* *How do changes in* ***land-atmosphere interactions****, including moisture recycling and carbon fluxes, vary with climate feedbacks, carbon storage capacity, and resilience of tropical forests under changing environmental conditions?*
* *Do* ***hydroclimatic thresholds****, such as critical soil moisture levels or thermal boundaries, vary within and between tropical continents, and how do hydroclimatic conditions vary along disturbance gradients?*

Scaling hydraulic traits - VOD and CWC knowledge gaps

* Cite Xu et al 2021 and tower based validation methods (Humphrey & Frankenberg 2023)
* CWC use in US - need to investigate in the tropics - Brodrick et al, etc.

Integrate human dimensions into knowledge gaps above - emphasize feedbacks and how that will impact ag production, agroforestry production, non-timber forest products - difference in [farmer] adaptation / resilience strategies emerging in response to different feedbacks between biophysical changes and socio, cultural, political context?

### 3.2 Process

#### 3.2.1 Species Interactions and Resilience

Our ability to understand and predict how environmental variables drive carbon fluxes and stocks remains hindered by the discrepancy between the scales and quality of data collected for environmental variables and forest responses. Much of our understanding relies on information collected from individual sites, while studies across space have relied on syntheses of forest plot networks. These studies have demonstrated strong spatial variation in tropical forest aboveground biomass carbon (e.g. Sullivan et al., 2020, other REFS), but rely on coarse environmental data. Variation in biomass carbon has been attributed to maximum temperature and rainfall, with little variation explained by cloud cover, wind speed, and edaphic properties, despite their importance at local scales (Sullivan et al., 2020). The lack of variation explained by some of these predictors likely reflects the lack of strong environmental data, rather than lack of relationships. For example, these environmental variables have been obtained from large gridded datasets such as WorldClim and SoilGrids (~a minimum of 250 to 1 km resolution), which rely on extrapolated ground data. However, remote sensing offers a huge opportunity to improve upon both environmental data, but also more accurately quantify forest carbon stocks and fluxes and their underlying drivers at ecologically and climatologically meaningful spatial scales.

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

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

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

**[a few sentences on methods]**

#### 3.2.2 TBD (Mortality / recovery / management)

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

Although we know what can kill trees, we know surprisingly little about what actually kill trees. Specifically, we do not know the relative contributions of natural agents of disturbance to trends in biomass turnover or tree death (McDowell et al. 2018, Gora and Esquivel-Muelbert 2021), much less how these patterns vary over space and time. This substantial knowledge gap is even more troubling in the context of the divergent trends of tree mortality across tropical continents (Hubau et al. 2020, Bennett et al. 2021). Because of the small-scale and aggregated nature of most natural disturbance events (Espírito-Santo et al. 2014), addressing this major knowledge gap requires agent-attributed, high-resolution, high-frequency data on tree mortality at scale (>10km). To understand how these trends vary over space and time, these measurements need to be continued for several years and replicated across several sites. PANGEA addresses these knowledge gaps by asking:

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

Apart from tree mortality, disturbances also strongly influence carbon cycling by altering belowground processes. However, the contributions of forest disturbance to carbon cycling and nutrient dynamics are challenging to scale and highly uncertain. Successfully quantifying patterns of agent-specific forest disturbance will inherently produce the large-scale experimental framework needed to quantify the downstream effects of disturbance on belowground biogeochemical cycling and their contributions to carbon cycling. Varying time scales over which above and belowground dynamics play out and interact with disturbance type, intensity, and frequency requires coordinated ground, airborne, and satellite measurements, spanning multiple gradients, including edaphic, disturbance history, and land-use gradients. PANGEA addresses this need and knowledge gap by answer the following question:

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

There is great potential to

In doing so, we can deliver a mechanistic understanding of tree mortality including models of tree trait-based vulnerability to each of the major agents of forest disturbance. By incorporating information on forcing processes (e.g., climate trends or drivers of human disturbance), we can then upscale to explain pantropical variation in tropical forest carbon stocks and fluxes. Moreover, this mechanistic information will be crucial to the proper management of tropical forests, informed reforestation efforts, and any effort to quantify forest vulnerability to ongoing climate change.

SES APPROACH/METHODS

Remote sensing [Maria Santos]

* Detection of LULCC
* Identification of crop types; yield mapping (opportunities for RS-based precision ag in the tropics)
* Identification of agroforestry systems

Field data

* Using qualitative methods like interviews and focus groups to complement remote sensing data ,
* Governance [MVE]
* Economics
* Perceptions & culture [Ale Echeverri Ochoa?]
* Methods: network analysis, social capital, modeling (biophysical models)
* 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?

#### 3.3.3 TBD

Fire and land-use related disturbances reflect human interactions with tropical forests through various land-use practices and may potentially exert significant climate feedback via the interactions with terrestrial hydrological cycles (Li et al., 2022). This includes changes at the surface such as river discharge and floods (Ndehedehe et al., 2022, Bogning et al., 2022, Oliveira et al., 2021) as well as in the atmosphere such 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). [1-2 sentences on variability in shifting drought and storm frequencies resulting from climate change —]

Despite advances in understanding the causes and consequences of deforestation, forest degradation, and regrowth using remote sensing (Lapola et al. 2023, Heinrich et al., 2021), there is the knowledge gap to understand the process of disturbance impacts on land surface biophysical properties, including carbon cycle dynamics, their climate feedback mechanisms (Li et al., 2022). Specifically, surface evapotranspiration, albedo, roughness, land surface temperature, and humidity can all be altered by shifting disturbance regimes.

In addition, understanding variation in feedbacks across disturbance type, intensity, and frequency warrants improved understanding to inform management land-use practices (e.g., farmer adaptation, urbanization, NTFP collection) are supposed to influence the surface biophysical properties of tropical forests and generate climate feedback.

Capabilities for measuring XYZ using remote sensing data to improve

The mechanisms controlling tropical forest land-atmosphere interactions represent one of the most uncertain aspects of the terrestrial climate system, in part due to the complex pathways through which they can take place and large variations in the spatial scales at which they occur (Lintner and Neelin, 2009, Betts and Silva Dias, 2010, Gentine et al., 2019). Investigating these interactions requires extensive use of models and reanalysis products that can vary significantly within the tropics due to factors such as heavy parameterization, the lack of ground-based data to constrain estimates, and different representations of key processes (e.g., [Fisher et al., 2009](https://doi.org/10.1111/j.1365-2486.2008.01813.x), [Sibret et al., 2022](https://doi.org/10.3389/fsoil.2022.883236),[Lopez-Ballesteros et al., 2018](https://iopscience.iop.org/article/10.1088/1748-9326/aad66c/meta), [Seinfeld et al., 2016](https://doi.org/10.1073/pnas.1514043113)). For example, large variations exist in current carbon, water, and energy fluxes that cannot be measured directly over large scales, such as evapotranspiration and gross primary productivity (e.g., [Baker et al., 2021](https://doi.org/10.5194/hess-25-2279-2021), [Weerasinghe et al., 2020](https://doi.org/10.5194/hess-24-1565-2020), [Zhang and Ye 2021](https://www.sciencedirect.com/science/article/pii/S0048969721020350)). Meanwhile, studies investigating how land-atmosphere interactions influence large-scale atmospheric thermodynamic and dynamic conditions, as well as water and energy cycling, must heavily rely on climate models and reanalysis products (e.g., Staal et al., 2023, Xu et al., 2022, [Brown et al., 2021](https://www.nature.com/articles/s41467-020-20482-9), Te Wierik et al.,2022, Sori et al., 2022, [Seinfeld et al., 2016](https://doi.org/10.1073/pnas.1514043113), Liu et al., 2020).

* *Mention hydroperiods, convective development, and the atmospheric boundary layer in the related text - these are included in precipitation regimes/dynamics*
* *Bring details from previous questions below into the main text - link to the need to understand impacts of deforestation and degradation on hydrological cycles to inform how forest restoration can influence hydrological cycles*
  + *What are the feedback processes between LCLUC and physical climate systems during specific climate variability events (e.g., ENSO, AMOC, MJO, IOD)?*
  + *How do LCLUC, forest regrowth, and degradation alter recycling, patterns, frequency, and intensity of precipitation and what are the associated feedbacks?*
  + *How do tropical forest disturbances (e.g., wildfire and their aerosols) interact with clouds and influence continental precipitation?*
* How are climate and land-use changes altering **land surface biophysical properties** that influence the strength of land-atmosphere feedbacks and teleconnections?
* What are the direct and indirect **hydroclimate controls** on tropical forests and how does this influence the resilience or vulnerability of their carbon balance with shifting disturbance regimes, land cover and land-use change, and increasing atmospheric CO2?
* How do **deforestation**, **degradation**, and **forest regrowth** alter regional **hydrological cycles** in tropical regions, including precipitation regimes, freshwater resources, and water quality, and river connectivity?

### 3.3 Projections

PANGEA will address specific knowledge gaps related to how tropical forest changes will influence positive and negative feedbacks to local, regional, and global social-ecological systems. …. future change and evaluation of impacts on co-benefits emphasized here…

Since many tropical forests are situated on nutrient-poor soils in topographically varying landscapes that are actively undergoing land-use changes, improved understanding of the role of nutrient limitations, water cycling, and land-use activities is needed to reduce large uncertainties around interactions with carbon-climate feedbacks like increased respiration, carbon losses from tree mortality, changes in CH4 fluxes, and constraints on a CO2 fertilization effect (REFS; Townsend et al 2008).

[a few sentences motivating the following question]

* How will increasing temperatures, atmospheric CO2, and extreme events impact **nutrient availability** and **soil-vegetation interactions**?
* *(e.g., drought, fires, flooding)*

[a few sentences motivating the following question]

* 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?

Future trends in disturbance regimes and tree mortality are among the largest sources of uncertainty for the future of tropical forests and the contributions to global climate (Pugh et al. 2018). We must develop a mechanistic understanding of tree mortality in association with forcing processes (i.e., temperature, hydrological cycling, convective activity) and use this information to parameterize mechanistic models of tree mortality within demographic vegetation models. By incorporating the role of functional biodiversity in regulating forest response to specific agents of tree mortality, we can begin to predict the vulnerability of different tropical forests to ongoing climate change. Moreover, we can identify the tree taxa and forest types that are most resistant to climate change and should therefore be prioritized for conservation.

* *Link to how climate warming and increasing extreme events will shift tropical forest structure and function via influences on plant ecophysiology and shifts in functional composition*

[a few sentences motivating the following questions]

* Include human dimensions in motivation and knowledge gaps
* *Mention drought, heat, and flooding explicitly*

We have incomplete knowledge about how both natural and human-induced (anthropogenic) changes influence the fire regimes for tropical forests (Andela et al., 2017) and the associated feedback associated with the complex interactions among climate extremes (e.g., drought, heatwave, and flooding) and anthropogenic land cover and land-use change (Flores and Staal, 2022). In the near future, Earth system models (ESMs) project a continued warming with a variety of drought hotspots in the Amazonia (Douville et al. 2021), which indicates a substantial risks for wildfire due to increased warming, atmospheric dryness, and reduced relative humidity (e.g., Amazonia, Li et al., 2023). However, the magnitude and direction of these fire-climate-vegetation feedback remains largely uncertain.

* 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?

Current literature stresses that the observational coverage of CH4 fluxes from wetlands and aquatic systems in the tropics is extremely limited compared to temperate and boreal regions (Johnson et al., 2022; Melack et al., 2022; Stanley et al., 2023). The lack of flux observations for use in mechanistic model development and statistical upscaling has led to poorly quantified tropical wetland (Ganesan et al., 2019) and inland water system (Rosentreter et al., 2021) CH4 emissions. Existing mechanistic wetland models have large differences in tropical CH4 emissions (Melton et al., 2013; Bloom et al., 2017) and do not capture observed seasonality of CH4 in tropical regions dominated by forested wetlands (Melack et al., 2022). Much of this difference is driven by the lack of fine-scale measurements detailing the drivers of wetland and aquatic emissions (Melack et al., 2022) and the threefold difference in wetland/inundation extents applied in individual models (Peng et al., 2022). Tropical forested wetlands are an uncertain component of the global CH4 budget due to the: a) complexity of the meteorology, hydrology, ecology, land-use practices, and CH4 emission drivers in these regions; and b) extreme data limitations amplified by cloud cover prevalence that inhibits satellite retrievals (Ganesan et al., 2019; Melack et al., 2022). Given these complexities in the main flux drivers (e.g., meteorology, hydrology, biomass, vegetation type, soil moisture, edaphic factors, aquatic constituents/quality, etc.) and the persistent cloud coverage in the tropics inhibiting our understanding of tropical forest GHG fluxes, PANGEA will acquire vital suborbital remote-sensing and in situ data coincident with ground-based observations to improve regional CH4 model capabilities and emission budget estimates.

* How will changes in precipitation patterns (e.g., ITCZ displacement), increasing temperatures, and shifting disturbance dynamics in tropical forests alter the **terrestrial water balance** via changes in seasonal rainfall timing and duration, evapotranspiration, and soil water?
* *Mention that stream, groundwater, runoff are included in the terrestrial water balance.*
* How will **future changes in vegetation**, including deforestation, degradation, and regrowth, impact local, regional, and cross-continental climate and hydrology?
* *Include in related text that htis includes precipitation patterns and timing, land surface temperatures, evapotranspiration, soil and groundwater, stream and river flows, and runoff*
* How will these future changes in climate and extreme events impact carbon cycling within tropical rainforests, and at what point will this lead to a **large-scale transition** in functional composition and/or the regions becoming a net carbon source?
* 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?
* *Mention bioeconomies, incliuding forest-friendly economic activities*
* *Explicitly mention that this includes Indigenous Peoples and Local Communities"*

## 4. Scientific Advancement from PANGEA

* Expand ability to interpret satellite data
  + Remote sensing has great potential, especially instruments coming on line in coming years, but lack of ground data hinders accurate and precise interpretation
  + Scales mismatch

RS related methods advances enabled by PANGEA

* Cal/Val and algorithm development
  + SBG, CHIME, ECOSTRESS, NISAR, BIOMASS, OCO-2/3, SMAP, GRACE, TROPOMI, GEDI, Landsat, VIIRS,
  + Commercial Satellite providers through CSDA program
* Model-[RS] data integration
  + Processes we need to get right in models
    - Dynamic vegetation (incl post-disturbance recovery and structural and functional diversity)
    - Plant water use efficiency
    - Drought stress response (incl. natural vs. managed lands)
    - Partitioning of ET
    - Hydraulic redistribution
    - Root-groundwater interactions
    - Surface water quality
    - Planetary boundary layer diurnal evolution, advection, and entrainment
    - Drivers of land-use change?
    - Feedbacks of climate change in tropics on people (e.g., ag production, water quantity and quality, fire & air quality)
* RS indicators of:
  + Vulnerability to tree mortality
  + Biodiversity – in most biodiverse region (what taxonomic/functional scales of diversity matter for carbon cycle dynamics?)
  + Productivity
* Improved climate model predictions for the tropics (has global climate prediction implications)
  + ERA5 and CHIRPS discrepancies / lack of weather stations
  + Land-atmosphere interactions

PANGEA leverages NASA’s history of successful field and airborne campaigns in the tropics to measure ecosystem dynamics and status at the beginning and end of the dry season, when tropical forest systems are least and most stressed, and differences in function are most apparent [19]. We will leverage decades of scientific efforts including, XYZ, expanded international forest inventory plot networks (ForestPlots.net et al 2021) and NGEE-Tropics E3SM-FATES model development efforts (Tollefson 2015, Powell et al 2018, Koven et al 2020), all of which will benefit from improved integration with remote sensing measurements. PANGEA emphasizes integration of ground measurements, remote sensing datasets, and models, supporting remote sensing algorithm development and model-data integration in the tropics. We foresee significant scientific advances from a coordinated scoping effort and campaign, including:

1. ***Explaining heterogeneous tropical forest responses to change with an emphasis on comparisons between the Americas and Africa;***
2. ***Advancing the integration of ground and remote sensing measurements;***
3. ***Developing data-model-integration workflows to more adequately represent the functionally important components of tropical forest diversity that are scalable with remote sensing; and***
4. ***Advancing scientific capacity in underserved regions.***

Attempts to assess the stability of forests to changes have garnered inconsistent results. Field studies suggest Central African forests may be more resistant or resilient to changing climatic conditions and may offer a longer-term carbon sink compared to other tropical forests [6], [10]. 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 [7], [11]. ***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.*** Hypotheses that may explain these inconsistencies include: 1) changing rates of tree mortality, 2) varying sensitivity of photosynthesis, respiration rates, and other ecosystem processes that alter net carbon and water fluxes, to natural and anthropogenic disturbances, 3) differing intensities and patterns of deforestation and degradation on ecosystem structure and function, and 4) different evolutionary trajectories that have resulted in unique biodiversity and species interactions that directly influence ecosystem resilience (e.g., varying megafauna abundances across tropical forests).

Ecosystem structure and function is characterized across multi-dimensional gradients of intact to degraded and low- to high-diversity tropical forest ecosystems. PANGEA measures floristic and phylogenetic diversity as well as demographic rates, using existing ground data from permanent inventory plots, and functional and structural diversity using airborne lidar. Coincident airborne VSWIR data and in situ leaf trait measurements are used to map canopy traits and distinct functional communities, in addition to evaluating scalable models leveraging satellite measurements. Using this output, we characterize differences across abiotic, land-use, and animal abundance gradients. Airborne measurements are then used to model ecosystem fluxes under climate change and evaluate differences in ecosystem responses. In doing so, PANGEA addresses how varying tropical forest structure and function influences tropical forest stability in the face of climate change impacts.

Climate Feedbacks & Interactions: PANGEA will provide data and knowledge to advance our understanding of climate interaction, including studies to determine (1) how increased CO₂ levels and rising temperatures specifically affect carbon sequestration rates in tropical forests, (2) the impacts of extreme weather events, such as severe droughts, on forest health and carbon emission, (3) the consequences of land use changes—like deforestation for agriculture—on forest fragmentation and its effects on biodiversity and ecosystem services is crucial, (4) how altered forest cover influences both biophysical factors (e.g., albedo changes) and biochemical processes (e.g., nutrient cycling) will help clarify their role in climate feedbacks, (5) the effectiveness of various forest restoration strategies in improving resilience and mitigating climate impacts is essential for developing practical solutions.

Spaceborne remote-sensing and top-down emission estimates in the tropics are known to be challenging (Tunnicliffe et al., 2020, Wilson et al., 2021); thus, PANGEA’s sustained aircraft and ground-based observations are essential. Given the complications due to cloud coverage, large regional emission variability, and inability to separate different wetland/aquatic sources and processes, satellite data alone cannot provide a mechanistic understanding. Airborne and finer scales of observations are vital to connect airborne and space-based remote-sensing observations of XCH4 to specific emission source types and drivers. By leveraging increased spatial, temporal, and spectral data from airborne observations, we can delineate between wetland/aquatic ecosystem types in order to assign the appropriate magnitude of flux contributions to different source types, which is currently a large source of uncertainty in quantifying the tropical CH4 budget.

Attempts have been made to estimate tropical wetland CH4 fluxes using aircraft in situ measurements in the Amazon (Miller et al., 2007, Beck et al., 2012, Wilson et al., 2016, Basso et al., 2021) and Africa (Shaw et al., 2022); however, these observations only help identify the spatiotemporal differences in emissions. In contrast, PANGEA will take advantage of multiple scales of observations: a) regional-scale – 1 km2 to 1000 km2 (crewed aircraft); b) ecosystem-scale – 1 m2 to 100 km2 (sUAS and tall towers); c) near-surface (sUAS platforms); and d) fine-scale – <1 m2 to 1 km2 (ground-based systems) to connect spatiotemporal flux variability to: 1) specific wetland/aquatic sources (i.e., wetlands, floodplains, lakes, reservoirs, rivers); 2) intra-system emission characteristics (e.g., open-water versus vegetation-mediated fluxes; ebullition versus diffusion); and 3) primary biological and physiochemical flux drivers.

## 5. Critical Role of NASA Remote Sensing

PANGEA aims to determine whether different tropical forests will share the same fate or vary in their responses to the effects of climate and land-use change, with a particular focus on Earth’s two largest tropical forests. Identifying processes that result in tropical forest stability is paramount for constraining uncertainty in predictions of future terrestrial carbon flux dynamics. To reconcile differences between ground and satellite measurements and improve scaling strategies to advance future monitoring, coordinated airborne measurements are necessary to characterize how and why Central African and American tropical forests differ in their ability to remain stable in the face of rapid climate change. For example, sufficiently high spatial resolution (~2-4 m) is needed to adequately scale organismal level leaf and tree dynamics to landscapes, serving as an intermediary between field and satellite observations (Fig. 1). PANGEA builds directly upon the scaling developments and successes from the NASA Arctic Boreal Vulnerability Experiment (ABoVE) in North America (e.g., Virkkala et al 2021; Peltola et al. 2019, Braghiere et al., 2023), which shed new light on previously understudied Arctic systems.

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

Persistent cloud coverage is a significant issue when using space-based XCO2 and XCH4 to constrain tropical greenhoues 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 x 7.0 km]) and XCO2 (e.g., OCO-2 [1.3 km x 2.2 km]) over 95% of retrieved information is filtered due to clouds in the tropics (Qu et al., 2021). Higher spatial resolution XCO2 and XCH4 satellite sensors such as the recently launched MethaneSat (100 m x 400 m) will greatly improve the ability to retrieve tropical flux measurements through cloud gaps. Other point-source mapping satellite sensors (e.g., EMIT, GHGSat, Carbon Mapper, PRISMA) have been launched with very high spatial resolution (<100 m x 100 m). However, these target mode observations will not provide the global coverage needed to constrain tropical greenhouse gas budgets.

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

## 6. Research Strategy and Study Design *(scientific feasibility)*

### 6.1 Overall Study Design

PANGEA stands on the shoulders of highly successful NASA field and airborne campaigns to Africa and South America, including but not limited to SAFARI 2000, LBA, AfriSAR-1 and -2, and BioSCape. PANGEA will build on these well-learned precedents to enable NASA funded investigators to answer big scientific questions by comparison among major tropical forest formations. Research will integrate ground, airborne, and satellite-based science investigations such that the study design will enable effective interpretation of present and future satellite-based science investigations. The PANGEA strategy will facilitate collaborations and build new relationships within the scientific community, with a special emphasis on interactions among US scientists and scientists from tropical forest countries. PANGEA research and future NASA studies will benefit from opportunities for training and educating the next generation of scientists, including scientists from tropical countries where field research will be based. The strategy will leave a legacy of open data, open science, and strengthened partnerships between the US and tropical institutions, providing a basis for future research.

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

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

All science team members will either conduct integrative analysis (including modeling) or participate in integrative analyses. Building an interdisciplinary science team from the earliest stages and involving all the minds and experience on the team will result in deeper insights. Collected data will be made available to the full team as soon as possible, always following NASA requirements as a minimum. Open science practices will make integrative analyses and model studies as transparent as possible to the full team. The PANGEA campaign will benefit from years of field-campaign experience in the TE program including ABoVE, LBA, and earlier campaigns. Moreover, the team will learn from experience outside of NASA through collaboration with partner projects and institutions and the use of existing protocols for data collection. Examples abound from NASA projects and facilities (e.g. BioSCape, AVIRIS, EMIT,), as well as outside organization (e.g. CEOS, NEON, ICOS, AmeriFlux, FLUXNET, Forestplots.net, GEO-TREES, and more) (Baldocchi et al. 2024; Delwiche et al. 2024; ForesPlots.net et al 2021; Ordway et al. 2021; [Nagy et al. 2021](https://doi.org/10.1002/ecs2.3833); [Phillips 2023](https://doi.org/10.3390/plants12213710)).

In the following sections, we provide and overview of XYZ.

* include brief mention of scaling strategy concept/framework here

### 6.2 Essential Scientific Measurements

**PANGEA's overarching science goal is to understand differences in tropical forest ecosystem stability in terms of pattern and process, and reduce uncertainties in projected tropical forest responses to climate and land-use change.** Addressing this gap requires a coordinated ground and airborne campaign spanning the two largest tropical forests in Africa and the Americas.

PANGEA leverages NASA’s history of successful field and airborne campaigns in the tropics (**Fig. 2**) to measure ecosystem dynamics and status at the onset and end of the dry season, when tropical forest systems are least and most stressed and differences in function are most apparent (Yang et al. 2021). Recent achievements that demonstrate feasibility include the highly successful AfriSAR-2 campaign that collected airborne L- and P-band UAVSAR data over Cameroon, the Democratic Republic of Congo (DRC), Gabon, Ghana, the Republic of Congo, and Sao Tome and Principe. In spite of these campaigns, there remains a critical need for collocated and coincident measurements across the highly variable tropical landscapes to capture variation in ecosystem structure and function within and across continents, particularly in Africa, where data gaps are the greatest, and process-based understanding is poorest. Achieving PANGEA’s objectives requires flight campaigns that meet the measurement requirements in **Table X**, based out of multiple countries in Central Africa and the tropical Americas to span the range of environments present in these systems. These observations provide an essential scaling bridge linking high resolution, process measurements (forest plots, chamber measurements, flux towers, eDNA, animal movement data, Indigenous ecological knowledge) with spatially extensive measurements (satellite) which are becoming increasingly spectrally resolved with new sensors. Combined measurements will provide a baseline snapshot through which we can understand sustained field and spaceborne measurements, as well as hindcast and contextualize previous studies.

PANGEA will establish a network of centrally coordinated field and airborne campaigns that are distributed across targeted tropical forest ecosystems to fill data gaps and enable scaling between field and remotely sensed datasets, and regional and pan-tropical scale modeling. PANGEA provides a framework for scaling and integrating airborne and satellite measurements with in-situ field observations, eddy-covariance flux tower measurements, and terrestrial biosphere modeling to **advance scientific understanding and remote sensing capabilities across thematic areas that directly address the goals of NASA’s Carbon Cycle and Ecosystems Focus Area, in alignment with the Water and Energy Cycle and Climate Variability and Change Focus Areas**. Using PANGEA measurements, differences will be characterized across biotic, abiotic, and land-use gradients. Integrated output from ground, airborne, and satellite measurements will then be used to model ecosystem structure, function, and fluxes under climate and land-use change scenarios to evaluate differences in ecosystem responses. In doing so, PANGEA addresses how varying tropical forest dynamics influences tropical forest stability in the face of climate and land-use change impacts.

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 allow us to derive the **Optimal**, **Baseline, and Threshold Essential Scientific Measurements** detailed in **Table X** and described below.

| **Table X.** | |
| --- | --- |
|  | **Investigation Functional Requirements** |
| O | **Airborne Campaign:**   * **Brief description**   **Ground Campaign:**   * Brief descriptions   Field Infrastructure   * **Brief description**   **Satellite Observations** |
| B | **Airborne Campaign:**   * **Brief description**   **Ground Campaign:**   * Brief descriptions   Field Infrastructure   * **Brief description**   **Satellite Observations** |
| T | **Airborne Campaign:**   * **Brief description**   **Ground Campaign:**   * Brief descriptions   Field Infrastructure   * **Brief description**   **Satellite Observations** |

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

1. For Objective 1, PANGEA will:
   1. Collect airborne measurements via wall-to-wall flightline mosaics and sampling transects over a minimum of two priority landscapes in Africa and and two priority landscapes in the Americas.
      1. **Note:** Landscapes will be selected from candidates included in Table 3 during the development of the Concise Experimental Plan.
   2. Airborne measurements will include one successful capture of the wet-to-dry transition and one successful capture of dry-to-wet transition at each landscape. Wet-to-dry and dry-to-wet captures can occur in different years on different continents.
      1. **Note:** A variability analysis is underway, which will inform important endmembers to capture. This will be included in the final white paper, and will contribute to landscape selection during the development of the Concise Experimental Plan.
   3. Coincident ground measurements will be collected during the collection of airborne measurements. The temporal degree of coincidence required will vary with sensor and measurement. Canopy leaf traits from in situ samples require coincident acquisition with VSWIR data.
   4. Model foliar functional traits, canopy water content, and structural attributes.
   5. Model functionally distinct forest types, using trait maps and structural attributes.
   6. Model tree mortality rates from static and dynamic canopy gap detection using single and repeat lidar data.
   7. Model forest degradation using small footprint lidar data.
2. For Objective 2, PANGEA will:
   1. Develops data-model integration algorithms and evaluates trait model generalizability.
3. For Objective 3, PANGEA will:
   1. Model carbon and water fluxes, using terrestrial biosphere models parameterized and benchmarked with airborne data, at regional scales under future climate scenarios.
   2. Model tropical forest stability within and among all investigation landscapes and regionally based on terrestrial biosphere model results.
   3. Model the relative role of climate, soils, and divergent evolutionary histories in determining variation in tropical forests’ stability in the face of climate change impacts.

The **Baseline Investigation** fulfills all Science Objective (Section 1.1) and the core Science Questions XYZ at only 2 American and 2 African tropical forest landscapes. The Baseline Investigation requires one successful airborne capture of the wet-to-dry transition and one successful airborne capture of the dry-to-wet transition at each landscape. Our investigation requirements drive our Measurement, Model, and Functional Requirements (see Tables A1 & A2).

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

**Temporal revisit requirements:** Two focused airborne campaigns with wall-to-wall mosaics and transects at multiple landscapes, as opposed to higher repeat frequency airborne measurements at one landscape, is necessary to capture shoulder-season (wet-to-dry and dry-to-wet) variation across landscapes that span important within and among continental heterogeneity in a standardized way. Single airborne campaigns during the wet-to-dry and during the dry-to-wet season transitions will capture necessary endmembers for scaling seasonal differences in fluxes, stocks, traits, plant-animal interactions, hydrodynamics, land-atmosphere interactions, and fire and agricultural land-use activities. The time elapsed between the two captures and between different landscapes will not affect the ability to capture these endmembers, building in valuable airborne campaign flexibility. In addition, while we are unable to predict whether an extreme event will happen during PANGEA, the likelihood of a major fire, drought, or ENSO event is high. Over a 6- to 9-year campaign, it is essentially inevitable that there will be one or more extreme events that the team will be able to analyze.

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

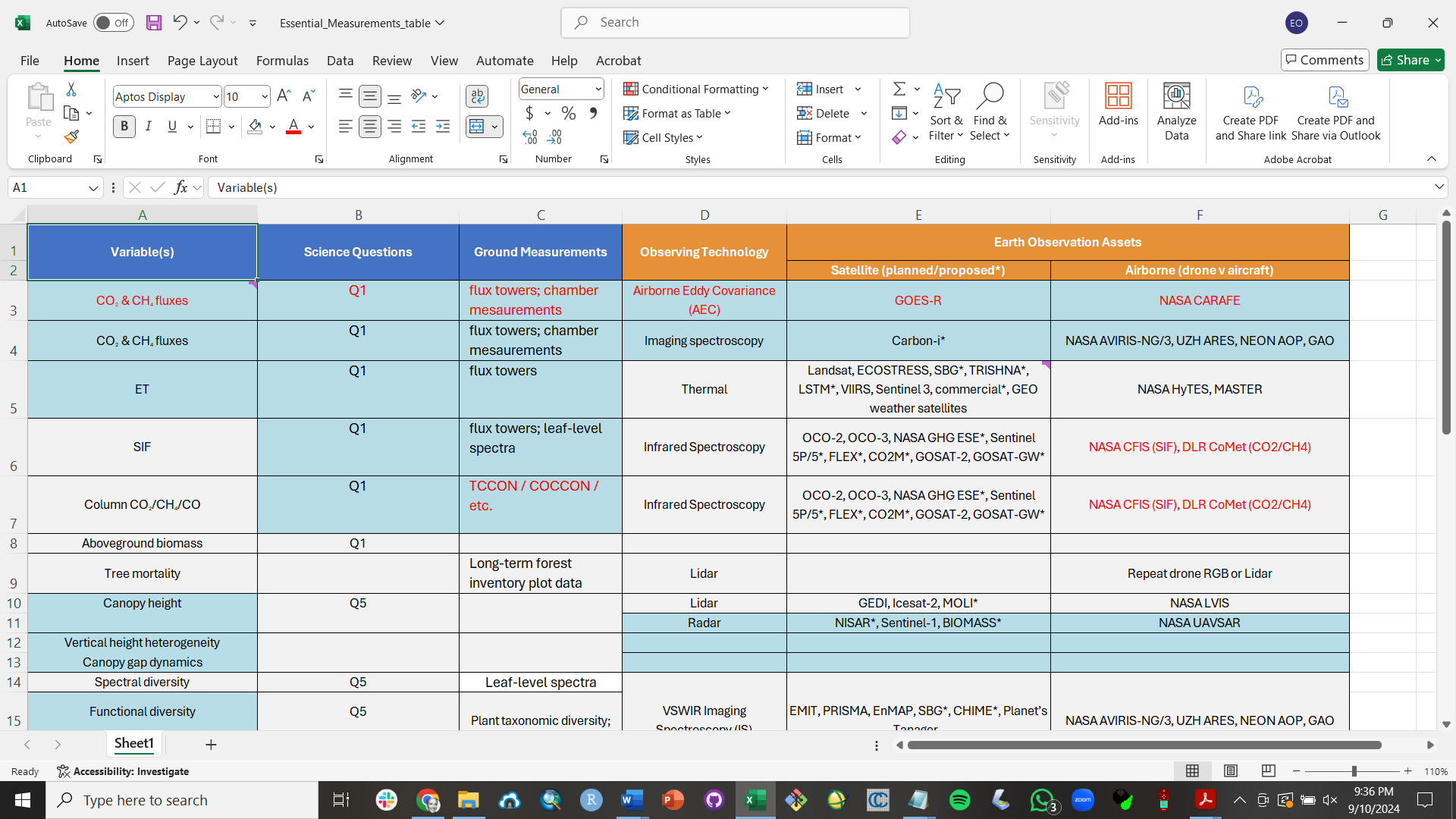
*The proposed airborne data (e.g., VSWIR, XYZ) has only been collected in a few locations across the tropics to date, at different points in time and by different organizations with different methods. PANGEA allows for direct comparisons and evaluations of the role of tropical forest heterogeneity in ecosystem dynamics. These data include collecting VSWIR reflectance and small footprint lidar to measure canopy leaf traits, vegetation structure, and X, thus allowing us to model functionally distinct forest types, advance data-model integration to generalize mapping capabilities across the tropics, and model carbon, water, and energy fluxes to examine the stability of tropical forests under future climate projections (see Section 6.4). Our optimal, baseline, and threshold Science Objectives are allocated to measurements and modeling across landscapes in both Africa and the Americas (Optimal and Baseline) or just in Central Africa (Threshold). Investigation Functional Requirements include airborne VSWIR data collection coincident with field leaf sample collection, as well as lidar acquisitions that can be paired with VSWIR flights for cost saving or collected using a second aircraft, as described in our Science Observational Profile (see Table 2 and Section 1.4).*

*PANGEA measures floristic, faunal, and phylogenetic diversity as well as tree demographic rates, using ground data from existing and, where needed, new forest inventory plots, and functional and structural diversity using airborne lidar. Coincident airborne VSWIR data and in situ leaf trait measurements are required to map canopy traits and distinct functional communities, in addition to evaluating scalable models leveraging satellite measurements. Collocated data on plant-animal interactions derived from animal movement data, camera traps, bioacoustics, and eDNA XYZ.*

*Despite multiple existing spaceborne lidar sensors (e.g., GEDI, ICESat-2) and forthcoming radar sensors (NISAR and BIOMASS), small footprint airborne lidar and radar data are also essential to achieving PANGEA’s objectives. 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). [1 sentence from Marc or Naiara on why airborne radar is critical for scaling in tropics] Spaceborne lidar and radar yield ecosystem-scale observations that, although incredibly valuable, remain insufficient to pair with tree level in situ measurements. Because these data are sampled across forests (Dubayah et al. 2020), they do not support retrieval of crown and tree-level metrics, or fine-scale ecosystem metrics like canopy gap detection.*

*Final Paragraph that clearly summarizes what can be done within the NASA scope - what's the safe science we can commit to delivering just from NASA. State that we can expand on threshold (Baseline 2 and 3) with contributions from other agencies (ESA, USAID, NSF), initiatives (OFV), and donor community (but needs to be consistent with that’s stated in the Co-Funding section!)*

* overall table here that can trace back to the Scoping Tracability Matrix, since many questions may require similar measurements.
* Elsa building out large table which will be inserted here



| **Table A1. Science Measurement Requirement Matrix.** B=Baseline; P=Priority; Qs=Questions; T=Threshold; TA=Threshold: Africa; BA&N=Baseline: Africa & Neotropics | | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| **Scientific Measurement Requirement** | | | | | **Science Q Addressed** | **T/B** |
| **Physical Parameters** | **P\*** | **Observables** | **Measurement Platform** | **Required Value** |
| * Canopy foliar traits⁑ | 1 | VSWIR wall-to-wall mosaics and transects | NASA King Air B-200 is preferred | * 380-2500 nm range * ≤ 10 nm spectral sampling * 2-5m ground sampling distance (GSD) where ground is top of canopy * Composite maps 100 – 5,000 km2 * Transects > 100 km * 598 cross-track elements, translates to ~1196 m swath width @ 2 m GSD, ~2990 m @ 5 m GSD. | **Q1-HQ1-1; Q1-HQ1-4; Q2**; **Q3** | TA, BA&N |
| * Canopy water content | 1 | **Q1-HQ1-3** |
| * Canopy Height | 1 | Lidar transects and wall-to-wall mosaics with full vertical height profile | NASA King Air B-200 is preferred | * Minimum Point Density of 5 points/m2 * 2-5m ground sampling distance (GSD) where ground is top of canopy * Composite maps 100 – 5,000 km2 * Transects > 100 km * ≥ 300 m swath width; variable with aircraft altitude | **Q1-HQ1-2; Q2; Q3** |
| * Vertical heterogeneity | 1 | **Q1-HQ1-2; Q1-HQ1-4; Q2**; **Q3** |
| * Vertical LAI distribution | 2 | **Q1-HQ1-2; Q1-HQ1-4; Q2**;**Q3** |
| * Canopy gap size and frequency | 1 | **Q1-HQ1-2; Q1-HQ1-4** |
| * Tree mortality | 2 | **Q1**; **Q2**; **Q3** |
| * Forest degradation | 2 | **Q1**; **Q2**; **Q3** |
| *\* 1 = required, 2 = desired, 3 = useful*  ⁑ *Calcium, carbon, carotenoids, cellulose, chlorophyll-a, copper, fiber, flavonoids, leaf mass per area, lignin, magnesium, non-structural carbohydrates, nitrogen, phenolics, phosphorus, potassium, starch, sugars, sulfur, leaf water content, δ13C, δ15N* | | | | | | |

#### 6.2.1 Satellite Remote Sensing Observations

* get specific about satellites and how they'd be used - **not just a list of sensors**
* Paragraph on synergies with partner agencies (ESA, JAXA, ISRO…)
  + Use of sensors from partner agencies:

| Satellite Observations | Cal/Val & Algorithm Advances | Science Advances |
| --- | --- | --- |
| *NISAR*, BIOMASS, Sentinel-1 |  |  |
| EMIT, *CHIME, SBG* |  |  |
| *Carbon-i* |  |  |
| GEDI, ICESat-2, *EDGE* |  |  |
| SMAP | SMAP exhibits a notable bias in tropical forests (Cho et al. 2023).However, significant advancements have been achieved by employing the Maximum Entropy Algorithm on SMAP (Wang et al. 2023).The scarcity of ground-based soil moisture observations remains a critical barrier to further enhancements | PANGEA will expand the involvement of tropical countries, including those in Africa and Asia, in soil moisture measurement efforts. These data will enhance SMAP's current algorithms (but also NISAR), leveraging remote sensing data to improve global soil moisture monitoring capabilities |
| OCO, TROPOMI, FLEX |  |  |
| SWOT |  |  |
| GRACE |  |  |
| Geostationary: GOES-R (americas) & X (Africa) |  |  |
| ECOSTRESS |  |  |
| Landsat, Sentinel-2 |  |  |

#### 6.2.2 Airborne Remote Sensing Observations

PANGEA airborne observations will include aircraft and drone measurements. Based on learned experience from ABoVE, recent recommendation from the AfriSAR-2 team, and information gathered during the PANGEA scoping effort, flight plans will be co-designed with local partners. Exact sensors and aircraft will be determined during the development of the Concise Experimental Plan.

**[demonstrate precedent - 1 paragraph on track record of JPL-Goddard successful flights in Africa and Central/South America]** PANGEA leverages NASA’s history of successful international airborne campaigns, including many in the tropics. NASA successfully executed AfriSAR and AfriSAR-2, 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. The BioSCape campaign recently flew two NASA aircraft integrated with four airborne instruments, acquiring, for the first time ever, contemporaenous observations from the UV through the VSWIR and into the thermal range as well as full wave-form LiDAR data. This unprecedented combination of instruments was accompanied by an extensive field observation campaign, executed by a diverse science team with ~50% local participation. BioSCape, through thoughtful co-development of the capaign with local partners, secured letters of support from 18 public institutions including numerous government departments and has been featured in multiple complimentary media items in print, on radio, and on television. 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) campaigns have also demonstrated feasibility in Costa Rica, Panama, XYZ …across the tropics. NASA also flew AVIRIS-NG over Chile, Colombia, and Ecuador in South America for methane point source measurements in 2023. NASA has planned AVIRIS-3 flights in Panama and India, which include installing AVIRIS-3 on an Indian aircraft for data acquisitions over India.

[1-2 paragraphs on AfriSAR-2 campaign here - successes and lessons learned; plan to refly these transects and include Yangambi area in DRC - will require flight to Rwanda]

AfriSAR-2 was recently executed on cost and on schedule.

Importantly, PANGEA airborne data collection does not necessarily require NASA assets or NASA aircraft to be deployed. There is strong alignment with and interest from partner space agency airborne data acquisitions. A series of Amazon 2025/26 campaigns coordinated between Brazil’s National Institute for Space Research (INPE) and the European Space Agency (ESA) will collect airborne fluorescence and in-situ measurements, as well as possible helipot carbon flux and species measurements, including CO2 and CH4. The German Aerospace Center (DLR) is planning a coordinated campaign in Brazil in 2026 (CAFE Brazil) with the goal of deploying lidar 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, including a network of EM27/SUN spectrometers. CNES may also include wind lidar to evaluate fluxes and a balloon component oriented to upper atmosphere measurements.

The European Space Agency is also planning airborne campaign activities over Africa focused on validating satellite greenhouse gas observations. Plans are ongoing and will be further defined following a large workshop in Morocco in the spring of 2025. Nominally, Phase 1 will last approximately 2 years with an emphasis on ground measurements. Airborne systems will be deployed following that. The timing of PANGEA is such that it stands to greatly benefit from and contribute to these types of international collaborations.

Commercial data-buys and flights on commercial aircraft are also viable options for PANGEA airborne acquisitions. NASA sensors can be flown on commercial aircraft. For example, AVIRIS has flown repeatedly on a Dynamic Aviation aircraft. Commercial data-buys will also greatly expand airborne capabilities. For example, commercial lidar transects span the entire countries of Brazil and the Democratic Republic of Congo, demonstrating feasibility in important PANGEA geographies. The Airborne Research Facility for the Earth System (ARES), run by Dr. Michael Schaepman and Andreas Hueni out of the University of Zürich, is another important partner supporting PANGEA airborne acquisitions. ARES has successfully acquired data for collaborative NASA and ESA campaigns in XYZ countries. Sensors onboard ARES include an imaging spectrometer, multispectral LiDAR, and a high-performance photogrammetric camera.

* Marc, how was this done for Delta-X?

PANGEA will also leverage rapidly advancing technologies, including drone capabilities to supplement aircraft data collection. Drone data acquisitions will be particularly valuable for capturing measurements that require higher temporal frequency acquisitions (e.g., tree mortality, phenology). PANGEA will utilize TRL 9 lidar and RGB UAV instruments. Current commercial UAV-based VSWIR imaging spectrometer (i.e., hyperspectral) offerings do not provide science quality data and are not suitable for decadal survey-relevant ecosystem measurements. However, these technologies are advancing rapidly. PANGEA PI Ordway submitted a NASA IIP proposal (#23-IIP23-0032) in collaboration with the JPL Imaging Spectroscopy group, led by Dr. Robert Green and Dr. David Thompson, to develop 𝜇AVIRIS, a UAV VSWIR sensor levering JPL’s imaging spectrometer technology. This work would advance the technology beyond its current TRL of 4, and support making the technology available for PANGEA, significantly enhancing measurement capabilities. PANGEA will build in protocols to leverage these types of rapidly evolving technologies.

PANGEA will likely rely on multiple aircraft and will prioritize the integration of instrumentation on the same aircraft when coincident measurements are required. Instruments on the same aircraft will aim for similar swath widths where possible, unless continuous coverage of both instruments is not required. Flights will be planned to avoid flying in the same area multiple times at different altitudes to achieve continuous coverage. Since the timing of flights will largely be dependent on weather, an expert weather forecaster with extensive local knowledge will participate in PANGEA flight planning. PANGEA will avoid integrating instruments with different weather requirements (e.g. cloud tolerance) on the same aircraft wherever possible.

PANGEA will create custom L3 data products that will see all airborne observations mosaicked and tapped to a common grid, as was done in BioSCape. This will create an analysis-ready airborne data product that can easily be integrated with field observations. This will increase PANGEA’s impact by supporting Open Science and making the data more interoperable as well as more accessible, especially to users who have never worked with airborne data before.

Some PANGEA measurements will require contemporaneous field observations and airborne observations (e.g., XYZ). This will require advance planning of field observations and clear, reliable methods of communication between the flight and field teams. Clear lines of communication will be established at the outset between field teams and flight teams. Field teams will be oriented to the flight campaign at the beginning of each PANGEA flight campaign and will be required to develop a plan that builds in flexibility in terms of when field samples will be collected. In preparation for and during the campaign, PANGEA will rely on near real time quicklooks and flight planning tools available through JPL’s Multi Mission Geographical Information System (MMGIS) platform, which will not only optimise airborne data collection and facilitate better field match ups but will also increase transparency and therefore trust across the science team.

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

#### 6.2.3 Field Observations and Studies

Ground-based measurements are necessary for 1) validation of spaceborne measurements of ecological traits, and fluxes; 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, underscoring the importance of PANGEA field-based mesaurements and studies. Field observations broadly include the following:

* **Biological and Ecological Sampling** includes all data that must be directly measured by individuals with boots-on-the-ground, and cannot be easily automated. Examples include leaf traits (although drone data collection of leaf samples is possible), terrestrial laser scanning, chamber flux measurements, species identification, eDNA, animal movement data, and Indigenous, Traditional, and Local Ecological Knowledge (IEK, TEK, and LEK). These data are important for understanding the mechanistic relationships between pattern and process and for the validation of drone, aircraft, and satellite measurements.
* **Biological and Ecological Observations** includes all ground measurements that support validation and understanding of ecologic processes but does not require frequent revisits and is more easily automated. Examples include dendrometer and sap flux measurements, camera trap and bioacoustics data, XYZ. …. Similar to biological sampling, these observations are important for developing and understanding process and validating remote measurements.
* **Flux and Meteorological data** includes all data collected at a flux-tower or weather station, including carbon, water, and energy fluxes, air temperature, soil temperature, soil volumetric water content, relative humidity, and precipitation. The eddy-covariance technique primarily uses scaffolding towers above the forest canopy and measures high-frequency wind and scalar (gas concentration, energy, momentum) data to estimate ecosystem water and carbon fluxes. The eddy-covariance technique is the presently accepted ‘gold standard’ for site level fluxes and provides critical ground truthing for spaceborne and modeled estimates of carbon, water, and energy fluxes. Eddy-covariance data have also dramatically improved understanding of the drivers of carbon and water fluxes and the infrastructure around flux towers will be highly beneficial for the installation of additional support data.
* **Tower-based Proximal Remote Sensing** includes all data collected at the site/stand level that can be observed optically from airborne or spaceborne platforms. Spaceborne remote sensing observations are typically not captured at a spatial and temporal resolution sufficient to directly link ecosystem traits and fluxes with the optical observations we can make from space. Tower-based proximal remote sensing plays a critical role in closing that gap, uncovering new mechanistic relationships in ecosystem structure and function, and can serve as a proxy for other biologic traits (e.g., leaf traits) that require more intensive field campaigns. Specifically visible-to-shortwave infrared hyperspectral reflectance, solar-induced fluorescence, thermal infrared radiation, microwave backscatter, and lidar are particularly useful at a site level. - phenocams
* **Drone-based Proximal Remote Sensing** includes lidar, rgb, mention development of hyperspectral sensor - critical for high-frequency revisits for things like tree mortality, phenology, changes in functional traits with seasonal variation, …

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

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

PANGEA will address these limitations by building lasting, mutually beneficial, collaborative partnerships with local tropical organizations to leverage, reinforce, and gap-fill existing infrastructure and efforts. Partners have been engaged in the scoping process and will be involved throughout PANGEA, including during the development of the PANGEA Concise Experimental Plan. See Section 7.3 - Community Engagement Strategy for more information. The following partnerships will be essential to the success of PANGEA field obserations and studies:

* **Alliance for Tropical Forest Science (ATFS)**, including sub-organizations **AfriTRON**, **ForestGEO**, **GEM**, and **RAINFOR,** comprises an international network-of-networks. The goal of the 11 tropical forest research networks is to advance tropical forest science and help build a new generation of scientists to achieve a more complete understanding of how tropical forests contribute to a healthy, functioning Earth. Forest inventory plots in the ATFS network includes 11,656 plots in 56 countries, including more than 50% of the world's tree species.
* **AndesFlux:**
* **Congo Basin Institute:**
* **Congo Basin Science Initiative:**
* **CongoFlux:**
* **FLUXNET**, including sub-organizations **AmeriFlux** and **ICOS**, is another international network of networks. FLUXNET connects regional networks of primarily field-based earth system scientists and research sites. FLUXNET has produced consolidated data across sites processed following a standardized pipeline. Flux sites typically have sufficient infrastructure and power supply to host additional support measurements such as proximal remote sensing instruments. Because of this PANGEA will prioritize field observations that are partnered with FLUXNET sites to make use of existing infrastructure and build collaborations with existing sites.
* **GEO-TREES:**
* **LBA:**
* **NGEE-Tropics** is a 10-year, multi-institutional project funded by the U.S. Department of Energy (DOE). NGEE-Tropics primarily goal is to develop a predictive understanding of how tropical forest carbon balance and climate system feedbacks will respond to changing environmental drivers in the 21st Century. NGEE-Tropics has focused on data collection in the tropical Americas and Asia (Brazil, Panama, Puerto Rico, Malaysia, and Australia). NGEE-Tropics will be sunsetting by the time PANGEA enters its most active phase*.* PANGEA will build directly on NGEE-Tropics data collection efforts, by extending similar measurements to Africa and collecting collocated remote sensing data, in addition to building on NGEE-Tropics modeling efforts (see Section 6.4).

### 6.3 Candidate Landscapes

PANGEA will collaborate closely with in-country partner institutions to ensure the smooth execution of field and airborne activities across selected Landscapes. **PANGEA’s nested sampling design supports a sampling-to-scale approach, with a nested sampling design.** Ground measurements span gradients within a landscape, and landscapes span climatic and biodiversity gradients within a continent (**Figure X**). PANGEA will prioritize countries that encompass landscapes where there is a confluence of intact, disturbed, and degraded forest, peatland, wetland, and mangrove ecosystems, with adjacent agro-ecosystems within roughly 100 km2 area. Coordinated, coincident ground data collection on XYZ will be collected across these gradients within each landscape. **Table X** summarizes candidate landscapes based on information provided by partners. PANGEA landscapes will prioritize locations where the following already exist or have strong potential to be established:

* Existing eddy covariance flux tower data. CO2 and CH4 measurements can be extended with chambers (not water and energy though, right, or wrong?)
* Long-term forest inventory plots, enabling re-censusing to support new measurements (e.g., canopy traits, bioacoustics, camera traps) that build on rich forest demographic rates information (mortality, growth and recruitment rates).
* Camera traps, bioacoustic sensors, weather station data, and eDNA data;
* Ground and/or drone-based phenology datasets;
* Partnerships with Indigenous and/or Local Communities

PANGEA will coordinate landscape selection closely with efforts that are actively in the process of selecting sites for complementary data collection and investment in infrastructure. These include GEO-TREES, the INPE-ESA Amazon airborne campaign, One Forest Vision, Alison Hoyt & Rob Jacksons CH4 flux + peatland/wetland, as well as multiple Schmidt Science Virtual Institute for the Carbon Cycle proposals focusing on the tropics. A landscape and site selection process will be formalized during the Concise Experimental Plan to ensure transparent selection and approval of landscapes and sites within landscapes for ground and airborne data collection. This process will build on ongoing discussions with local institutional partners and site managers that began during the scoping process, and will include co-design with Indigenous Peoples and Local Communities (see Section X for more information).

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

### 6.4 Modeling, Data Synthesis, and Integrative Analyses

#### 6.4.1 Modeling and Data Integration Approach

**Notes from writing workshop:**

* Data synthesis: how can we scale the field observations to upscale to other domain using the satellite with machine learning, create wall to wall maps
* Model data integration: how to use remote sensing data and incorporate into mechanistic models, machine learning into process based models
* Mechanistic model, statistic model, hybrid models (leverage AI with satellite, field feed into mechanistic models) to make predictions
* Use models to select sites
* Space for time time series to constrain modeling
* Emphasize data fusion
  + Carlos Silva (and Laura Duncanson?) [has CMS funded project](https://carlos-alberto-silva.github.io/silvalab/cms4d/cms4d_workshop.html) that emphasizes data fusion
    - Include as case study of data-model fusion and stakeholder engagement
    - iterative process
    - Carlos in Brazil - August and September, but otherwise can help with figures and text

**Notes for the Modeling folks from SES**

* One potential angle to explore could be: "Integrated assessment models that incorporate biodiversity and ecosystem services could be an important tool for improving our understanding of interconnected social-economic-ecological systems", <https://www.sciencedirect.com/science/article/pii/S0959378024000955>
* Examples for agent-based models that include social and ecological components in the tropics:
  + von Essen and Lambin, 2023, Agent-Based Simulation of Land Use Governance (ABSOLUG) in Tropical Commodity Frontiers
  + Iwamura et al, 2014 - Agent-based modeling of hunting and subsistence agriculture on indigenous lands: Understanding interactions between social and ecological systems
  + Iwamura et al, 2016 - Socio-environmental sustainability of indigenous lands: Simulating coupled human-natural systems in the Amazon
  + ANDERSEN, L. E., Groom, B., Killick, E., Ledezma, J. C., Palmer, C., & Weinhold, D. (2017). Modelling land use, deforestation, and policy: A hybrid optimisation-Heterogeneous agent model with application to the Bolivian Amazon. *Ecological Economics*, *135*, 76–90. [[doi:10.1016/j.ecolecon.2016.12.033]](https://doi.org/10.1016/j.ecolecon.2016.12.033)

Modeling and data syntheses will be fundamental components of the PANGEA throughout the entire duration of the experiment. The goals are (1) identify key processes that are poorly represented and regions within the PANGEA domain that drive uncertainty of key variables and processes in existing models, (2) develop Observing System Simulation Experiments (OSSEs) that will help inform the optimal location and gradients needed to capture to maximize the representativeness of the intensive sites within the PANGEA domain, (3) synthesize and scale measurements from intensive sites to the core PANGEA domain, and (4) implement new processes and techniques, as well as improve existing ones in models and apply them to answer PANGEA’s scientific questions.

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

Over the past decades, terrestrial biosphere models have expanded scope and incorporated many new processes that could not be addressed during LBA (Fig. XX). 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), and we are now in a time in which ecological processes in diverse ecosystems driving energy, water, carbon and nutrient cycling on Earth must be accounted for (Bonan et al. 2024). Likewise, several classes of models have been increasingly leveraging the broad range of remote sensing observations, and throughout PANGEA we will have participation of a broad range of models that can use remote sensing for initialization, uncertainty quantification and data assimilation. Examples of such models include, but are not limited to, (1) process-based vegetation demography models such as ED2 (Antonarakis et al. 2014; Longo et al. 2020; Schneider et al. 2023), ED (Hurtt et al. 2004; Ma et al. 2023) and FATES (Negrón-Juárez et al. 2020), (2) data-driven hybrid models that solve processes with a strong data assimilation approach such as CARDAMOM (Bloom et al. 2016, 2020) and CliMA (Braghiere et al. 2023; Wang et al. 2023), (3) top-down inverse modeling approaches that link column measurements with fluxes through atmospheric transport models such as CarbonTracker (Peters et al. 2007) and CMS-Flux (Liu et al. 2020), and (4) models that are based on Artificial Intelligence and machine learning (Schneider et al., 2017; Reichstein et al., 2019; Eyring et al. 2024). We already identified several opportunities for which models can be used to investigate processes relevant to PANGEA to help answer the key research questions (Table XX). The data collected by PANGEA will allow further advancing both the representation of processes relevant to tropical forests under a changing Earth (Fig. XX) and methods to integrate between remote sensing and models in the upcoming years.

| **Table A2. Modeling Traceability Matrix.** | | | | | | |
| --- | --- | --- | --- | --- | --- | --- |

| **Process** | **Model** | | | **Data–Model integration opportunities** | | **Science Questions Addressed** |
| --- | --- | --- | --- | --- | --- | --- |
| **Class\*** | **Examples**  **(not exhaustive)** | **Variables of interest** | **Remote sensing** | **Other data** |
| Change in forest structure over time | PB | ED2, FATES | Vertical LAI profile | Lidar | Forest inventory | **Q1-HQ1-2; Q1-HQ1-4; Q2**;**Q3** |
| PB | CLM, FATES | Total LAI |
| Change in carbon fluxes | PB | ED2,FATES,  CLM,ELM, etc | GPP, NPP | SIF, fAPAR | Flux tower |  |
| HM | CARDAMOM, CliMA | GPP, NPP | SIF, XCO2 | Flux tower |  |
| TBC … |  |  |  |  |  |  |
| \* PB: Process-based terrestrial biosphere models; HM: Data-driven hybrid models; TD: top-down models; AI: Models based on Artificial Intelligence Machine Learning | | | | | | |

* Highlight that the model activities will be closely coordinated with the science themes throughout the duration of PANGEA. Highlight examples from direct potential applications of models to address the scientific questions in the PANGEA Science Themes (e.g., pick one direct case for each of the themes). Also highlight how models will help integrate questions across the science themes. Bonan et al. (2024) figure 7 may be a good conceptual figure, though it somewhat overlaps with the PANGEA figure. [Marcos; Félicien, Renato, Yanlei, César]
* Another paragraph that highlights how data synthesis activities will be coordinated with science themes.[Cesar, Yanlei]

In PANGEA, data synthesis activities are integral to our scientific approach, facilitating the upscale of intensive site measurements to regional and pan-tropical scales. By measuring key variables at intensive sites and coupling these with high-quality ancillary data on environmental predictors (e.g. soil moisture, nutrient availability, plant functional traits), we can establish robust empirical relationships. These relationships can enable us to use statistical models to interpolate wall-to-wall variations in critical variables. For example, field-based measurements on biomass carbon losses due to droughts across multiple sites, can be used to develop statistical models that predict biomass changes in response to varying soil moisture, VPD, drought frequency, plant functional groups, etc. This model can then be used to map pan-tropical impacts on forest biomass following specific drought scenarios, enhancing our understanding of ecosystem responses to environmental stressors across diverse tropical landscapes.

PANGEA will leverage multiple data synthesis approaches to enhance our understanding of tropical forest dynamics. For example, we recognize the potential of AI/ML models for data synthesis due to their robustness in handling non-linearities and interactions among predictors, which are particularly critical in the complex ecosystems of tropical forests dominated by multi-factorial processes. To improve the interpretability of these AI/ML models and to 'open the black box,' we advocate for several techniques such as Feature Importance Analysis, which quantifies and highlights the most influential factors driving the model's predictions. Partial Dependence Plots can be employed to visualize how changes in specific variables impact predicted outcomes, providing insights into the underlying ecological processes. Additionally, incorporating non-AI techniques like Causal Inference can help us understand cause-and-effect relationships within PANGEA data, offering a complementary perspective that enhances our mechanistic understanding. These strategies will not only improve our grasp of tropical forest dynamics but also provide valuable insights that can be integrated into process-based models for more accurate predictions.

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

#### 6.4.2 Coordination with other modeling and data integration communities

* List potential partners.
  + ILAMB. data collected through PANGEA could become new benchmarking data sets in ILAMB, which can be used directly by many global modeling efforts, potentially the land component of CMIP [Renato]
  + NGEE-Tropics (caveat that NGEE-Tropics will be sunsetting by the time PANGEA enters the most active phase) [Marcos]
  + [GMAO](https://gmao.gsfc.nasa.gov/seasonal/)? [Elsa]
  + TRENDY
  + CMIP

#### 6.4.3 Scaling Strategy

The NASA Terrestrial Ecology (NASA TE) Program has been instrumental in the development of scaling strategies for Earth system science research. The first NASA TE field campaign, the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) explicitly aimed to upscale soil-plant-atmosphere models designed for the cell and leaf level and apply them at the larger scales (kilometers) appropriate to atmospheric models and satellite remote sensing (Sellers et al. 1992). Likewise, scaling approaches were central to following field campaigns such as BOREAS, LBA, and ABoVE. The development and diversification of sensors over the past decades allow us to characterize relevant properties from leaf organs (LiCOR) and individuals (Terrestrial Laser Scanners) to forest stands (UAV-borne sensors), regions (airborne scanners) and continents (satellite sensors) (Bustamante et al. 2016). Likewise, several terrestrial biosphere models now include processes with time scales of minutes (photosynthesis, energy cycles) to days (phenology), months (growth, mortality) and years (disturbances) that also span across spatial scales from plant tissues to continents (Fisher et al. 2018; Longo et al. 2019; Koven et al. 2020). In such models, the large-scale ecosystem scale state and fluxes emerge directly from competition between individuals happening at fine spatial scale. Consequently, a campaign designed across multiple scales provides opportunities for assimilating data and benchmarking various processes in next-generation ecosystem models, which can significantly advance the ability of applying these models for process understanding and long-term prediction.

To ensure processes are captured across a broad diversity of environmental conditions, the field and airborne campaigns in PANGEA will include sampling across gradients in nutrient availability, ecosystem structure, climate, and disturbance regimes. Incorporating this variability will be critical for informing models and ensuring that they can be assessed and benchmarked under different limitations, and thus reducing the risk of equifinality (right answers due to compensating wrong reasons). Likewise, the choice of priority gradients will consider the current uncertainties in models, and novel processes that have not hitherto been assessed with remote sensing data at scale (e.g., X, Y, Z).

* Emphasize sampling to scale - see mention of this in Section 6.2 - Essential Scientific Measurements
* Ground, tower, drone, aircraft,
* Integrate into existing coordination efforts and gap-fill
* Drone lidar standards - KC Cushman
  + would build something similar out for other sensors
* Great collaborative example: https://arcticdrones.org/ - Welcome to the High-Latitude Drone Ecology Network (HiLDEN)
* Collaborative example of **mycorrhizal fungi** field sampling in historically poorly sampled areas: SPUN (<https://www.spun.earth/>)

#### 6.4.4 Modeling and data integration timeline

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

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

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

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

* Emphasize model intercomparison efforts (CMIP) and ensemble modeling approaches
* NASA [Global Modeling and Assimilation Office](https://gmao.gsfc.nasa.gov/)
* Also DOE models (ELM, E3SM), and NSF models (CLM, CESM)
* ILAMB, TRENDY, Rubisco
* Integration of observations and models
  + Emphasize on RS data - model integration (CARDAMOM, CliMA)
  + Process-based models: opportunities for improved initial conditions of diverse ecosystems (lidar, imaging spectroscopy), uncertainty quantification and reduction (PEcAn, ILAMB)
  + Inverse modeling (top-down approaches) [Junjie]
* Advancing process-based understanding - specify a couple of key processes that PANGEA can advance
  + Focus on things that are now being modeled that did not exist or was in very early stages back in the LBA time (demography, eco-hydrology, nutrient cycling coupled with vegetation dynamics, spectroscopy/hyperspectral)
* Need to work on constraining uncertainty and getting the right answers for the right reason(s)
* It needs to show strong connections with the other working groups (so models are fully integrated with PANGEA)

## 7. Technical and Logistical Feasibility

[don’t start with challenges - start with successes - soften repeated use of word “challenges’]

PANGEA will leverage NASA’s history of successful international field and airborne campaigns, including recent campaigns in the Americas, Africa, and Asia. Specifically, NASA has done extensive research in Africa very successfully, including AfriSAR-1, AfriSAR-2, BioSCape, as well as many R&A projects. In addition, there are immense investment in Africa currently that will support important feasibility elements of PANGEA, including XYZ.

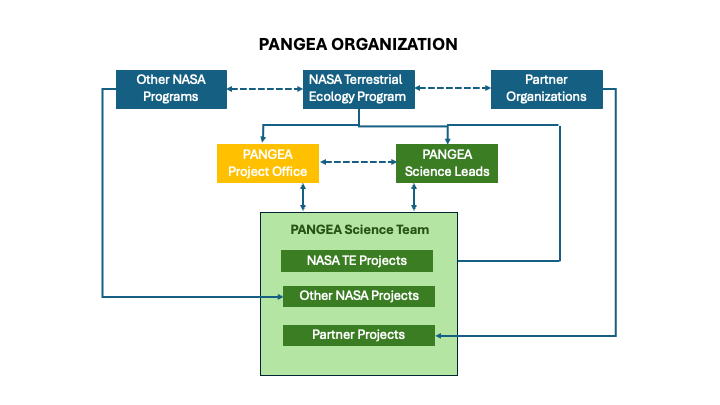
The research being proposed as part of PANGEA will not involve the deployment of new remote sensing technologies or development of new sensors. Rather, PANGEA research will utilize existing airborne and spaceborne remote sensing systems and datasets. While much of the research for PANGEA will be conducted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

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

In cases where NASA aircraft cannot obtain overflight permission or acquire data using its own instrumentation, PANGEA will deploy commercial or other assets, such as commercial ALS, commercial drone based instrumentation, or local instruments and aircraft to acquire the required airborne datasets. This is particularly important in Brazil, where we have historically encountered challenges for ground observations using non-Brazilian instruments and aircraft. PANGEA will leverage the existing practice employed by NASA and the USG of using commercial airborne data providers to collect the required datasets.

### 7.1 Organization and Management

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



#### 7.1.1 Program Management

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

#### 7.1.2 Project Office

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

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

7.1.3 Science Definition

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

#### 7.1.4 Project Implementation

The PANGEA project will be implemented by the selected PANGEA Science Team supported by the Project Office over a nominal period of six to nine years as called for in the NASA announcement A.4 of 2022. A Project *Implementation Plan* will be elaborated based on the Concise Experimental Plan. The Project Office shall be responsible for the Implementation Plan including regular updates the frequency of which will be determined in consultation with the Science Team and Program Management. The implementation plan shall detail the research activities to be conducted and specify roles and responsibilities for investigators involved in those activities during the execution of PANGEA. A notional timetable for project implementation is presented in section 7.10 (**Figure X**). At the outset of the project, roughly one year will be spent preparing for field and airborne data collection activities. The main period of data collection will extend from three to six years depending upon the overall project duration and scope. Analysis of the data collected will be continuous throughout the project. We expect data collection to draw gradually to a close one to three years prior to the conclusion of the project to allow time for data analysis, integration, and synthesis. PANGEA will leave a legacy of data and open science that will support future scientific investigations that will respond to the PANGEA science questions and to new science themes.

#### 7.1.5 Science Team and Science Leadership

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

Communication is a critical role of the PANGEA scientific leadership. Experience with past campaigns informs us that timely communication is important to manage the expectations of the PANGEA Science Team and researchers from partner projects and organizations. The PANGEA Project Scientist and a Deputy Project Scientist (Science Leadership, SL) will communicate the research objectives and outputs of the NASA-funded science team to diverse audiences. The SL will work with local partners to set expectations of PANGEA. The SL will accurately and promptly communicate project updates to local research partners. Presentations, webinars, and town halls will employ interpretation services and project materials will be made available in the languages of participating countries. Throughout the lifecycle of PANGEA, conversations with partners should be recorded and expectations clearly tracked as guidance for actions. After PANGEA data has been collected and as science data products become available, the SL will be responsible for ensuring that local partners continue to receive regular updates. The SL will set the tone of PANGEA, and will be mindful about setting an example to the rest of the Science Team about inclusive and respectful collaboration and the value of co-producing research. The SL and all members of the PANGEA Science Team will adhere to the PANGEA Community Guidelines[[1]](#footnote-0).

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

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

**PANGEA will emphasize and prioritize diversity, equity, and inclusion in all aspects of the campaign**, including diverse representation in its leadership. As such, PANGEA’s Science Team will prioritize diverse representation in terms of scientific expertise, technical specialties, national origin, race, gender, native language, different career stages, and more. Early career researchers will be included from the beginning, as will representatives from participating countries where field research will take place. Team members must commit to cultural sensitivity, with respect for local collaborators and extra care taken to uphold NASA’s reputation internationally. **Leadership and engagement in the PANGEA scoping process demonstrates diverse support for the campaign and diversity of candidates who have the capacity to and interest in contributing to PANGEA.** The scoping effort also exemplified PANGEA’s ability to implement scientific diplomacyinternationally. The Science Team will meet regularly, and for virtual meetings will endeavour to arrange meetings considerate to the time zones of persons represented.

#### 7.1.6 Disciplinary Skills Required

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

### 7.2 International and Other Agreements

As soon as PANGEA is selected, the team will begin to officially engage institutional partners and develop formal MOU’s, with the help of NASA’s OIIR office, ESPO, and the US State Department. International airborne campaigns have been repeatedly plagued by slow landing clearances and associated bureaucracy, and much of this can be avoided by beginning the formal MOU process early.

* *As soon as selected - [re-]initiate partnership conversations at the outset*
  + *call a PANGEA meeting with all PMs - but also have Earth Action there from the beginning*
  + *Engage international partners at the outset*
  + *PANGEA leadership team start relationship building with partner govts on Day 1 (or 2) to start developing MOUs for PANGEA campaign*
    - *Point to lessons learned from LBA and AfriSAR-2*

#### 7.2.1 Government agreements and MOUs

* *We will build relationships with in-country partners and establish contacts to develop signed agreements and work with NASA OIIR…*

[1-3 paragraphs on successes and lessons learned from AfriSAR-2 campaign]

- SUCCESSES and lessons learned from AfriSAR

- collaboration with partners

- Gabon - built that relationship

- started that with other countries in AfriSAR

- if PANGEA selected, spend the year establishing MOUs with governments or space agencies or institutions b/w NASA & Space Agencies

- define who those partners are

- get letters of support from govt

- Science diplomacy that needs to be done before and during campaign - Lola, Marc, Elsa (Adia) need to do that

#### 7.2.2 NASA airborne campaign Indigenous agreements, permissions, and treaties

* Indigenous land and sovereign territories.
* [Draft being co-written (in multiple languages) can be found here](https://drive.google.com/drive/u/1/folders/1Gw5jlwLzT7Z_KHRGMwto6nnl4nSpxRIX)
* State that IPs have different international human rights than other communities

### 7.3 Community Engagement Strategy

PANGEA will engage with diverse communities to address PANGEA’s science questions, identify synergies with local research priorities, and implement PANGEA in a manner that is broadly beneficial in the landscapes and countries targeted for research. The strategy draws upon the knowledge, expertise, and experiences shared throughout PANGEA’s scoping campaign, which engaged with over 500 individuals and 150 organizations from 42 countries across five continents through (a) consultative workshops, (b) outreach events, (c) working group discussions, (d) bilateral meetings, and (e) web surveys. A more detailed description of engagement methods used during the scoping campaign is provided in **Appendix A**. Here, we present a list of the communities prioritized for engagement in PANGEA, the principles that underpin PANGEA’s engagement efforts, and PANGEA’s strategy for engaging local communities and cultivating a long-term, positive legacy during and beyond the campaign.

#### 7.3.1. PANGEA Partners

PANGEA research on tropical forests will complement and expand upon many existing efforts. Some of these efforts are limited to small geographical domains or represent networks of individual sites. Others, such as One Forest Vision, have pantropical ambitions like PANGEA. The range of partnership opportunities is illustrated with examples in **Table X**. **Appendix X** describes the different communities that PANGEA will engage in greater detail, 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 certain group, which may share interests, experiences, resources, activities, professions, livelihoods, culture, geography, origins, language, or any combination of the above. The scoping campaign identified ten types of communities with which PANGEA will prioritize engagement: (1) NASA; (2) other US government agencies; (3) internatonal space agencies and support facilities; (3) foreign government agencies and national research institutes; (4) scientific institutions; (5) coordinated international research initiatives; (6) civil society organizations; (7) Indigenous peoples and local community alliances and organizations; (8) the donor community; (9) the private sector; and (10) intergovernmental agencies.

One key aspect of PANGEA’s engagement strategy, which reflects countless recommendations from scoping events throughout the tropics, is a commitment to engage with the communities identified above in an inclusive and non-hierarchical way. Each community will play a critical role in PANGEA’s planning, implementation, and its long-term legacy. Engagement with Indigenous Peoples and CSOs, for example, is essential for accessing research sites, empowering long-term, ground-based data collection, and connecting PANGEA’s research to local land management decision-making. PANGEA must engage with local and international scientific institutions to build upon their work, identify synergies, and leverage co-funding and resources to collaboratively accomplish more, and invest in formal training and curricula so that current and future generations of scientists may benefit from the PANGEA Program. The support of government agencies will be critical to PANGEA’s airborne data collection efforts and Earth Action strategies. National and sub-national government agencies are also well positioned to immediately apply the key findings of PANGEA’s research to improve country-wide, climate and biodiversity monitoring and reporting, and to develop more informed climate change mitigation and adaptation strategies. Collaboration with climate-concerned intergovernmental organizations and donors may enable PANGEA to transcend NASA’s funding requirements and engage with local institutions in a more financially inclusive and equitable manner. Many private companies and industry associations are eager to learn more about their changing environments and collect ground-, air- and space-borne data to understand their impact and ensure the sustainability of their supply chains. Although the interests, objectives, and potential points of engagement and collaboration vary widely, all of these communities will be instrumental to the success and positive long-term legacy of PANGEA.

| **Table X.** Overview of engagement strategies and example partners for each target group | | | | |
| --- | --- | --- | --- | --- |
| **Community** | **Description** | **Relevance to PANGEA** | **Engagement Strategy & Goals** | Example Partners |
| NASA | NASA Research & Analysis and Earth Action Programs, NASA Capacity Building Program, and NASA initiatives | NASA is the driving force behind PANGEA | Integrative approach to advancing scientific understanding, calibration and validation, algorithm and product development, partnerships, and capacity building across the NASA enterprise | · Terrestrial Ecology, Biological Diversity & Ecological Conservation, LCLUC, Hydrology  · Climate & Resilience, Disasters, Wildland Fires, NASA Harvest, Water Resources  · SERVIR, ARSET, DEVELOP, GLOBE, Indigenous Peoples Initiative |
| Other US Government Agencies |  |  |  | · DOE NGEE Tropics\*  · NSF BIO, NSF DEB, NSF GOLD-EN, NSF RISE  · USAID CARPE, USAID-PEER\*\*  · USFS-International Program  · USGS SilvaCarbon |
| International Space Agencies and Support Facilities |  |  | Support international collaboration on existing joint missions and airborne campaigns; build capacity to support greater engagement between NASA and space agencies in the tropics | · Central African Satellite Observatory (OSFAC)  · Gabonese Space Agency (AGEOS)  · European Space Agency (ESA)  · French National Space Agency (CNES)  · The German Aerospace Center (DLR)  · Indian Space Agency (ISRO)  · Brazil's National Institute for Space Research (INPE)  · Japan Aerospace Exploration Agency (JAXA) |
| Foreign Government Agencies and National Research Institutes | National & local sectoral ministries; Geospatial specialized institutions; Government-led multi-stakeholder platforms | These partners take large-scale action (economic and environmental planning and modelling, law enforcement, investment in research, etc.), and support long-term data and analysis (e.g. weather). | Inform PANGEA science questions and activities via research institutions; set enabling conditions (institutional, financial, and programmatic) for the ownership of PANGEA’s research outputs; capacity-building for staff at national and local levels. | · Brazil National Institute of Amazonian Research (INPA)  · Cameroon National Climate Change Observatory (ONACC)  · Ministries of Environment, Forests, Fauna, Agriculture, and Scientific Research  · Congo Basin Forest Partnership (CBFP)  · São Paulo Research Foundation (FAPESP)  · Gabon National Center for Scientific and Technological Research (CENAREST)  · PERU  · COLOMBIA |
| Scientific Institutions | Universities and colleges; national labs; research consortiums; research institutes | These partners facilitate knowledge and tech transfer to generate capacity in the local and regional institutions to train the next generation of scientists | Review the current language in the White Paper  Special focus on female and youth researchers | · Alexander von Humboldt Biological Resources Research Institute  · Alliance Bioversity International & CIAT  · Congo Basin Institute (CBI)  · International Institute for Tropical Agriculture (IITA)  · LBA  · Woodwell Climate Research Center |
| Coordinated international research initiatives |  |  |  | · Alliance for Tropical Forest Science (ATFS)  · AndesFlux  · ASCEND  · Congo Basin Science Initiative (CBSI)  · FLUXNET Regional Networks (e.g., AmeriFlux, ICOS, AsiaFlux)  · GEO-TREES  · One Forest Vision |
| Civil society organizations | National and international non-governmental organizations (NGOs) and non-governmental research initiatives with a presence in the target countries | These partners facilitate knowledge consolidation on carbon, biodiversity, and social-ecological systems; translate research outputs into ongoing CSO-led campaigns and actions |  | · Conservation International  CTREES  · World Resources Institute (including Global Forest Watch)  · Mapbiomas  · Small Mammal Conservation Organization |
| Indigenous Peoples and Local Community Alliances and Organizations | Indigenous people-, local community-, and women- led organizations and alliances active in the target countries | These partners are connected with most relevant communities, leaders, and partners in targeted countries | Co-design science questions and applications that directly affect IPLCs, women, and other groups; co-design ground and airborne field campaign activities in territories and local communties; provide training to empower IPLCs in data collection, research, and communication | · Global Alliance of Territorial Communities  · Rights and Resources Initiative  · CBI School for Indigenous and Local Knowledge  · Dynamique des Groupes des Peuples Autochtones (DGPA-DRC) |
| Donor community | Classic donors (bilaterals, family foundations, philanthropic organizations)  Specialized (geospatial) agencies from donor countries | These partners raise complementary funding that offer targeted support to extend PANGEA beyond NASA funding support. | Targeted investment in PANGEA applications and product development, support for international collaborators, joint workshops, and the development of IPLC data collection and management tools | · Bezos Earth Fund  · Ford Foundation  · Individual donors  · Mellon Foundation  · Moore Foundation  · Norwegian Agency for Development Cooperation (Norad)  · Norway’s International Climate and Forest Initiative (NICFI)  · USAID |
| Private sector | Review the current language in the White Paper | Review the current language in the White Paper | Review the current language in the White Paper | · Roundtable on Sustainable Palm Oil; Cocoa; Soy; Biomaterials  · Unilever  · Olam  · Green Resources  · CNaught  · Carbon Equity  · Carbon Credit Capital |
| Intergovernmental agencies | Review the current language in the White Paper | Review the current language in the White Paper | Review the current language in the White Paper | · Committee on Earth Observation Satellites (CEOS)  · Group on Earth Observations (GEO)  · Inter-governmental Panel on Climate Change (IPCC)  · Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)  · International Union for Conservation of Nature (IUCN)  · United Nations Framework Convention on Climate Change (UNFCCC) |
| \*DOE NGEE-Tropics is entering Phase 3 and will be sunsetting as PANGEA begins, enabling important continuity on constraining model uncertainty and data-model integration efforts.  \*\*USAID PEER is going to be replaced by a new program called SPARK. | | | | |

#### 7.4.2. Principles

**Table X** outlines PANGEA’s principles of engagement. These principles adapt the CARE 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 X.** PANGEA Principles of Engagement based on CARE. Adapted from Jennings et al. 2023 and Carroll et al. 2020. | | |
| --- | --- | --- |
| CARE Principles | Issues | PANGEA Strategy |
| Collective benefit | Research that benefits communities | Prior to research, explain and demonstrate how your research and potential results are relevant and are of value to the interests of the community and individual members; research should support community-led initiatives and secure funding for long-term investments in community.\* |
| Data grounded in community values, aspirations and well-being | Develop and/or use and/or link to Indigenous Peoples and Local Communities (IPLC) data classification and analysis frameworks that reflect community values, needs and aspirations; include and value local community experts in the research team. |
| Data for self-determined development | Collect and code using categories that identify and individuals in ways that they define; disaggregate data, especially in global or large geospatial datasets, to increase relevance for IPLCs |
| Compensate local experts | 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 | Establish institutional principles or protocols for research development, data management and publication (for example, scholarly works, presentations and datasets) that support IPLC’s Data Sovereignty; include metadata fields available for disclosure of Indigenous rights and interests. |
| Recognize the rights of IPLCs to free, prior and informed consent | Ensure data use is consistent with individual and community consent provisions; ensure ongoing consent processes, including the ability to refuse, withdraw and reconsent. |
| Data available for IPLC governance | Ensure IPLCs have access to data, metadata about their people, communities and non-human relations in a usable format; return all outputs to the appropriate tribal authorities. |
| Develop and enact IPLC Data Governance protocols | Foster community control and ownership of data and data protocols; use and/or incorporate IPLC frameworks and principles to inform data management protocols and processes; IPLC guidance influences how, what, who and where research is conducted and data is managed; publication standards require documentation of community support, participation and approval for publishing data and authorship. |
| Responsibility | Enable capability and capacity sharing for research design and digital infrastructure | 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 | Record the Traditional Knowledge and biocultural labels in metadata; ensure local review of draft publications before dissemination; identify and address sensitive data, including privacy issues for individuals and communities. |
| Data-generating resources for languages, worldviews and lived experiences | Use the local and Indigenous languages; link research to community worldviews; upload data with appropriate metadata labels in culturally accessible formats (digital storytelling, seasonal calendars, visual art forms, etc.). |
| Community-defined benefit sharing | 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 | Assess research using Indigenous ethical frameworks; community-defined review processes and appropriate reviewers (for example, community advisory boards) for activities delineated in data management plans. |
| Maximize benefits from the perspectives of IPLCs | Researchers explain benefits to IPLCs; identify and contribute to community-defined benefits; disclose potential financial gain and share benefits with communities from research outputs and/or economic value of data. |
| Minimize harms from the perspectives of IPLCs | Use IPLC ethical frameworks; community-defined code of conduct is accessible; data-access protocols consider the potential for community harm and remedied through sharing data; ensure ongoing consent. |
| Data governance accounts for potential future use | Apply community protocols for infrastructure, metadata and secondary use; include Traditional Knowledge and biocultural labels and metadata fields for community and/or tribal affiliation; use community guidelines for the use and reuse of data; allow data removal and/or disposal requests from aggregated datasets; record and recognize provenance. |

#### 

#### 7.4.3 Engagement Strategy

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

During LBA, the SSC met twice annually and served as a clearinghouse for information across national projects. This committee had a number of attributions including recommendation of projects for inclusion in LBA based on criteria such as subject matter, adequacy of counterpart arrangements, and capacity building plans. The SSC shouldered much of the burden that may have otherwise fallen to agency managers who had more difficulty interacting with their international partners regardless of an abundance of good will. Some existing organizations such as the Congo Basin Science Initiative can already help with coordination and the still extant Brazilian LBA (the SSC still exists but it is not effectively international) can serve as partners for coordination of scientific studies.

***Indigenous Peoples and Local Communities***

* [Draft being co-written (in multiple languages) can be found here](https://drive.google.com/drive/u/1/folders/1Gw5jlwLzT7Z_KHRGMwto6nnl4nSpxRIX)

Even before the science definition team was brought together, the NASA Carbon Cycle and Ecoystems Office began consultations with Canadian First Nations and Alaskan Indigenous groups. ABoVE proactively engaged with first nations members to finalize the experimental design in Phase 1, before field activities began. The ABoVE team continued engagement with first nations members to update them on activities, particularly related to relevant disturbances (e.g., fires). For example ABoVE prioritized revisiting burned areas and providing information to help communities understand, adapt to, and overcome disasters. PANGEA will build on important lessons learned from the ABoVE campaign. The process of co-production began during the scoping of PANGEA and the writing of this white paper, which has been carried out in collaboration with Indigenous leaders from the Global Alliance of Territorial Communities (GATC), the Rights and Resources Initiative, XYZ. If PANGEA is selected, co-production with Indigenous Peoples and Local Communities will begin immediately and will be sustained throughout. [1-2 sentences about the what - science priorities, sites, training, applications]

***Women***

* Address gender balance overall. Highlight specific efforts PANGEA could take to address this and key performance indicators we’ll track over time.
* Gender-responsive vs gender transformative (is 9 years enough to transform a system?) acknowledge that we may not transform the system in 6-9 years, but describe the type of impact PANGEA would like to achieve

***Scientific Institutions***

For the purpose of this White Paper, we use the term scientific institutions primarily for universities, colleges, national laboratories, national professional institutions, and research institutes that through their leaders, faculty, researchers, and students are fundamental partners of PANGEA. PANGEA seeks to partner with scientific institutions located or with research expertise related to any part of the pan tropical forest region to collaborate and carry out its proposed research programs. This partnership will establish a world leading network of research experts and scientific institutions collaborating in response to the grand environmental challenges in the Pan Tropical Forest region due to global atmospheric warming and changes in land use. A particular interest of this partnership is to facilitate the co-development of knowledge and whenever necessary to do technology transfer to generate capacity and capability building in local and regional institutions. One overarching goal of the partnership is to train the next generation of technical personnel and scientists. This partnership seeks to focus on:

* Co-development of the research, analysis, and potential applications of the proposed programs by PANGEA.
* Identification of field sites, research infrastructure, and capabilities that are critical to achieve PANGEA proposed research goals.
* Co-production, sharing, and management of data, development of data infrastructure, equipment, and management expertise at local and regional institutions; creation of regional or national data banks to curate field and remote sensing data, and numerical model outputs so that the emerging knowledge can be integrated with and applied to regional and national demands for the socioeconomic development and policy development.
* The strengthening and broadening of the state-of-the-art research infrastructure and instrumentation for the local and regional scientific institutions to be able to develop and carry out long-term critical research plans
* The design and implementation of strategies to do capacity building for faculty and early career researchers at local and regional universities and research institutes to train and guide the new and diverse generation of scientists at local and regional institutions (for instance, co-lead technical workshops to train junior research faculty and students, and create visiting scholars programs at participating US-based scientific institutions).

Based on ongoing efforts, engage national governments and relevant government agency leaders to showcase benefits and expected impacts to generate financial and policy support for PANGEA related programs in their jurisdictions.

***Government agencies***

* Policymakers
* Administrators and program directors of government funding agencies
* At national and sub-national levels

***Non-governmental organizations***

* International
* Local

***Intergovernmental organizations***

***Private sector***

We use the term Private Sector to refer to for-profit entities of all sizes that are privately owned and managed. Private sector entities relevant to PANGEA include, but are not limited to; legally-registered (a) agribusiness which cultivate and/or will harvest agricultural, timber and forest non-timber products; (b) extractive industries which alter land cover and/or below-ground ecosystems in search and extraction of oil, minerals, metals and other products from the ground; (c) energy companies that alter ecosystems by installing equipment on or below the surface of the ground; (d) big data companies that develop software or hardware that facilitates the collection and/or analysis of ecosystem data (e.g. forest carbon, biodiversity, etc.); (e) conglomerates and financing institutions that invest in, buy, and/or sell any of the aforementioned types of companies; and (f) companies involved in ecotourism. Although the scope of companies deemed relevant may be vast, the profile of companies present in each landscape where PANGEA is implemented will vary ranging from corporates to SMEs, cooperatives, and associations. This section describes a basic engagement strategy that can be adapted in each context.

Private value chain actors are under increasing legal pressure to comply with social, economic, and environmental standards and regulations. On the other end of the corporate responsibility spectrum, a growing number of companies strive to surpass minimum standards, potentially to improve competitiveness and sustainability in production areas, to report positive socio-economic changes to customers and clients, plan more efficient allocation of resources for future projects and improve accountability. This has fueled an increasing demand amongst private sector entities for Earth observation and ground-based data related to ecosystem extent, structure, function, and condition, as well as the social, economic, tenure, and governance systems that may impact ecosystems and communities. More specifically, many private sector entities seek data addressing (1) soil health and fertility, (2) land use (including forest) and land use change, (3) fire risk and occurrence, (4) ecosystem carbon stocks and greenhouse gas emissions, (5) fresh water availability and consumption, and (6) biodiversity conservation and enrichment.

Governance and market mechanisms that drive this demand include national and regional legislation (e.g. US Lacey Act, FLEGT, EU DR), international agreements (e.g. UNFCCC Kyoto Protocol, Paris Agreement, New York Declaration on Forests, UN CBD Aichi Targets, Bonn Challenge, etc.), carbon markets (e.g. voluntary, Clean Development Mechanism), certification schemes (e.g. FSC, Fair Trade), and industry-led associations (e.g. Roundtable for Sustainable Palm Oil / Biofuels / Cocoa, etc.). Evidence-based data, applied scientific research, capacity building and technical assistance is needed for private sector to move beyond commitments to action PANGEA’s engagement with the private sector has five objectives:

* Strengthen the use of Earth observation data to understand the impacts of companies on ecosystems and monitoring their degradation, mitigation and/or ecosystem enhancement efforts
* Develop standardized methodology/protocols for land use change, forest cover, fire alerts)
* Engage the private sector in a collaborative network, based on best practices and lessons learned and geared toward improving the collection, analysis, and sharing of ground-based data related to ecosystem extent, structure, function, and condition, as well as the social, economic, land tenure, and governance systems that may impact ecosystems and livelihoods.
* Capacity building and technology sharing/development
* Targeted dissemination of research outcomes via business briefs…

Corporates and value chain actors can be major contributors to GHG emissions and biodiversity loss. However, without those actors it will be all but impossible to put the agriculture sector on track towards net zero and sustainability. Engaging the private sector in information and data sharing, fostering a business-friendly collaborative learning environment and providing ad-hoc (practical, operational?) capacity building and technical assistance could enhance the long-term impact of PANGEA (beyond the duration of the program’s funding) on people and nature in areas of operation.

***Foundations & Donors***

← Funding agencies or foundations?

* Public (USAID, Sida, NORAD, etc.)
* Private (e.g. Bezos)

### 7.5 Cost Elements

[Will be included in the final white paper]

* We need money for XYZ
* The determination of whether PANGEA will pursue threshold, baseline 1, or baseline 2 will be decided based on available NASA funds and match funding during the Concise Experimental Plan phase
* Even in spite of last minute elements beyond the team’s control, AfriSAR-2 was executed on time and at cost and data were collected.
* **Cost** - Leveraging additional funding sources
  + Related relevant NASA funding opportunities
    - Topical Workshops, Symposiums, and Conferences (TWSC) in Space and Earth Sciences and Technology
    - ARSET, ….

(move Required resources here)

### 7.6 Co-funding Opportunities

PANGEA is designed to leverage a Terrestrial Ecology investment at its core. The optimal, baseline, and threshold mesaurements defined in Section 6.2 are a stand-alone NASA campaign with no dependencies. However, given the urgency and importnace of the topic, and such widespread interest from the community, there is strong potential to match (double or triple) NASA’s contributions. During the scoping effort, the PANGEA leadership team has already made significant strides towards securing diverse sources of funding to leverage NASA’s potential investment, to the benefit of the US taxpayer. Resources from other U.S. government science, development, and conservation agencies, private foundations, international governments, and philanthropists can support complementary activities that are outside of NASA’s scope, including direct support for international partners and taking NASA Earth Science to Action efforts to implementation. Opportunities to leverage additional support from partners interested in teaming up with NASA include example partners listed in Table X. For further details, see Appendix X - Letters of Support.

The PANGEA team will work with other supporters to detail their contributions while drafting the Concise Experimental Plan. This process will include defining activities and funders to ensure support is complementary and not duplicative, streamlining management, communication, and oversight between donors, and addressing any data security concerns. PANGEA hopes to be a leader in operationalizing blended financial support to Terrestrial Ecology projects and to provide learnings to advance such partnerships with NASA in the future. To do that, PANGEA will seek to answer the following question:

* *How can diverse funding institutions work synergistically to support the advancement of remote sensing and terrestrial ecological research?*
* *How can complementary funding enhance NASA’s work?*
* *What data sharing and security approaches work when there are multiple funders?*
* *How can reporting and communications be streamlined?*

| **Table X.** PANGEA co-funding opportunities. | | | | |
| --- | --- | --- | --- | --- |
| **Remote Sensing** | **Data Hosting** | **Research** | **Capacity Building** | **Applications** |
| NASA TE | NASA TE | NASA TE | NASA ARSET | NASA SERVIR |
| AGEOS | DAACs | NASA R&A more broadly | NASA DEVELOP | Bezos Earth Fund |
| ESA | AmeriFlux | NSF | NASA SERVIR | NICFI |
| INPE | ICOS | DOE | NASA Harvest | WRI |
| other space agencies | other | UK NERC |  | Moore Foundation |
|  |  | EU...? |  | USAID |
|  |  | FAPESP |  | **other donors** |
|  |  | Schmidt Sciences |  |  |
|  |  | Moore Foundation |  |  |
|  |  | other |  |  |
| NASA TE |  |  |  |  |
| NASA other |  |  |  |  |
| US government |  |  |  |  |
| International govt |  |  |  |  |
| Other |  |  |  |  |

### 7.7 Open Science - Data Management and Sharing

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

PANGEA will integrate data streams from multiple measurement systems, partners, countries,

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

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

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

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

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

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

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

Data provenance and reproducibility are important aspects of open-source science. Sampling protocols, metadata, data cleaning, codes, algorithms, and workflows associated with data creation, processing, and validation for PANGEA will be made openly available to the extent possible. Active code development will ideally be through open collaborative platforms, like GitHub, when appropriate. PANGEA will establish consistent formats and practices for data and metadata and optimization for cloud-based access and analysis, especially for emerging types of data, like drone-based datasets. These activities will work with, rather than attempt to replicate, existing data- and disciplinary-specific efforts. For example, FLUXNET XYZ.

In addition, the drone XYZ.

For example, LBA

For example, ATFS

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

PANGEA will leverage and integrate with existing and emerging capabilities and systems offered by NASA Earth Science Data Systems as much as possible. These include the Distributed Active Archive Centers (DAACs) for airborne data, DAAC tools and services to make airborne and orbital data easier to use for terrestrial ecology research, NASA’s Visualization, Exploration, and Data Analysis (VEDA) platform (<https://www.earthdata.nasa.gov/esds/veda>), and ongoing efforts to coordinate data standardization and protocols. PANGEA is an opportunity to harmonize protocols across research communities to support scaling. As an example, the SBG VSWIR Terrestrial Vegetation algorithm team is developing data collection protocols, airborne data extraction and processing strategies, and database structures that will allow community generated joint airborne-field data collection to be more easily integrated into the model training datasets needed to improve algorithms for underrepresented ecosystems. Another example is contributing collected LiDAR data to the NISAR cal/val network. By engaging and partnering with these types of activities early, PANGEA will be well positioned to both contribute to mission algorithm generation and verification activities, as well as ensuring that tropical ecosystems in these basin ….

[ Include text regarding models ]

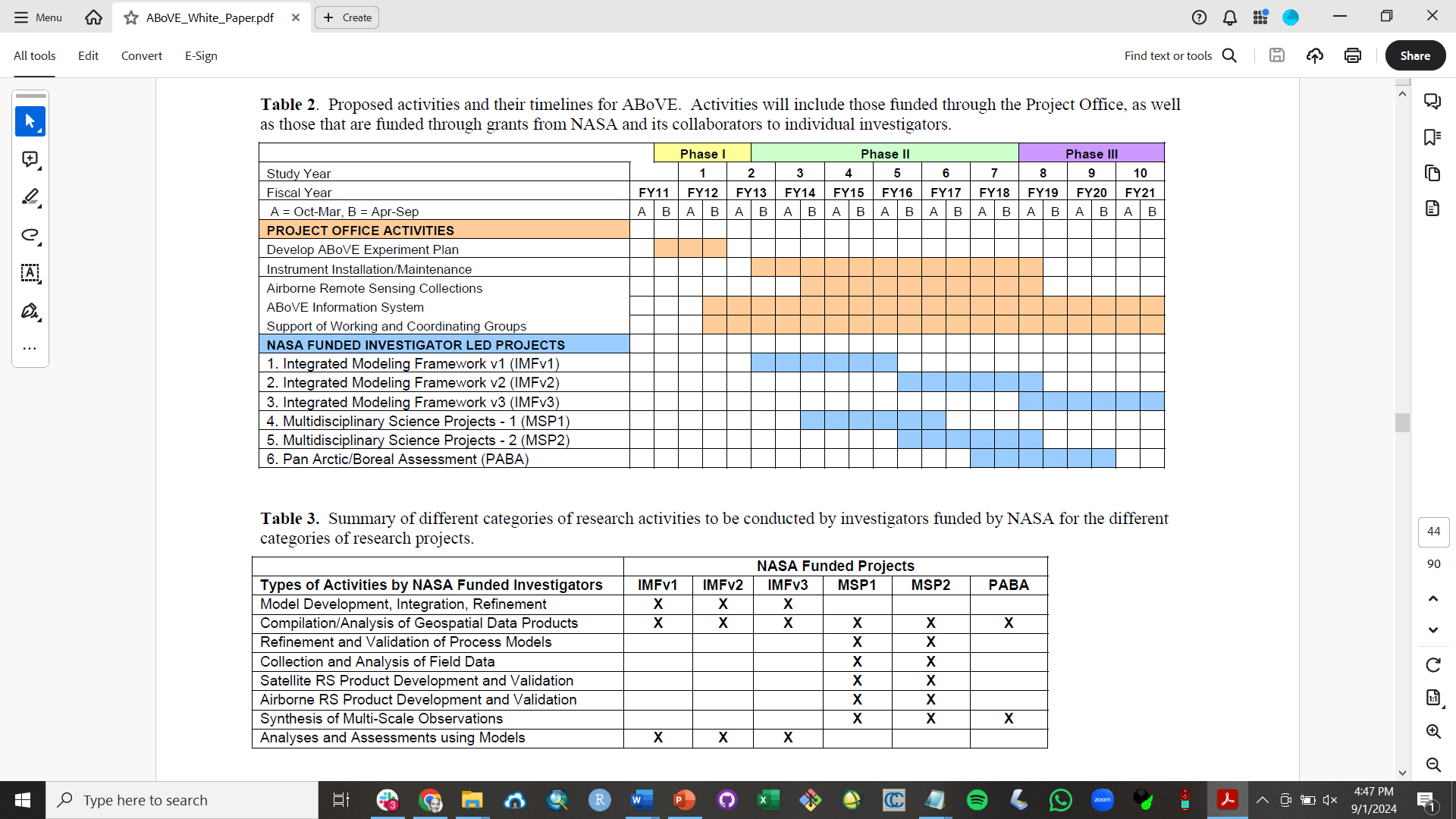
PANGEA will develop an open **cloud-based data analysis platform** for PANGEA investigators to support open and collaborative research. PANGEA’s data analysis platform will be based on successful science clouds implemented by ABoVE, SHIFT, BioSCape, and NASA’s Multi-Mission Algorithm and Analysis Platform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

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

### 7.8 Timetable

(number of years?)

* We need to develop tables like Table 2 & 3 in the AboVE white paper (copied below for reference)



### 7.9 Risk and Risk Mitigation / Risk Assessment

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

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

1. Risks to health and safety

2. Risks to meeting science objectives

3. Risks to meeting community engagement and applications objectives

**Health and Safety:**

The project will keep apprised of health and safety guidelines issued by <US source for this information> for the study areas and will consider changes in risk level under that 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 campaign, following <aircraft safety guidelines> for aircraft operations and on the ground. Given that many of the proposed study regions are tropical forests which include a risk for malaria and related diseases, the project will ensure participants are advised on relevant vaccines and medical treatments prior to participation in the campaign.

**Meeting Science Objectives:**

Given that the study areas are located in different countries, the project will work proactively to <insert brief description of MOU’s from above>. While using NASA aircraft for the airborne measurements have certain benefits, use of these aircraft require diplomatic clearance in both the country with the study area and all countries the NASA aircraft lands in during transit (and also uses airspace?), and there is a risk of last-minute not getting diplomatic clearance for the NASA aircraft (which must happen within x number of days of the flights). In addition, as NASA aircraft are operated by US civil servants, there is a demonstrated risk of a US government shutdown delaying or canceling science flights, especially in the October-December timeframe. PANGEA will consider these and other risks, and may consider using commercial aircraft to mitigate these risks.

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

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

## 8. Enabling Earth Science to Action

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

### 8.1 Applications of PANGEA research outputs

#### 8.1.1 Climate Change and Carbon Monitoring

| Science question | Research application | Partners/channels for implementation |
| --- | --- | --- |
| Q1, Q4 | Improving carbon accounting for credits and climate change mitigation |  |
| Q2, Q4, Q6, Q7 | Improving carbon flux predictions for global climate predictions (IPCC) |  |
| Q1, Q7 | Improving precision around impacts of forest loss and gain on carbon sequestration |  |
|  | Deforestation and degradation alerts - associated with drivers?   * Mining, roads, urbanization, etc. to be used by local and Indigenous communities and/or jurisdictional governments | SERVIR, |

Carbon mapping is critical for climate change projections and for improving measurement, reporting, and validation of carbon credits, offering clear applications for PANGEA data, analysis, and methodological improvements.

Improving climate change projections, especially decreasing uncertainty around carbon fluxes of tropical forests, tropical land use change, and tropical forest responses to climate change are critical to deliver per the National Science and Technology (NSTC) Fast Track Action Committee (FTAC) on Climate Services March 2023 report. Results from PANGEA will improve our understanding of the carbon content of tropical forests, currently a significant source of uncertainty in the global carbon budget in the following ways:

Improving carbon accounting

Improving carbon flux predictions

Increasing the precision of estimates of carbon sequestration impacted by forest cover change

* Carbon mapping
  + Carbon credit Standards, uncertainties, harmonization
  + Do trade agreements and market policies (ex. EU Deforestation Regulation, African Continental Free Trade Area Agreement) between Global North/South countries affect SES?
  + Refining predictions, specifically IPCC, to make them more accurate
    - Expected changes to carbon stocks under climate change
* Mapping of risks to carbon stocks in the tropics - important for carbon markets

#### 8.1.2 Biodiversity Conservation

| Science questions | Research application | Partners/channels for implementation |
| --- | --- | --- |
| Q10, Q11, Q12 | Biodiversity mapping to support landscape connectivity |  |
| Q5, Q6, Q7, Q19 | Biodiversity mapping to support tropical forest restoration |  |
| Q5, Q10, Q11, Q12 | Empowering and elevating Indigenous, local, and traditional communities |  |

The rate of global biodiversity loss is intensified by a poor understanding of the emergent contributions of biological assembly to the structure and function of ecosystems. Throughout the evolutionary history of life on Earth, the tropical biosphere has served as an “engine” for generating biodiversity (Antonelli et al., 2015) and remains identified as the contemporary biodiversity hotspot. Applied Biodiversity science in the tropics has the potential to reveal reciprocal social-ecological mechanisms preserving resilient global biodiversity hotspots, and inform strategies for local-scale adaptation and resilience to climate and land-use change.

The Earth Science to Action strategy urges that now is the time for the Earth information of global biodiversity collected and archived by NASA to be applied towards the existing gap between technological advancements and the needs of society to adapt resilient strategies.

International goals and standards for global biodiversity recovery will make considerable progress with large-scale observations across gradients of ecological habitat and function intactness in diverse tropical forests. Participatory land use planning with NASA Earth Observation that integrates biodiversity considerations can empower collaborative users to analyze and then effectively apportion the spatial and temporal distribution of land use activities. The 2030 targets for the Global Biodiversity Framework ambitiously commences with the goal to ensure all areas are under holistic land use planning to reduce biodiversity loss in areas of high biodiversity importance while respecting the rights of indigenous peoples and local communities (CBD 2030). The incredible spatial and temporal coverage of active and planned NASA Earth Observatory satellites motivates collaborative land use planning with accessible capacity exchange between traditional ecological knowledge and spectral data interoperability. PANGEA proposes a unique application of Earth Science to Action through direct mapping of biodiversity in the tropics which is currently insufficient and a model region of high biocultural diversity to determine which authorities and stakeholders, and at which levels, play an active role in spatial land use planning. Active partnerships in the tropics developed through the scoping campaign can address Target 2 & 3 of the GBF by restoring degraded tropical ecosystems to make progress towards restoring 30% of all global degraded ecosystems (CBD 2030). A decadal field campaign structures an experimental approach to explore the temporal role of adaptive management for biodiversity, especially for considering potential climate projections and adaptation costs to prioritize options for reducing vulnerability to environmental, social, and economic impacts of the various drivers of change in nature and its contributions to people. A process for integrated land use planning informed by frontier biodiversity remote sensing with the NASA Earth Observatory will be developed through active partnerships with diverse tropical communities to create accessible data platforms. In accordance with Target 8 of the GBF, the objective of these holistic platforms is to inform nature-based solutions and ecosystem-based approaches to strategically evaluate possible mitigation, adaptation, and disaster risk reduction and management strategies (CBD 2030). NASA remote sensing of Essential Biodiversity Variables (EBVs) like the biological effects of fire disturbance and irregular inundation are at the highest priority identified by the Group on Earth Observations Biodiversity Observation Network (GEO BON; Skidmore *et al.*, 2021). During the scoping campaign, irregular fire and flood disturbances were identified as the most pressing variable for partners and land managers (Figure or Image on Disturbance,ie. Rio Grande do Sul).

Partnerships with key collaborators identified in the scoping campaign will accelerate the development of user platforms for protecting biodiversity and its contributions to people. In June 2024, a joint workshop with the Governor’s Climate and Forests Task Force included a presentation from the scientific lead of MapBiomas Dr. Julia Shimbo proposing science-informed biodiversity management and conservation strategies with mapping and monitoring of land cover, land use, surface water, and fire scars. Partners like the Max Planck Institute, Smithsonian Tropical Research, and other tropical organizations contribute comprehensive surveys of biodiversity in tropical forests that require technical processing capacity from NASA and partners to develop accessible and user-friendly platforms. This global network of pan-tropical scientists will contribute significantly to strategic NASA Earth Science to Action goals for closing the gap between rapidly advancing technology and the needs of society to access science-informed decision-making platforms. PANGEA emphasizes a historically understudied tropical biome to empower a region most vulnerable to the consequences of climate and land use change while also acknowledging the global contributions of tropical biodiversity to resilience in the interconnected Earth System.

* **biodiversity-inclusive spatial planning and ecological connectivity**
* Speak to the Kunming-Montreal Global Biodiversity Framework - PANGEA can directly support mapping biodiversity in the tropics which is currently insufficient, but necessary to support Target 1 of the KM GBF - [**TARGET 1**](https://www.cbd.int/gbf/targets/1)**: Plan and Manage all Areas To Reduce Biodiversity Loss** 
  + **Could also support** [**TARGET 2**](https://www.cbd.int/gbf/targets/2/)**: Restore 30% of all Degraded Ecosystems**
* Material here pulled from [IPBES Scoping report for a methodological assessment of integrated biodiversity-inclusive spatial planning and ecological connectivity:](https://files.ipbes.net/ipbes-web-prod-public-files/2024-06/decision_10_1_annex-ii.pdf) 18. Chapter 2: Implementing target 1 of the Kunming-Montreal Global Biodiversity Framework on biodiversity-inclusive spatial planning (indicative length: 25,000 words). Chapter 2 will focus on target 1 of the Kunming-Montreal Global Biodiversity Framework. It will highlight the importance of including biodiversity in all spatial planning (including urban planning) for conserving and enhancing nature and nature’s contributions to people, including outside protected and restored areas, and the role of connectivity in enhancing the resilience of such areas in order to meet goal A of the framework. Chapter 2 will also focus on the role that spatial planning can play in relation to the elements of target 1 that refer to “effective management processes addressing land and sea use change” and in relation to bringing the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero by 2030, while respecting the rights of Indigenous Peoples and local communities and the achievement of the Sustainable Development Goals. It will explain the need to meet target 1 in order to meet other targets of the framework, including targets 2, 3, 8, 10 and 12, and will explain the interlinkages. The chapter will show how target 1 provides a spatial context for those other targets, and it will explore the importance of spatial planning for reducing trade-offs and increasing synergies between different uses of land (including inland waters) and sea in the context of the nexus among biodiversity, food, water, health and climate change, taking into account different economic activities and the wide range of sustainable practices available at the regional and national levels to scale up positive impacts. 19. The chapter will take a landscape/seascape approach to exploring the various demands and interests involved as well as the interactions between them. It will assess how biodiversity-inclusive spatial planning influences biodiversity and nature’s contributions to people. It will assess applications in different contexts, such as urban planning, protected area and ecological network planning, restoration planning, regional land use planning, marine and coastal planning, and other types of integrated spatial planning, including customary practices of Indigenous Peoples and local communities. The chapter will assess available methods and indicators for measuring progress in biodiversity-inclusive spatial planning and will, as necessary, provide options for other indicators to complement those of the monitoring framework for the Kunming-Montreal Global Biodiversity Framework.
* The Global Biodiversity Framework reported four long-term goals for 2050 and 23 targets to be achieved by 2030 (CBD, 2022) of which two are directly related to the Pangea. Goal A focuses on expanding the area of healthy ecosystems by maintaining, enhancing, or restoring the ecosystems, through the prevention of species extinction, and preservation of genetic diversity. Goal B emphasizes the sustainable utilization and management of biodiversity and recognizes nature's contributions to people. The 23 global targets aim to reduce threats to biodiversity, meet people's needs through sustainable use and equitable benefit sharing, and develop tools for conservation implementation.
* IPBES and Convention on Biological Diversity
* [Global Biodiversity Framework 23 targets for 2030](https://www.cbd.int/gbf/targets)
  + Reduce biodiversity loss
  + Restore 30% degraded ecosystems

#### 8.1.3 Agriculture and Livelihoods

| **Science questions** | **Research application** | **Partners/channels for implementation** |
| --- | --- | --- |
|  | Intensifying agricultural production and improving yields | SERVIR, IITA, NASA Harvest: remote monitoring of farming practices to assess efficacy of interventions; remote assessment of crop yields |
|  | Increasing the sustainability of agricultural production, including under climate change | SERVIR, IITA, Bioversity/CIAT: drought and flood monitoring, water accounting; remote assessment of agricultural practices |
| Q3 | Improving traceability of agricultural commodities | Bioversity/CIAT: |
|  | Disaster Alerts & Response (e.g., fire, flooding, drought) | SERVIR, IITA, Biodiversity/CIAT: |

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

***Improved intensification*:** Spatial monitoring of crops offers the possibility to assess production levels in real time, potentially comparing intervention and control areas across significant distances to provide critical data on the efficacy of intensification efforts. 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.

***Increased sustainability and capacity for adaptation:*** Agriculture under climate change will require farmers to grow more food under different circumstances, including unpredictable precipitation and periods of intense heat. As a major contributor to climate change, there is also a movement to make agriculture more sustainable, through decreased use of fertilizers and pesticides, curtailed water use, and increased efforts to control erosion. Colleagues from partners IITA, Bioversity-CIAT, and the International Water Management Institute (IWMI) have already shared thoughts on how PANGEA products could be useful for water accounting and

***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. PANGEA’s assessment of disturbance regimes will help refine processes for ensuring deforestation free supply chains. Methodological improvements from PANGEA’s data acquisition may also improve our ability to use remote sensing tools to distinguish between complex agroforestry and secondary forests, a critical current gap that hamstrings the ability to recognize and map coffee and cocoa farms that use more sustainable shading methods, allowing them to prove compliance with deforestation free commodities requirements.

PANGEA is also well-positioned to impact other livelihood sectors, like payments for ecosystem services and non-timber forest products*.*

To deliver on potential gains for food security and livelihoods, PANGEA has engaged agricultural research partners like NASA Harvest, the Consultative Group for International Agricultural Research (CGIAR), including the International Institute for Tropical Agriculture, and the Alliance Bioversity and the International Center for Tropical Agriculture (CIAT).These research partners have already shared the kinds of data that would be useful for their research into agricultural production for inclusion in PANGEA’s data acquisition priorities. As an example, IITA has a robust Partnerships for Development arm, which specializes in translation of findings from their research into practice, and builds on decades of experience with private sector and government partners to guarantee the translation of research into practice.

* **Sustainable agriculture and deforestation-free supply chains (ultimately supporting intensification efforts in the tropics to reduce defor pressures from extensification - requires improving yields and providing alternative livelihoods)** 
  + Yield and crop type mapping
  + Water use and supply
  + Precision ag
  + Focus on applications that support Early Warning, Early Action, Early Finance - related to drought, flooding, pest impacts on ag in the tropics
* Supply chain traceability and management / Supply chains / Value chains - EUDR
* Bioeconomy
  + Non-timber forest products
* Ecosystem service mapping
  + What ecosystem services are readily mappable via remote sensing and/or integration with ancillary data and information (LEK, TEK, IEK)?
  + What ecosystem service mapping capabilities could be advanced by PANGEA?
* Use the information we gathered during the DC workshop session on flows of information → specifically call out we worked to engage potential end users from the beginning. This should make the applications suggestions more realistic
* Draw upon lessons learned from ABOVE (Debjani Singh, Libby Larson, Kimberly Minor). Divide all the user cases into different stakeholder group. These groups will have different needs and how we will address these needs. Maybe have 4-5.
* Sort potential partners into groups
* Visualization of partners and different types of uses
* **what's the outcome we want at the end of all of this and how are going to measure it at the end?**
* Be realistic about data expectations from airborne campaigns
  + not data that's going to be around beyond the campaign (for the most part)
  + more episodic than is necessarily needed

### 8.2: Process to enable Earth Science to Action

Substantive interest alone is insufficient to guarantee that NASA products will be used. Effective research application requires that end user communities be identified and engaged early, and must be partners in research design and tool development. This requires advanced planning, intent, and resources. That is why PANGEA has invested since the inception of the scoping phase in laying the groundwork for research translation. Specifically, PANGEA addresses the following Guiding Principles from NASA’s ES2A Strategy (2024-2034):

* **Amplify impact through partnerships:** PANGEA’s investment in community engagement has attracted a diverse array of partners, including international governments, donors, and local communities (see *Section 7.3* for details about community engagement). These partners include potential users, data contributors, and potential funders for applications—the last of which will help make PANGEA’s work cost effective by supplementing NASA’s Earth Science resources with funds to support capacity building, community engagement, and research translation (see [*Section 7.6*](#_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 9*](#_8t6ay0v9gizk)) help ready the next generation of scientists.
* **Use a balanced approach:** PANGEA builds on prior decadal campaigns both for science questions and data (e.g. LBA), and for process improvement (e.g. LBA, ABoVE). By asking bold and critical science questions that were formulated based on prior campaigns and today’s needs, PANGEA maximizes value.

During the Scoping Phase, PANGEA led extensive outreach to potential users (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 sometimes difficult gap between what science questions are being asked and what end users need for decision making. Community engagement is central to PANGEA’s ES2A strategy (see *Section 7.3* for details on how PANGEA will engage the community). This process is especially important for a decadal campaign that will likely not offer users data sets that meet their needs. PANGEA is aware that with community engagement comes with the risk of creating expectations that cannot be met by the project, largely because the airborne data being collected is spatiotemporally limited in scope and will be more episodic than is needed to meet many user applications and decision-making needs. PANGEA will make every effort to repeatedly and clearly convey the impact limitations of the airborne data. PANGEA will also endeavor to leverage the momentum created by an airborne campaign to create, grow, and strengthen a new and more diverse user community for NASA Earth data beyond the airborne campaign.

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

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

During the decadal campaign, PANGEA will use the following activities to facilitate translation of research to action:

* + Include conversations with end users (user needs assessment) as part of the Concise Science Plan
  + Environment scan to find existing tools that could integrate data

Decision Support Systems / Impact & Vulnerability Assessments

NASA, along with other domestic and international agencies, are increasingly leading an important role in the development and implementation of decision support systems. These systems are designed to incorporate the results from research activities within a modeling framework in order to provide information to land managers, regional governments, among others who require information in a specific context.

* The PANGEA Information System (PIS) will provide a platform to conduct further research on the use of satellite information products to support decision making
* The PIS will also 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
* The Integrated Modeling Framework will provide the basis to create unique information products based upon integrated assessments.

There is increasing recognition by NASA and other U.S. and international agencies on the need to co-develop decision support systems to exchange information and analysis with land managers, regional governments, and other policy and decision makers.

* Development of programs within national and international land management agencies whose mandate is to provide data required for climate and land cover change monitoring.
* Aligned with program mission to refine and develop the same process-driven models that will be the focus of research in PANGEA
* Two-way benefits: Similarity of interests aligns opportunity to coordinate modeling activities and associated research

## 9. Capacity Building, Training, and Education

We strongly believe PANGEA can achieve an estimated 100 first-author papers from scientists in Africa. Reference Culotta et al. 2024

- NASA PANGEA campaign is enabling that

- the start of the giant tsunami

- NATUREA paper on flyover campaigns; PANGEA will turn that on its heads

- when PANGEA ends, these scientists will still be there

PANGEA is an important opportunity to increase understanding of Earth observations and expand the use of NASA Earth data, products, and services around the world. As PANGEA advances knowledge of tropical forests and their vulnerability and resilience to climate change, PANGEA will develop innovative methods, compile valuable datasets and produce critical findings that can help communities understand their environmental impacts and take urgent actions to mitigate and adapt to climate change. PANGEA shares NASA Earth Science’s strategic goal of advancing and integrating Earth science knowledge to empower humanity to create a more resilient world over the next decade (NASA Earth Science to Action Strategy 2024-2034). Strengthening capacity and investing in education associated with PANGEA is central to benefit local and national communities in the tropics. PANGEA will partner with existing NASA programs, as well as with local collaborating organizations, to plan and execute training activities that are appropriate for a range of potential trainees, including: students, early career scientists, the broader workforce, and Indigenous Peoples and Local Communities …..

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

The scope of each PANGEA capacity building, training, or education activity will depend on which individuals from which institutions are being targeted for training. Intermittently throughout PANGEA, a brief needs assessment will be carried out to assess what the community requires and desires in terms of capacity building, training, and education activities. The intention of this assessment will be to identify who needs what kind of development activities and what resources are available and what resources are needed to support any planned activities (e.g. host institution can provide venue and catering, instructors and teaching materials are needed). PANGEA is not funded to deliver capacity building, training, and education activities and therefore complementary funding will be sought to support these activities (tablexx??). Evaluating the needs assessment will help PANGEA identify which complementary funding opportunities are most appropriate to pursue.

The primary goal of PANGEA’s capacity building strategy is to strengthen and grow the NASA Earth data user community in the tropics. PANGEA’s airborne activities will generate a lot of excitement around the potential of remote sensing for ecological applications. While capacity building activities focused on teaching users how to access and analyze PANGEA’s airborne data products will be essential to ensure these data produts are applied to their full potential, it is PANGEA’s intention to leverage the momentum created by the airborne campaign to promote broader application of NASA orbital data sets, 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. As such, all of PANGEA’s capacity building activities will use field, airborne, and orbital NASA Earth data, and instructors will constantly remind users that the potential of these multi-scalar datasets is far greater than if only one or two types of data are examined alone. An added benefit of this approach is that users will know, from the beginning, that while PANGEA airborne data is limited in spatiotemporal scope, NASA’s satellite datasets can help fulfil their data needs. PANGEA’s approach to capacity building intends to build NASA Early Adopter user groups in the tropics - particularly for SBG and NISAR, but also for ESA missions like BIOMASS and CHIME.

PANGEA will draw upon NASA Earth Science’s strategy to “build capacity through an extensive and diverse set of partnerships, both traditional and new… [including with] national and international governmental agencies, academia, non-governmental and international organizations, the private sector, and philanthropies.” Here, we outline the “Enhanced Partnerships” PANGEA has already cultivated during the scoping campaign with other institutions involved in education and capacity building at local, regional, national, and global scales – with an emphasis on activities in the tropics.

1. NASA’s Applied Remote Sensing Training program (ARSET): ARSET offers training pitched at various levels of applied Earth observation users and with experience training both US and international participants. PANGEA would work with ARSET and the PANGEA science team to deliver a multi-part training webinar series. Additionally, PANGEA would hope to replicate the in-person training model trialled during BioSCape, that saw ARSET and the ORNL DAAC work together for the first time to deliver a 5-day in-person training in South Africa to conservation decision makers, university lecturers, and diverse researchers.
2. NASA’s Distributed Active Archiving Centers (DAACs): PANGEA hopes to emulate the success of EMIT working with the LP DAAC and BioSCape working with ORNL DAAC to produce capacity building materials, particularly training notebooks, and conduct training workshops at conferences. The materials produced for these workshops will be tailored to the needs of the PANGEA science team, and therefore especially useful to them, but will be appropriate and engaging for a broad audience. Delivering these materials at conference workshops, such as AGU, ESA, and ATBC, will help to engage diverse researchers at a variety of career stages and with various levels of prior engagement with NASA Earth data.
3. NASA’s DEVELOP program: DEVELOP partners with decision makers who are interested in using NASA Earth data to support their work. Each partner will have a DEVELOP team of 4-5 people work with them over 10 weeks to assess how NASA Earth data can help address their needs. The 10 week period can be renewed for up to 3 terms. DEVELOP proposals submitted by non-US PANGEA partner organizations can help develop capacity within partner organizations and may lead to the generation of applied data products. For example, during BioSCape, the South African National Botanical Insitute partnered with DEVELOP to help develop data products to map ecologically important riparian vegetation.
4. NASA Global Learning and Observations to benefit the Environment Program (GLOBE): GLOBE delivers educational activities to K-12 students, teachers, and citizens. During BioSCape, GLOBE traveled to South Africa to deliver an educational program to 170 high-school students from 10 under-resourced schools and delivered a “train the trainer” program to high school teachers. The South African iteration of this program was a success, due largely to the tailoring of the program to the South African context, and with the train-the-trainer program likely leading to larger impact in the future. PANGEA intends to emulate this success, caplitalizing on the excitement surrounding an airborne campaign to engage the next generation of scientists in STEM.
5. NASA/USAID SERVIR: SERVIR works through hubs across the tropics to support sustainable development through capacity building and incorporating perspectives from women, Indigenous Peoples and their communities. PANGEA would work with SERVIR to develop custom services/data pipelines to serve the specific decision making needs of local partner organizations. SERVIR has an excellent Planning Toolkit that provides instruction on how to assess and deliver impactful interventions, and we hope to work with SERVIR and the PANGEA science team to execute this.
6. Indigenous Peoples Initiative:
7. Association for Biology and Tropical Conservation (ATBC) - 1-2 sentences about aligning with their training efforts - workshop at annual conference
8. NSF Research, Innovation, Synergies, and Education (RISE): The NSF’s new RISE program aims to foster transdisciplinary collaborations that engage the broader geosciences community to drive transformative discoveries, innovations in workforce development, and use-inspired solutions for urgent Earth system challenges. The program will specifically focus on supporting work that will build a resilient planet, and therefore there may be opportunities for PANGEA to engage with NSF around certain capacity building and training activities. The details of RISE are not yet available.
9. USAID’s Strategic Partnerships For Advancing Research And Knowledge (SPARK) program: SPARK awards are a new USAID mechanism to support research generation in collabroration with USAID partner countries. SPARK has a focus on collaborative work towards addressing international development challenges and values co-creation of knowledge as well as Collaborating, Learning, and Adapting practices. As such, PANGEA’s activities would be synergistic with this program, and we hope to encourage PANGEA partners and members of the science team to apply for this funding.
10. NSF Geoscience Opportunities for Leadership in Diversity (GOLD-EN): GOLD-EN is an NSF funding call that explicitly supports activities to increase and sustain including people from diverse backgrounds in the geoscience education and research community. PANGEA’s ethos is synergistic with that of this NSF program, and we hope that members of the science team and broader PANGEA community will apply for this funding.

As an international project, PANGEA’s biggest opportunity for capacity development and training is within the science team. PANGEA’s ROSES funding call would explicitly indicate that proposals co-developed with local researchers are more likely to be funded. This was done in the BioSCape funding call and was a significant contributor to ~50% of their science team being local. This co-development of research will enable skills and knowledge transfer within each project team, and create opportunities for the science team to learn from each other more braodly. Additionally, the PANGEA ROSES funding call would encourage proposers to commit time to co-mentor and co-supervise students and postdocs, further helping to build capacity. Once formed, PANGEA’s science team will abide by a Code of Conduct that has both advice for ethical and equitable collaboration as well as clear authorship guidelines that everyone must abide by. These guidelines will be based on the Contributor Role Taxonomy (CRediT, credit.niso.org), which values the diversity of roles that make a research product possible.

| Partner | Country | Regions active | Forms of capacity building | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Formal education (3 months or more) | In-person workshops & short courses | Online workshops & courses | Technical consul- tations with experts | Network- ing & learning events | Scholar- ships |
| NASA ARSET | USA | Global & Online |  | 1 | 1 |  |  |  |
| NASA ORNL DAAC | USA | Global & Online |  | 1 |  |  |  |  |
| NASA GLOBE |  |  |  |  |  |  |  |  |
| NASA SERVIR |  |  |  |  |  |  |  |  |
| NASA Indigenous People’s Initiative |  |  |  |  |  |  |  |  |
| NSF RISE |  |  |  |  |  |  |  |  |
| NSF GOLD-EN |  |  |  |  |  |  |  |  |
| USAID SPARK | USA | Global |  |  |  |  |  |  |
| ESA | EU | Global |  |  |  |  |  |  |
| One Forest Vision | France | Global |  |  |  |  |  |  |
| CEOS |  | Global |  |  |  |  |  |  |
| UN FAO | Italy | Global |  |  |  |  |  |  |
| UNFCCC | Germany | Global |  |  |  |  |  |  |
| University of Cameroon Yaoundé | Cameroon | Central Africa |  |  |  |  |  |  |
| WRI | USA | Global |  |  |  |  |  |  |
| PUCP | Peru | Latin America |  |  |  |  |  |  |
| University of Oklahoma | USA | Latin America |  |  |  |  |  |  |
| Penn State University | USA | Latin America |  |  |  |  |  |  |
| SilvaCarbon |  |  |  |  |  |  |  |  |
| SMACON | Nigeria | West Africa |  |  |  |  |  |  |
| Geospatial Girls & Kids | Cameroon | Central Africa |  |  |  |  |  |  |
| CIAT-Bioversity | USA | Global |  |  |  |  |  |  |
| Conservation International | USA | Global |  |  |  |  |  |  |

## 10. References

## 11. Figure and Photograph and Credits

## 12. Glossary

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

***Biodiversity***- tree functional composition, tree functional diversity, liana abundance, liana functional composition, microbial composition, megafaunal abundance, abundance of seed-dispersing animals, abundance and composition of flora and fauna more generally / Functional, phylogenetic, and taxonomic (think trait and spectral diversity and phylogenetic diversity likely at the genus and family levels), faunal and floral diversity

* More generally: Functional, phylogenetic, and taxonomic (think trait and spectral diversity and phylogenetic diversity likely at the genus and family levels), faunal and floral diversity

**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 in soils, vegetation, ….. Includes carbon dioxide (CO2), methane (CH4), and lateral flows of carbon.

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

***Ecosystem*** - PANGEA uses the IPCC working definition of ecosystion, which includes people as key organisms, thus including agroeocsystems 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*** - All the contributions, both positive and negative, of living nature (i.e. all organisms, ecosystems, and their associated ecological and evolutionary processes) to people’s quality of life.

***Environmental variables***- Current and past climate (amount and seasonality of rainfall, temperature, solar radiation, and more), geology, soils, topography (including elevation), current and past disturbance regimes (storms, flooding, drought, fire, etc.), current and past land use, and their interactions.

***Forest carbon stocks and fluxes*** - biomass stocks, woody productivity and woody mortality

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

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

***Forest function*** - GPP, NPP, woody productivity, ecosystem respiration, tree mortality, woody residence time, evapotranspiration, sensible heat flux, net radiation, water-use efficiency, carbon-use efficiency, nutrient-use efficiency, and nutrient cycling

***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.

***Landscapes -***

***Land-use change*** - deforestation, degradation, fragmentation, restoration, and regeneration

***Resilience -*** The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising 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/))

***[forest?] Resistance*** - Forest resistance to a certain disturbance type = the relationship between forest stand mortality rates and disturbance intensity - define more clearly

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

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

## 13. List of Acronyms

**AMSR-E** - Advanced Microwave Scanning Radiometer for EOS Mission

**CH4** - Methane

**CHIME** - Copernicus Hyperspectral Imaging Mission for the Environment

**CO2** - Carbon dioxide

**EMIT** - Earth Surface Mineral Dust Source Investigation

**ENSO** - El Niño Southern Oscillation

**FLEX** - Fluorescence Explorer Mission

**GHG** - Greenhouse gas

**IPLCs** - Indigenous Peoples and Local Communities

**ITCZ** - Intertropical convergence zone

**LCLUC** - Land cover and land-use change

**NISAR** - NASA-ISRO SAR Mission

**SBG** - Surface Biology and Geology Mission

**SST** - Sea surface temperature

**SWOT** - Surface Water and Ocean Topography Mission

**TRL** - Technology Readiness Level

**TIR** - Thermal Infrared

**UAV** - Uncrewed Air Vehicle

**VSWIR** - Visible to Shortwave Infrared

## 14. Appendices

### A - PANGEA Partners

* *Coordinating with existing external efforts - mechanisms and responsibility - link to existing mechanisms for coordination including CBSI, LBA, etc.*
* *Categorize potential PANGEA partners according to specific user groups*
* *Map geographically and thematically potential partners*

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### B - Engagement during the Scoping Campaign

The Community Engagement and Research Applications Working Group engaged with over 500 individuals from X number of countries across five continents during the PANGEA Scoping Campaign through (A) an international working group, (B) short information sharing events, (C) multi-day consultative workshops, and (D) bilateral meetings with potential partners.

(A) The Community Engagement and Research Applications (CERA) working group (1) was comprised primarily of students, researchers and professors from academic institutions, practitioners from non-governmental and intergovernmental organizations, and some private sector representatives. Similar to the other PANGEA working groups, CERA membership was open and advertised online, at PANGEA events, and within “word of mouth.” In total, approximately 100 individuals signed up to the CERA working group and participated in one or more of the 12 CERA meetings conducted online and/or contributed to the team’s collaborative documents. Many members also participated in CERA-relevant sessions at the PANGEA multi-day workshops in Cameroon, US, Brazil and Peru.

(B) The PANGEA Leadership Team engaged with X NUMBER OF PEOPLE through twelve information sharing events conducted on five continents. These events include 1-2 hour presentation and discussion sessions at international academic conferences (e.g. American Geophysical Union Town Hall, USA, December 2023; Ecological Society of America webinar, March 2024; European Geosciences Union presentation, Austria, April 2024), regional events (e.g. Smithsonian Tropical Research Institute, Barro Colorado Island 100th Anniversary Symposium presentation, Panama, June 2024; Congo Basin Forest Partnership 20th Meeting of the Parties presentation, June, 2024), and special meetings organized by the PANGEA community (e.g. Africa women’s session, April 2024; Meeting with Indigenous Communities in Panama, April 2024).

(C) The PANGEA Leadership Team organized four, multi-day regional scoping workshops that included sessions focused on community engagement best practices and regional demand and preferences for research applications. PANGEA Scoping workshops include a 3-day event in Yaoundé, Cameroon in February 2024; a 3-day event in Washington, DC in April 2024; a 3-day workshop in Manaus, Brazil in May 2024; and a 2-day workshop in Lima, Peru. All events were organized in close collaboration with local PANGEA partners representing the academic community, government agencies, and non-governmental organizations.

(D) The PANGEA Leadership Team and CERA working group members conducted bilateral meetings with 33 potential PANGEA partners, including. Many (ADD EXACT NUMBER HERE) have shared letters of support to confirm their interest in collaborating on the PANGEA program (if funded).

### C - Planned and Ongoing Research and Monitoring Activities

### D - Summary of Level II and III Ecoregions in PANGEA Study Region

### E – Summary of Airborne and Spaceborne Remote Sensing Systems for PANGEA

### F - Summary of PANGEA Participants

Detailed overview of PANGEA Community Engagement Activities

1. Community Engagement and Research Applications working group meetings online
   * February 13th
   * March 14th
   * March 21st
   * March 28th
   * April 3rd
   * May 15th
   * June 7th
   * June 27th
   * July 11th
   * July 25th
   * August 8th
   * August 22nd
2. Short (1-2 hour) information sharing meetings
   * Kick-off webinar, November 2023
   * American Geophysical Union (AGU) Town Hall, San Francisco, California, December 2023
   * Ecological Society of America (ESA) webinar, March, 2024
   * Information sharing (hybrid) meeting with Indigenous Communities in Panama, April 2024
   * Africa regional women’s session, online, April 2024
   * European Geosciences Union (EGU) presentation, Vienna, Austria, April 2024
   * Smithsonian Tropical Research Institute, Barro Colorado Island 100th Anniversary Symposium presentation, Panama, June 2024
   * Congo Basin Forest Partnership (CBFP) 20th Meeting of the Parties presentation, June, 2024
   * Congo Basin Institute, presentation, July, 2024
   * Ecological Society of America (ESA) update webinar, August, 2024
   * NASA Biological Diversity and Ecological Conservation meeting in Maryland, May, 2024
   * Association for Tropical Biology and Conservation (ATBC), Kigali, Rwanda, July 2024
3. Multi-day workshops
   * Africa Regional Consultation 3-day workshop, Yaoundé, Cameroon, February 2024
   * PANGEA Scoping 3-day workshop, Washington, DC, April 2024
   * Amazon Climate 4-day workshop, Manaus, Brazil, May 2024
   * PANGEA/Governors' Climate & Forests Task Force (GCFTF) Americans regional 2-day workshop in Lima, Peru, June 2024
   * Asia Regional Consultation X # of days? workshop, LOCATION?, July, 2024
4. Bilateral meetings with potential partners

### G - Letters of Support

1. Alliance Bioversity & CIAT  
   <https://alliancebioversityciat.org/>
2. Climate Modeling Alliance  
   Caltech, MIT, and NASA’s Jet Propulsion Laboratory  
   <https://clima.caltech.edu/>
3. National University of Piura, PERU  
   Agronomy Department  
   <https://www.gob.pe/unp>
4. PennState University, USA  
   Department of Meteorology and Atmospheric Science  
   <https://www.met.psu.edu/>
5. Society for the Protection of Underground Networks  
   <https://www.spun.earth/>
6. Université Catholique de Louvain  
   Earth and Life Institute  
   <https://uclouvain.be/en/research-institutes/eli>

Critical letters:

* ESA - one or multiple? - Elsa will work on this
* Ares - Elsa email Michael Schaepman & Andy Huni
* Other space agencies - connect with Pamela Collins about this ([pamela.collins@nasa.gov](mailto:pamela.collins@nasa.gov))
* State Department - Frances Seymour - if not letter, mention somewhere in white paper - Elsa will work on this
* USAID -
* USFS-IP - Michael work on this
* DOE - Michael work on this - in coordination with separate letter from NGEE tropics NGEE-Tropics - Michael work on this - with Robinson & Marcos - get from Jeff or Charlie
* GEO-TREES - Elsa will work on this -
* CongoFlux -
* NASA Harvest -
* NEON - Dana work on this
  + Work w AVIRIS and EMIT teams to standardize and harmonize datasets and advance algorithm development
* Users
  + Conservation International
  + WCS - Kemen
  + FAO regional offices - biodiversity, agriculture, climate resilience
  + Govt agencies:
    - ONACC - Elsa can work on this
    - Other ‘end-users’
* Roger Wakimoto - Elsa will work on this

Maybe important?

* Johnson Center & Langley? - pilots and other ppl who can speak to feasibility

### H - Stuff that’s beyond scope that could be developed in collaboration with PANGEA

* Ideas from PANGEA scopes that have been deemed beyond scope buy relevant
* List of complementary funding

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PANGEA Organizational Suggestions from 7.2 (much too much detail for now)

*PANGEA Participation Structure (LESS is MORE at this point)*

* + *Annual PANGEA Team Meeting*
  + *Working Group Membership*
    - *Co-chairs*
      * *Global N*
      * *Global S*
      * *Early Career*
    - *Members*
      * *NASA-sponsored PIs and researchers*
      * *Scientists funded by other organizations who have agreed to participate in PANGEA*
    - *Responsibilities*
      * *Synthesizing results of PANGEA research*
      * *Conveying results and addressing knowledge gaps to Modeling WG*
      * *WG Meetings as needed*
  + *Multidisciplinary “Coordinating Groups”*
    - *Remote Sensing*
    - *Field Studies*
    - *Modeling and Data Synthesis*
      * *Formed in Phase 1 of PANGEA*
      * *Basis for integration and synthesis across themes*
      * *MDS WG members are expected to participate in other WGs*
        + *Coordinate activities/meetings between WGs and MDS*
        + *Start with PIs and Co-Is, collaborating researchers/managers, new members added as funding allows*
        + *Objective:*

*A. Coordinating with participating land*

*management agencies who are conducting impact assessments*

*(b) coordinating PANGEA modeling activities with those being carried out for other programs, such as X*

*(c) creating an Integrated Modeling Framework (IMF) that utilizes remotely-sensed observations of key surface characteristics to allow for assessments of the impacts of climate and land use change in tropical latitudes*

* + - *Working Group Members nominate participants to Coordinating Groups*

From a planning and logistics perspective, it will be necessary to coordinate a number of activities associated with the Intensive Study Period of Phase II and the synthesis and assessment of Phase III activities. These include the collection, documentation, analysis, and processing of remote sensing and field data, the retrieval of information needed to carry out research for PANGEA, and archiving data products within a PANGEA information system. Each of these activities will be carried out by a separate coordinating group, as discussed below.

* *Remote Sensing Coordinating Group*
* *Field Studies Coordinating Group*
* *PANGEA Information System Coordinating Group*

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-0)