PANGEA Draft White Paper

[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): A Concise Plan for 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**

**Biogeochemical Cycles & Carbon Dynamics:**

**Ecosystem Structure, Function & Biodiversity:**

**Social-Ecological Systems:**

**Climate Feedbacks & Interactions:**

**Community Engagement & Research Applications:**

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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 the tropical forest biomes. PANGEA will answer 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 a special emphasis on interactions between US scientists and scientists from tropical forest countries, and provide opportunities for training and educating the next generation of scientists including obligatorily scientists from countries where field research will be based. PANGEA will leave a legacy of open data, open science, and strengthened partnerships between the US and tropical institutions as the basis for future research.

[tropical forests are important]

Tropical forests represent 45% of the world’s forested area, of which less than 40% of the total extent is in Brazil, the Democratic Republic of the Congo and the mega-islands of the tropical East (Hartshorn, 2013). Tropical forests regulate climate locally, regionally, and globally and retain the greatest share of biodiversity of any terrestrial biome. Tropical forests store vast amounts of carbon [quantify] (REF) and provide the critical global service of removing carbon dioxide from the atmosphere rapidly, especially in young tropical forests ([Pan et al., 2024](https://www.nature.com/articles/s41586-024-07602-x)). In contrast, tropical deforestation and degradation accounted for 22% of annual anthropogenic carbon dioxide (CO2) emissions in the past two decades (1990-2019; [Pan et al., 2024](https://www.nature.com/articles/s41586-024-07602-x)).

Methane (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 ~30% of the increase in radiative forcing from anthropogenic emissions and is 25× more effective as a GHG compared to CO2 (Masson-Delmotte et al., 2021). Furthermore, tropical forests and floodplains, which are frequently laden with wetland and aquatic ecosystems, play a critical role in the global CH4 and CO2 budgets (Sjögersten et al., 2014; Peng et al., 2022). Tropical wetland and inland water systems contribute the vast majority of global aquatic CH4 emissions and make up ~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 currently known to be the most uncertain component of the global budget (Saunois et al., 2020, 2024).

Control of tropical deforestation and forest degradation and regeneration of tropical forest carbon can be a cost-effective tool for mitigating climate change (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 the high rates of regional precipitation through rainfall recycling (Salati et al. 1979; recent refs Amazon; Worden et al. 2021; Worden et al. 2024). Deforestation and forest degradation reduce evapotranspiration in the dry season (Sampaio et al. 2007; Longo et al. 2020; 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” (Lovejoy and Nobre 2018).

**Tropical forests are highly threatened by climate change and land use change.** Forests in the hot 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). Tropical forest canopy temperatures are more frequently dangerously close to the critical temperature (~47⁰ C), at which irreversible damage to the photosynthetic machinery occurs (Doughty et al. 2023). 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).

[punchy first sentence - evidence] **The biogeochemical response of tropical forests to changing climate forcing and climate extremes varies strongly across the globe.** From 1985 through 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 East Asia, all had similar net released CO2 to the atmosphere (Liu et al. 2017). However, heterogeneous processes determined these net carbon losses (Figure 1). **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.**

**Future predictions of the role of the tropical carbon land flux in the Earth system also 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 (cite Anthony Bloom’s paper here), AI (Massoud et al. 2023) and Pierre Gentine’s papers*]  
Traditionally, ESMs represent forest canopies in simple and aggregated ways and thus fail to capture how disturbance history affects biomass accumulation and ecosystem stability (Levine et al. 2016; Yang et al. 2023). The need for representing ecological processes of diverse ecosystems is becoming increasingly recognized by the modeling community (Bonan et al. 2024). Newer generations of terrestrial biosphere models—vegetation demography models (Fisher et al. 2018)— namely represent 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) based on unreasonable distributions. Recent advances in remote sensing provide a unique opportunity to describe the structure, composition and diversity of ecosystems (Schimel et al. 2019).

Critically, **tropical forests are also the least investigated of all of the Earth’s major biomes**. Few tropical forest countries maintain systematic repeated forest inventories because inventories are costly and require technical and management expertise. Collections 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). Perversely, latitudinal distribution of both forest inventory plots and eddy covariance flux towers is nearly inversely proportional to gross primary productivity (Baldocchi et al 2022, Schimel et al. 2015) (Figure X).

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 …

* 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
* **Societal need** - lots of people depend on those forests
  + local, regionally, or globally
* **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
* 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
* equitable science and not extractive science

### 1.1 Science Questions and Objectives/Issues

As a result of climate change and land-use change, the globally important tropical carbon balance, heretofore mainly a sink, is now often reversing to become a source of carbon emissions to the atmosphere in response to extreme events and climate and land-use change feedbacks. Critically, tropical forest landscapes appear to differ in their recent carbon sink trends, sensitivity to extreme events, and interactions with climate and land-use change. Understanding long-term tropical carbon flux trends and the resilience of the tropical carbon sink to extreme events has globally important implications and requires an improved understanding of patterns and processes. PANGEA aims to answer the following overarching research question:

**~~How vulnerable or resilient are tropical ecosystems and society to carbon cycle perturbations and environmental change in the tropics?~~**

**Over the past decades, the tropical forest carbon flux has represented a globally important sink of atmospheric carbon. As a result of climate change induced extreme events and land-use change feedbacks, this sink is now often reversing to become a source of carbon emissions to the atmosphere in response to extreme events and climate and land-use change. However, this reversal does not appear uniform, with tropical forest landscapes differing in their recent carbon sink trends, sensitivity to extreme events, and interactions with climate and land-use change. Understanding the controls on tropical forest carbon flux, the resilience of the sink to climate warming and drying trends, and the response of the carbon sink to extreme events has globally important implications and requires an improved understanding of patterns and processes in tropical forests.** [1-2 more paragraphs in the white paper after this about why this is uniquely suited to satellite remote sensing → the central, critical role of NASA remote sensing]

* Data-rich and model-rich moment
* We now have remote sensing capabilities that allow for more direct measurement of diversity (structural, functional, maybe taxonomic)
* We now have numerical models that represent processes that mediate forest diversity the interactions of structurally heterogeneous forests with climate, land use and biogeochemical cycles
* Also cloud computing / computational resources
* But we can’t use those satellite data effectively without coordinated cal/val measurements
* Cut and paste from ROSES solicitation, and reviewer comments, and slide that emphasizes things from solicitation
* Tropical forests have a major role on global climate and teleconnections with non-tropical climate

PANGEA will study the complex interactions of society and the carbon cycle in the tropics by addressing the following questions.

1. **How does ongoing and projected changing climate impact the resilience of the tropical carbon sink, and how does the weakening of the carbon sink feedback on climate-related events (e.g., drought, biomass burning)?**
2. **How does variation in biodiversity, ecosystem structure and function, land-use change, and human interactions within and among regions in the tropics contribute to geographic variation in tropical forest responses to climate change?**
3. **How will potential future changes to the tropical terrestrial carbon flux interact with geographical variation in ecosystem structure, function, biodiversity, and human interactions to influence climate feedbacks, biogeochemical cycles, and society?**

### 1.2 PANGEA Science Themes

### 1.3 Role of Remote Sensing Observations

Notes from breakout:

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

* We cannot answer the big questions of PANGEA without pan-tropical satellite observations, integrative analyses, and models.
* Need to clearly state the rationale for why a campaign is needed
  + Why does this require going beyond the use of just satellite data or just ground data?
* point to satellite observations and drone and airborne capabilities for scaling
* Link science themes and questions to variables, measurements, and geographies
  + 'scoping' traceability matrix
* 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

RS related methods advances enabled by PANGEA

* Cal/Val and algorithm development
  + SBG, CHIME, ECOSTRESS, NISAR, BIOMASS, OCO-2/3, SMAP, GRACE, TROPOMI, GEDI
* 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

### 1.4 PANGEA Study Domain

* Modeling and satellite RS at pan-tropical scale
  + Specify domain still - see FAO boundaries
  + Includes moist tropical forests, wetlands, peatlands, mangroves
  + include montane forests??
* Coordinated ground, tower, drone, and aircraft measurements will be collected in landscapes that capture variation in ….
  + See Section X for more detailed information
* Define a core PANGEA domain (mostly Americas/Africa) and extended PANGEA domain (includes SE Asia, but not focus of data acquisition). This is similar to ABoVE’s two domains.

### 1.5 PANGEA’s critical timing

* the "context" section that will address all of the nascent and ongoing activities that will have strong synergy with PANGEA. We clearly state that our TE proposal will work as a stand-alone campaign but can benefit greatly from other activities (and not unimportantly will greatly support other activities).
* Clearly articular

### 1.6 Earth Science to Action

## 2. PANGEA Science Themes

### 2.1 Carbon Stocks and Fluxes

In recent decades, tropical forest regions as a whole have been a strong and persistent carbon sink. As a result of climate and land-use change, the tropical carbon sink is now fragile, at times reversing to become a source of carbon emissions to the atmosphere in response to extreme events. Critically, tropical forests appear to differ in their sensitivity to extreme events and future climate and land-use change feedbacks (e.g. Habau et al., 2020). We do not currently know how sensitive tropical forests are, how much that sensitivity differs across the three continents, or the mechanisms that account for those differences. Additionally, traditional methods in carbon monitoring are costly and time-consuming, resulting in a discrepancy between the scales of information available across relevant spatial and temporal gradients.

How do edaphic properties control tropical forest productivity and carbon storage? Soils provide physical support, water holding capacity, and nutrients required for growth and reproduction. Many tropical forests are situated on nutrient-poor soils, leading to large uncertainties around nutrient constraints on a CO2 fertilization effect and how that will interact with carbon-climate feedbacks like increased respiration, carbon losses from tree mortality, and changes in CH4 fluxes (Townsend et al 2008). In addition, variation in land-use change drivers also displace different nutrients through different processes, with large consequences on downstream nutrient cycling. While phosphorus is largely assumed to be the most limiting nutrient (e.g. Cunha et al., 2022), recent observations reveal the heterogeneity of nutrient limitation across tropical forests, including limitation and colimitation by calcium, potassium, nitrogen, and phosphorus (Davidson et al 2004, Wright et al 2011, Manu et al 2022). High biodiversity in tropical forests causes results from manipulative experiments that test where and when nutrient limitation affects productivity to be highly localized. However, 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 2016b, 2018, Martins et al 2018).

The dominant tropical wetland ecosystem types are forested peatlands, swamps, and floodplains (Aselmann and Crutzen, 1989). These tropical forested wetlands and floodplains, which are frequently laden with various aquatic ecosystems, 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 forested wetlands, floodplains, and inland waters (i.e., defined here as non-wetland systems such as 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).

We recommend leveraging airborne and satellite campaigns with field campaigns to understand variation in detection of canopy foliar nutrients. Regarding how foliar nutrients vary from canopy to the forest floor and with soils, sampling in the tropics (and in general) is relatively scarce (Lira-Martins et al., 2019, Heineman et al., 2016); most vegetation models use standardized extinction coefficients based on optimality; a scoping mission can test these assumptions. Furthermore, do airborne lidar (i.e. leaf biomass distribution, LAI analogs, etc.) and hyperspectral trait retrievals (from NASA products) help to scale from local measurements?

Syntheses of plot networks demonstrate strong spatial variation in biomass carbon (e.g. Sullivan et al., 2020, other REFS), but temporal and spatial variation in carbon fluxes remains largely unknown. At a coarse scale, variation in biomass carbon across forest plots has been attributed to maximum temperature, rainfall, with little variation explained by cloud cover, wind speed, and edaphic soil properties, obtained from large gridded datasets such as WorldClim and SoilGrids. Remote sensing offers a huge opportunity to improve upon ground-based weather station and soil property data that have been extrapolated to large scales to create gridded datasets.

1. What are the patterns of spatial and temporal variation in tropical forest carbon stocks and fluxes (CO2 & CH4)?
2. **What are the roles of climate, hydrology, and edaphic properties in contributing to spatial and temporal variation in tropical forest carbon stocks and fluxes?** (Formerly BCCD Question #1)
   1. Climate
   2. Hydrology
   3. How are current and historical trends and variability of carbon cycling linked to variation in soil nutrient availability and fluxes of nitrogen and phosphorus?
      1. How do nitrogen and phosphorus limitations on tropical forest carbon stocks and fluxes vary across the tropics?
      2. Does variation in land-use and land cover change within and between tropical continents affect nutrient dynamics and limitation
      3. How does broader variation in soil physical and chemical properties interact with N and P limitations to control tropical forest productivity and carbon storage?
3. How do changing hydroperiods and river connectivity affect carbon (CO2/CH4) source/sink behavior of tropical flooded and wetland forests? (formerly BCCD Q#1a)
   1. What is the spatial distribution of soil carbon stocks across tropical forests, and how do climate and land-use change, edaphic controls, aboveground stocks, and biomass carbon residence time drive the variability in soil carbon stocks?
   2. How does variability in primary biological and physicochemical factors drive CH4 and CO2 fluxes from tropical inland waters, floodplains, and wetlands?
4. How can we quantify the long-term effects of CO2 fertilization by integrating data from previous/current long-term experiments? (Formerly MDS Question #1)
   1. What is the relative role of climate change, elevated CO2, nutrient deposition, and land cover on the current and historical trends in vegetation and soil carbon stocks, as well as carbon fluxes (photosynthesis, respiration)?

### 2.2 Biodiversity

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. Forest's potential for carbon sequestration is highly linked to its biological and functional diversity. Many experimental studies have found that more diverse assemblage of plants are more productive and hold higher carbon stocks (ref). The exact mechanisms contributing to this phenomenon are not clear. Species with diverse traits and resource requirements may utilize a larger number of resources available in an ecosystem trout reduces competition, increased facilitation, or both, which leads to overall more efficient resource use.

Ecosystem service models do not always account for the effects of biodiversity. For example, Earth System Models (ESMs) typically model terrestrial ecosystems using a small number of plant functional types and do not include biodiversity-carbon sequestration or biodiversity-productivity mechanisms (ref).

1. How does geographic variation in **tropical biodiversity** contribute to differences in carbon cycling (CO2 and CH4)? / What is the role of biodiversity in driving spatial variation in tropical forest carbon stocks and fluxes?
   1. How does biodiversity covary with forest structure, function and abiotic variables that control tropical forest carbon stocks and fluxes within and among biogeographic regions in the tropics?
   2. How does variation in functional composition relate to variation in woody productivity (GPP, CUE, and allocation to wood production) and woody residence time, and thus to spatial variation in tropical forest biomass?
2. **How does functional composition influence ecosystem processes and tropical forest vulnerability and resilience to environmental change?** (formerly ESFB #3)
   1. How do tropical forest plant functional traits vary vertically and across forest types and environmental gradients?
   2. How do species- and organismal-scale plant functional traits aggregate to ecosystem-scale functional composition (e.g., community-weighted means and variances of particular traits), and does this vary among tropical ecosystems?
   3. How do tropical forest functional traits relate to interspecific variation in responses to spatial and temporal environmental variation, and how do these traits contribute to forest function?
   4. What are the plant functional traits that confer resilience to environmental change, and how do they vary across different forest types and environmental gradients?
   5. To what degree are changes in tropical carbon cycle dynamics caused by shifts in [woody plant] functional composition?
3. **How does biodiversity, including plant-animal interactions, mediate the vulnerability or resilience of tropical forest carbon stocks and fluxes?** (formerly ESFB #4)
   1. How well does variation in structural diversity, functional composition, and spectral diversity - mappable with remote sensing datasets - correspond to tropical plant, animal, and microbial taxonomic diversity?
   2. To what degree does biodiversity (including tree functional composition and diversity, liana abundance and composition, megafaunal abundance, abundance of seed-dispersing animals, microbial biodiversity, and diversity networks) contribute to explaining spatial variation in tropical forest carbon cycle dynamics?
   3. How vulnerable or resilient are species interactions underpinning tropical forest function to climate and land-use change?
4. **What are the major dimensions or axes of tropical plant life strategies (e.g., physiological traits, drought tolerance strategies, structural allocation) functional trait variation that need to be captured in models to understand spatial variation in plant functional composition today and compositional shifts under global change?** (formerly MDS #2, before which it was an ESFB question)
   1. What are the functional properties (trait distributions) of forests on different continents, and how do differences in these trait distributions and trade-offs between traits affect forest responses to extreme events, climate change, and land use change on different continents?
   2. How sensitive are land model projections to different parameterizations of plant functional diversity (e.g., pantropical vs. continent-specific diversity parameterizations)?

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

### 2.3 Climate Interactions and Feedbacks

Climate interactions and feedbacks facilitate key exchanges of carbon, water, and energy between the terrestrial biosphere and the atmosphere. Rainfall, atmospheric demand for moisture, radiation, and temperature influence vegetation function, structure, and resilience to disturbances (Gentine et al., 2018; 2019). In turn, this influences photosynthesis, respiration, and long-term carbon storage as vegetation choose different growth strategies to respond to these background climatic conditions. For example, tropical forests are near their thermal tolerance limit, with photosynthesis rates decreasing sharply at temperatures above 32-35°C as photosynthetic machinery declines and photoinhibition occurs ([Doughty & Goulden, 2008](https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2007JG000632); [Doughty et al., 2023](https://www.nature.com/articles/s41586-023-06391-z)). Meanwhile, tropical forests are able to alter surface properties, including land surface albedo, latent and sensible heat fluxes, and roughness, which in turn exerts biophysical climate feedbacks [(Bonan 2008; Lee et al. 2011; Chen et al. 2020](https://paperpile.com/c/gMdJbo/dMNQm+1PcSG+R5xrE)). For example, moisture recycling from tropical rainforests influences the onset and timing of their own rainy seasons and provides large proportions of atmospheric moisture for rainfall not just locally but also for regions downwind (Wright et al., 2017, Sori et al., 2022, Worden et al., 2021, van der Ent et al., 2010, Staal et al., 2018, [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)). Additionally, forest rooting systems and soil texture will regulate soil moisture [(Fan et al. 2017)](https://paperpile.com/c/gMdJbo/BuQDj), exerting strong impacts on surface energy and water balances [(Seneviratne et al. 2010; Zhou et al. 2021)](https://paperpile.com/c/gMdJbo/wuoeY+FUYUI).

However, large spatial and temporal variability in interactions between climate and forest ecosystems on both sub-continental and pantropical scales exists, which is not adequately captured by current observations of carbon, water, and energy. For example, current satellite-based, reanalysis, and model estimates of carbon assimilation, precipitation and evapotranspiration estimates display large variations in seasonality and magnitude (e.g., Baker et al., 2021, Crowhurst et al., 2021, Weerasinghe et al., 2020, Pan et al., 2020, [Zhang and Ye 2021](https://www.sciencedirect.com/science/article/pii/S0048969721020350)). This is in part due to inadequate ground-based observations needed to constrain these estimates, large proportions of clouds that interferes with satellite-based estimates, and heavy parameterization of key processes that affect these cycles ([Fisher et al., 2009](https://doi.org/10.1111/j.1365-2486.2008.01813.x), Sibret et al., 2022, Alsdorf et al., 2016, Lopez-Ballesteros et al., 2018, insert cloud and parameterization references here).

Therefore, PANGEA stands as the first cross-continental initiative to better understand these complex interactions between tropical forests and climate systems. This includes investigating and quantifying the extent to which these interactions are distinct both within and between the major tropical rainforests (e.g., Amazon, Congo, and east Asian).

In particular, we aim to address the following scientific questions related to climate-feedback interactions:

1. **How do tropical forests alter land surface biophysical properties, which in turn influences the strength of land-atmosphere feedback and teleconnections within and across continents?**
   1. **How do surface biophysical properties affect local and regional weather and climate?**
   2. **How does tropical vegetation affect the seasonality of the land-surface energy balance, water exchange, and carbon fluxes, and their feedbacks with the climate?**
2. **What are the direct and indirect hydroclimate controls on tropical forests and how does this influence the fragility of their ecosystem carbon balance?** 
   1. What are the differences in hydrological controls on the terrestrial carbon cycle between the Amazon and the Congo?
   2. Are there key hydrological thresholds, such as critical soil moisture levels, and/or elevated temperatures that limit forest photosynthesis and sustainability, varying within and between tropical continents?

Tropical forests → land surface biophysical properties → land-atmosphere feedbacks

Albedo, surface fluxes, surface roughness, surface temperatures (perhaps through relative influence of SSHF vs SLHF)

Hydroclimate controls on tropicals and how it influences fragility of ecosystem carbon balance?

Water availability/loss via VPD and soil moisture (and their interactions), flooding, distribution of evaporation vs transpiration in ET, windthrow, storms, nutrient/soil organic matter transport via rivers or rainfall washing off nutrients from leaves, moisture recycling, topography influence in moisture distribution/storms, large-scale temperature gradients influencing moisture transport

What we know in the Amazon (including sub-variability within the basin and comparisons to the Amazon)

What we know in the Congo (including sub-variability within the basin and comparisons to the Amazon)

Temperature: Higher elevations mean that temperatures are generally cooler in the Congo than in the Amazon. Rare ground-based data shows increases in temperature. Re-analysis and satellite-based data shows ecosystem level increases in temperature. This will directly affect vegetation through heat stress, changing evaporation, altering photosynthesis, . Indirect effects of temperature: Land-ocean temperature gradients influence moisture brought into the region from the Atlantic Ocean, Indian Ocean, and other parts of Africa by altering the strength of zonal overturning circulation systems such as the Congo Basin Cell and Walker Circulations. Meridional land temperature gradients influence meridional winds (AEJ-N/AEJ-S) which control rainfall over the region. They also influence moisture drawn out of the region towards due to meridional overturning circulations that themselves are controlled by heat lows (Sahara heat low, Kalahari/Angola heat lows) and the AEJ (in particular, the AEJ-N, less so the AEJ-S). This moisture availability and influence on dynamical systems in turn controls precipitation as well as atmospheric instability/thermodynamic structure important for MCSs, which provide most of the rainfall for the region.

Vapor pressure deficit: Congo basin is dryer than the Amazon, which can

Natural climate disturbances (current and legacy effects from far past climate variations) versus changes to those disturbances

What controls precipitation? Or flooding? Or changes in river discharge? Or fog/mist for leaf interception of water/radiation changes

Differences in water cycle - rain gauges, discharge, - point to existing observations

Keep in atmospheric modeling -

Clouds and aerosols?

Topography influence on climate - temperature, atmospheric moisture being trapped or unable to enter, alterations in energy reflection, absorption, refraction, where surface water comes from/goes

Organizational - what content should be included within (data to be collected, models to be used, etc, is the organization of this section matching what should be done)

However, tropical forests are increasingly threatened by confluence of environmental stressors such as climate change, extreme weather events, and changes in land cover and land use, triggering complex feedback mechanisms that extend far beyond the affected areas. These stressors not only disrupt the functionality of tropical forest ecosystems but also undermine their ability to provide essential services and maintain resilience in the face of ongoing environmental change.

For instance, deforestation promotes changes in rainfall patterns, impacting regional water availability. The ability of tropical continents to absorb carbon from the atmosphere has been decreasing in recent decades, directly affecting the atmospheric CO2 concentration and climate. Understanding the complex feedbacks and interactions associated with these stressors is pressing. PANGEA stands as the first cross-continental initiative to better understand the complex interactions between tropical forests and climate systems and their roles in regulating the Earth's environmental systems.

1. To identify crucial gaps in our understanding of climate interactions and feedbacks by assessing what aspects of these complex Earth system dynamics are currently observable with various remote sensing techniques, like ground, lidar, radar, hyperspectral, and multispectral sensors across different platforms (geostationary, polar-orbiting, etc.). By highlighting critical gaps in our ability to gather information about space, time, the spectrum, and biophysical properties, we can address those gaps, or inform the development of new sensor technologies and data analysis methods. By filling these knowledge gaps in representing climate interactions with improved remote sensing capabilities, we will ultimately improve our understanding of a changing planet, leading to more robust climate models. Climate feedbacks and interactions studies for PANGEA will address the overarching questions: **How do changes in atmospheric CO2, climate, extreme weather events, and land cover/land use (LCLUC) interact to affect local and regional ecosystem services, resilience, and biogeochemical cycles and the regional water cycle in tropical forests**

* Ecosystem Functioning, Services, and Resilience
* Mechanisms in Land-Atmosphere Interaction and Biophysical Feedback Linked to Land Cover and Land Use Change
* Patterns of Rainfall and Climate Variability
* Dynamics in Water Balance and Carbon-Water Coupling

**(Ecosystem Functioning, Services, and Resilience)**

1. 1. **What is the seasonality and inter-annual variations in water and energy and how does this influence carbon**
   2. energy balance, water exchange, and carbon flux exchange
   3. Are there key hydrological thresholds, such as critical soil moisture levels, and/or elevated temperatures that limit forest photosynthesis and sustainability, varying within and between tropical continents?
   4. What are the differences in hydrological controls on the terrestrial carbon cycle both pantropically and within each continent?

Climate change, characterized by increasing temperatures, shifting precipitation patterns, and increased atmospheric CO2 concentrations, affect tropical forest functioning. Higher temperatures can increase tree respiration, which may reduce net primary productivity (NPP) and change how carbon is cycled in these forests [(Lloyd et al. 2023; Das et al. 2023; Choury et al. 2022; Liu et al. 2017)](https://paperpile.com/c/gMdJbo/mqDuV+uaFNp+xkpd7+6Uzb7). Prolonged dry seasons [(Marengo et al. 2018)](https://paperpile.com/c/gMdJbo/vtFeE) or increased frequency of droughts [(Jenkins 2009)](https://paperpile.com/c/gMdJbo/OpTTE), can lead to water stress [(Santos et al. 2018; Rifai et al. 2019)](https://paperpile.com/c/gMdJbo/HiOu0+d6CwM), reduce tree growth [(Yang et al. 2018; Ouédraogo et al. 2013; Sullivan et al. 2020)](https://paperpile.com/c/gMdJbo/asZnB+4Tm8p+rZjcv), and increase mortality rates, particularly for drought-sensitive species [(Phillips et al. 2009; Malhi et al. 2009)](https://paperpile.com/c/gMdJbo/Sdem6+Z8KaW). Additionally, the current and projected increase of intensity and frequency of extreme weather events can cause widespread damage to forest structure, leading to treefall, 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).

Land cover and land use changes, particularly deforestation and forest degradation, pose significant threats to tropical forest ecosystems [(Longo et al. 2020; Davidson et al. 2012)](https://paperpile.com/c/gMdJbo/ydSLE+b3f4f). The conversion of forests to agricultural land, urban areas, or other land uses leads to habitat loss, fragmentation, and a reduction in forest cover, which in turn affects biodiversity and ecosystem functioning [(Gibson et al. 2011; Truong et al. 2022; Wei et al. 2014)](https://paperpile.com/c/gMdJbo/SlHIN+cKbKV+eTw1y). Deforestation and wildfires also contribute to climate change by releasing stored carbon into the atmosphere, further exacerbating the impacts of global warming [(Houghton 2012; Gatti et al. 2021; Li et al. 2022; Harris et al. 2021; Bauters et al. 2018)](https://paperpile.com/c/gMdJbo/NfoJ+QrN0+M0ek+WVni+y0P1). Forest degradation, often resulting from selective logging or fire, can diminish the resilience of tropical forests by altering species composition, reducing biodiversity, and making forests more susceptible to invasive species and further disturbances [(Baker et al. 2007; Laurance et al. 2008; Bourgoin et al. 2024)](https://paperpile.com/c/gMdJbo/m10J8+IwPWt+Rqs0e).

Resilience, the ability of an ecosystem to maintain its fundamental structure and function [(Holling 1973)](https://paperpile.com/c/gMdJbo/agClR), is critical for the continued provision of ecosystem services . The resilience of tropical forests is increasingly challenged by the synergistic impacts of different disturbances including climate change, extreme weather events, and alterations in land use. When disturbances exceed certain thresholds, forests may undergo abrupt shifts to alternative states, such as degraded landscapes or savannas, which are less capable of supporting biodiversity and ecosystem services [(Scheffer et al. 2001; Flores et al. 2024; Nobre et al. 2016; Aguirre-Gutiérrez et al. 2020)](https://paperpile.com/c/gMdJbo/dq9WA+UflAT+hck0N+5dG5I). Furthermore, the spatial variations of these thresholds across continents are still not well understood [(Bennett et al. 2021; Wigneron et al. 2020)](https://paperpile.com/c/gMdJbo/gc2Z6+clnnk). Understanding the interactions between these stressors and their cumulative impacts on tropical forests is crucial for developing strategies to conserve these ecosystems and enhance their resilience in the face of ongoing environmental change.

**(Mechanisms in Land-Atmosphere Interaction and Biophysical Feedback Linked to Land Cover and Land Use Change)**

* 1. How will shifts in tropical forest structure and function affect the seasonality of land surface energy balance, water exchange, and carbon flux exchange, and their feedbacks with climate?
  2. How does changes in surface biophysical properties (e.g., evapotranspiration, albedo, roughness, land surface temperature, and humidity) by plant physiology and LCLUC affect local/regional weather and climate and disturbance risks (e.g. wildfire)?
  3. How do LCLUC, climate change, and extreme events govern the land-atmosphere feedback strength in the tropics?
  4. How can weather forecast duration and reliability be improved in the tropics? (Formerly MDS # 4, If you think this is out of scope, please put it in the out-of-scope document)

Climate and LCLUC-induced changes in large-scale dynamics ofTAccumulation of satellite evidence shows that the conversion of tropical forests to other land use types exert significant surface warming effects due to declined evaporative cooling effects [(Li et al. 2015; Devaraju et al. 2018)](https://paperpile.com/c/gMdJbo/D6pI0+764BI). The magnitude of biophysical temperature effects of tropical forests is constrained by the forest cover fraction [(Alkama and Cescatti 2016)](https://paperpile.com/c/gMdJbo/IN7pI), and may exert asymmetry in response to forest cover gain and loss [(Su et al. 2023; Zhang et al. 2024)](https://paperpile.com/c/gMdJbo/o9RjT+xFn4r). Due to a similar mechanism, surface temperature warming from this biophysical effects of forest degradation is found to be comparable to its biogeochemical climate effects [(Zhu et al. 2023)](https://paperpile.com/c/gMdJbo/L9zxN), highlighting the need of consider the biophysical climate feedback of tropical forests in climate policy [(Windisch et al. 2021)](https://paperpile.com/c/gMdJbo/Oqo0O), and carbon accounting system [(Li et al. 2022)](https://paperpile.com/c/gMdJbo/M0ek).

. Rainfall in the tropics is strongly associated with mechanisms of land-atmosphere interactions, with its magnitude and pattern tightly linked to LCLUC activities (e.g., deforestation) that change land surface heterogeneity [(Khanna et al. 2017)](https://paperpile.com/c/gMdJbo/ZtadU) and at various spatial scales [(Lawrence and Vandecar 2014; Leite-Filho et al. 2021; Smith et al. 2023)](https://paperpile.com/c/gMdJbo/NSE6d+FyWz9+1Zo8D). Along with atmospheric circulation, local and regional moisture and heat anomalies will be transferred to generate teleconnection on downstream circulation patterns [(Snyder 2010; Mahmood et al. 2014)](https://paperpile.com/c/gMdJbo/M8qSz+yo6Z1) and cross-continental nutrient cycles [(Li et al. 2021)](https://paperpile.com/c/gMdJbo/0uVaS). Despite the uncertainties in understanding the local and nonlocal rainfall feedback from tropical forests, it is crucial to move forward this process to better understand the impacts of these feedbacks on ecosystem carbon stocks [(Uribe et al. 2023)](https://paperpile.com/c/gMdJbo/8aJWF), biodiversity [(Peters et al. 2019)](https://paperpile.com/c/gMdJbo/q4lha), and socioeconomics across continents in the tropics.

**(Patterns of Rainfall and Climate Variability)**

Climate and LCLUC changes have modified the pantropical water cycle, including changes in atmospheric moisture, surface water, ground storage, and precipitation distribution, intensity, and variability ([Gentine et al., 2019](https://iopscience.iop.org/article/10.1088/1748-9326/ab22d6/meta), [Allan et al., 2020](https://nyaspubs.onlinelibrary.wiley.com/doi/full/10.1111/nyas.14337)). 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)). In addition, changes to the thermodynamic structure of the atmosphere, such as increases in convective available potential energy (CAPE; [Nicholson et al., 2022](https://iopscience.iop.org/article/10.1088/1748-9326/ac61c4/meta)) and atmospheric instability ([Taylor et al., 2018](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018GL080516)) can affect precipitation intensity and frequency (Taylor et al., 2018, [Yin et al., 2014](https://doi.org/10.1002/2013JD021349)). Meanwhile, anthropogenic and climate disturbances alter tropical rainforest moisture recycling ([Wright et al., 2017](https://www.pnas.org/doi/abs/10.1073/pnas.1621516114), [Sori et al., 2022](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/9781119657002.ch11), [van der Ent et al., 2010)](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010WR009127), leading to changes to monsoon systems ([Boers et al., 2017](https://nature.com/articles/srep41489#ref-CR15)), atmospheric drying ([Xu et al., 2022](https://iopscience.iop.org/article/10.1088/1748-9326/ac4c1d/meta)), and decreases in precipitation ([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)). Therefore, tropical rainforests are experiencing significant changes in their water cycle such as 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)). At the surface, these changes in climate and LCLUC have induced fluctuations in river discharge ([Nhedehede et al., 2022](https://doi.org/10.1002/9781119657002.ch5), [Heerspink et al., 2020](https://www.sciencedirect.com/science/article/pii/S2214581820302299)). Increases in precipitation can increase streamflow and induce heavy floods within primarily rain-fed watersheds ([Marengo et al., 2012](https://link.springer.com/article/10.1007/s00704-011-0465-1)), while deforestation increases 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)).

Meanwhile, climate phenomena such as ENSO, the Madden-Julian Oscillation, the Indian Ocean Dipole, and Atlantic Meridional Overturning Circulation can control 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)). For example, the 2015/2016 ENSO induced large meteorological and soil water droughts and increases in vapor pressure deficits that were exacerbated due to warming trends from climate change ([Rifai et al., 2019](https://iopscience.iop.org/article/10.1088/1748-9326/ab402f/meta)). These phenomena can also covary to further modulate tropical climate, such as 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)).

However, the mechanisms controlling present and future changes to tropical rainforest water cycling are not yet fully understood, in part due to large uncertainties in model representation of these processes ([Tamoffo et al., 2019b](https://doi.org/10.1007/s00382-019-04751-y), [Baker et al., 2021](https://iopscience.iop.org/article/10.1088/1748-9326/abfb2e/meta)), the anthropogenic impacts on these processes ([Dagan et al., 2023](https://doi.org/10.1038/s41561-023-01319-8)), and lack of data to constrain model estimates ([Washington et al., 2013](https://doi.org/10.1098/rstb.2012.0296)). For example, intense amounts of biomass burning within and nearby the tropical regions ([Chen et al., 2024](https://doi.org/10.5194/essd-15-5227-2023)) alter atmospheric conditions both locally and in non-local regions down-wind, even extending to cross-continental transport ([Adebiyi and Zuidema 2016](https://doi.org/10.1002/qj.2765), [Barkley et al., 2019](https://doi.org/10.1073/pnas.1906091116)). Aerosol-cloud and aerosol-radiation interactions, through direct and indirect effects, can alter cloud formation and lifetime ([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 that control key dynamic systems within tropical regions ([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)). These impacts on tropical water cycling are highly uncertain in models ([Brown et al., 2021](https://www.nature.com/articles/s41467-020-20482-9), and in part contribute to large disagreements to projections of future climate conditions over tropical rainforests ([Dosio et al., 2019](https://link.springer.com/article/10.1007/s00382-019-04900-3)).

Ultimately, previous studies indicate variability in tropical rainforest carbon cycling in response to changes to its water cycle, although with spatial heterogeneity between continents and within the rainforests themselves. For example, in response to meteorological anomalies induced by the 2015/2016 El Nino, tropical rainforests temporarily became net carbon sources, but for different reasons depending on the continent ([Liu et al., 2017](https://www.science.org/doi/full/10.1126/science.aam5690)). In addition, these rainforests exhibit different responses to drought, with the Congolese rainforests less responsive to such perturbations 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)). This extends to inter-basin variability with intact, wetter rainforest generally less vulnerable to these perturbations ([Bennett et al., 2023](https://www.nature.com/articles/s41558-023-01776-4)).

**(Dynamics in Water Balance and Carbon-Water Coupling)**

Tropical forests are vita-l components of the global carbon cycle, acting as significant carbon sinks. However, their carbon balance is increasingly fragile due to a range of hydrological and thermal conditions. Understanding carbon-water coupling mechanisms and identifying key thresholds, such as critical soil moisture levels and elevated temperatures, that limit their capacity to continue absorbing carbon from the atmosphere is essential for understanding forest resilience and predicting responses to climate change.

Critical thresholds are often linked to the point at which soil water availability drops below the needs for maintaining stomatal conductance, leading to reduced carbon assimilation ([Blinks et al., 2016](https://nph.onlinelibrary.wiley.com/doi/10.1111/nph.13927)). The critical soil moisture threshold can vary between tropical regions. In the Amazon, deep-rooted trees can access water from deeper soil layers, which delays the onset of water stress compared to African or Southeast Asian forests where root systems are often shallower ([Fan et al., 2017](https://www.pnas.org/doi/full/10.1073/pnas.1712381114)). However, with increasing temperatures and changing rainfall patterns, these thresholds are being tested [(Esquivel-Muelbert et al., 2019)](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.14413). Forests in the Congo Basin face longer dry seasons and generally shallower soils, making them more vulnerable to reaching critical soil moisture thresholds. These regional differences highlight the importance of local hydrological conditions in determining forest resilience to drought. The seasonal variability in rainfall across tropical continents also plays a role in defining critical soil moisture levels. In the Congo Basin, for example, a prolonged dry season creates higher susceptibility to soil moisture depletion, potentially reaching critical thresholds more frequently than in the Amazon ([Zhou et al., 2014](https://www.nature.com/articles/nature13265)). Southeast Asian forests, characterized by high humidity and relatively stable temperatures, may face less frequent but potentially more intense droughts, which could push them towards critical thresholds more abruptly ([Corlett & Westcott, 2013](https://www.cell.com/trends/ecology-evolution/abstract/S0169-5347(13)00105-5?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0169534713001055%3Fshowall%3Dtrue)).

Prolonged exposure to elevated temperatures, especially when coupled with drought, can lead to widespread tree mortality. For instance, during the 2015 El Niño event, parts of the Amazon experienced temperatures that exceeded critical thresholds, leading to significant forest dieback. 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.

The combination of low soil moisture and high temperatures exacerbates stress on tropical forests. Drought conditions reduce the cooling effect of transpiration, leading to further increases in leaf temperatures, which can push forests beyond critical thresholds faster than either factor alone. Reduced soil moisture can also lead to decreased evapotranspiration, further intensifying local temperature increases . This feedback loop can drive regions into a state of persistent stress, where recovery becomes increasingly difficult.

During extreme events, the Amazon’s carbon cycle is highly sensitive to both droughts and floods, while the Congo is more vulnerable to droughts. These differences highlight the need for region-specific strategies to manage and protect these critical ecosystems in the face of climate change.

### 2.4 Social-Ecological Systems

[maria.j.santos@geo.uzh.ch](mailto:maria.j.santos@geo.uzh.ch)The question below was moved here by Elsa for us to comment on whether we think it would be a good fit for the SES section. Feel free to add to my comments.

1. To what extent can the impact of human land management on subsurface-surface-atmosphere coupling of water-energy-carbon cycle processes in the tropics be measured and modeled, and does it represent a significant source of subseasonal to seasonal hydroclimate predictability? (Formerly MDS Question #3)
   1. What are the minimum levels of change in forest structure and composition caused by forest degradation that cause detectable shifts in the magnitude and seasonality of energy, water, and carbon fluxes relative to intact forests? How do these minimum levels of degradation vary across precipitation gradients and across continents?
   2. What are the typical time scales in which the energy, water and carbon fluxes of degraded forests become indistinguishable from non-degraded forests? How does the time scale vary as a function of degradation type (e.g., fires, logging, fragmentation) and climate?
   3. At which spatial scales the impact of forest degradation on energy, water, and carbon cycles is sufficiently strong to impact the dynamics of the planetary boundary layer and convective development, and thus impacting climate?

**ONE-SENTENCE SUMMARY OF WHAT THIS SCIENCE THEME DOES**

This science theme addresses the interactions and feedbacks between social and ecological systems from which co-benefits for nature and societies arise across scales, such as food, water, energy and livelihood security, biodiversity conservation, retention of organic matter and nutrients, and resilience of tropical systems.

**CONTEXT**

**Paragraph 1 (MJS):** Description / definition of social-ecological systems in the tropics, highlighting that humans are part of the ecological systems

* integrated system comprising ecosystems and human societies with complex and interdependent relationships
* recognizing that human activities impact ecological processes and, conversely, ecological changes affect human well-being
* Mention the term co-benefits and that interconnectedness and interdependencies exist from which multiple benefits to nature and societies emerge (see also [Levis et al, 2024, NatEcoEvo](https://www.nature.com/articles/s41559-024-02356-1)

Social-ecological systems are shaped by diverse actors, placing multiple functions and motives on land and differing in terms of their values, capacities, aspirations, and goals that shape their interaction with nature (Meyfroidt et al., 2018, 2022).

Despite providing benefits to local communities, particularly indigenous populations, environmental changes in tropical ecosystems are likely to disrupt plant growth rates, leading to changes in species composition, survivorship and productivity, affecting various provision products, including timber and non-timber forest products (Siyum, 2020).

Land-use change and forest degradation contribute to carbon emissions (Houghton and Castanho, 2022). Climate change and land-use change are closely related (Dale et al., 2001), as CC affects agricultural practices and yields, leading to agricultural expansion to compensate for the yield reductions (Mendoza-Ponce et al., 2021; North et al., 2023). Climate change and land-use change together induce changes in nature's contributions to people (Díaz et al., 2018).

**Paragraph 2:** Describe feedbacks and their importance [Maria Santos]

* Feedbacks between human and natural systems are critical for understanding the dynamics of SES, can be positive or negative and influence the resilience, stability, and sustainability of these systems
* Can be complex and occur across scales (e.g., (inter)national policy and local action)
* Examples for positive and negative feedbacks

The resulting decline in species richness can have far-reaching implications, potentially undermining ecosystem services (e.g. pollination, pest control, seed dispersal), affecting food security by disrupting the food-networks, and modifying the functional diversity of the ecosystem, impeding the ability of local population to adapt to global environmental changes.

**Paragraph 3:** Demonstrate the relevance of better understanding SES (for NASA, and in general)

There have been many calls for ecosystem management and conservation to better consider social-ecological context (Fischer et al. 2017), to recognize that most landscapes are human dominated (Sanderson et al. 2002, Ellis et al. 2021), and to pay closer attention to human agency and context specificity of human activities (Ramankutty and Rhemtulla 2013, Pratzer et al. 2024).

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).

Weak consideration of the complexity of social-ecological systems can not only conceal threats but also lead to missed opportunities in forest conservation. For instance, positive effects of Indigenous land-based stewardship on forest conservation and ecosystem service provisioning have recently been identified by several scientific studies (Vasco et al 2018, Baragwanath and Bayi 2020, Pratzer et al. 2023), in addition to Indigenous knowledge holders who have long provided contextual evidence of the various ecological values of their territories (Cajete 2000, Salmón 2000, Umeek 2011). Indeed, Indigenous land-based stewardship is often compatible with, and frequently actively supports, forest conservation and restoration (Newton et al. 2016, Fernández-Llamazares et al. 2024). This recognition has spawned innovative ways to design multi-functional reserves, policy instruments and management programmes (Garnett et al 2018).

**Modeling**

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>

LITERATURE REVIEW

* To provide appropriate literature background for the context sections
* And to demonstrate that the questions we ask are relevant, and have not been answered before (i.e., showcasing the literature gaps)

**SCIENCE QUESTIONS**

1. How do human activities and socio-economic conditions affect the provisioning of and access to social-ecological co-benefits?
2. How will climate and land-use change affect the geographic distribution and scalability of forest-friendly economic activities?
3. How do varying tropical forest land-atmosphere interactions affect water availability and food security, human health, and cultural practices, including Indigenous Peoples and Local Communities?

APPROACH/METHODS

Remote sensing [Maria Santos]

* Detection of LULCC
* Identification of crop types
* 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)

### 2.5 Disturbance Dynamics

* Motivate knowledge gaps related to how disturbance regimes are changing and how disturbance regimes are altering the carbon cycle via climate, biodiversity, hydrologic cycling, and nutrient availability.

1. **How do disturbances (e.g. droughts, floods, biomass burning, storms, deforestation, and degradation - including fires) impact tropical forest biogeochemical cycles and carbon dynamics?** (formerly BCCD Q3)
   1. How does forest resistance or resilience to disturbances vary across climate and disturbance history gradients within biomes and across continents?
   2. What are the post-disturbance recovery time scales of forest structure, composition, ecosystem functions (e.g., evapotranspiration, gross primary productivity), and carbon stocks?
   3. **How do different land-uses and deforestation and degradation patterns interact with climate to impact fire regimes and ecosystem recovery?** (formerly SES Q3)
   4. How do disturbance type and intensity influence post-disturbance recovery time scales?
   5. How have disturbances impacted the carbon use efficiency (CUE) and water use efficiency (WUE) of tropical forests?
   6. What are the spatial and temporal CO2 and CH4 flux differences associated with climate variability, wildland fires, and human modifications in tropical forests laden with inland waters and wetlands?
2. **How are tropical forest phenology and mortality responding to temporal and spatial variability and systematic shifts in forcing processes, including climate, land-use, and disturbance regimes?** (formerly ESF Q2)
   1. How does temporal variation in tree mortality rates, especially of large trees, relate to temporal variation in climate, land-use, and disturbance regimes
      1. How do these relationships differ among tropical forests, and how do these temporal responses vary spatially in relation to environmental variables?
   2. What are the main causes of tropical tree mortality?
      1. How does this differ geographically across the tropics?
      2. How are the drivers of mortality-associated carbon fluxes changing in space and time?
   3. How does geographic and temporal variation in tropical forest phenology influence carbon stocks and fluxes?
   4. How is tropical forest phenology changing in response to climate and land-use change?
3. **How do changes in climate, extreme events, and land cover/land use alter ecosystem functionality, including processes, services, and resilience?**
   1. What are the impacts of climate warming, increase of atmospheric CO2, and extreme events (e.g., drought and flooding) on ecosystem resilience, nutrient availability, and soil-vegetation interactions within and across tropical forests?
   2. How will climate warming and increasing extreme events shift forest structure and function by influencing plant physiology, functional traits, and ecosystem health?
   3. How do climate warming and trends in extreme events interact with LCLUC to influence forest and agricultural productivity and their feedbacks with climate within and between tropical continents?
4. **How do climate change, land cover/land use, and disturbances interact with tropical forests in ways that alter terrestrial water balance via changes in precipitation, atmospheric moisture, and surface water components?** (formerly CFI Q2)
   1. How do changes in precipitation patterns (e.g., ITCZ displacement) affect tropical forests, and how do these forests feedback to seasonal rainfall timing and duration?
      1. including trends in evapotranspiration, soil water, runoff, stream flow, river flow, and groundwater
   2. How do LCLUC, forest regrowth, and degradation alter recycling, patterns, frequency, and intensity of precipitation and what are the associated feedbacks?
      1. What are the feedback processes between LCLUC and physical climate systems during specific climate variability events (e.g., ENSO, AMOC, MJO, IOD)?
   3. How do tropical forest disturbances (e.g., wildfire and their aerosols) interact with clouds and influence continental precipitation?
5. **How do hydroclimate controls vary due to effects from extreme events, land cover/land use, and increases in atmospheric CO2?**
   1. How do these controls vary during extreme events (droughts, flooding, etc)?
   2. How do forest regrowth, and LCLUC alter regional hydrological cycles, freshwater resources, and water quality in tropical regions?

## 3. Scientific Advancement from PANGEA

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).

PANGEA leverages NASA’s history of successful field and airborne campaigns in the tropics to measure ecosystem dynamics and status at the end of the dry season, when tropical forest systems are most stressed and differences in function are most apparent [19]. 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.

## 4. Critical Role of NASA Remote Sensing

PANGEA aims to determine whether the two largest tropical forests will share the same fate or vary in their responses to the effects of climate change. Identifying processes that result in tropical forest stability is paramount for constraining uncertainty in predictions of future terrestrial carbon flux dynamics. Airborne measurements are necessary to characterize how and why Central African and neotropical forests, the two largest tropical forests on Earth, differ in their ability to remain stable in the face of rapid climate change. 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 NASA Arctic Boreal Vulnerability Experiment (ABoVE) in North America (e.g., [17], [18]), 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 our science objectives. Obtaining high spatial and spectral resolution data in these regions supports unprecedented evaluation of forest dynamics, including growth, mortality, and functional strategies (e.g., nutrient- and water-use efficiency) at the resolution of individual trees across large landscapes that vary in their species composition, soil characteristics, topography, and level of degradation.

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## 5. Research Strategy and Study Design (scientific feasibility)

### 5.1 Overall Study Design

The PANGEA research strategy will 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 so 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 obligatorily 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 scientific 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 establishment and augmentation of field sites including installation of new instrumentation. Satellite based analyses can begin immediately in the first year along with development of models and execution of model studies and analysis of existing data to reveal greatest sensitivities that will guide the details and emphases of measurement campaigns. 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.

Analysis and synthesis of data will not be restricted to later phases of the campaign but will be carried out from the initial phases starting with model studies that facilitate and inform effective measurement design. All science team members will either conduct integrative analysis (including modeling) or participate in integrative analyses. Building the 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 Terrestrial Ecology program including ABoVE, LBA, and earlier campaigns. Moreover, the team can learn from experience outside of NASA through collaboration with partner projects and use of existing protocols for data collection. Examples abound from NASA projects and facilities (e.g. AVIRIS, EMIT, SBG) as well as outside organization (e.g. CEOS, NEON, ICOS, Ameriflux, Fluxnet, Forestplots.net, GEO-TREES, etc.). [MAY BE USEFUL TO ADD REFERENCES HERE]

Functional requirements:

| **Table 2.** | |
| --- | --- |
|  | **Investigation Functional Requirements** |
| T | **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** |

* + g data from many people in many countries and many sources

### 

Scaling subsection?

### 5.4 Essential Scientific Measurements

Note - could consider an overall table here that can trace back to the Scoping Tracability Matrix, since many questions may require similar measurements.

| **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* | | | | | | |

#### 5.4.1 Satellite Remote Sensing Observations

* get specific about satellites and how they'd be used - **not just a list of sensors**
  + EMIT / CHIME / SBG / *Carbon-i*
  + NISAR / BIOMASS
  + GEDI / ICESat-2 / *EDGE*
  + ECOSTRESS
  + OCO
  + Geostationary
  + SMAP
  + GRACE
  + SWOT
* Synergies with partner agencies
  + ESA, JAXA, ISRO
  + Use of sensors from partner agencies:
  + BIOMASS

#### 5.4.2 Airborne Remote Sensing Observations

* need to define what other aircraft assets could be deployed
  + commercial aircraft
  + why don't we just hire companies to hire data there
  + then don't have to worry about flight permissions for NASA aircraft
  + what about sensors
  + AVIRIS has flown a lot on a Dynamic Aviation aircraft
  + use ARES (Switzerland) - other assets?
* INDIA: shipping AVIRIS-3 over and installing on an Indian plane
  + is there a short write-up about Indian deployments
* **Will co-design the flight plans - recommendation from AfriSAR-2**
* **demonstrate precedent wherever possible**
* AfriSAR-2
* AVIRIS in India (ISRO putting up money on that)
* lidar in Brazil and DRC
* ARES?
* ESA?
* mention tech advancing so rapidly
  + describe current drone capabilities
  + are currently these instruments at this level of readiness
  + will have protocols in place to leverage rapidly evolving technologies

#### 5.4.3 Field Observations, Studies, Experiments

Field infrastructure

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

#### 5.5.1 Modeling & Data Integration approach

Modeling and data syntheses will be fundamental components of the PANGEA throughout the entire duration of the experiment. Models will be used to (1) identify key processes that are poorly represented and regions within the PANGEA domain that drive uncertainty of key variables in existing models, (2) develop Observing System Simulation Experiments (OSSEs) that will 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 in existing models and apply them to answer PANGEA’s scientific questions.

* Add paragraph highlighting the key uncertainties identified through the scoping phase (go back to the notes) to ensure that we have clear vision on how to identify specific processes/data needs [A:Renato, R:Marcos, R:Cesar, R:Yanlei, R: Felicien]
* Describe the roles of different classes of models and data synthesis techniques. Model traceability matrix goes somewhere in here. *The modeling traceability matrix really could be something as simple as a table of models that can be used to address each question, maybe with some of the key features of each model. I think it adds value to the white paper, but there is no precedent for such a matrix, let’s make version 1.0 a very simple one.* We should add examples of process-based models (e.g., FATES, ED2, CliMA), statistical models (PLS-based), and AI/ML-based models (add specific examples). [A:Marcos, R:Renato, R:Cesar, R:Yanlei, R: Felicien]
* 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]
* Another paragraph that highlights how data synthesis activities will be coordinated with science themes.[Cesar]

#### 5.5.2 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) [Renato]
  + [GMAO](https://gmao.gsfc.nasa.gov/seasonal/)? [Elsa]
  + TRENDY

#### 5.5.3 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). [MK1] Scaling approaches were central to successive BOREAS, LBA, and ABoVe campaign. Over the four decades since initial FIFE planning, scaling has been central to Earth system science. Our science demands studies at the level of plant organs and whole plants, forest plots, towers, small UAVs, piloted aircraft, and satellite observations with parallel models and analytical approaches at all scales.

sampling to scale

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)

#### 5.5.4 Modeling and data integration timeline

* Phase 1 (Y1-Y2). Establish MDSWG whose tasks will be to identify key areas and processes that drive uncertainty in models of energy, water, carbon, nutrients, and biodiversity in tropical moist forests through a combination of synthesis studies and model assessment / model intercomparison using established benchmarking (e.g., TRENDY, CMIP, ILAMB). This effort will be used to inform the campaigns’ design and feasibility WGs on what are the key regions and processes that are the most uncertain and thus that could benefit the most from PANGEA measurements. MDSWG will also identify the key datasets and data synthesis products derived from a fusion of field, airborne remote sensing and spaceborne remote sensing data that are needed for model initialization, assessment and benchmarking.
  + Maybe a ROSES or a directed funds to carry out OSSE-type of modeling efforts to identify priority areas and priority variables/processes for the field campaign. Representativeness studies (Marcos’s thesis figure or something better, like uncertainty maps)
* Phase 2 (Y3-Y6). Model development to leverage the observations that will be measured during PANGEA, as well as from the new generation of satellites that will be launched during PANGEA and add key processes, variables and dimensions relevant to answer PANGEA’s key questions. The goal of this phase is not the creation of a single, unified model, as this would limit the ability to perform multi ensemble modeling exercises. Rather, in this phase, we aim for a process of data synthesis using one category of model that allows for scaling of space-time limited measurements to the entire pantropical region together with uncertainty quantification, e.g, AI/machine learning methods such as random forest,
* Phase 3 (Y7-Y9). Synthesis studies that use the data collected during PANGEA’s intensive campaigns to answer the key questions across the 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, and NSF models
* 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)
* 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)
* 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)

1. **How can we quantify the long-term effects of CO2 fertilization by integrating data from previous/current long-term experiments?**
2. **What are the major dimensions or axes of tropical plant life strategies (e.g., physiological traits, drought tolerance strategies, structural allocation) functional trait variation that need to be captured in models to understand spatial variation in plant functional composition today and compositional shifts under global change?**
   1. What are the functional properties (trait distributions) of forests on different continents, and how do differences in these trait distributions and trade-offs between traits affect forest responses to extreme events, climate change, and land use change on different continents?
   2. How sensitive are land model projections to different parameterizations of plant functional diversity (e.g., pantropical vs. continent-specific diversity parameterizations)?
3. **To what extent can the impact of human land management on subsurface-surface-atmosphere coupling of water-energy-carbon cycle processes in the tropics be measured and modeled, and does it represent a significant source of subseasonal to seasonal hydroclimate predictability?**
   1. What are the minimum levels of change in forest structure and composition caused by forest degradation that cause detectable shifts in the magnitude and seasonality of energy, water, and carbon fluxes relative to intact forests? How do these minimum levels of degradation vary across precipitation gradients and across continents?
   2. What are the typical time scales in which the energy, water and carbon fluxes of degraded forests become indistinguishable from non-degraded forests? How does the time scale vary as a function of degradation type (e.g., fires, logging, fragmentation) and climate?
   3. At which spatial scales the impact of forest degradation on energy, water, and carbon cycles is sufficiently strong to impact the dynamics of the planetary boundary layer and convective development, and thus impacting climate?
4. **How can weather forecast duration and reliability be improved in the tropics?**
5. **How can predictions of climate variability and change be improved in the tropics?**

### 5.6 Candidate Study Sites / Regions

* Need to demonstrate the feasibility
* Clearly define what can be done within the NASA scope
  + what's the safe science we can commit to delivering just from NASA
  + baseline mission
  + expand on that with contributions from other agencies
    - ESA, USAID, NSF,
    - and donor community
* need to have a process for selecting and approving ground sites
  + locations for ground campaigns will be the hard part
  + Engage with existing efforts
  + Opportunities for training to expand existing data collection to fill in gaps
    - Drones
    - lab facilities
* There are many tropical forests - different tropical continents/forests are different - floristically, function, in terms of pressures faced
  + comparisons within and across continents is critical
* include statement about two continents - why tropical Americas (Amazon especially) and Africa (Congo Basin especially) are an important comparison
  + biggest extent; biggest impact on climate dynamics

Strawman Baseline/Threshold Mission Concept:

* **Baseline A:** extend to Amazon & Africa
  + - comparative - to include Africa - repeat AfriSAR with other sensors
* Brazil (and DRC / other risky countries)
  + Plan A - ARES first
  + Plan B - commercial aircraft and commercial sensor
* talk to Marc to see how he did it for Delta-X
* Emphasize gradients!
  + Climatic gradients
  + Elevation gradients
    - Peru, Rwanda,
* **Threshold:** Panama and French Guiana
  + Panama and French Guiana) are safe choice
  + Both are very well studied, lots of data available, NASA has flown, very different in important respects
  + Guiana with the exception of a coastal plain is very old continental shield.
  + Panama is an island arc terrain that is younger and more fertile.
    - Disadvantages to Guiana are twofold: (1) it is quite wet meaning that we do not get the window on climate change (hot drought) that we might like; (2) it is highly preserved and there is very little active land use.
* **Baseline A:** extent to Amazon
  + better if extend to Amazon

|  | **Landscape** | **Country** | **Description** | **Prior NASA Flights** |  |
| --- | --- | --- | --- | --- | --- |
| ***Potential Central African Tropical Forest Landscapes*** | | | | | |
|  | Lopé | Gabon | Existing airborne lidar and SAR data; 50+ repeat census plots (0.5-1 ha); planned 2023 lidar/SAR data acquisition | AfriSAR 2016, 2023P |  |
| Mondah |
| Mabounié | Existing airborne lidar and SAR data; 50+ repeat census plots (0.5-1 ha); 25-ha repeat census ForestGEO plot (Rabi) | AfriSAR 2016, 2023P |  |
| Rabi |
| Dja | Cameroon | ~20+ repeat census AfriTron plots; drone LiDAR and multi-spectral data; planned 2023 lidar/SAR data acquisition | AfriSAR 2023P |  |
| Mbalmayo |
| Korup | ~20+ repeat census AfriTron plots; drone LiDAR and multi-spectral data; 50-ha repeat census ForestGEO plot (Korup) | AfriSAR 2023P |  |
| Campo Ma’an |
| Bokatola | Republic of Congo | 8 AfriTRON plots, 2+ censuses | N/A |  |
| Kolongomba |
| Lac Tele |
| ***Potential Neotropical Forest Landscapes*** | | | | | |
|  | Iquitos | Peru | 200+ RAINFOR plots, 2-10 censuses; existing airborne SAR data | UAVSAR |  |
| Madre de Dios |
| Ucayali |
| Paracou | French Guiana | GuyaFor forest disturbance experiment & field plots, Guyaflux tower; 10+ repeat census RAINFOR plots; existing drone/airborne LiDAR and multispectral data | LVIS 2021 |  |
| Amacayacu | Colombia | 25-ha ForestGEO plot, 2 censuses | UAVSAR |  |
| Amazonas |
| La Planada |
| Tiputini | Ecuador | 50-ha ForestGEO plot, 6 censuses; 3 RAINFOR plots, 2 censuses | UAVSAR |  |
| Yasuní |
| Amazónica | Bolivia | 10 RAINFOR plots, 2+ censuses | N/A |  |
| Vida Silvestre |
| Bokatola | Republic of Congo | 8 AfriTRON plots, 2+ censuses | N/A |  |
| Kolongomba |
| Lac Tele |

### 5.7 Why coordinated teamwork is required

## 6. Technical and Logistical Feasibility

PANGEA will also leverage NASA’s history of successful international field and airborne campaigns in the Americas and Africa. 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.

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 and NGOs 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 co-design of flight plans and site selection.

In cases where NASA aircraft cannot obtain overflight permission or acquire data, PANGEA will deploy commercial or other assets, such as commercial ALS, commercial drone based instrumentation or local instruments/aircraft to acquire the required airborne datasets. This is particularly important in Brazil, where there are challenges associated with acquiring nadir-looking data, such as LiDAR, multispectral, and hyperspectral data. Here we will leverage the existing practice employed by NASA and the USG of using commercial airborne data providers to collect the required datasets.

* Start with a statement showing that we are following on well learned precedents
  + ABLE 2a and 2b
  + SAFARI
  + LBA
  + AfriSAR 1 a 2
  + BioSCape
  + Multiple airborne campaigns in Central and South America using AVIRIS on a variety of platforms
* Will will go through NASA OIIR
  + We will build relationships with in-country partners and establish contacts to develop signed agreements
* not requiring NASA assets (NASA aircraft) to be deployed in Brazil or DRC
* NASA or other (ARES, commercial) can be used
* Interest from / alignment with partner agencies ESA, ISRO, Canadian Space Agency
* Emphasize that PANGEA will take advantage of what's happening locally
* Notes based on recent conversations with Ryan about scope
  + need to turn grand ambition into modular / scalable campaign
    - a few million / 10 million/ 30 million / 50 million -
  + depends on second PM though (an offer was made, date TBD, will likely start this summer)
  + could be bolstered by contributions from Biodiversity and/or Hydrology (also LCLUC, X, and X?)
  + possibly also Earth Action (Tom, Nancy, Keith)
* Provide threshold and baseline(s)
  + 5 years - $30 million
    - emphasize that we've already put in a PANGEA EVS
* 6 years - $50 million
* 8 years - $100 million
* 10 years - $150 million
* need proof that we've had discussions with partners who can allocate additional resources - actual funding or in-kind through existing activities (e.g., USAID, European Space Agency, NERC, donor community) - letters!
* **Synergies**
  + ride AfriSAR-2 - on budget, on schedule, for the most part no major glitches (describe successes and lessons learned)
  + LVIS flight(s) in SE Asia - talk to GEDI team
  + Amazon 2026 - Jack committed to trying to make NASA aspect equal to or exceed ESA component - talk to Clement Albergel & Dirk
  + talk to Barry Lefer about possibly sharing costs with Africa air quality campaign (not guaranteed, just being explored)
    - Building on Asia-AQ - Phillipines, Malaysia, Thailand, South Korea
  + possibility for synergies with Laura Lorenzoni's interest in lateral fluxes in rivers - especially in Amazon
  + India - AVIRIS-3 - in 2025 - other plans?

### 6.1 Cost Estimates

* **Cost** - Leveraging additional funding sources
  + Related relevant NASA funding opportunities
    - Topical Workshops, Symposiums, and Conferences (TWSC) in Space and Earth Sciences and Technology
    - ARSET, ….
  + Existing opportunities to solicit complementary funding
    - NSF RCN, AccelNet
    - NSF RISE
    - NSF EArly-concept Grants for Exploratory Research ([EAGER](https://new.nsf.gov/policies/pappg/24-1/ch-2-proposal-preparation#ch2F3)) Proposal
    - NSF DEB & BIO calls (alignment with NEON)
    - USAID CARPE
    - USAID SPARK (in prep)
    - USAID - other…
    - Belmont Forum
    - DOE calls?
  + In-kind support
    - AmeriFlux, ICOS
  + Seeking additional funding from new sources
    - Donor community

(move Required resources here)

## 7. Organization and Management

Who will lead this section?

ABOVE WHITE PAPER: <https://drive.google.com/file/d/1r9vFP5H4r7QVy379OSeGuPAWdINTQuRj/view>

The scientific guidance, management, and coordination of PANGEA will be provided through the use of a hierarchical structure that includes:

1. Program Leadership and Management
2. Project Coordination and Logistical Support
3. Coordination, Planning, Conducting, and Synthesis of Research

This organizational structure will provide the process to organize and manage a long-term project with significant investment from inter-disciplinary partnerships and collaborations at the national and international scale.

### 7.1 Scientific Leadership

PANGEA science will be directed by a Science Leadership Team. This team will be responsible for defining and managing the execution of the science of PANGEA. This Science Leadership Team should endeavour to be diverse in scientific expertise and gender. Early career researchers will be included from the beginning, as will representatives from each of the participating countries. The leadership team members must show a commitment to leading with cultural sensitivity, with the utmost respect for local collaborators, and with extra care taken to uphold NASA’s reputation internationally. The Science Leadership Team will meet regularly, and endeavour to, where possible, arrange meetings considerate to the time zones represented. The Science Leadership Team will receive feedback from the Science Team and local partners via an anonymous form. All feedback received will be discussed at Leadership meetings, and members of the Leadership Team will hold each other accountable to lead with empathy and efficacy.

The Science Leadership Team will be responsible for communicating the research objectives and anticipated outputs of the NASA-funded science team to a diversity of audiences. In doing so, they will largely be responsible for setting local partner’s expectations of PANGEA, and of NASA. This team will make every effort to accurately and promptly communicate project updates to local partners, and be careful to not raise expectations beyond what is likely to be delivered by the science team. Throughout the lifecycle of PANGEA, conversations with stakeholders should be recorded and expectations clearly tracked and followed up on. After PANGEA data has been collected and as science data products become available, the Science Leadership Team is responsible for ensuring that local partners continue to receive regular updates, and do not feel neglected after their large on-the-ground contribution may have wrapped up. The Science Leadership Team is responsible for setting the tone of PANGEA, and should 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.

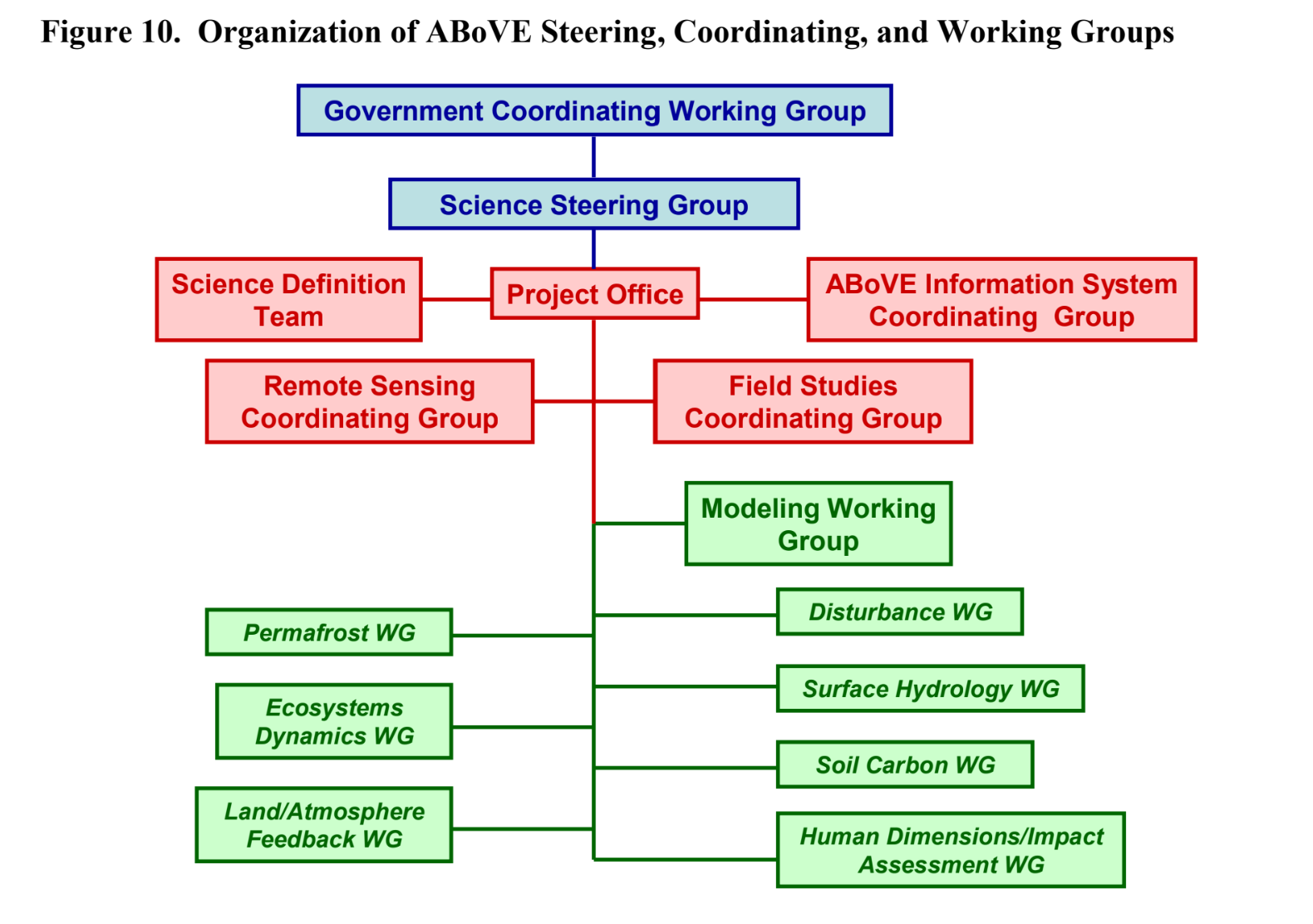
* Guided by ATBC codes of conduct and etiquette, already thinking about differences regionally, culturally, etc
* Speak to measures of accountability embedded in PANGEA design - How to ensure our walk follows our talk - what’s the accountability for PANGEA and projects to ensure follow through on commitments (in terms of science, co-production, engagement, training, etc.)?
  + Organizational structure
    - Science Definition Team - diverse representation
    - Early Career Group established from the outset

PANGEA will include several levels of scientific leadership (Figure X). At the highest level, there will be a “Government Coordinating Working Group” (GCWG), which is needed because of the involvement of research sponsored by international partners if the required agreements are negotiated, with representatives from partner agencies from countries including but not limited to: Brazil, Peru, Panama, Cameroon, DRC. Additionally, there is potential to form collaborative relationships with a number of domestic U.S. agencies (Appendix X with list of partner agencies) involved in research, monitoring, and assessment activities. The GCWG membership will include program managers who are directing and managing scientific research, monitoring, and assessment projects that involve climate and land use change in tropical latitudes. The GCWG would also provide coordination between PANGEA and frontier research programs that are coordinated at the national and international scale such as the U.S. Climate Change Research program, Convention on Biological Diversity, and others. For example, the Science Panel for the Amazon and the Science Panel for the Congo Basin were created to coordinate a continental-scale approach to help inform and accelerate local and regional solutions to strengthen nature conservation and advance sustainable development. Including a member from the Science Panel for the Amazon and Science Panel for the Congo Basin would provide the basis for coordination of these activities with those being sponsored by PANGEA at a regional scale. The GCWG will need to negotiate with other international space agencies (ESA, ISRO) to establish secure access to satellite remote sensing data that will be used during above. The GCWG will establish data-sharing agreements at the national and international agency level that outline data ownership, usage rights, and storage plan to address data sovereignty.

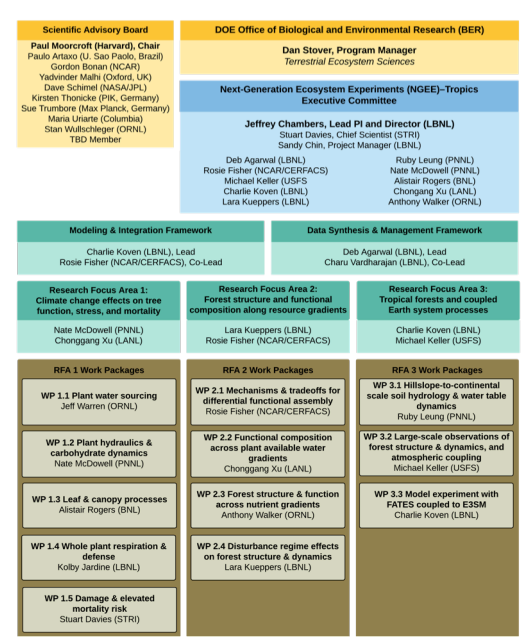
An International Science Steering Group (SSG) will provide additional oversight and guidance for PANGEA. The SSG will include scientists with expertise in each of the different PANGEA science themes. Depending on the level of sponsorship provided to support PANGEA activities (either directly or indirectly through active collaborations), this group will be led by a co-chair from each representative country whose agencies support the research that is part of PANGEA (e.g., Cameroon, Brazil, and the U.S., see section X). The SSG will provide guidance to the GCWG and Project Office for transference to the various coordinating and working groups that will be part of PANGEA. The SSG will provide oversight for developing the detailed PANGEA Concise Experimental Plan based on the feasibility constraints defined by the GCWG.

* Establish data-sharing agreements at nation-/agency-level that outline data ownership, usage rights, storage, etc. issues. This will help with the data sovereignty issue.

PLACEHOLDER Figure: Organization Chart: leadership, coordination, working groups. (ABOVE White Paper)



Another example from NGEE-tropics : https://ngee-tropics.lbl.gov/wp-content/uploads/sites/16/2020/01/NGEE-TROPICS-Phase-2-Proposal\_Final\_distributable.pdf



### 7.2 Project Organization

Activities for PANGEA will be coordinated and directed by NASA’s Earth Science Project Office (ESPO) sponsored by the Terrestrial Ecology Program to coordinate aircraft and airborne instrument logistics and act as the primary liaison between the science leadership team and the aircraft teams. The Project Office will support a Project Manager in addition to an appropriate level of staffing and a Project Scientist. The Project Office will be responsible for (a) providing oversight and management of PANGEA research activities and projects being sponsored by NASA’s Terrestrial Ecology Program and other NASA program offices; (b) coordinating and providing logistical support for NASA-sponsored field research and airborne remote sensing campaigns; (c) providing logistical support to the PANGEA working and coordinating groups, including support of meetings and workshops; and (d) developing and maintaining of the PANGEA Information System.

The Project Manager will be responsible for facilitating the development of a concise experimental plan and an implementation plan. The Project Manager is also responsible for:

* 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
* Coordinating with existing NASA efforts
* a more resilient world
* Committee on Earth Observation Satellites WGCapD
  + Working group on Capacity Building and Data Democracy with outreach to over 164 countries
* ARSET Earth Observations - ARSET offers online and in-person trainings for beginners and advanced practitioners alike - **targeting decisions and actions,** not science
  + can't use NASA money to fund international science, but if it's a training, can use ARSET money
  + Not for training scientists - for training decision-makers how to use RS data / data products, not scientific workforce - training for next gen grad students different than a working professional
    - Emphasize ARSET for training working professions in PANGEA
  + Takes at least a year to spin something up
* NASA-USAID Joint Global SERVIR Initiative - Sustainable development through capacity building and incorporating perspectives from women, Indigenous Peoples and their communities
  + it's USAID $ that allows for SERVIR activities to be conducted internationally
  + New USAID SPARK solicitation - mention this!
  + include letters that speak to alignment with / support from USAID - country missions, SERVIR hubs, etc., CARPE in Central Africa
* NASA DEVELOP
  + DEVELOP - 10 week programs; can last up to 3 week terms
  + fellows pitch those
  + tool out there in the toolbox
  + DEVELOP has done projects with airborne data/campaigns
    - usually focused on integrating airborne & satellite data
  + **one of the most flexible mechanisms** 
    - can turn around a DEVELOP project/initiative fairly quickly - 6 months
    - Only a 1/4 or less of budget from DEVELOP for international, but little bites can be really helpful
* Indigenous Peoples Initiative - Est. 2017 for engagement with Indigenous geospatial community in US and globally
* Coordinating with existing external efforts - mechanisms and responsibility - link to existing mechanisms for coordination including CBSI, LBA, etc.
  + FluxNet (especially ICOS & AmeriFlux)
  + GEO-TREES
  + One Forest Vision
  + [GEO](https://earthobservations.org/)
  + [USGCRP LACI](https://www.globalchange.gov/our-work/laci)
  + Indigenous and Local Community Partners: GATC, RRI, SILK

PANGEA Participation Structure

* + 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

### 7.3 Disciplinary Skills Required

7.X Field/research/ecological/ecophysiological sites

We are collaborating closely with our in-country partner institutions to ensure the smooth execution of field site activities. Together, we will plan for field measurements during the project. In consultation with NASA Property Management, we will identify the necessary pathways for managing instrumentation, materials, and supplies deployed at our international research sites. We will also coordinate with these institutions and in-country partners to facilitate the importation of items designated for return to project participants within the U.S., ensuring compliance with all shipping, export control, and customs requirements. To maintain the continuity of core measurements crucial to NASA and our collaborators during PANGEA, we will establish foreign loan agreements with responsible parties to oversee sensor maintenance.

### 7.4 International and Other Agreements

#### 7.4.1. NASA airborne campaign Indigenous agreements, permissions, and treaties (KEEP this section)

* 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)

### 7.5. Community Engagement Strategy

This section provides an overview of our strategy for engaging with diverse communities to address PANGEA’s science questions and mobilize and apply research findings for action.

* General principals (CARE & FAIR, FPIC, Stephanie Caroll)
* PANGEA Engagement goals
  + How would PANGEA engage with existing efforts?
* Overall strategy…   
  Address these questions  
  Cross-Cutting
* How can scientists, local institutions, and communities work together throughout the PANGEA program to develop a set of engagement methods for effective collaboration in diverse geographic and cultural contexts?
* How can diverse funding institutions work synergistically to support the advancement of remote sensing and terrestrial ecological research
  + How can complimentary funding enhance NASA’s work?
  + What data sharing and security approaches work when there are multiple funders?
  + How can reporting and communications be streamlined?
* How can we develop and sustain long-term a network of networks\* that enhances the accessibility, usability, transferability and benefits of the data, methods, models and knowledge about tropical ecosystems during and after PANGEA?
* Description of PANGEA-relevant communities and specific engagement considerations.
* Mention that the list below is non-exhaustive, but the overall strategy will provide a framework for also all engaging other under-represented communities

**Knowledge Exchange Opportunities:**

1. Are SES connections, cycles, and feedback perceived similarly between IPLCs and Western-trained scientists? How are these documented and/or mapped similarly or differently?
2. How can the knowledge/training on remote sensing and its capabilities enable (indigenous/traditional) communities to protect forests? What are the educational needs to support PANGEA? How can ILPC need and knowledge guide PANGEA funded research?
3. What are the most important sustainable alternative sources of income for ILPC?
4. What is the role of research and a science-based economy in this process?
5. How can PANGEA support or begin to establish a science-based economy and long-term research collaborations with IPLC across the tropics?
6. How can Indigenous Peoples & Local Communities be empowered to use remote-sensing data to conserve and restore their landscapes?

#### 

Table X PANGEA Target Groups for Community Engagement

| Target group | Description | Relevance to PANGEA |
| --- | --- | --- |
| Indigenous Peoples and local, forest-dependent communities |  |  |
| Women |  |  |
| Scientific Institutions |  |  |
| Government agencies |  |  |
| Non-governmental organizations |  |  |
| Intergovernmental organizations |  |  |
| Private sector |  |  |
| Donor community |  |  |

Indigenous Peoples and local, forest-dependent communities

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

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 proposal, we use the term scientific institutions primarily for universities, colleges, national labs, national professional institutions, and research institutes that through their leaders, faculty, 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 responding to the grand environmental challenges in the Pan Tropical Forest region. A particular interest of this partnership is to facilitate knowledge and tech transfer to generate capacity and capability building in the local and regional institutions to train the next generation of scientists. This partnership seeks to focus on:

* Co-development of the research, analysis, and potential applications of the proposed programs by PANGEA.
* Identify field sites, research infrastructure, and capabilities that are critical to the PANGEA proposed research.
* Co-production, sharing, and management of data, development of data infrastructure, equipment, and management expertise at local and regional institutions.
* Seek to strengthen/expand 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
* Capacity building for faculty and early career researchers at local and regional universities and research institutes to train and guide the new generation of scientists at local and regional institutions (for instance, co-lead technical workshops training junior research faculty and students, visiting scholars program in participating US-based scientific institutions).

Based on these 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
* 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 wil 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, coops 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 technical assistance…
* Targeted research dissemination 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 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.

Donor community

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

### 7.6 PANGEA Partners

* *Categorize potential PANGEA partners according to specific user groups*
* *Map geographically and thematically potential partners*

1. AndesFlux (research initiative conducted by institutions in the US, Canada, Germany, and Peru)
2. ASCEND
3. Australia
4. BELOW
5. Congo Basin Initiative
6. CBSI
7. CIAT - Alliance Bioversity International (International Center for Tropical Agriculture + Bioversity)
8. European Space Agency (ESA)
9. ESDT
10. Food and Agriculture Organization of the United Nations
11. FLUXNET
12. Global Alliance of Territorial Communities (GATC)
13. GeoTrees
14. IITA
15. IREES
16. MapBiomas
17. NASA ARID
18. NASA Biodiversity and Ecological Conservation (BDEC)
19. NASA Earth Science to Action (ES2A)
20. NASA Harvest
21. NASA Hydrology
22. NASA Jet Propulsion Lab / AfriSAR
23. NASA Land Cover Land Use Change (LCLUC)
24. NASA Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA)
25. NASA SERVIR
26. NASA Soil Moisture Active Passive (SMAP)
27. Observatoire National sur les Changements Climatiques (ONACC)
28. Penn State University
29. Poverty Action Lab at MIT
30. SilvaLab
31. Smithsonian
32. Sylvera
33. US Agency for International Development (USAID)
34. US Department of Energy (US DOE)
35. University of California Santa Cruz
36. United Nations Framework Convention on Climate Change
37. Woodwell
38. World Resources Institute

### 7.7 Co-funding

PANGEA has already made significant strides towards securing diverse sources of funding to leverage NASA’s potential investment. Resources from other U.S. government science funders, U.S. government development and conservation funders, private foundations, international governments, and philanthropists will support complementary activities that are outside of NASA’s scope. This will be critical to provide support to collaborators from tropical countries, and to support research application work. During the scoping phase, the PANGEA team met with XX potential funders, many of whom have expressed interest in providing complementary??? funding to support activities outlined in this white paper (see Letters of Support).

[PANGEA White Paper Figures & Tables](https://docs.google.com/presentation/u/0/d/1I1VCZSjVCHu4JMfPi1QtXO5UI4u8tuRA-mqUeMGHtvM/edit)[See Table 5 for table of potential co-funders/supporting projects]

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 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 in the future (link to science questions if the question about partnership stays).

### 7.8 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. This strategy will follow NASA Scientific Information Policy requirements and guidelines, be guided by community principles and practices, and keep ethical guidelines and cultural sensitivity in mind.

The PANGEA data management will adhere to the Findable, Accessible, Interoperable and Reusable (FAIR) guiding principles.

* Explain how data management considerations will be addressed during the campaign.
  + NASA Terrestrial Ecology field campaigns must be committed to NASA’s Earth Data and Information Policy, NASA Open Science Philosophy, and NASA’s Open Data, Services, and Software Policy.
  + See ABoVE data management strategy - CCE
  + work with CCE and DAACS to ensure meet XYZ policies
    - NASA Earth Science Data Preservation Content Specification: https://www.earthdata.nasa.gov/esdis/esco/standards-and-practices/preservation-content-spec
  + FAIR guiding principles: <https://doi.org/10.1038/sdata.2016.18>
  + CARE principles: <https://www.gida-global.org/care>
  + Community input on data management plan
  + Refer to new NASA open science policy
* New data collection, but also collate and rely on existing data sources
  + How to ensure we do this collaboratively and ethically - respecting rights and ownership of data already collected
* Different data support for different data products linked to via central PANGEA Data Portal
  + DAACs for airborne data
    - Coordinated VSWIR data cleaning by (SBG/EMIT/AVIRIS/NEON coordinated team)
    - Coordinated …
  + AmeriFlux & ICOS for flux tower data
    - Including commitment to support resuscitation of LBA Phase 1 flux tower data??
  + Forest Inventory plot networks…
  + LBA
  + [KADI](https://kadi-project.eu/)
* DAACS, tropical DAACs, data sovereignty, cloud computing - access for partners (Centers for Excellence & trainings)
  + Also though, DAACs are a pain - make things available on apps - GEE - for upload and download
* highlight working with existing training programs (specify)
  + if they don't exist - describe and explain how PANGEA could implement
* How could PANGEA advance goal of democratizing data?
* Opportunity to harmonize protocols across research communities to support scaling
  + Point to work Dana is already doing w NEON, SBG, EMIT, other groups
  + Feedback from workshop: valuable to have standardized protocols - but not too rigid recognizing varying access to resources/capabilities
* Data accessibility, usability, and visualization
  + Need user-friendly data platform!!!!
    - Appears.earthdata - mentioned as useful by graduate student researchers from the tropics at various workshops
  + How to make data more accessible to non scientists? - think about applications side of things - partner with existing efforts like Global Forest Watch, Land and Caron Lab, GIS efforts via Rights & Resources Initiative

### 7.9 Timetable

(number of years?)

### 7.10 Challenges/areas for growth

* *Proactively discuss limitations in our engagement methods.*
* *Identify the gaps and explain why certain groups were under-represented groups in our consultative process (e.g. private sector, government esp in Africa, IPLC logistical challenge + ethical concerns). Explain how the funded PANGEA program could address these gaps.*
* *Riks????*
* *Inclusiveness. PANGEA will interact with people with different backgrounds and levels of instructions. Simple language is needed,*
* *Interaction with Stakeholders. Approach/better approach with national and international stakeholders and point out current gaps.*
* *Inter-agency effort: PANGEA is conducting research in a region highly sensitive to climate change, making this work particularly valuable to several U.S. research institutions*
* *Proprietary data from collaborators? how will we deal with this limitation?*
* *Universality: PANGEA documents will be translated into, english, spanish, portuguese, and french.*
* *Formation: PANGEA will strive to integrate the next generation of scientists, though this effort may be constrained by budget limitations.*

## 8. Enabling Earth Science to Action

Earth Science to Action - Est. 2024 decadal goal to co-develop with partners and users across sectors nationally and internationally to create - describe PANGEA Earth Science to Action priorities and opportunities - link to partners mentioned in section 7

### 8.1 Carbon

### 8.2 Biodiversity

* Moved here by MVE (Aug-26) from section 2.4; contribution from the SES WG:
  + 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.

### 8.3 Agriculture

Community engagement is central to PANGEA’s Earth Science to Action strategy.

* Work with partners to make these data products as accessible as buying something on Amazon - e.g., Global Forest Watch
  + Include info on how scaling was done so users understand
  + Educational materials - summer schools, MOOCs,
  + Raise awareness across communities - about PANGEA, about needs, also about existing datasets
* Use an example pyramid of PANGEA -> ES2A
  + use ES2A language
  + Provide specific examples
  + Maybe one pyramid for each Carbon, Biodiversity, and Agriculture
* In ABOVE referred to as "applications and decision support"
* 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
  + how do we feather into other ongoing services / satellite missions
    - E.g. SAR training / readiness for SERVIR
      * Engage in something simliar for hyperspectral w relevant mission leads
  + can use the airborne campaign as candy
  + training before, after, alongside
  + Focus on operational data - already in the DAAC, as opposed to simulated data
    - Not so much early adopters workshops (e.g., for NISAR)
    - Nancy tries to keep ARSET out of 'simulated data' space

Applications that have the potential to be advanced by PANGEA

* Carbon mapping
  + 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?
* Mapping of risks to carbon stocks in the tropics - important for carbon markets
* Biodiversity Conservation
  + IPBES and Convention on Biological Diversity
* Sustainable agriculture and deforestation-free supply chains
  + Yield and crop type mapping
  + Water use and supply
  + Precision ag
* Supply chain traceability and management / Supply chains / Value chains - EUDR
* Deforestation and degradation alerts - associated with drivers?
  + Mining, roads, urbanization, etc. to be used by local and Indigenous communities and/or jurisdictional governments
* Bioeconomy
  + Non-timber forest products
* Restoration
* 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?
* Disaster Alerts & Response
  + Fires
  + Flooding
* Weather prediction
* Empowering and elevating Indigenous, local, and traditional communities
* Integration of RS data with LEK, IEK, and TEK

## 9. Capacity Building, Training, and Education

* Address capacity building
* Training that goes beyond data collection - learn to collaborate, plan, write papers, write grants, do analysis
* Workforce development, particularly, in the areas of emerging technologies such as machine learning and artificial intelligence (in addition to RS)
  + Emphasize that PANGEA will count on the participation of researchers from EPSCoR states as a part of NSF’s Broadening Participation portfolio.
  + Work with NASA ARSET and [NSF RISE](https://www.nsf.gov/div/index.jsp?div=RISE) programs
* GLOBE: <https://www.globe.gov/>
  + Support schools and teachers in landscapes to participate in GLOBE
  + Engage and connect elementary school students across the globe
* NSF Geoscience Opportunities for Leadership in Diversity ([GOLD-EN](https://new.nsf.gov/funding/opportunities/geoscience-opportunities-leadership-diversity-gold)) - Supports creating a network of professionals to implement evidence-based best practices and resources that improve diversity, equity and inclusion within the geosciences

## 10. Risk and Risk Mitigation / Risk Assessment

MvE: 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. It might be worth considering this as a 'risk' considering the potentially 'short' duration of Pangea field work.

## 11. References

## 12. Figure and Photograph and Credits

## 13. 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

***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>

***Degradation*** = selective logging, mining, defaunation, human-ignited fire

***Ecosystem*** = natural ecosystem, agro-ecosystem, social-ecological system

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

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

***Human activities =*** formal, informal, and illegal economic, subsistence, and development practices by humans that lead to the exploitation, alteration, and degradation of forest ecosystems, including logging, construction of infrastructure, agriculture, livestock rearing, fire, mining, hunting and wildlife exploitation, charcoal production

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

***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"*

## 14. List of Acronyms

## 15. Appendices

### A - 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).

### 

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

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

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

### E - 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

### E - Letters of Support

1. National University of Piura, PERU  
   Agronomy Department  
   <https://www.gob.pe/unp>
2. PennState University, USA  
   Department of Meteorology and Atmospheric Science  
   <https://www.met.psu.edu/>
3. Université Catholique de Louvain

### D - 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