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 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 researchers from countries with tropical forests. PANGEA will also 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 and applications.

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; moist tropical forests in particular comprise about 40% of global biomass carbon (Xu et al., 2021, Pan et al. 2011) 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)).

Furthermore, tropical forests and floodplains, which are frequently laden with wetland and aquatic ecosystems, play a critical role in the global methane (CH4) and CO2 budgets (Sjögersten et al., 2014; Peng et al., 2022). 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). 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 carbon 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, van der Ent et al., 2010, Staal et al., 2018). Deforestation and forest degradation reduce evapotranspiration in the dry season (Sampaio et al. 2007; Longo et al. 2020; Zemp et al., 2017recycling models refs) potentially leading to forest mortality and a positive feedback loop resulting in forest ecosystem collapse that has been called a “tipping point” (Xu et al., 2022,Lovejoy and Nobre 2018).

**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, these net carbon losses were caused by heterogeneous processes (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 (Bloom et al. 2016), 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 terrestrial 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). The latitudinal distribution of both forest inventory plots and eddy covariance flux towers is nearly inversely proportional to gross primary productivity, demonstrating the underrepresentation of sampling in these critical ecosystems (Baldocchi et al 2022, Schimel et al. 2015) (Figure X).

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, land-use change and biodiversity loss, the globally important tropical carbon balance, heretofore mainly a sink, is now often reversing to become a source of carbon emissions to the atmosphere. 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 as well as 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, Landsat, VIIRS,
  + Commercial Satellite providers through CSDA program
* Model-[RS] data integration
  + Processes we need to get right in models
    - Dynamic vegetation (incl post-disturbance recovery and structural and functional diversity)
    - Plant water use efficiency
    - Drought stress response (incl. natural vs. managed lands)
    - Partitioning of ET
    - Hydraulic redistribution
    - Root-groundwater interactions
    - Surface water quality
    - Planetary boundary layer diurnal evolution, advection, and entrainment
    - Drivers of land-use change?
    - Feedbacks of climate change in tropics on people (e.g., ag production, water quantity and quality, fire & air quality)
* RS indicators of:
  + Vulnerability to tree mortality
  + Biodiversity – in most biodiverse region (what taxonomic/functional scales of diversity matter for carbon cycle dynamics?)
  + Productivity
* Improved climate model predictions for the tropics (has global climate prediction implications)
  + ERA5 and CHIRPS discrepancies / lack of weather stations
  + Land-atmosphere interactions

### 1.4 PANGEA Study Domain

The initial focus of PANGEA will be on tropical biomes in Africa and South America. The PANGEA study region covers the major ecosystems and landscapes found in the tropics and the spatial scale required to address the primary questions in the X major science themes. The location of these Primary Research Areas will be based on opportunities to conduct integrated research across science themes as well as the existence of ongoing or planned research funded by NASA, as well as local and international partner agencies and organizations.

* 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 articulate

### 1.6 Earth Science to Action

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

* investigation of potential risks due to crossing thresholds for climate tipping points and the possibilities for cascading environmental and societal impacts.
* supporting efforts to Earth resilience, including the development of strategies for mitigation, adaptation, and the assessment of various risks and contingencies associated with global change and its impacts.
* building efficient and interactive end-to-end tools, models, and assessment systems with the needed latencies, at the appropriate temporal and spatial scales, and with the appropriate uncertainty quantification to serve people, communities, decision- and policy-makers, enabling them to take science-based actions.

*Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space* directs us to “Pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observations and

analysis to the nation and to the world in a way that delivers great value ….”

### 1.7 [What PANGEA is and is not - section title TBE] - section that explicitly defines what NASA PANGEA covers

* Science themes
  + Data collection
  + Data curation
  + Open science
* Training activities directly related research
* Community engagment, including engagement w partners who are:
  + Leading on the applications development and decisions support
  + Leading on the workforce development training

## 2. PANGEA Science Themes

[reminder - these should each cover the following:

1. The science questions and issues
2. The current state-of-the-science
3. The potential for a major, significant scientific advancement

Probably about 5 pages per science theme]

### 2.1 Carbon Stocks and Fluxes

**This PANGEA Science Theme will investigate spatial and temporal variation in tropical forest carbon stocks and fluxes and the roles of climate, hydrology, and edaphic properties in driving this heterogeneity.**

[a lot of the background for this theme is in the proposal introduction, so the material here should be more specifically what is most relevant to motivate these questions and summarize the state-of-the-science]

[subsection: motivation / background, not titled]

[paragraph] Global importance of tropical forest carbon stocks and fluxes Stocks relative to C in atmosphere

* Fluxes - NPP, GPP, methane emissions in global context
  + The terrestrial biosphere is a large sink of atmospheric CO2 with a present-day global NEE estimated at 3.3 GtC yr-1 offsetting ~30% of the CO2 emitted by fossil fuels annually. Tropical terrestrial ecosystems are estimated to contribute up to 0.6±0.4 GtC yr-1 of this sink with large interannual variability (Friedlingstein et al., 2023). Tropical lands play a critical role in the global CO2 budget as they are a controlling factor of atmospheric CO2 interannual variability (Ahlström et al., 2015).
  + According to the most recent Global Carbon Project CH4 budget synthesis (Saunois et al., 2024), the tropics are the largest regional source of CH4 to the atmosphere contributing ~65% of total global emissions (364 Tg CH4 yr-1). A significant portion of total CH4 emissions from the tropics are from wetland and inland water body sources (151 Tg CH4 yr-1).
* Net flux - on average C sink over recent decades, but not everywhere or always

[paragraph] Yet still great uncertainty about tropical forest C stocks and fluxes and their drivers, and how they are changing under global change, in part because of tremendous heterogeneity of tropical forests, and reflecting relative dearth of data (paragraph)

* Heterogeneity
  + in climate (rainfall regimes especially), disturbance regimes (addressed more later),
  + In geomorphology, soils
  + in biotic factors such as biodiversity (addressed more later)
  + This heterogeneity matters for responses to global change
* Sparse and poorly distributed ground data
  + Aboveground woody carbon stocks and fluxes: Plots
  + Net ecosystem flux: Eddy flux
  + Methane: very few
  + Climate, disturbance regime
  + Soils, hydrology
* Remote sensing
  + Has great potential, especially instruments coming on line in coming years
  + But lack of ground data hinders accurate and precise interpretation
  + Scales mismatch

[subsection: questions]

Carbon stock and flux studies for PANGEA will answer the following questions:

* What are tropical forest carbon stocks and fluxes (CO2 & CH4) and how do they vary spatially and temporally?
* What are the roles of climate, hydrology, and edaphic properties in contributing to spatial and temporal variation in tropical forest carbon stocks and fluxes?

For carbon stocks, we focus on aboveground woody biomass, a large pool in tropical forests and one amenable to remote sensing. For C fluxes, we include woody productivity, woody biomass losses, net change in woody biomass, NPP, GPP, net CO2, as well as CH4 fluxes (uptake, emissions, net flux).

In later sections, we will further address the roles of biodiversity, disturbance dynamics, and land use in contributing to variation in tropical forest carbon stocks and fluxes.

[subsection: more on the state of the science related to the questions, and the potential for a major advance]

[paragraph]: spatial variation in tropical forest aboveground woody biomass carbon stocks - knowns, unknowns, needs, potential advances

* Field methods - ground plots, biomass allometry equations,
* Remote sensing of aboveground forest carbon stocks: airborne and spaceborne lidar, radar, but need calibration
* Fallacy of misplaced concreteness - key limitation of plot-based datasets, and their use in calibrating remote sensing
* TLS - can avoid this fallacy, provide better, more consistent calibration of remote sensing for woody volume
* To get from woody volume to woody biomass need wood specific gravity (wood density) averages… heart rot an issue
* Knowns - global patterns in lidar, radar signals, and associated biomass estimates from current calibration methods.
* Unknowns - true global patterns (published maps differ) based on better calibration
* Needs - better basis for calibrating global remote sensing, through consistent, high-quality, public ground-based data, and its use to produce better maps
  + (GEOTREES is a start, but need more…)
* Potential payoff:
  + Methods for obtaining unbiased estimates of tropical forest biomass from current, future, and past remote sensing data
  + Solid understanding of true pattern of spatial variation in tropical forest aboveground biomass C stocks and how these have changed and are changing heterogeneously.

[paragraph]: spatial and temporal variation in tropical forest aboveground woody biomass productivity, mortality, and net change fluxes - knowns, unknowns, needs, potential advances

* Ground-based:
  + Methods: ground plots, biomass allometry equations… differenced!
  + Productivity - high uncertainty due to buttressed trees, sensitivity to QAQC methods
  + Mortality and branchfall - mortality fairly straightforward, branchfall almost never calculated and when it is (from woody debris fluxes) there is high uncertainty
  + Net flux - error/uncertainty large relative to value, as net flux often close to zero.
* Remote sensing -
  + Methods: time series of lidar, radar, and even high-resolution optical for mortality
  + Net change is in principle doable by differencing stocks, but little calibration of this net flux specifically, usually just assumed that calibration of stocks is sufficient…
  + Mortality - with sufficiently high spatial and temporal resolution, can capture individual tree mortality events (and even branchfall), but needs to be fine resolution, and needs calibration.
  + Woody productivity: not really directly doable from remote sensing, is it? Or could this be done with sufficiently high spatial and temporal resolution?
* Knowns:
  + Spatial: some broad-scale literature syntheses, but based on sparse data
  + Temporal: continental-scale net fluxes over time from atmospheric inversion, but not just woody biomass…
* Unknowns: spatial and temporal patterns at fine spatial scales, for all of the fluxes.
* Needs:
  + Development of good, general methods for estimating woody biomass fluxes from remote sensing (at least for mortality and net flux should be directly estimable, and then woody productivity should be estimable as a difference). This requires more, better, consistent cal/val data. Repeat drone and/or airborne lidar could be key for scaling.
* Potential payoff:
  + Methods for obtaining unbiased estimates of tropical forest mortality and net biomass change fluxes from current, future, and some past remote sensing data
  + Solid understanding of true pattern of spatial variation in tropical forest aboveground biomass C fluxes and how these have changed and are changing heterogeneously.

[paragraph] spatial and temporal variation in tropical forest GPP and NEP - knowns, unknowns, needs, potential advances

* Ground methods: eddy flux, very limited availability
* Remote sensing methods:
  + GPP: Chlorophyll fluorescence… (is it worth mentioning model-based estimates from MODIS and the like?)
  + NEP: spectral measurements of atmospheric column CO2 combined with atmospheric inversion
* Knowns:
  + diurnal, seasonal, interannual patterns within sites with eddy flux
  + Spatial variation…. ?
* Unknowns
* Needs
* Potential payoff

[paragraph]: environmental drivers of spatial and temporal variation in tropical forest biomass stocks and fluxes

* Knowns
  + Broad-scale qualitative patterns of tropical forest aboveground biomass, woody productivity, mortality vs. environmental variables in literature reviews, e.g., Muller-Landau et al. 2021 New Phytologist, forest plots compared to coarse gridded datasets (Sullivan et al., 2020)
  + Leaf phenology patterns from satellite data
  + Phenomenological models grounded in current remote sensing estimates
  + Mechanistic models in ESMs… but only weakly linked to data
* Unknowns
  + Precise and accurate environmental driving variables at high spatial and temporal resolution (e.g., lack of good and comparable soils data across much of tropics)
  + Quantitative patterns, interactions, generality/specificity
  + True mechanisms, accurate and precise mechanistic models
* Needs:
  + Accurate and precise data on environmental variables and aboveground biomass carbon stocks and fluxes at high spatial and temporal resolution
  + Improved satellite-based leaf phenology estimates?
  + Data to inform key parameters in mechanistic models?
* Potential payoffs:
  + Mechanistic, accurate, precise understanding of how environmental variables influence tropical forest carbon stocks and fluxes (including but not only via leaf phenology), knowledge critical for projecting global change influences on tropical forest carbon budgets.

[paragraph] nutrients as drivers of spatial variation in tropical forest biomass and as limitations on tropical forest responses to global change

* Importance: of all the environmental factors contributing to spatial variation in tropical forest carbon stocks and fluxes, nutrients are the least well understood, and they are critical for projecting tropical forest responses to anthropogenic global change
* Past methods
  + Experiments - but mostly small-scale, short-term, and generalization is problematic because of heterogeneity of tropical forests
  + Observational studies along environmental gradients - but many nutrients and other factors covary, so tough to disentangle roles of different factors, and most studies include few sites
  + Remote sensing studies - soil variables generally poorly known across tropics, so limited ability to test their role from remote sensing
* Knowns
  + Nutrients matter and often limit tropical forest productivity; turnover / woody residence time and biomass also vary with nutrient availability
  + Nutrients could strongly limit response to elevated CO2…. or not so much.
  + Leaf nutrient concentrations and soil nutrient availability can be estimated from spectroscopy
* Unknowns
  + Which nutrients are how limiting and where/when
  + How nutrient limitation will affect responses to global change
  + Generality of spectra-nutrient relationships? Uncertainty of these estimates?
* Planned work
  + Public cal-val data for tropical forest leaf nutrients and soil nutrient availability, and resulting generalized relationships for estimating leaf and soil nutrients from spectra
  + Pantropical maps of leaf and soil nutrient availability
  + New analyses of role of nutrients in explaining spatial variation in productivity, mortality, biomass, and more
* Potential payoff
  + Mechanistic, accurate, precise understanding of how soil nutrients influence tropical forest carbon stocks and fluxes, knowledge critical for understanding nutrient limitation of global change responses
* From scoping study proposal:
  + 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).
  + While phosphorus is largely assumed to be the most limiting nutrient, 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; 2024).
  + High biodiversity in tropical forests causes results from manipulative experiments that test where and when nutrient limitation affects productivity to be highly localized.
  + 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).

State of the science of satellite remote-sensing GHG fluxes and drivers in the tropics

* What has been done?
  + Due to the improved observational coverage of column integrated CO2 (XCO2) and CH4 (XCH4) compared to ground-based and airborne in situ measurement networks, satellite remote-sensing retrievals have been used in inverse atmospheric models to estimate tropical GHG budgets.
  + The tropical CO2 terrestrial budget has been constrained using satellite remote-sensing XCO2 data from GOSAT, OCO-2, and TanSat (e.g., Liu et al., 2016; Lunt et al., 2019; Crowell et al., 2019; Palmer et al., 2019; Yang et al., 2021).
  + Tropical wetland emissions of CH4 have been estimated using satellite retrievals of XCH4 from GOSAT and TROPOMI (e.g., Parker et al., 2018; Ma et al., 2021; Feng et al., 2022; Yu et al., 2023).
  + These studies have made critical findings about how climate, hydrology, and vegetation characteristics impact the tropical carbon budget across multiple temporal scales.
* What are the challenges with using satellites in the tropics?
  + Persistent cloud coverage is a significant issue when using space-based XCO2 and XCH4 to constrain tropical GHG fluxes (e.g., Rayner et al., 2002; Qu et al., 2021). Even at the higher spatial resolution of the current low earth orbiting satellite sensors retrieving XCH4 (e.g., TROPOMI [3.5 km x 7.0 km]) and XCO2 (e.g., OCO-2 [1.3 km x 2.2 km]) >95% of retrieved information is filtered due to clouds in the tropics (Qu et al., 2021). Higher spatial resolution XCO2 and XCH4 satellite sensors such as MethaneSat (100 m x 400 m) have been recently launched which will greatly improve the capability to retrieve GHG in the tropics through cloud gaps. Other point-source mapping GHG satellite sensors (e.g., EMIT, GHGSat, Carbon Mapper, PRISMA) have also been launched with very high spatial resolution (<100 m x 100 m); however, these target mode observations will not provide the global coverage needed to constrain tropical GHG budgets.
  + Newer satellite remote-sensing GHG observing sensors (e.g., TROPOMI, OCO-2, CO2M, MethaneSat) have the spatial resolution and precision (<1.0%) needed to estimate tropical CO2 and CH4 fluxes. Improved precision and spatial resolution in future spaceborne GHG sensors will aid in the capability to constrain diffuse fluxes of CO2 and CH4 in the tropics.
* How can PANGEA improve our understanding of remote-sensing capabilities in the tropics?
  + PANGEA will obtain a large variety of airborne and ground-based observations coincident with overpasses of existing NASA (e.g., OCO-2, OCO-3, Landsat, MODIS, VIIRS, SMAP, GRACE, SWOT, AMSR-E, AMSR2, ICESat-II, EMIT, PACE), international (e.g., TROPOMI, GOSAT, GOSAT-2, CO2M, RADARSAT, Envisat, PRISMA, DESIS), and commercial (e.g., GHGSat, MethaneSat, WorldView, Quickbird/GeoEye, Planet) satellite products. These observations will aid in validation of these satellite’s retrievals of precipitation, atmospheric composition, inundation, terrestrial vegetation, and water ecology. They will also assist in assessing the capability of future planned satellite sensors (e.g., SBG, GLIMR, Carbon Mapper) and observation strategies. PANGEA will allow for investigating the required instrument characteristics (e.g., precision, accuracy, spatial/spectral resolution) and observational strategies (e.g., low Earth orbit versus geostationary) for monitoring GHG emissions, and flux driver variables, in the tropics.

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. 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 in situ 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.

Key knowledge gaps with biomass carbon. The recent emergence of high resolution satellite image availability has made larger-scale estimates on biomass carbon possible outside of field plot networks and airborne LiDAR which have extended mapping estimation. However, interpolating biomass still relies on calibration validation … which ….

Controls paragraph. Climate, water and nutrient availability, as well as edaphic properties drive variation in rates of photosynthesis, respiration, growth, recruitment, and mortality across the tropics. At a general level, productivity typically increases with temperature until water is limiting, and productivity typically increases with soil fertility (Muller Landau et al., 2021). However, our ability to predict how environmental variables drive these carbon fluxes and stocks remains hindered by the discrepancy between the scales of data collected for environmental variables and forest response. Much of our understanding relies on information collected from individual sites, while studies across space have relied on syntheses of forest plot networks. These studies have demonstrated strong spatial variation in tropical forest aboveground biomass carbon (e.g. Sullivan et al., 2020, other REFS), but rely on coarse environmental data. Variation in biomass carbon has been attributed to maximum temperature, rainfall, with little variation explained by cloud cover, wind speed, and edaphic soil properties, despite … (Sullivan et al., 2020). These environmental variables have been obtained from large gridded datasets such as WorldClim and SoilGrids (~a minimum of 250 to 1 km resolution), which rely on extrapolated ground data. However, remote sensing offers a huge opportunity to improve upon ground-based weather stations and soil property data … [Not quite sure how to set up the challenge and the opportunity here and would need some help from others!]

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

A large proportion of tropical forests are permanently or seasonally flooded wetlands (REFS?). 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).

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

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

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

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?

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 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

Biodiversity is the variation of life on Earth, including ecosystem, species, the inter-species trait variation and the diversity of functions that each organism, species, ecosystem possesses to access and create resources for life to persist. Biodiversity arises from the richness of interactions between plants and animals, rooted in mutual dependence. Plants as the primary producers provide food and habitats, while animals contribute to essential services such as pollination, seed dispersal and nutrient cycling.

Biodiversity underpins the structure, productivity, functionality and resilience of ecosystems, which in turn regulate the flow of critical biogeochemical cycles including those of carbon, water and nitrogen. However, the expected form of the relationship between biodiversity, structure, productivity and functionality as well as the strength and scale dependence of any underlying mechanism are uncertain.

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). There are several possible mechanisms for this phenomenon. Species with diverse traits and resource requirements may utilize a larger number of resources available in an ecosystem thought reduces competition, increased facilitation, or both, which leads to overall more efficient resource use. In parallel, more diverse tree species assemblages are more likely to contain the most productive species, which can increase overall functioning.

Despite the contribution of biodiversity to efficient carbon sequestration, nature-based solution initiatives often focus on increasing or conserving the spatial extent of natural ecosystems, and not in their diversity, composition. Protecting areas with high biodiversity, carbon and productivity value would increase conservation efficiency and help countries address their policy targets, namely in areas under pressure of land cover land use change (e.g. agriculture expansion).

A thorough understanding and monitoring of biodiversity still requires on-ground collection, as remotely sensed biodiversity variables do not replace yet an understanding of functional and genetic composition, discovery of species and oftentimes require experiments to separate the phenotypic and genetic components of functional variability (Cavendar-Bares et al., 2022). However, the combined use of several remote sensing tools can provide fresh insights and perspectives into the structure, function and dynamics of forest ecosystems, and elucidate how the taxonomic, functional and phylogenetic components of biodiversity are linked to changes in the environment.

For example, spectroscopy imagery has enhanced enormously our ability to map taxonomic, functional and phylogenetic diversities in tropical forests (Feret and Asner, 2011; Asner et al., 2014 ; Asner et al., 2017), but we have a poor understanding of phenotypic variability across tropical tree species given their spatial distribution and enormous diversity - indeed a single hectare in a tropical forest can harbor as many native tree species as the entire Western Europe (Valencia et al.). This enormous variation can lead to higher uncertainties in distinguishing tree species using purely remote sensing tools, and requires on-site data collection that calibrate local models for upscaling of physiological, morphological and reproductive characteristics of each species or group of species.

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](https://doi.org/10.5194/hess-23-4171-2019); [2019](https://iopscience.iop.org/article/10.1088/1748-9326/ab22d6/meta)). In turn, this influences photosynthesis, respiration, and long-term carbon storage as vegetation chooses 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](https://doi.org/10.1073/pnas.1621516114), [Sori et al., 2022](https://doi.org/10.1002/9781119657002.ch11), [Worden et al., 2021](https://doi.org/10.1029/2020JG006024), [van der Ent et al., 2010](https://doi.org/10.1029/2010WR009127), [Staal et al., 201](https://doi.org/10.1038/s41558-018-0177-y)8). 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](https://doi.org/10.5194/hess-25-2279-2021), [Crowhurst et al., 2021](https://doi.org/10.1007/s00382-020-05547-1), [Weerasinghe et al., 2020](https://doi.org/10.5194/hess-24-1565-2020), [Macharia et al 2022](https://doi.org/10.1175/JHM-D-21-0161.1), [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](https://doi.org/10.3389/fsoil.2022.883236), [Alsdorf et al., 2016](https://doi.org/10.1002/2016RG000517), [Lopez-Ballesteros et al., 2018](https://iopscience.iop.org/article/10.1088/1748-9326/aad66c/meta), [Seinfeld et al., 2016](https://doi.org/10.1073/pnas.1514043113)).

Therefore, PANGEA stands as the first cross-continental initiative to better understand these complex interactions between tropical forests and climate systems, a crucial component influencing whether tropical rainforests will act as a future carbon sink or source ([Zhang et al., 2015](https://doi.org/10.1111/gcb.12903), Gentine et al., 2019). This initiative 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:

1. **How do tropical forests alter land surface biophysical properties, which in turn influences the strength of land-atmosphere feedback and teleconnections?**

Tropical forests play a crucial role in moderating energy, water, and momentum exchanges between the surface and atmosphere (e.g., [Bonan, 2008](https://www.science.org/doi/full/10.1126/science.1155121?casa_token=1bgjxhpSvmQAAAAA%3A8spvkVOe-yK-8pxHgf5pXyCIkmX9HdY4uO46PFFzbn5lyuVXPMctEln3gApnmJreClEEnn8IA-HLv_c)). They are characterized by lower albedo, higher evapotranspiration rates, and greater surface roughness lengths than other terrestrial landscapes ([Bell et al., 2015](https://doi.org/10.1002/2014JD022586), [Shuttleworth et al., 1989](https://doi.org/10.1098/rstb.1989.0050)). In addition, biogenic volatile organic compounds produced by the rainforests are pre-cursors to the formation of cloud condensation nuclei and organic aerosols that scatter radiation, thus influencing cloud formation and albedo as well as the quality of light available for vegetation ([Artaxo et al., 2022](https://doi.org/10.1371/journal.pclm.0000054)). These aerosols can also interact with turbulent fluxes and other aerosols to alter the vertical profile of the atmosphere, and in turn, feedback to tropical convection and rainfall on time scales ranging from diurnal to decadal [(](https://paperpile.com/c/ovIUza/1Ghm+fNLl+2TA9+7XOK) [Betts and Silva Dias 2010; Suni et al. 2015; Gentine et al. 2019; Weber et al. 2024](https://paperpile.com/c/gMdJbo/gTtBt+MPMLM+TnAjI+EwxMa), [Chakraborty et al., 2021](https://doi.org/10.5194/acp-21-12855-2021)).

However, large uncertainties exist in measurements of these exchanges as they can be affected by many factors on local to synoptic scales. For example, radiation transfer in plant canopies is extremely complex as it can be influenced by the leaf area index, leaf angle distribution, and the type and density of vegetation. Therefore, this process is most commonly modeled at canopy level, confined to one dimension, and using simplifying assumptions such as canopy homogeneity ([Bailey et al., 2020](https://gmd.copernicus.org/articles/13/4789/2020/#bib1.bibx57), [Braghiere et al., 2021](https://doi.org/10.1016/j.rse.2021.112497)). Furthermore, the relative contribution of transpiration versus evaporation to evapotranspiration, which modulates turbulent fluxes at the boundary layer, is spatially and temporally complex, but is necessary to better understand both leaf-level and ecosystem-scale water use efficiency as well as changes in the water balance due to disturbances ([Shuttleworth 1988](https://doi.org/10.1098/rspb.1988.0024), [Medlyn et al., 2017](https://nph.onlinelibrary.wiley.com/doi/full/10.1111/nph.14626), [Mallick et al., 2016](https://hess.copernicus.org/articles/20/4237/2016/), [Green et al., 2020](https://www.science.org/doi/full/10.1126/sciadv.abb7232), [Konings and Gentine 2017](https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.13389), [O’Connor et al., 2019](https://hess.copernicus.org/articles/23/3917/2019/)) . Finally, clouds, aerosols, and their interactions significantly modulate water and energy regimes over the tropics, but their uncertainties are some of the largest within earth system models ([Seinfeld et al., 2016](https://doi.org/10.1073/pnas.1514043113), [Bercos-Hickey et al., 2020](https://doi.org/10.1175/JCLI-D-18-0661.1)).

In addition, a crucial ecosystem service tropical rainforests provide is maintaining their own rainy seasons through moisture recycling. For example, within the southern Amazon, increases in evapotranspiration during the dry season pre-condition the atmosphere for shallow convection, which in turn, drives deep convection, large-scale atmospheric moisture convergence, and thus the start of the rainy season (Wright et al., 2017). Other studies have found that through moisture recycling cascades, the Amazon rainforest provides atmospheric moisture for regions downwind, thus providing buffers against drought (Staal et al., 2018). Meanwhile, the Congo Basin appears to be more dependent on moisture recycling to provide atmospheric moisture for rainfall than the Amazon (Worden et al., 2021, Sori et al., 2022), while additionally supporting atmospheric moisture in neighboring regions where agricultural is primarily rainfed ([Nyasulu et al., 2024](https://doi.org/10.1016/j.agrformet.2023.109867)). Moisture recycling therefore has direct linkages to carbon cycling, with one modeling study finding a moisture-recycling-mediated increase in gross primary productivity of roughly 41 Mg carbon km-2 yr-1 within the Amazon carbon source region ([Gatti et al., 2021](https://doi.org/10.1038/s41586-021-03629-6)) if it is fully forested compared to any other land cover ([Staal et al., 2023](https://iopscience.iop.org/article/10.1088/1748-9326/acc676/meta)). Deforestation and degradation have strong impacts on carbon cycling via moisture recycling, as this can alter surface biophysical conditions that promote convection ([Khanna and Medvigy 2014](https://doi.org/10.1002/2014JD022278)), and change large-scale moisture circulations ([Commar et al., 2023](https://iopscience.iop.org/article/10.1088/1748-9326/acc95f/meta)). In turn, this can exacerbate drying in both local and nonlocal regions (Zemp et al., 2017), delay the rainy season onsets ([Leite-Filho et al., 2019](https://doi.org/10.1029/2018JD029537)). Overall, these changes can increase the risk of the forest reaching critical transition points ([Flores et al., 2024](https://doi.org/10.1038/s41586-023-06970-0)). However, it must be noted that most of this research has been done within the Amazon region and not the equatorial African rainforests, which operate under different hydrological and energy regimes and therefore have different thresholds for carbon responses to changes in the water cycle.

1. **What are the direct and indirect hydroclimate controls on tropical forests and how does this influence the fragility of their ecosystem carbon balance?**

The tropical forest carbon balance is increasingly fragile due to a range of hydrological and thermal conditions. 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)).

1. **How does water and energy differ within and between tropical rainforests, and how does that influence current vegetation carbon stocks and fluxes?**

Water and energy limitations in tropical rainforests show large variability both within and between rainforests. Central African rainforests appear to be more water-limited while Amazonian forests are more controlled by light variability ([Guan et al., 2015](https://doi.org/10.1038/ngeo2382), [Phillippon et al., 2019](https://iopscience.iop.org/article/10.1088/1748-9326/aaf5d8/meta), [Madani et al., 2020](https://iopscience.iop.org/article/10.1088/1748-9326/ab724a/meta), [Green et al., 2020](https://www.science.org/doi/full/10.1126/sciadv.abb7232), [Huete et al., 2006](https://doi.org/10.1029/2005GL025583)). However, variations in water and light regimes exist within the tropical forests. For example, large portions of the wet Amazon experience limited water deficits, while the western equatorial Africa experience extremely limited light conditions (e.g., [Yan et al., 2018](https://doi.org/10.1038/s41467-018-05668-6), Phillippon et al., 2019, [Dommo et al., 2018](https://doi.org/10.1175/JCLI-D-17-0082.1), [Champagne et al., 2023](https://doi.org/10.1175/JCLI-D-22-0364.1)). These different water and energy regimes can control forest traits, functions, and structure by altering water availability, the quality of light available, and atmospheric dryness (e.g., Green et al., 2020, Phillippon et al., 2018). However, this is not well understood due to large variability in time and space in vegetation response to these environmental controls. For example, the respective effects of soil moisture availability versus vapor pressure deficit (water availability versus water demand), as well as their interactions, on vegetation is not well understood within the tropics ([Liu et al., 2020](https://www.nature.com/articles/s41467-020-18631-1)). Vegetation responses, such as changes in stomatal conductance and carbon allocation ([Gentine et al., 2019](https://iopscience.iop.org/article/10.1088/1748-9326/ab22d6/meta)), are influenced by local water and energy conditions. This adds large uncertainties to model representation of factors such as dryness stress in plants, water use efficiency, and generally, future climate projections.

In addition, carbon-water cycles are tightly coupled within the tropics (Gentine et al., 2019); therefore, better understanding spatial and temporal precipitation patterns is crucial for understanding the direct and indirect effects of not just water availability, but also flooding, storms, and effects on other cycles. For example, mesoscale convective systems provide large proportions of rainfall within central Africa and the Amazon ([Andrews et al., 2024](https://doi.org/10.1007/s00382-023-06903-7), [Rehbein et al., 2017](https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/joc.5171)), while also influencing tree mortality via windthrow (e.g., [Negrón-Juárez et al., 2018](https://iopscience.iop.org/article/10.1088/1748-9326/aabe9f/meta), [Feng et al., 2023](https://doi.org/10.1038/s41467-022-35570-1)). Furthermore, precipitation controls flooding cycles within the African and Amazon rainforests ([Alsdorf et al., 2016](https://doi.org/10.1002/2016RG000517), [Hawes and Peres 2016](https://doi.org/10.1111/btp.12315)), which in turn, affects lowland floodplain forests as they adapt to long periods of submersion and water-logging that can affect oxygen availability, reduce photosynthesis, and decrease water conductance ([Parolin et al., 2004a,](https://doi.org/10.1007/BF02803209) [Parolin et al., 2016](https://doi.org/10.1007/978-3-319-27422-5_6), Hawes and Peres 2016). Indirectly, rainfall can also significantly influence local nutrient cycles via wet nutrient deposition onto the forest canopies (Bauters et al., [2018](https://doi.org/10.1073/pnas.1714597115), [2021](https://doi.org/10.1038/s41467-021-25428-3)), alter the amount and quality of light available for photosynthesis via clouds and fog (Phillippon et al., 2018, [Pohl et al., 2021](https://doi.org/10.1016/j.rse.2021.112620)), and alter evapotranspiration and photosynthesis via dew deposition and subsequent foliar water uptake or evaporation (e.g., [Gerlein-Safdi et al., 2018](https://doi.org/10.1016/j.agrformet.2018.05.015), [Binks et al., 2019](https://doi.org/10.1111/gcb.14666)).

All of these processes are not well understood both on a tropical and continental scale, with most past studies focusing on the Amazon rather than the central African rainforests. This is exacerbated by large differences in the mechanisms controlling rainfall within and between the Amazon and central African rainforests, such as the influence of surface versus mid-tropospheric atmospheric moisture, the unique regional dynamic systems that transport moisture and induce atmospheric instability, and the role of moisture recycling in initiating the rainy seasons (Wright et al., 2017, [Nicholson, 2022](https://doi.org/10.1002/9781119657002.ch3), [Yin et al., 2014](https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013JD021349)). This results in regionally unique spatial and temporal precipitation patterns which we do not fully understand, such as west-to-east gradients in precipitation seasonality and large instabilities in the occurrence of the rainy seasons within the equatorial Congo (Nicholson, 2022, [Herrmann and Mohr 2011](https://doi.org/10.1002/9781119657002.ch3)). This then impedes improvements in weather and sub-seasonal forecasting within the area, which is crucial for better serving rain-fed agricultural efforts, determining flood risks, and more ([Pascal et al., 2023](https://www.sciencedirect.com/science/article/pii/S2405880723000730#b0320), [Tanessong et al., 2020](https://link.springer.com/article/10.1007/S00704-020-03176-6)). Therefore, by better understanding the mechanisms controlling precipitation, PANGEA has the unique opportunity to simultaneously increase our understanding of how this can directly and indirectly affect vegetation and improve forecasting within the tropical regions.

### 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**

This PANGEA 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 & MOTIVATION**

Tropical ecosystems are the most biodiverse ecosystems on the planet, playing a crucial role in climate change mitigation and providing livelihoods for millions of people. They provide humans with a range of resources such as food, water, and timber, and other benefits like soil formation, nutrient cycling, and crop pollination. Tropical ecosystems are vital nests for cultural identity and heritage preservation that sustain native communities’ unique spiritual and religious sovereignty. For millennia, humans have modified tropical ecosystems to facilitate the provision of these benefits (Levis et al, 2024), and increase their resilience to disturbances like fire, droughts, and pests.

Traditional management practices have more recently been complemented or replaced by larger scale management practices, intensification of land use and informal and illegal activities that have led to large scale deforestation, changes in biogeochemical cycles, water cycling and major and irreversible losses of biodiversity. Such unsustainable practices led to the emergence of a web of private, public, and civil governance systems that regulate the access to and use of land and its natural resources (von Essen & Lambin, 2021, Lambin et al, 2018). The development of social-ecological systems in tropical ecosystems has been shaped by complex interactions that result from a diversity of actors, each differing in their values, capacities, and goals that influence their relationships with nature. (Meyfroidt et al., 2018, 2022). Despite their critical role in climate regulation, biodiversity conservation, and provision of essential benefits to human well-being, tropical ecosystems are increasingly threatened by environmental changes and overexploitation, leading to shifts in species composition, declines in ecosystem health, reduced resilience, and diminished productivity across key resources and benefits (Siyum, 2020). These shifts affect the functioning of natural systems from local to planetary scales, inducing changes in social-ecological feedbacks and affecting benefits that humans derive from and contribute to nature (Houghton and Castanho, 2022, Mendoza-Ponce et al., 202).

Several conceptual frameworks have been developed to understand the relationships between and within social and ecological systems. Prominent approaches include the Club of Rome report (Donella et al, 1972), the sustainable livelihoods framework (Scoones, 1998), and various models of social-ecological systems (Anderies et al., 2004; Folke, 2006; Ostrom, 2009). Other frameworks focus on coupled human-nature systems (Liu et al., 2007), ecosystem services (Costanza et al., 2017; Daily, 1997), nature’s contributions to people (Díaz et al., 2018; Pascual et al., 2017), and social-ecological co-benefits (Levis et al, 2024). While these frameworks may differ in their definitions (Colding & Barthel, 2019), they converge on key principles and variables that describe the social-ecological system, facilitating comparability and systematic operationalization, often through the use of remote sensing and auxiliary data.

Therefore, adopting a systems perspective that integrates human and environmental processes, interactions, and feedbacks is critical for assessing the sustainability of natural systems (Ostrom, 2009), in particular for the highly dynamic ecosystems of the tropics.

**THE IMPORTANCE OF FEEDBACKS IN TROPICAL SOCIAL-ECOLOGICAL SYSTEMS** [Maria Santos]

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).

<https://www.nature.com/articles/s41559-020-1230-6>

The trajectories of social-ecological systems are determined by feedbacks between human and natural systems (XXX).

Example of 'phases' of social-ecological feedbacks over time (from the Chinese Loess Plateau)

https://www.science.org/doi/10.1126/sciadv.abc0276

Examples for tropical systems

<https://www.sciencedirect.com/science/article/pii/S0301479718312143?casa_token=cxfFkv6F_igAAAAA:DLaHvuw4agyahJvei9iTwgW4FjqQTycbefcbpXVP8_a1om8VP5zBymunTFWOJx00o3dxMuYCUw>

<https://www.sciencedirect.com/science/article/pii/S0301479721007374?casa_token=o8G0pMiVb_IAAAAA:TkA3MJhwzaGWDCKEVrjs5fESxFN6Y7HxyOx2q1AmVv8WquV9zoBsNXiLlwHYP-3wIbhR9BaK6g>

https://besjournals.onlinelibrary.wiley.com/doi/full/10.1002/pan3.10167

**PIONEERING SOCIAL-ECOLOGICAL SYSTEMS RESEARCH IN THE TROPICS THROUGH PANGEA**

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

* The tropics are culturally and biologically diverse, and a variety of human activities pose threats to their integrity, e.g., small scale & subsistence agriculture, commercial agriculture, ranching, (illicit) mining, timber harvesting, etc.; creating countless interactions and feedbacks between the social and ecological systems
* Research on these feedbacks in the tropics is sparse
* Understanding these feedbacks is critical for predicting future trajectories of tropical ecosystems, and providing local communities and decision makers with crucial information for governing these ecosystems

Current knowledge gaps / research frontiers

* Linking SES to their drivers and effects, and tracing that over time in regions with long management history; "*Our approach may shed light on other large SES management regions with long development histories and cross-scale effects, e.g., the Amazon, the Congo, and the Mekong River basins*" (Wu et al, 2024)
* Five research frontiers identified in Chaplin-Kramer et al, 2024:

1. downscaling impacts of direct and indirect drivers on ecosystems;
2. incorporating feedbacks in ecosystems
3. linking ecological impacts to human wellbeing
4. disaggregating outcomes for distributional equity considerations
5. incorporating dynamic feedbacks of ecosystem services on the social-economic system

* Look at Liu et al, A Review of Social–Ecological System Research and Geographical Applications

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Note: we don't need to have a research strategy for how to address our science questions; those will be addressed in section 5 Research Strategy and Study Design. Maybe we can include a short mention of research strategy and then refer to section 5, the quote from the ABoVE WP below can be used as inspiration for how to write about it.

Quote from ABoVE as inspiration for how to write about this section: "Research to address these human dimensions questions will require an integrated approach using the results from studies being carried out for other science themes. Specifically, the questions on human impacts on fire and insect regimes will be coordinated with research for the disturbance science theme, with data on land management activities being integrated with other disturbance data sets to determine the role of human activities. The research on the impacts of human disturbances will be coordinated with those activities being carried out for the permafrost and surface hydrology science themes. In these cases, it will be necessary to obtain high-resolution airborne or satellite remote sensing imagery (e.g., IKONOS, QuickBird) or aerial photography to quantify the location and extent of the disturbances."

Text-snippets that we can consider integrating in the sections above:

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.

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).

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).

Link to the science questions

**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?

**Notes for the Modeling folks**

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

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.

Tropical forests are home for more than half of the world’s biodiversity and play a significant role in global carbon cycling. They are increasingly threatened by both natural disturbances (such as storms, fires, and pests) and human activities (such as logging, agriculture, and land-use change). Land-use change, particularly the conversion of forests to agricultural land, represents one of the most significant drivers of tropical deforestation. This not only results in the direct loss of biomass but also fragments the forest landscape, reducing connectivity and resilience (Hansen et al., 2013). The transformation of land often leads to soil degradation and the loss of critical ecosystem services, which can further impede forest recovery even if the land is later abandoned or restored. Fires, whether natural or anthropogenic, have increasingly become a concern due to their capacity to cause widespread damage. Fires can drastically reduce biomass, alter species composition, and create feedback loops that make forests more prone to future fires (Cochrane & Laurance, 2002). The frequency and intensity of fires are exacerbated by land-use changes that create drier, more fire-prone conditions. These lead to alterations in forest structure, affecting tree species composition and potentially leading to long-term consequences for forest resilience and global climate regulation.

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. 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.

Accumulation 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.

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. 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.

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)).

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)).

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.

## 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]

[brief mention of scaling strategy concept/framework]

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

### 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**
* Paragraph on synergies with partner agencies
  + ESA, JAXA, ISRO
  + Use of sensors from partner agencies:
  + BIOMASS

| Satellite Observations | Cal/Val & Algorithm Advances | Science Advances |
| --- | --- | --- |
| NISAR, BIOMASS, Sentinel-1 |  |  |
| EMIT, CHIME, SBG |  |  |
| *Carbon-i* |  |  |
| GEDI, ICESat-2, *EDGE* |  |  |
| SMAP |  |  |
| OCO |  |  |
| SWOT |  |  |
| GRACE |  |  |
| Geostationary-List!! |  |  |
| ECOSTRESS |  |  |
| Landsat, Sentinel-2 |  |  |

#### 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 and processes in existing models, (2) develop Observing System Simulation Experiments (OSSEs) that will help inform the optimal location and gradients needed to capture to maximize the representativeness of the intensive sites within the PANGEA domain, (3) synthesize and scale measurements from intensive sites to the core PANGEA domain, and (4) implement new processes and techniques, as well as improve existing ones in models and apply them to answer PANGEA’s scientific questions.

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

* ~~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]~~

Over the past decades, terrestrial biosphere models have expanded scope and incorporated many new processes that could not be addressed during LBA (Fig. XX). For example, processed-based models now resolve structural and functional diversity, a broad variety of natural and anthropogenic disturbance dynamics, and strong coupling with biogeochemical cycles (Fisher et al. 2018; Fisher and Koven 2020), and we are now in a time in which ecological processes in diverse ecosystems driving energy, water, carbon and nutrient cycling on Earth must be accounted for (Bonan et al. 2024). Likewise, several classes of models have been increasingly leveraging the broad range of remote sensing observations, and throughout PANGEA we will have participation of a broad range of models that can use remote sensing for initialization, uncertainty quantification and data assimilation. Examples of such models include, but are not limited to, (1) process-based vegetation demography models such as ED2 (Antonarakis et al. 2014; Longo et al. 2020; Schneider et al. 2023), ED (Hurtt et al. 2004; Ma et al. 2023) and FATES (Negrón-Juárez et al. 2020), (2) data-driven hybrid models that solve processes with a strong data assimilation approach such as CARDAMOM (Bloom et al. 2016, 2020) and CliMA (Braghiere et al. 2023; Wang et al. 2023), (3) top-down inverse modeling approaches that link column measurements with fluxes through atmospheric transport models such as CarbonTracker (Peters et al. 2007) and CMS-Flux (Liu et al. 2020), and (4) models that are based on Artificial Intelligence and machine learning (REF). We already identified several opportunities for which models can be used to investigate processes relevant to PANGEA to help answer the key research questions (Table XX). The data collected by PANGEA will allow further advancing both the representation of processes relevant to tropical forests under a changing Earth (Fig. XX) and methods to integrate between remote sensing and models in the upcoming years.

* 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 bottom-up approaches including process-based models (e.g., FATES, ED2, CLM, ELM), statistical models (PLS-based, Random forest), AI/ML-based models (add specific examples), and data-driven hybrid models (CARDAMOM, CliMA), as well as top-down approaches (e.g., inverse modeling CMS-Flux, CAM, see OCO2-MIP). [A:Marcos, R:Renato, R:Cesar, R:Yanlei, R: Felicien]

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

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

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

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

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

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

In the first year of the campaign, existing research on 5 science themes at pan-tropical level will be synthesized, integrating with ongoing synthesis efforts (add citations) to inform decisions on key variable measurements with the fewest data points but the greatest potential research impacts. Beginning at the end of peak data acquisition and continuing into the final Phase, PANGEA will integrate individual site-level measurements with regional-scale airborne and spaceborne remote sensing imagery to upscale to a pan-tropical level. Projects and datasets collected within the peak data acquisition period, primarily located in Amazonia and tropical Africa will be reviewed and synthesized. This process will enable the upscaling of findings from local and regional to the global scale. In addition, the synthesis can determine what further modifications need to be made to the modeling effort. Based upon these syntheses and assessments, further adjustment to the models will be made during the final Phase to account for the global scale process.

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

#### 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 campaigns. 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.

* Emphasize 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)
* Collaborative example of **mycorrhizal fungi** field sampling in historically poorly sampled areas: SPUN (<https://www.spun.earth/>)

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

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 |
|  |  |  |  |  |
|  |
|  |

### 5.7 Why coordinated teamwork is required

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

## 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 Organization and Management

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.

Phasing of project. Science Defintion, Science execution …

* Describe different organization structures during different phases of PANGEA

Revise organization of this section to describe the following organization structures:

* Program Management
* Project Office
  + Open science and data support
  + Field implementation support
  + Flight implementation support
* Science Defintion
* Project implementation
* Science Team and Science Leadership

#### 6.1.1 Program Management

*NASA Terrestrial Ecology research addresses changes in Earth’s carbon cycle and ecosystems using space-based observations in order to improve understanding of the structure and function of global terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in the cycling of the major biogeochemical elements and water. The Program Manager provides overall direction and budgetary control for ABoVE, with assistance from the Program Scientist. [CUT AND PAST FROM ABOVE]*

#### 6.1.2 Project Office

Implementation and management of ABoVE is provided by the Carbon Cycle and Ecosystems Office (CCE Office) at the NASA Goddard Space Flight Center. Field activities and operations conducted within the ABoVE Study Domain are organized, coordinated, and supported through the efforts of the CCE Office. Important aspects include coordination and support for field operations and logistics, safety and risk management, and interactions with local and regional stakeholders. The CCE Office provides cyberinfrastructure for data analysis and management (e.g., the ABoVE Science Cloud). The CCE Office assists Science Team members with permit applications to appropriate authorities. Depending on the needs of the Science Team, the CCE Office may also arrange for the collection of core variable data and installation of infrastructure at ABoVE field sites. The CCE Office is responsible for managing the airborne science campaigns. Science Team Members should work closely with the CCE Office and rely upon guidance from its staff for field activities, communications with local and regional stakeholders and authorities, and utilization of ABoVE cyberinfrastructure. [CUT AND PASTE FROM ABOVE]

#### 6.1.3 Science Definition

#### 6.1.4 Project Implementation

#### 6.1.5 Science Team and Science Leadership

The ABoVE Science Team Leader and Deputy are responsible for providing scientific leadership and direction for ABoVE, providing scientific inputs regarding ABoVE priorities and activities to NASA management, and communicating about ABoVE to a wide variety of scientific, governmental, and public audiences. In close coordination with the ABoVE Science Team, the CCE Office, ABoVE program management at NASA HQ, and ABoVE partner organizations, they are responsible for writing and keeping up to date the ABoVE Implementation Plan detailing the research activities to be conducted and specifying roles and responsibilities for investigators involved in those specific activities during the execution of ABoVE. They are responsible for calling and organizing ABoVE ST meetings and related activities in coordination with NASA HQ managers and CCE Office. The Science Team Leads meet with NASA HQ and CCE Office management on a quarterly basis to review progress, resolve problems, and discuss next steps for implementation. [CUTE AND PASTE FROM ABOVE]

discuss articulation of Science Definition Team transition to Scientific Leadership Team (include Project Implementation??)

PANGEA science will be executed by a Science Team composed of the PIs and Co-Is of selected NASA investigations coordinated by a Science Leadership Team (SLT) led by a Project Scientist and Deputy Project Scientist selected by NASA management. These two people will be responsible for writing the Concise Experimental Plan. Membership in this SLT will be based on self-nominated members of the PANGEA Science team and selection by the Project Scientist in coordination with NASA management. The SLT members will serve three-year terms consistent with duration of the research projects supporting their investigations. In special cases, with agreement of the Project Scientist and NASA management, investigators not funded by NASA may serve on the SLT. The SLT will define and manage the execution of the science of PANGEA. This Science Leadership Team will be diverse. Necessarily, the team will include a diverse group in scientific expertise and technical specialties. To the extent possible the team will reflect the diversity of US society in terms of gender identity, race, ethnicity, geography, other??.. Early career researchers will be included from the beginning, as will representatives from participating countries where field research will take place.. The leadership team members must show a commitment to cultural sensitivity, withrespect for local collaborators, and with extra care taken to uphold NASA’s reputation internationally. The Science Leadership Team will meet regularly, and for virtual meetings will endeavour to, arrange meetings considerate to the time zones of persons represented.

Responsiveness of team to NASA management and coordination with NASA management. – where is this? Coordination of SLT with Project Management. (Section above the SLT 7.1 section?)

The Science Leadership Team (SLT) will be responsible for communicating the research objectives andoutputs of the NASA-funded science team to a diversity of audiences. The SLT will work with local partners to set expectations of PANGEA, and of NASA. This team will accurately and promptly communicate project updates to local partners. Throughout the lifecycle of PANGEA, conversations with potential end users? 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, The Science Leadership Team is responsible for setting the tone of PANGEA, and will 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.

. aT

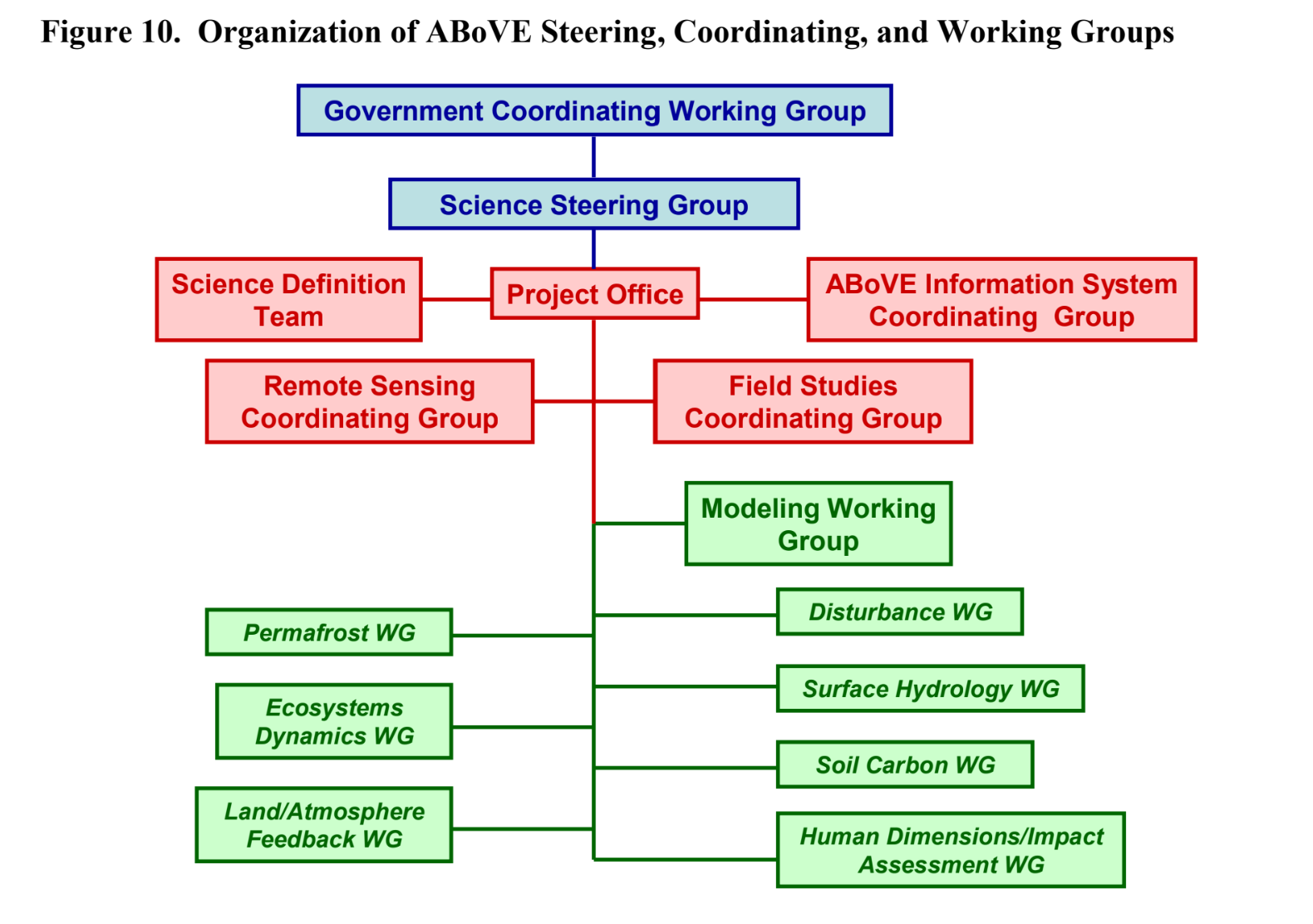
* Guided by ATBC codes of conduct and etiquette, already thinking about differences regionally, culturally, etc
* Speak to measures of accountability embedded in PANGEA design - How to ensure our walk follows our talk - what’s the accountability for PANGEA and projects to ensure follow through on commitments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

PANGEA will include several levels of organization (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.

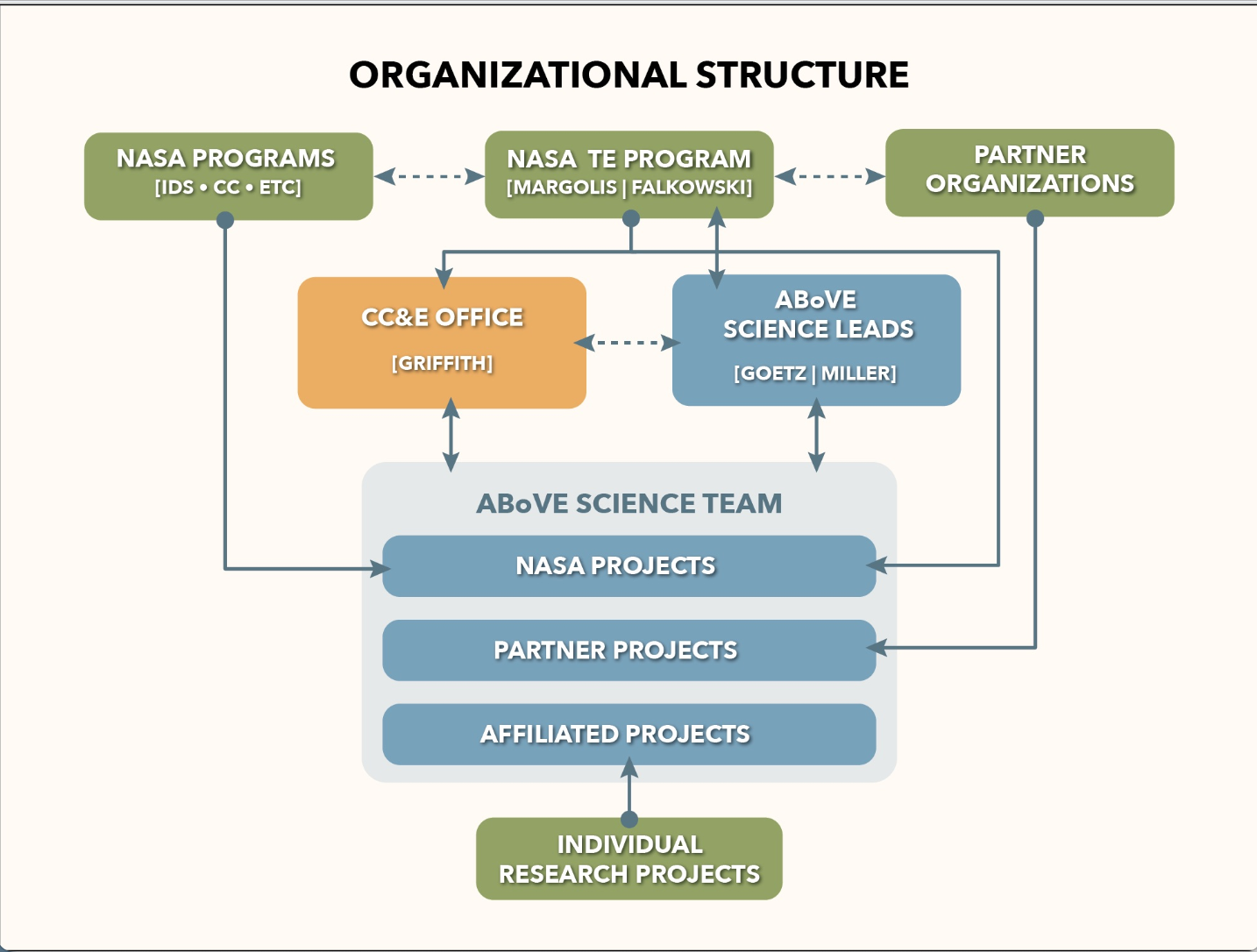
An International Science Steering Group (SSG) will provide additional oversight and guidance for PANGEA. The SSG will include scientists with expertise in each of the different PANGEA science themes. Depending on the level of sponsorship provided to support PANGEA activities (either directly or indirectly 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.

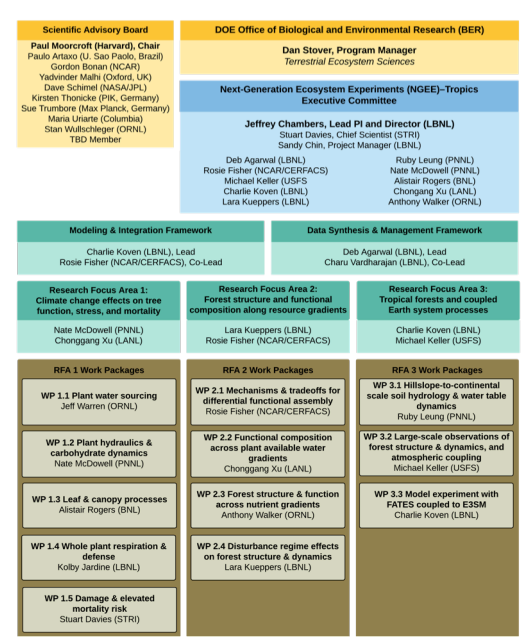
PLACEHOLDER Figure: Organization Chart: leadership, coordination, working groups. (ABOVE White Paper)



ANOTHER SIMPLER ABOVE ORG CHART (https://above.gsfc.nasa.gov/contact.html?)



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 the implementation plan. The Project Manager is also responsible for gathering and synthesizing scientific requirements from each of the funded science team projects and, with the leadership Team, coming up with a strategy to maximize PANGEA’s scientific impact given the science team that was funded. This process will include managing the science team’s expectations, specifically of airborne data requirements.

The Project Manager will serve as the primary point of contact for Science Applications for PANGEA, acting as a liaison between the science team and potential end users and decision makers. In this role, the Project manager will monitor expectations that applications partners may have of the PANGEA science team, and flag expectations that may not be met to avoid disappointment and a loss of goodwill in the future, as well as to protect NASA’s reputation internationally. To avoid a mismatch between science team capability and end user expectation, as soon as PANGEA is selected the project will reinitiate conversations with potential application partners, and begin a process of identifying those most feasible to continue with given the scope of the project. Regular and transparent communication with potential application partners will continue at all stages of PANGEA, and updates on decisions to pursue or not pursue potential applications will be communicated promptly.

* 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

### 6.2 Disciplinary Skills Required

6.3 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.

### 6.4 International and Other Agreements

#### 6.4.1. 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)

### 6.5. 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.

* 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 engagement methods for effective collaboration in diverse geographic and cultural contexts?
* 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.
* We need to mention that the list below is non-exhaustive, but the overall strategy will provide a framework for 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

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 White Paper, we use the term scientific institutions primarily for universities, colleges, national laboratories, national professional institutions, and research institutes that through their leaders, faculty, researchers, and students are fundamental partners of PANGEA.

PANGEA seeks to partner with scientific institutions located or with research expertise related to any part of the pan tropical forest region to collaborate and carry out its proposed research programs. This partnership will establish a world leading network of research experts and scientific institutions collaborating in response to the grand environmental challenges in the Pan Tropical Forest region due to global atmospheric warming and changes in land use. A particular interest of this partnership is to facilitate the co-development of knowledge and whenever necessary to do technology transfer to generate capacity and capability building in local and regional institutions. One overarching goal of the partnership is to train the next generation of technical personnel and scientists. This partnership seeks to focus on:

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

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

Government agencies

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

Non-governmental organizations

* International
* Local

Intergovernmental organizations

Private sector

Foundations (e.g., the Ford Foundation, the Mellon Foundation, etc.),

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

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

Donor community ← Funding agencies or foundations?

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

### 6.6 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

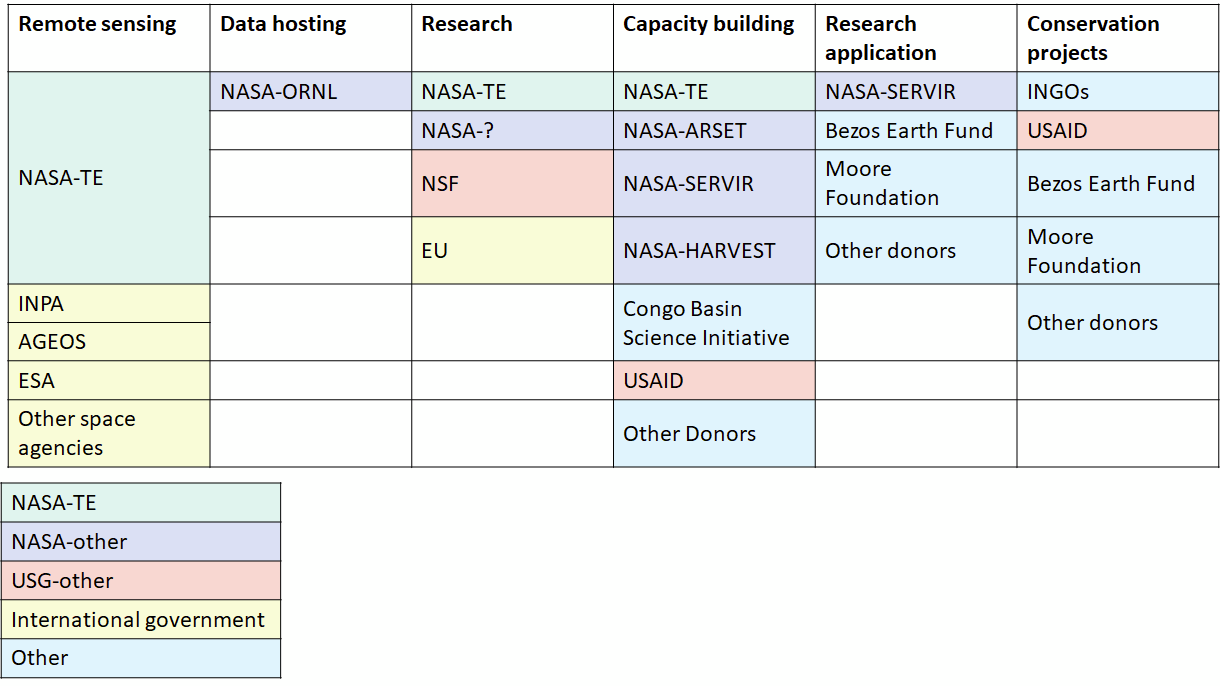
### 6.7 Cost Estimates

* **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)

### 6.8 Co-funding

PANGEA recognizes that NASA-TE is limited in the amount and type of funding that it can provide. PANGEA has been designed to leverage a Terrestrial Ecology investment in its core purpose to attract funding from other donors that can support complimentary work that will expand the impact of PANGEA. The project has already made significant strides towards securing diverse sources of funding to leverage TE’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. To do that, PANGEA will seek to answer the following question:

* How can diverse funding institutions work synergistically to support the advancement of remote sensing and terrestrial ecological research
  + How can 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?

### 6.9 Open Science / Data Management and Sharing

The PANGEA data management and sharing strategy aims to facilitate open source science, promote collaboration, and maximize the value of PANGEA data more broadly and longer into the future. This strategy will follow NASA Scientific Information Policy requirements and guidelines, adhere to community principles and practices, and keep ethical guidelines and cultural sensitivity in mind. PANGEA will build on top of the success from past field campaigns and leverage new advances in open science and data management concepts and technologies.

The PANGEA data management will adhere to the FAIR (Findable, Accessible, Interoperable and Reusable) guiding principles to improve data discoverability and accessibility, promote data interoperability and integration, and enhance data reusability and reproducibility. The PANGEA data collection, management, and use will align with the CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles, which emphasize the importance of considering the rights and interests of Indigenous peoples when managing data related to their communities, lands, and resources. The CARE principles complement the FAIR principles by focusing on the ethical, cultural, and social dimensions of data management.

Coordinated through the GCWG, data and information sharing agreements at the national and international agency level will be established to outline data ownership, usage rights, and storage plan. Such agreements are an important first step to address challenges, such as data sovereignty, associated with data and information management involving multiple countries and agencies.

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

Data provenance and reproducibility are important aspects of open source science. Algorithms, codes, and workflows associated with data creation (such as models), processing, validation, etc. for PANGEA will be made openly available to the extent possible. Active code development will ideally be through open collaborative platforms, like github, when appropriate.

PANGEA Information Portal

* Data planning tool: obtain information on the planned and ongoing activities of PANGEA investigators and collaborators, including inventories of the location, timing, and types of data collected. It will also compile inventories of the location and types of data collected by other researchers that are being used by PANGEA investigators and collaborators. The tool will include a web-based GIS that allows for review of the data within the tool, including information on previous and ongoing investigations.
* Provide easy discovery and access to data collected by PANGEA and also existing data useful for PANGEA research. The PANGEA Data Portal needs to be user friendly and support both researchers and the public community at large. Visualization and GIS support will be critical to maximize the value of PANGEA data to a broader audience.
* Leverage and integrate with existing and emerging capabilities and systems offered by NASA Earth Science Data Systems as much as possible.
  + DAACs airborne data: AVIRIS, MASTER, LVIS, etc.
  + DAACs tools and services to make airborne and orbital data easier to use for terrestrial ecology research
  + NASA’s Visualization, Exploration, and Data Analysis (VEDA) platform: <https://www.earthdata.nasa.gov/esds/veda>
  + Coordinated VSWIR data cleaning by (SBG/EMIT/AVIRIS/NEON coordinated team)
  + AmeriFlux & ICOS for flux tower data
  + …

Cloud-based Data Analysis Platform

* Setup a cloud-based data analysis platform for PANGEA investigators to support open and collaborative research.
* Low barrier for entry, especially for international partners
* Something like NASA’s Multi-Mission Algorithm and Analysis Platform (MAAP, <https://www.earthdata.nasa.gov/esds/maap>), which demonstrated a success collaboration between NASA and ESA

Improve open source science and data management practices across PANGEA through trainings:

* Collaborate with DAACs on data management workshops
* NASA’s Open Science 101 curriculum: <https://nasa.github.io/Transform-to-Open-Science/os101-modules/>

Open Science Coordinating Group

* Involves members from both US and international teams
* Establish data workflows
* Establish consistent formats and practices for data and metadata and optimization for cloud-based access and analysis, especially for emerging types of data, like drone-based.
* Provide guidance on capturing data quality information in a consistent manner
* Coordinate and provide guidance on open science and data management activities
* …
* 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

[ Include text regarding models ]

### 6.10 Timetable

(number of years?)

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

### 6.11 Risk and Risk Mitigation / Risk Assessment

* *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.*
* *Lack of alignment between NASA priorities (e.g. answering novel science questions) and end-user priorities (e.g. consistent monitoring of landscapes)*
* 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.

## 7. Enabling Earth Science to Action

There are two main requirements for effective application of NASA research: (1) substantive overlap between NASA science and end user needs, and (2) a process that brings potential end users and scientists together. This section will first discuss the substantive ways PANGEA can enable Earth Science to Action (ES2A), and then detail the current and future processes that the project employs to ensure uptake of research outputs by end users.

### 7.1: Substantive applications of PANGEA research outputs

#### 7.1.1 Carbon

* 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

#### 7.1.2 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.
  + IPBES and Convention on Biological Diversity

#### 7.1.3 Agriculture and Livelihoods

* 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
* Bioeconomy
  + Non-timber forest products
* Ecosystem service mapping
  + What ecosystem services are readily mappable via remote sensing and/or integration with ancillary data and information (LEK, TEK, IEK)?
  + What ecosystem service mapping capabilities could be advanced by PANGEA?

#### 7.1.4 Disturbance Dynamics

* Deforestation and degradation alerts - associated with drivers?
  + Mining, roads, urbanization, etc. to be used by local and Indigenous communities and/or jurisdictional governments
* Restoration
* Disaster Alerts & Response
  + Fires
  + Flooding
* Weather prediction
* Empowering and elevating Indigenous, local, and traditional communities
* Integration of RS data with LEK, IEK, and TEK

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

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

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

* Amplify impact through partnerships: PANGEA’s investment in community engagement has attracted a diverse array of partners, including international governments, donors, and local communities (see for details about community engagement). These partners include potential end users, data contributors, and potential funders for applications—the last of which will help make PANGEA’s work cost effective by supplementing NASA’s Earth Science resources with funds to support capacity building, community engagement, and research translation (see [Section 7.5](#_w90m76cd6k00): Co-funding for additional information). PANGEA also brings extensive international partnerships, ranging from national space agencies that could provide complementary data to tropical communities who will participate in data collection and potentially in end use. PANGEA has engaged these partners early in the process to increase their investment and their input in co-development of potential end products.
* Engage a diverse workforce and broader Earth Science community: PANGEA transdisciplinary goals are supported by a diverse team that ranges from data scientists to economists and hail from NASA, academia, non-profit organizations, other federal agencies, and governments from around the world. PANGEA’s extensive international engagement also offers opportunities to work with and recruit the best minds globally to NASA’s Earth Science efforts, while the capacity building and training efforts (see [Section 9](#_8t6ay0v9gizk)) help form the next generation of scientists.
* Use a balanced approach: PANGEA builds on prior decadal campaigns both for science questions and data (e.g. LBA) and for process improvement (e.g. LBA, ABOVE). By asking bold and critical science questions that were formulated based on prior campaigns, while focusing geographic scope, PANGEA maximizes value.

During the Scoping Phase, PANGEA led extensive outreach to potential end users (see [Section 7.5](#_w90m76cd6k00)), and engaged with potential end users about what questions and data are most valuable to them. As a result, PANGEA has worked since its inception to bridge the sometimes difficult gap between what science questions are being asked and what end users need for decision making. This process is especially important for a decadal campaign that will not offer end users long term data sets. PANGEA has also prioritized seeking a diverse range of funding partners, recognizing that NASA is well-suited to support data collection and analysis and tool/platform development, while other sponsors are better positioned to support conservation projects that apply data and some forms of training and capacity building. The Scoping Phase also included a visioning exercise, where diverse teams collaborated to draw translational pathways that included data acquisition, potential end uses, co-development of products, and listing of stakeholders

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

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

Decision Support Systems / Impact & Vulnerability Assessments

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

* The PANGEA Information System (PIS) will provide a platform to conduct further research on the use of satellite information products to support decision making
* The PIS will also be a critical platform for PANGEA researchers to interact at multiple levels with scientists and managers at agencies who are responsible for assessing the impacts of climate change in tropical regions, as well as the media and general public
* The Integrated Modeling Framework will provide the basis to create unique information products based upon integrated assessments.

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

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

## 8. 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

## 9. References

## 10. Figure and Photograph and Credits

## 11. 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"*

## 12. List of Acronyms

## 13. 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).

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### 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

### F - 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

### G - 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