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

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Lead Authors

* Denotes coordinating authors

Elsa M. Ordway* (University of California, Los Angeles [UCLA]), Michael Keller* (United States Forest Service [USFS], Jet Propulsion Laboratory [JPL]), Marcos Longo (Lawrence Berkeley National Laboratory [LBNL]), Robinson Negron-Juarez (LBNL), Yanlei Feng (Massachusetts Institute of Technology [MIT]), Hannah Stouter (UCLA), Isaac N. Aguilar Rivera (California Institute of Technology [Caltech]), Ane Alencar (Amazon Environmental Research Institute [IPAM]), Adia Bey (NASA Goddard Space Flight Center [GSFC], University of Maryland [UMD]), Renato K. Braghiere (Caltech, JPL), Anabelle Cardoso (University of Buffalo & University of Cape Town), Dana Chadwick (JPL), Jose D. Fuentes (Pennsylvania State University [Penn State]), Regina Eckert (JPL), Temilola Fatoyinbo (GSFC), António Ferraz (JPL), Liane Guild (NASA Ames Research Center [ARC]), Matthew Johnson (ARC), Esi Kane (University of Energy and Natural Resources, Sunyani-Ghana), Lydie-Stella Koutika (Research Center on Productivity and Sustainability of Industrial Plantations [CRDPI]), Yue Li (UCLA), Junjie Liu (JPL), Ian McCubbin (JPL), Félicien Meunier (Ghent University), Charles Miller (JPL, Caltech), Helene C. Muller-Landau (Smithsonian Tropical Research Institute [STRI]), Teodyl Nkuintchua (World Resources Institute), Matheus Nunes (UMD), Le Bienfaiteur Sagang Takougoum (UCLA), Maria J. Santos (University of Zurich), Fabian D. Schneider (Aarhus University), Marc Simard (JPL), Bonaventure Sonké (University of Yaounde I), César Terrer (MIT), Marius von Essen (UCLA), Michelle Y. Wong (Yale University), Sarah Worden (JPL), Xiangming Xiao (University of Oklahoma [OU]), Virginia Zaunbrecher (UCLA)

Contributing Authors

Marijn Bauters (Ghent University), Pascal Boeckx (Ghent University), Jennifer Bowen (Stanford University), Iniquilipi Chiari (Global Alliance of Territorial Communities [GATC]), Ovidiu Csillik (Wake Forest University), Gloria Diez (GATC), Marcelo Doroso (GATC), Deborah Delgado Pugley (Pontifical Catholic University of Peru [PUCP]), Wannes Hubau (Ghent University), Alejandra Echeverri Ochoa (University of California, Berkeley), Evan Gora (Cary Institute of Ecosystem Studies), Alison Hoyt (Stanford), Juan Carlos Jintiach (GATC), Victor Maqque (OU), Clarice Perryman (Stanford), Zoe Pierrat (JPL), Leila Saraiva (GATC), Debjani Singh (Oak Ridge National Laboratory [ORNL]), Iroro Tanshi (Washington University & Small Mammal Conservation Organisation [SMACON]), Jill Thompson (UK Centre for Ecology & Hydrology [UKCEH]), Hans Verbeeck (Ghent University)

Foreword

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

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

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

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

The PANGEA concept reflects the voices of many and was developed in collaboration with over 800 individuals representing over 300 organizations from 42 countries across 5 continents. Workshops were held in Washington DC, Cameroon, Peru, Brazil, and Thailand, with approximately 275 in-person participants and 298 virtual attendees. Participants in the scoping process represented many communities, including the academic community in the tropics, as well as in the U.S. and Europe; Indigenous and local communities from the tropics; the NASA community and other U.S. federal agencies; international space agencies; foreign government agencies; civil society organizations; and private industry (see *Appendix C*). The scoping effort underscored the overwhelming need for PANGEA and the timely opportunity it presents to collaborate and coordinate with many existing and forthcoming activities described in this white paper.

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Biogeochemical Cycles and Carbon Dynamics Working Group: Abhishek Chatterjee (JPL), Alfred Ngomanda (Gabon National Center for Scientific and Technological Research), Alysson Bery (Congo Basin Institute), Anne Ola (INRS), Ashley Ballantyne (University of Montana), Asmadi Saad (Jambi University), Bassil El Masri (Murray State University), Beisit Luz Puma Vilca (Sylvera), Ben Taylor (Harvard), Bila-Isia Inogwabini (WWF), Carla Restrepo (University of Puerto Rico), Chima Iheaturu (University of Bern), Corneille Ewango (Okapi Faunal Reserve), Danielle Potocek (Spark Climate Solutions), David Lagomasino (East Carolina University), Dheeresh Kumar (Univ. of Delhi), Doug Morton (NASA Goddard), Ekene Rangel, Elhadi Adam (University of the Witwatersrand), Eric Cosio (PUCP), Farrel Boucka (AGEOS), Fernanda Santos (ORNL), Fiona Soper (McGill), Flavia Durgante (Karlsruhe Institute of Technology), Francis Manfoumbi (AGEOS), Gerbrand Koren (Utrecht University), Gillian Galford (University of Vermont), Gislain MOFACK II (UN Food and Agriculture Organization [FAO]), Gretchen Keppel-Aleks (University of Michigan), Hankui Zhang (SDSU), Hans Verbeeck (Ghent University), Jim Dalling (UIUC), Jingfeng Xiao (UNH), Joe Mohan (UCI), Joshua Fisher (Chapman University), Kate Nelson (McGill University), Krista Anderson-Teixeira (Smithsonian), Laura Duncanson (University of Maryland), Luis Fernandez NGOULA (University of Yaounde), Marcia Macedo (WHRC), Marijn Bauters (Ghent University), Moses Cho (University of Pretoria), Na Chen (MIT), Nate McDowell (PNNL), Patrick Namulisa (Columbia), Nick Parazoo (JPL), NIMPA NGUEMO Christiane Guillaine (University of Bamenda), Nohemi Huanca-Nunez (Yale), Norma Salinas (PUCP), Pascal Boeckx (Ghent University), Paul Arellano (NAU), Paulo Brando (Yale), Petya Campbell (University of Maryland Baltimore County), Robinson Negron-Juarez (LBNL), Rogelio Corona (UNAM), Rolf Obame (USTM), Ruofei Jia (MIT), Sarah Batterman (Cary Institute), Sparkle Malone (Yale), Steve Kwatcho Kengdo (UC Berkeley), Tana Wood (USDA Forest Service), Timothy Filley (University of Oklahoma), Tomasso Jucker (University of Bristol), Trevor Cambron (MIT), Vincent Medjibe (USDA Forest Service), Wu Sun (Carnegie Science), Yann Nouvellon (CIRAD), Yoseline Angel (NASA Goddard), Zeli Tan (PNNL)

Structure, Function and Diversity Working Group: Jesus Aguirre-Gutierrez (Oxford Univ.), Loren Albert (Oregon State University), Luciana Alves (UCLA), Junior Amboko (Florida Atlantic Univ.), Nicolas Barbier (IRD), Stephanie Bohlman (University of Florida), Jeanine Cavender-Bares (Harvard), Caroline Chaves Arantes (West Virginia Univ.), Moses Cho (Univ. of Pretoria), Rogelio O. Corona-Núñez (UNAM), Claudia Coronel Enríquez (Instituto Mora), KC Cushman (ORNL), Stuart Davies (Smithsonian), Laura Duncanson (UMD), Alvaro Duque (Univ. Nacional de Colombia Sede Medellín), Sandra M Duran (Colorado State Univ.), Bassil El Masri (Murray State Univ.), Joshua Fisher (Chapman), Evan Fricke (MIT), Evan Hockridge (Harvard), Miroslav Honzak (ASU), Tommaso Jucker (University of Bristol), Matthias Kunz (GFZ Potsdam), Moses Libalah (Univ. of Yaounde I), David Luther (George Mason Univ.), Tim Mayer (Univ. of Alabama Huntsville), Paul Moorcroft (Harvard), Doug Morton (GSFC), Luis Fernandez Ngoula (Univ. of Yaounde I), Christopher Nytch (Univ. of Puerto Rico), Jack Orebaugh (ORNL), Dina Rasquinha (WWF), Nicholas Russo (Harvard), Norma Salinas (PUCP), Arturo Sánchez-Azofeifa (Univ. Alberta), Wu Sun (Carnegie Institution for Science), Jennifer J Swenson (William & Mary), Nathan Swenson (Univ. of Notre Dame), Simon Tamungang (Univ. of Bamenda), Jill Thompson (UKCEH), Marcelle Johnson (Wageningen) , German Vargas (Oregon State Univ.), Rodrigo Vargas (University of Delaware/Arizona State University), Jiaming Wen (Carnegie Institution for Science), Michael Wimberly (Univ. of Oklahoma), Lin Xiong (Univ. of Maryland), Xi Yang (Univ. of Virginia)

Climate Feedbacks and Interactions Working Group: Nate McDowell (PNNL), Chi Chen (Rutgers Univ.), Manuel Lerdau (Univ. of Virginia), Rogelio O. Corona-Núñez (Facultad de Ciencias, UNAM), Joshua Fisher (Chapman), Daniela Francis Cusack (CSU), Eric Davidson (Univ. of Maryland), Luiz A. T. Machado (IFUSP), Maricar Aguilos (NCSU), Sam Rabin (NCAR), Rob Spencer (FSU), Zhuonan Wang (CSU), Isela Jasso (UNAM), William F. Laurance (James Cook Univ.), Leila Constanza Hernandez Rodriguez (LBNL), Susan Laurance (James Cook Univ.), Jingfeng Wang (Georgia Inst. Of Tech.), Gabrielle De Lannoy (KU Leuven), Gerbrand Koren (Utrecht Univ.), Jie Hsu (National Taiwan Univ.), Tomas Ferreira Domingues (Univ. de São Paulo), Carl Norlen (USGS), Jiafu Mao (ORNL), Mingjie Shi (PNNL), Yanlei Feng (MIT), Jonathan Wang (Univ. of Utah), Amy Zanne (Univ. of Miami), Emmanuel Barde Elisha (ANI Foundation), Evan Gora (Cary Institute), Xiangzhong Luo (National Univ. of Singapore), Marie Brigitte Makuate (MSRI, Cameroon), Landing Mané (OSFAC), Denis Sonwa (WRI), Louis Defo (Univ. of Yaounde I), L. Ruby Leung (PNNL), Yoshiaki Hata (Univ. of Tokyo), Cynthia Wright (USFS), Eric Bastos Gorgens (Univ. Federal dos Vales do Jequitinhonha e Mucuri), Manh-Hung Le (GSFC), Debora Regina Roberti (Univ. Federal de Santa Maria), Kevin Njabo (Texas A&M), Victor Aimé Kemeuze (University of Ngaoundere), John Adams Katikomo (EDA), Nyong Princely Awazi (Univ. of Bamenda, Cameroon), Martin Arthur Meka Zibi II (Univ. of Dschang), Peke Koukou Léon c'est la vie (ONG), Donald-l'or Nyame Mbia (Univ. de Yaounde I), Nkemnkeng Francoline Jong (Univ. of Bamenda, Cameroon), Vanessa Mavila (Fondation Eboko), Olivier Bosela (IFA Yangambi), Akwayopanga Denis (Pakwach District Local Government), Bakeleki Bohin Jean Marie (IRIC), Carmen Loncthi Fobasso (APDD), Apene Derek Aziwoh (African Environmental Network), Cyrille Bienvenu Bediang (IRIC), Susanna B Hecht (UCLA), Jancy Kelly Boungou Matoumouna (Wildlife Conservation Society), Jonathan Tahiri Heri (University of Kindu, DRC), Bertrant James Taya Saah (Univ. of Yaounde I), Nzanzu Mulimirwa Philémon (Congolese Youth Parliament), Regis Koumba Mouissou (Univ. of Arkansas), Amour Macelvi Matoumouene Goma (LBGE), Paul Martial Tene Tayo (Univ. of Yaounde I), Nanda Silatsa Serge (STA), Alain Okito (UNEP), Stella Songwe Tikeng (Univ. of Yaounde I), Ncangu Bahindwa Benjamin (Univ. Officielle de Bukavu), Sandjo Phallin Romeal (Higher Institute of Environmental Sciences), Timothy Bonebrake (Univ. of Hong Kong), James Okwiri (Agribusiness Innovation), Matthieu Aksanti Cizungu (UEFA/RDC), Thierry Michel Tene (Akdeniz University), Igor Akendengué Aken (Omar Bongo Univ.), Clovis Nzuta Kengne (Univ. of Dschang), Essama Essama Mathurin (CERAD), Dolorès Mache (Planet One—Mboa Hub), Emmanuel Kohbe Wanso (BEDD), Vadel Eneckdem Tsopgni (Univ. of Yaounde I), Usongo Patience Abaufei (Univ. of Buea, Cameroon), Djorwe Enock (Univ. of Yaounde I), Ravinder Sehgal (SFSU), Donato Ndong Ndong Nzang (UNGE), Nguimalet Cyriaque Rufin (Univ. de Bangui), Hubert Yamvu (Programme National de Santé au Travail), Foupouapegnigni Moihamette (Univ. of Yaounde I), Amadou Bossiomo Mfela (Soldats pour la Nature), Hugues Irenge Nganiza (Pan African Univ.), Zacharie Mounkene Bounyahre (Univ. de Ngaoundere), Junior Baudoin Wouokoue Taffo (Univ. of Maroua), Djosebe Azaria (IRAD), Fritz Betchem (IRIC), Alysson Bery (IBAY-SUP), Robert Vancelas Obiang Zogo (Univ. Omar Bongo), Daniel Brice Knko Nkontcheu (Univ. of Buea), Eric Fokam (Univ. of Buea), Marcel Caritá Vaz (Wilkes Univ.), Armand Okende (ULB), Greg Jongsma (New Brunswick Museum), Joost van Haren (Univ. of Arizona), Rui Cheng (Univ. of Minnesota), Peter Ssimbwa (Muteesa 1 Royal University)

Social-Ecological Systems Working Group: Shivani Agarwal (Columbia), Caroline Arantes (West Virginia Univ), Adia Bey (GSFC), Ana Buchadas (Humboldt), Glenn Bush (Woodwell), Sophia Carodenuto (Univ. of Victoria), Min Chen (Univ. of Wisc - Madison), Oliver Coomes (McGill), Rogelio Corona (UNAM), Deborah Delgado Pugley (PUCP), Fanny Djomkam (IITA), Alejandra Echeverri (UC-Berkeley), Marius Ekue (Alliance Bioversity & CIAT), Jessica Fayme (Univ. of Michigan), Gillian Galford (Univ. of Vermont), Angélica María Gómez (UNC - Chapel Hill), Burak Güneralp (Texas A&M), Chima Iheaturu (Univ. of Bern), Marciel Jadith Móstinga Rodriguez (UNALM—Peru), Matthais Kunz (GFZ—Potsdam), Mody Lacour (UC-Irvine), Victor Maqque (OU), Mia Mitchell (LANL), Paulo Murillo (Univ. del Tolima), Florence Palla (OFAC), Johanne Pelletier (CGIAR), Marie Pratzer (Humboldt), Catherine Potvin (McGill), Dina Rasquinha (Univ. of Georgia), Casey Ryan (Univ. of Edinburgh), Asmadi Saad (Jambi Univ.), Evandro Marcos Saidel Ribeiro (USP), Michaela Shope (MSU), Denis Sonwa (WRI), Jocelyne Sze (UAB)

Modeling and Data Synthesis Working Group: Shivani Agarwal (Columbia University), Rachel Albrecht (University of São Paulo, USP), Luciana Alves (UCLA), Andrés Baresch (University of Maryland), Ana Bastos (Leipzig University), Carly Batist (Raiforest Connection), Anthony Bloom (JPL), Damien Bonal (INRAE, Université de Lorraine, AgroParisTech, UMR Silva), Santiago Botia (Max Planck Institute for Biogeochemistry), Na Chen (MIT), Bradley Christoffersen (The University of Texas Rio Grande Valley), Michael Coe (Woodwell Climate

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Community Engagement and Research Applications Working Group: Yoseline Angel (GSFC), Shivani Argawal (Columbia University), Kemen Austin (WCS), Carly Batist (Raiforest Connection), Ruksan Bose (IITA), Glenn Bush (Woodwell), Rogelio O. Corona-Núñez (National Autonomous University of Mexico, UNAM), Fanny Djomkam (IITA), Marius Ekué (Bioversity), Matt Hansen (UMD), Simon Hoyte (UCL), Nohemi Huanca-Nunez (Yale), Chima Iheaturu (Univ. of Bern), Yovita Ivanova (Alliance Bioversity & CIAT), Gerbrand Koren (Utrecht University), Matthias Kunz (Helmholtz Centre Potsdam), Patrick Meyfroidt (Université catholique de Louvain), Catherine Nakalembe (UMD), Tatiana Nana (UMD), Christiane Guillaine Nimpa Nguemo (University of Bamenda), Kevin Njabo (Texas A&M), Carl Norlen (USGS), Florence Palla (OFAC), Catherine Potvin (McGill), Danielle Rappaport (UMD), Nick Russo (Harvard), Denis Sonwa (WRI), Hannah Stouter (UCLA), Lucie Félicité Temgoua (University of Dschang), Stella Songwe Tikeng (Univ. of Yaounde I), Beisit Luz Puma Vilca (Sylvera)

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1 Introduction and Motivation

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

PANGEA is urgently needed to

1. *Maximize the value of current and next-generation satellite missions by filling data gaps and integrating mechanistic ecological insights.*
2. *Bridge critical knowledge gaps to support global climate and biodiversity goals based on understanding of processes that control heterogeneity in tropical forest vulnerability.*
3. *Develop new capabilities to observe, predict, and monitor tropical forest responses, while fostering the formation of the next generation of scientists and global leaders.*

Tropical forests have far-reaching impacts, encompassing globally significant quantities of carbon, nutrients and water, fluxes of carbon and energy, and the largest proportion of Earth's biodiversity. Over 75% each of flowering plants, amphibians, terrestrial mammals, freshwater and marine fish, and 91% of Earth's terrestrial birds have ranges that intersect tropical latitudes (Barlow et al., 2018). Tropical forests store vast amounts of carbon in soils and biomass, with moist tropical forests comprising about 40% of global plant biomass (Xu et al., 2021a). As the largest carbon sink among all the forests globally (Pan et al., 2024), they play a critical role in mitigating rising atmospheric carbon dioxide (CO_2), acting as essential buffers against climate change. Tropical forests also mitigate rising global temperatures through evaporative cooling (Bonan, 2008; Artaxo et al., 2022). Moreover, tropical forests interact with the atmosphere through complex feedbacks that regulate local weather and regional and global climate. Tropical forests ultimately influence the entire Earth system. For example, Amazon deforestation threatens rainfall patterns in the U.S., potentially reducing precipitation in the Midwest and Northwest (Lawrence & Vandecar, 2015) and causing a 50% decrease in California's Sierra Nevada snowpack, which supports agriculture and urban water needs (Medvigy et al., 2013). Such changes could alter water availability, reduce crop yields, and destabilize ecosystems, posing risks to food security and societal stability. Additionally, many globally significant commodities such as coffee, palm oil, cocoa and timber originate from the tropics, underpinning global markets and supply chains while contributing to U.S. household basic needs.

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

Tropical deforestation and degradation accounted for 22% of annual anthropogenic CO_2 emissions from 1990 to 2020 (Pan et al., 2024), although these emissions are partially offset by regrowing secondary tropical forests (Aragão et al., 2014; Rosan et al., 2024). Prolonged hot and dry conditions increase forest vulnerability to fires and already burned forests in turn become hotter and drier leading to a positive feedback that has been called a "gathering firestorm" (Brando et al., 2020a). Deforestation, forest degradation, direct exploitation (e.g., hunting, harvesting), and climate change have drastically altered tropical forests disturbance dynamics and now threaten many tropical species with extinction (Feeley et al., 2012; Barlow et al., 2016; Benítez-López et al., 2017; Alroy 2017; Dirzo et al., 2014). This biodiversity loss could in turn compromise the resilience of tropical forest structure and function, biogeochemical cycles, and socio-ecological systems (Bunker et al., 2005; Peres et al., 2016). Even after factoring in the greater species diversity, tropical regions are experiencing defaunation at the highest rate globally (Dirzo et al., 2014).

Studies over the past 10 years have revealed that the trends and interannual variability of net biome carbon exchange of tropical forests varies markedly across continents (Brienen et al., 2015; Liu et al., 2017; Hubau et al., 2020). From 1985 to 2015, the carbon sink of intact African lowland tropical forests measured in forest inventory plots was effectively constant, while the carbon sink in Amazonian lowland tropical forests declined by one-third from 2005 through 2015 compared to the 1990s (Hubau et al., 2020; Brienen at al., 2015). Under El Niño conditions during 2015-2016, tropical America, Africa, and Asia all temporarily became net sources of CO_2 emissions to the atmosphere (Liu et al., 2017). However, these net carbon losses appear to be underpinned by distinct mechanisms that indicate differences in the stability of the carbon sink on different continents that will require regionally specific understanding and management to mitigate. The sources of atmospheric CO_2 concentrations, as observed by the Orbiting Carbon Observatory-2 (OCO-2), Greenhouse Gases Observing SATellite (GOSAT), and Measurements Of Pollution In The Troposphere (MOPPIT), suggest that in the tropical Americas, lower photosynthetic rates led to reduced carbon uptake that changed the CO_2 balance to net emissions (**Figure 1).** In Africa, increased temperatures led to increased respiration, which outweighed the sequestration benefits of Central African tropical forests (Liu et al., 2017). In Asia, a hotter and drier land surface resulted in more CO_2 emissions from fires (Liu et al., 2017).

Many tropical forests have floodplains and are interspersed with wetland and aquatic ecosystems, which play a critical role in global methane (CH_4) budgets as well as the CO_2 cycle (Sjögersten et al., 2014; Peng et al., 2022). Tropical wetland and inland freshwater systems contribute the vast majority of natural global aquatic CH_4 emissions and make up roughly 20% of the total global CH_4 budget of ~575 Tg CH_4 yr^{-1} (Saunois et al., 2020; Peng et al., 2022). Tropical CH_4 sources are also the most uncertain component of the global carbon budget (Saunois et al., 2020, 2024). The expansion of deforestation and forest degradation, combined with changes in climate, significantly impacts overland water flows, river discharge and water quality. These in turn affect biogeochemical cycles; habitat suitability for freshwater

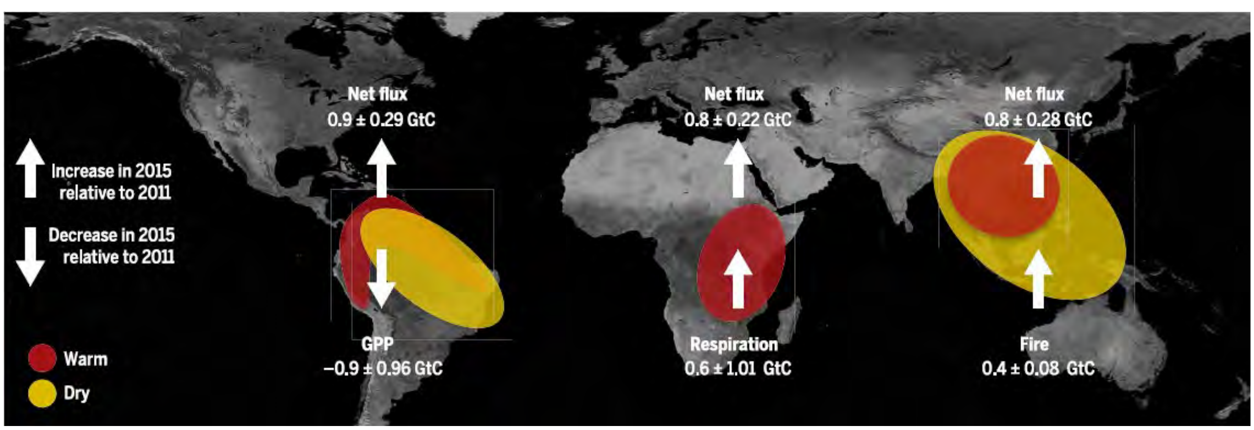

Figure 1. Analyses of OCO-2, GOSAT, and MOPPIT satellite data over tropical continents revealed that each became a net source of carbon emissions to the atmosphere in response to the 2015 El Niño. Critically, each continent exhibited distinct regional pathways that require improved understanding. Adapted from (Liu et al., 2017).

plant, animal, algal, and microorganism communities; water resources for humans; and hydropower production (Castello and Macedo, 2016; Guimberteau et al., 2017; Taniwaki et al., 2017; Arias et al., 2020).

Data from NASA satellite missions and airborne campaigns, validated by ground-based measurements, play a critical role in advancing understanding of how forest ecosystems and biodiversity are responding to environmental changes (Cavender-Bares et al., 2022). **However, before satellite data can be useful for scientific analysis or operational use, ground-based measurements are critical to calibrate and validate satellite observations. The scarcity of ground-based measurements and airborne retrievals in tropical regions has led to significant challenges in improving satellite products and interpreting scientific findings learned from these products.** For instance, the carbon and water cycles in the tropics are strongly dependent on soil moisture dynamics; however, recent ground-based observations revealed that Soil Moisture Active Passive (SMAP) satellite retrievals exhibit strong biases in tropical ecosystems (Cho et al., 2024). Importantly, these same ground-based data have provided an opportunity to improve SMAP's soil moisture retrievals in tropical forests (Wang et al., 2024). Another example of measurement scarcity in the tropics is the lack of ground-based validation data for space-based CO_2 retrievals over the tropics, especially tropical Africa, which has led to an ongoing debate about the magnitude of net biosphere exchanges over tropical Africa (Palmer et al., 2019; Gaubert et al.,2023). Similarly, in spite of the urgent need to assess global biodiversity at scale to evaluate the effectiveness of biodiversity conservation efforts, satellite remote sensing biodiversity monitoring capabilities are in their infancy.

Reducing biases in retrievals of soil moisture and atmospheric column CO_2 and advancing new measurement capabilities directly related to biodiversity (e.g., canopy tree beta diversity) and proxies (e.g., diversity networks) is critical to advance understanding of the water cycle, carbon fluxes, biodiversity, and ecosystem dynamics. Validating satellite and airborne observations with ground-based measurements is essential to the success of NASA's Earth observation missions, particularly with the advent of an exciting fleet of new and forthcoming sensors that have the potential to capture the multidimensionality of observed systems (e.g., via the NASA-Indian Space Research Organisation SAR [NISAR] and Surface Biology and Geology [SBG] missions). The development of more accurate satellite products, particularly in understudied tropical regions, directly supports NASA's mission to improve global environmental monitoring and advance predictive models.

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

Methods to validate satellite and airborne observations used in PANGEA include forest inventory plots, eddy-flux tower sites, other ground measurements, and Indigenous, Traditional, and Local Ecological Knowledge (IEK, TEK, LEK) that provide valuable insights into biodiversity, forest dynamics, and ecosystem functions (e.g., ForestPlots.net et al., 2021;

Anderson-Teixeira et al., 2014, Davies et al., 2021, Delwiche et al., 2024). However, because of accessibility and funding challenges, the current coverage of these measurements across the tropics, particularly in Africa, is sparse and seldom follows a pattern of random or systematic sampling required for statistical power and lower bias (Goetz et al., 2015; Bustamante et al., 2016). Consequently, extrapolation from limited plot locations may lead to significant uncertainties and biases (Saatchi et al., 2015; Tejada et al., 2019). The latitudinal distribution of both forest inventory plots and eddy covariance flux towers demonstrates the underrepresentation of tropical forests in global research efforts, revealing that the fewest towers and plots are found in tropical forest regions, despite having the highest gross primary productivity and methane emissions from natural sources (Baldocchi, 2020, Schimel et al., 2015) (**Figure 2**). Only one flux tower exists in all of Central Africa (Sibret et al., 2022). In addition, the glaring data, methods, and knowledge gaps in the tropics currently limit efforts to develop global maps of diversity using hyperspectral retrievals (e.g., functional trait maps) (Dechant et al., 2024). Expanding observations of structural and functional traits and ecosystem function metrics in tropical forest regions will provide calibration data and enable a significant improvement in characterizing patterns and processes that drive the dynamics of highly diverse tropical forests. In addition to statistical and process-based models, artificial intelligence and machine learning techniques have grown considerably over the last decade and can now be used to rigorously scale ground-based measurements to airborne and satellite observations regionally and globally (Aguirre-Gutiérrez et al., 2021; Dalagnol et al., 2022; Lines et al., 2022).

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

Earth System Model (ESM) predictions of carbon flux have three times greater uncertainty in the tropics than at other latitudes (Cavaleri et al., 2015; **Figure 3**). Robust remote sensing–based products describing the carbon, water, and energy cycles of tropical forests, as well as improved process characterization, are critical for understanding tropical forest-climate interactions and feedbacks and constraining predictions of ESMs. Predictions from ESMs participating in the Coupled Model Intercomparison Project (CMIP) diverge markedly in magnitude and in conclusions as to whether the land is a carbon sink or source (Arora et al., 2020; Friedlingstein et al., 2006; Friedlingstein et al., 2014; Negron-Juarez et al., 2015). While model development between CMIP - Phase 5 (CMIP5) and CMIP - Phase 6 (CMIP6) resulted in a major step toward constraining tropical carbon flux uncertainty, these reductions were primarily linked to the inclusion of nutrient limitations in models (Friedlingstein et al., 2023). Traditionally, ESMs ignore most biodiversity and represent tropical vegetation in simple, aggregated ways that do not capture tropical forest responses to climate variation and disturbance and contribute to model failure (Levine et al., 2016; Yang et al., 2023; Sakchewski et al., 2016; Schmitt et al., 2020).

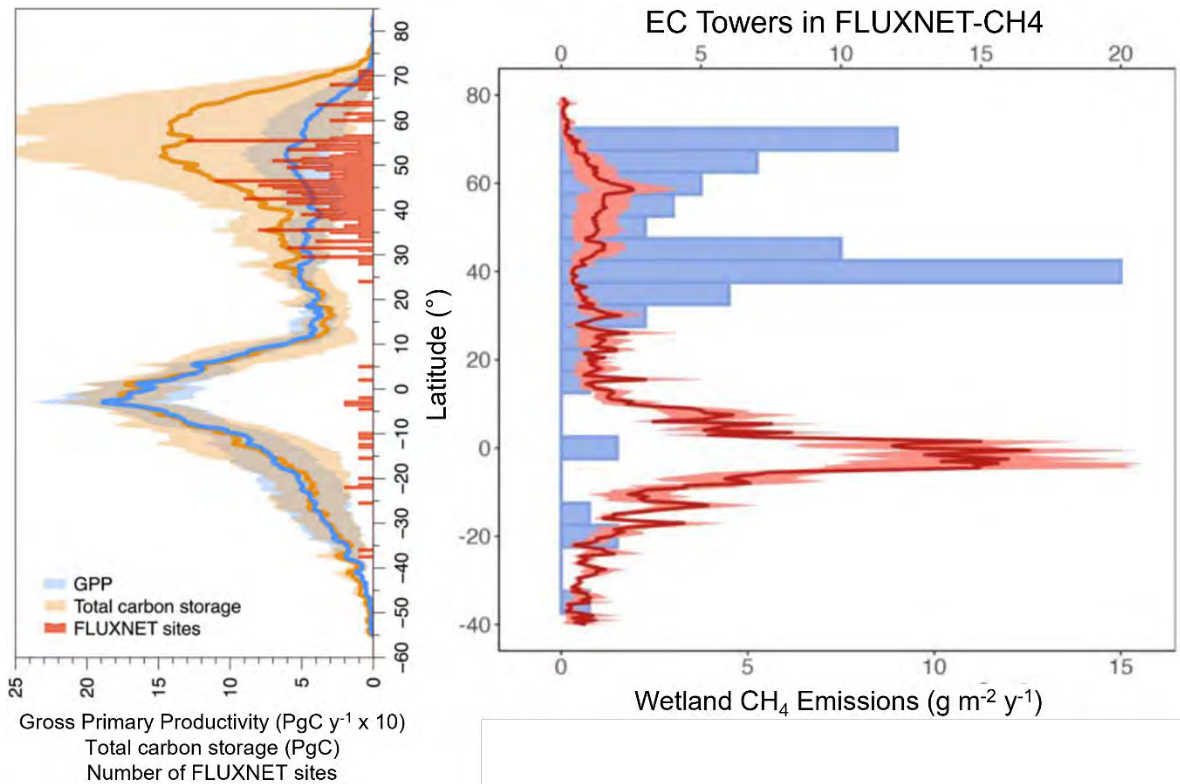

Figure 2. Forest function refers to the ecological roles of forests, such as regulating climate, supporting biodiversity, cycling nutrients, and providing habitat, which contribute to the overall health and stability of ecosystems. Forest functions include gross primary productivity (GPP), woody productivity, ecosystem respiration, and evapotranspiration. Panel (a) is adapted from Schimel et al. (2015). Panel (b) by Alison Hoyt, Clarice Perryman and Fa Li.

Constraining this uncertainty requires improved representation of ecological processes of diverse ecosystems (Bonan et al., 2024). Newer generations of terrestrial biosphere models and vegetation demography models, such as Ecosystem Demography Model version 2 (ED2), Functionally Assembled Terrestrial Ecosystem Simulator (FATES) and BiomeE, include more structurally and functionally diverse forest canopies (Fisher et al., 2018; Longo et al., 2019; Koven et al., 2020; Weng et al., 2022). Although vegetation demography models represent forest dynamics processes more directly, the additional complexity creates two challenges for regional and global simulations. First, initial conditions require detailed forest structure and composition data that can currently be derived only for small areas of interest from forest plots (Marvin et al., 2014). Second, existing model benchmarking systems, such as the International Land Model Benchmarking (ILAMB; Collier et al., 2018) are insufficient, because the newer generation of models may predict reasonable aggregated properties (e.g., total aboveground biomass) via compensating errors in process representation (e.g., overly high productivity and mortality). Recent advances in lidar, radar, and hyperspectral remote sensing provide a unique opportunity to collect data on the structure, composition, and biodiversity of tropical ecosystems at landscape scales and thereby improve model

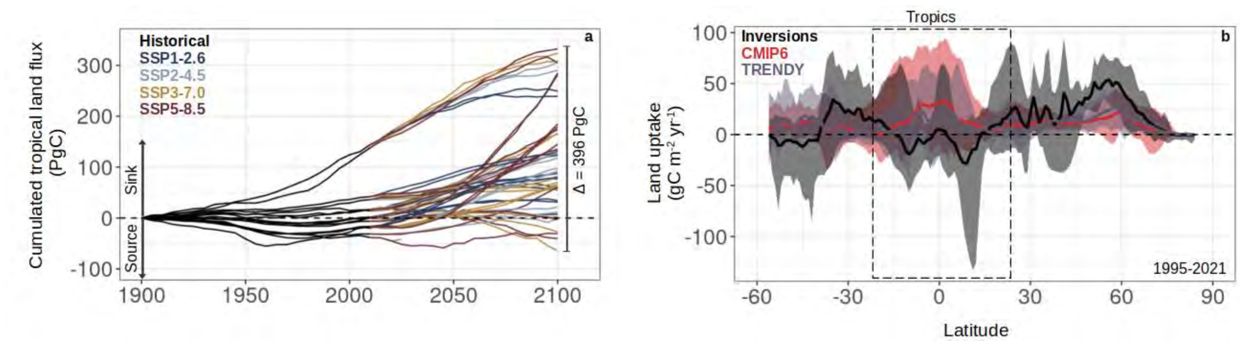

Figure 3. Historical and future cumulative land carbon flux from the tropics according to CMIP6 models with dynamic vegetation and multiple emission scenarios (a). Zonal mean of the land carbon uptake according to inversion models (black), CMIP6 models with dynamic vegetation models, and TRENDY land surface models for the recent period (b). The extent of the tropical region and its high uncertainty is highlighted with the dashed rectangle. Panel (a) was adapted from Friedlingstein et al., 2014 (update from CMIP5 to CMIP6). Panel (b) was redrawn from the IPCC AR6 with recent data.

parameterization, initializing, benchmarking, and process development (Schimel et al., 2019; Schimel and Carroll, 2024).

To address these needs and in response to a call from the NASA Terrestrial Ecology Program, we present below the scope of a terrestrial ecology field project, the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA), that will advance understanding of the processes controlling changes across pantropical forest biomes and their integrated feedbacks with Earth's climate (**Figure 4**).

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

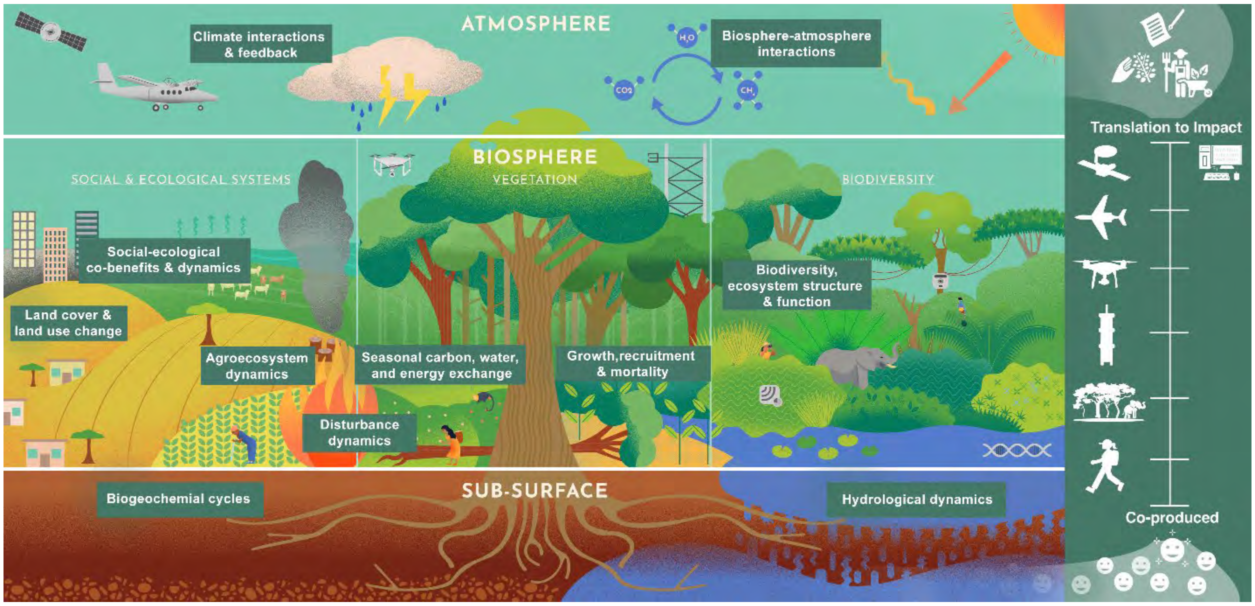

Figure 4. PANGEA measurements and scaling. PANGEA takes an integrated and transdisciplinary approach to science and applications, and will collect ground, tower, drone, and aircraft data in tropical forest landscapes across Africa and the Americas. Modeling and satellite remote sensing analyses will integrate this information to advance understanding of forests pantropically.

projects to Africa and the Americas, including SAFARI 2000, AfriSAR-1 and -2, Biodiversity Survey of the Cape (BioSCape), and several Earth Venture Suborbital (EVS) missions.

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

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

PANGEA will

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

PANGEA will go beyond LBA (Large-Scale Biosphere-Atmosphere Experiment in Amazonia) and beyond the Amazon, employing novel satellite technologies and observations unavailable during LBA, to advance science and monitoring capabilities pantropically (Figure 5).

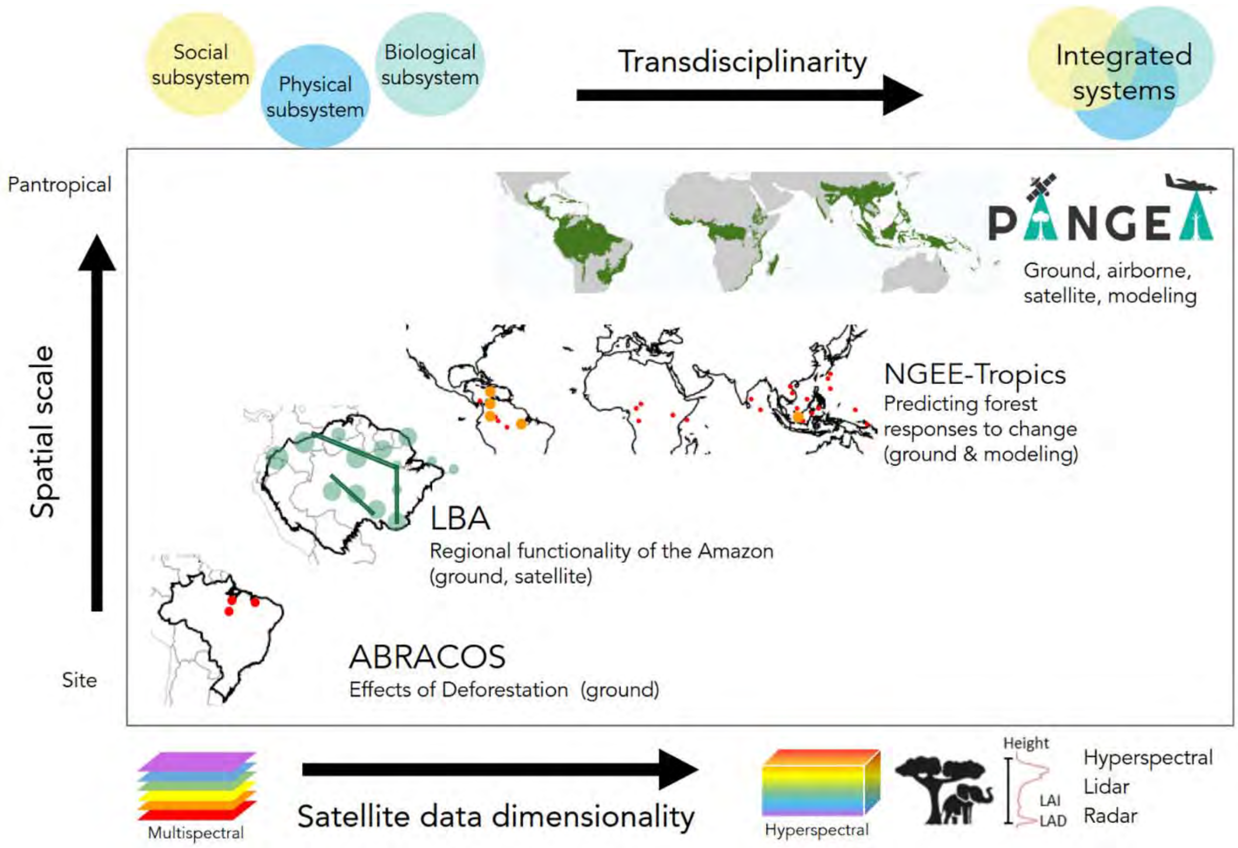

Figure 5. The evolution of PANGEA. PANGEA builds on previous efforts that have been more limited in geographic scope, data access, and/or transdisciplinarity, leveraging the data-rich, model-rich, computationally advanced, and timely opportunity to coordinate with pantropical activities.

PANGEA was developed based on the input of over 800 individuals representing over 300 organizations from 42 countries across 5 continents during the scoping effort through working group activities, 5 workshops, 10 town halls, 18 conference presentations and symposia, and over 150 bilateral meetings (**Figure 6**). Workshops were held in Washington DC, Cameroon, Peru, Brazil, and Thailand, with over 275 in-person participants and 298 virtual attendees. Participants in the scoping process represented many communities, including the academic community in the tropics, as well as in the U.S. and Europe, Indigenous and local communities from the tropics, the NASA community and other U.S. federal agencies, international space agencies, foreign government agencies, civil society organizations, and private industry. This scoping effort underscored the overwhelming need for PANGEA and the timely opportunity it presents to coordinate with many current and forthcoming activities as laid out in this white paper.

In the remainder of *Section 1*, we provide an overview of PANGEA. We then detail the PANGEA concept, including the PANGEA Science Themes (*Section 2*), Knowledge Gaps and Science Questions (*Section 3*), the scientific and technical advancement arising from PANGEA (*Section 4*), the critical role of NASA remote sensing (*Section 5*), PANGEA's research strategy and study design (*Section 6*), PANGEA's capacity-building, training, and education priorities (*Section 7*), community engagement strategy (*Section* 8), ability to enable Earth Science to Action (*Section 9*), and technical and logistical feasibility (*Section 10*).

1.1 Overview of Science Themes, Questions, and Objectives

Knowledge of tropical forest biogeochemical cycles, biodiversity, climate feedbacks and interactions, socio-ecological systems, and disturbance dynamics are critical for predicting the response of tropical forests to climate and land use change. Understanding these factors is also crucial for predicting the future of the Earth system and for developing forest and biodiversity conservation and change mitigation strategies. PANGEA's research themes and questions were developed through an inclusive consultative process with contributions from hundreds of scientists on five continents (See *Section 8.1*). The resulting themes and questions emphasize resolving uncertainties related to multidecadal trends and responses to extreme events across five thematic areas (**Figure 7**):

- **Biogeochemical Cycles** encompass the movement and transformation of essential elements (e.g., carbon, nitrogen, and phosphorus) through Earth's biosphere, atmosphere, hydrosphere, and lithosphere. In tropical forests, these cycles are highly dynamic, with rapid nutrient and biomass turnover; nonetheless tropical forests play a significant role in global carbon storage.
- **Biodiversity** is the variety of life on Earth, including its variation within and between species and ecosystems (genetic, phylogenetic, taxonomic, and functional diversity). In tropical forests, biodiversity is exceptionally high within and across forests, supporting complex interactions and ecosystem function, and causing heterogeneity in climate responses and resilience.
- **Climate Interactions and Feedbacks** are the bidirectional interactions between climate systems and ecosystems. Tropical forests directly regulate carbon, water and energy cycles. Climate changes (like temperature and rainfall shifts) and land-use and land cover changes (like fires and forest degradation) can alter forest ecosystem dynamics,

Figure 6. PANGEA by the numbers. The PANGEA scoping effort in 2024 engaged over 800 individuals from over 396 institutions during workshops, town halls, conferences, and via bilateral meetings and working group activities.

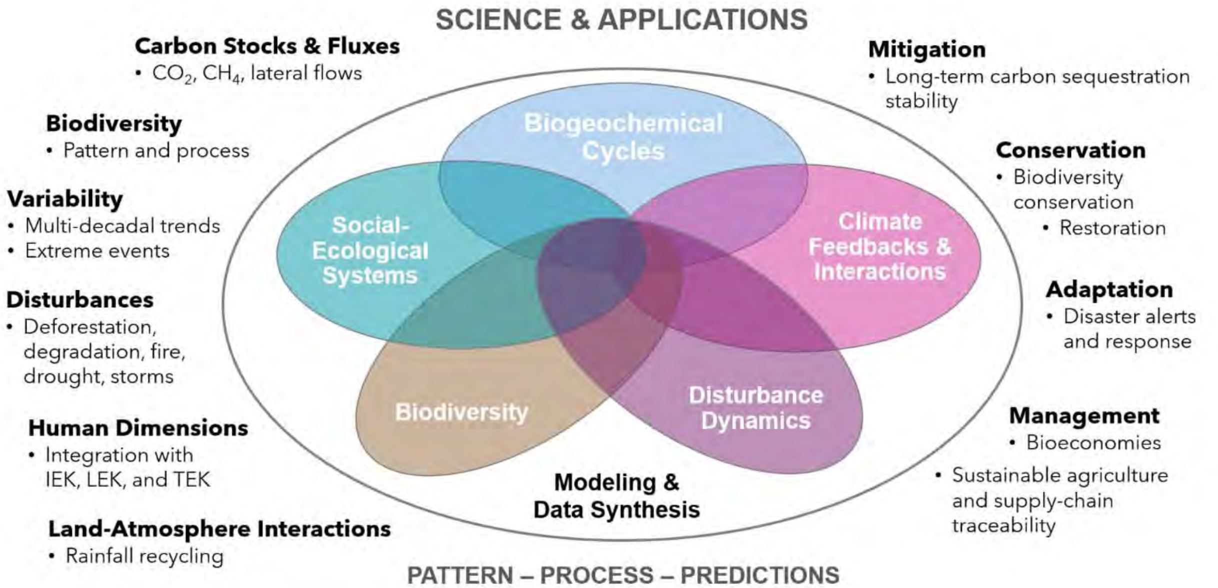

Figure 7. PANGEA science themes. The PANGEA science and applications themes emphasize resolving uncertainties related to multidecadal trends and responses to extreme events across five thematic areas.

creating feedback loops that affect global climate stability.

- **Social-Ecological Systems** are interconnected systems of humans and nature, where ecological and social components interact and influence each other. In tropical forests, these systems are shaped by the livelihoods, cultural practices, and resource-use of local- to global-communities, while ecological changes impact social well-being, creating complex feedbacks between human activities and ecosystem stability.
- **Disturbance Dynamics** vary by type, intensity, and frequency, and involve natural or human-induced events, such as fires, storms, drought, and logging, that disrupt ecosystems and affect their structure and function. In tropical forests, these disturbances can lead to shifts in biogeochemical cycling, biodiversity, and feedbacks to climate and to social-ecological systems.

Using these themes PANGEA will answer the overarching question (**Figure 8**): **How vulnerable or resilient are tropical forest landscapes to climate and land-use change and what are the feedbacks from forest change on the global carbon cycle and climate?**

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

1. What are the **patterns** of recent (5–30 years) and ongoing change in tropical forest landscape states, dynamics, and feedbacks, and how do they vary geographically?
2. What **processes** control heterogeneity in the vulnerability of tropical forest landscapes to structural and functional change in the Anthropocene?

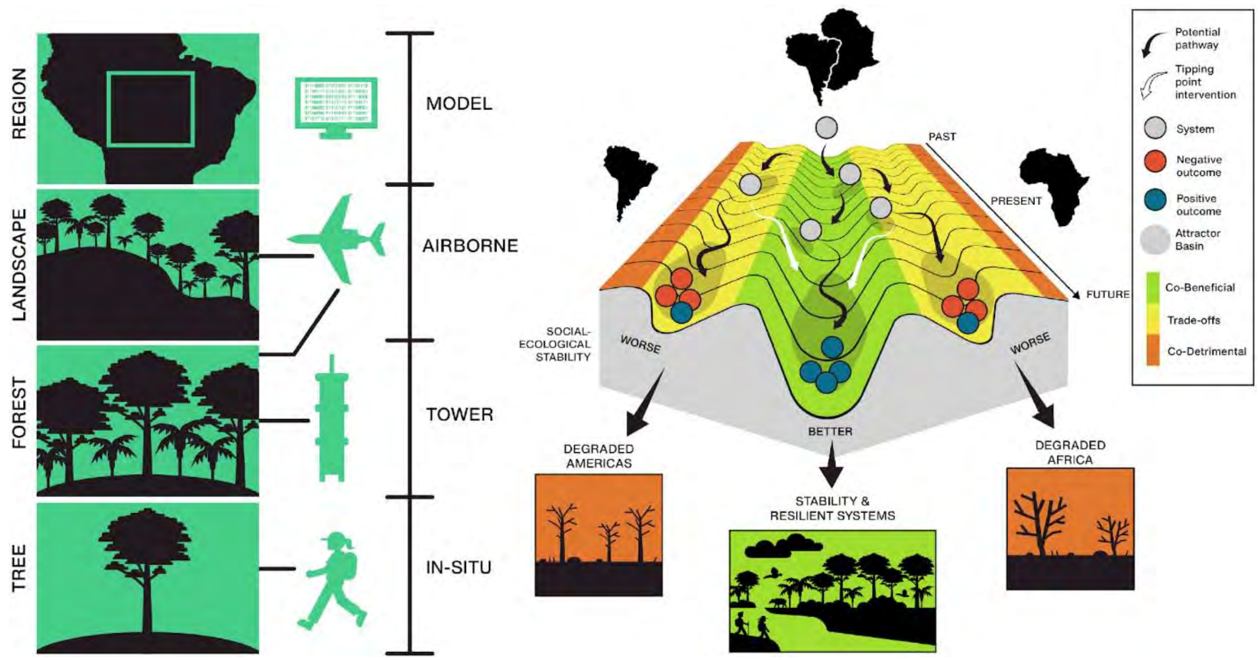

Figure 8. PANGEA examines how vulnerable or resilient tropical forest landscapes are, and their feedbacks to the global carbon cycle and climate. PANGEA's science and applications and collaborations employ an integrated approach to bridge the gap between rapid advancements in science and technology and society's ability to harness them for a more resilient world.

3. How will ongoing and **projected** future changes in tropical forest landscapes alter feedbacks to local, regional, and global climates and social-ecological systems?

To address the above questions, we have established five **PANGEA objectives**:

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

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

1.2 The Urgent Need for PANGEA

Implementing PANGEA is urgently needed for three reasons. First, studies suggest the potential collapse of tropical forest ecosystems within decades, which could drastically impact the global carbon and water cycles, exacerbating climate change (Lovejoy and Nobre 2018, Malhi et al., 2009; Boulton et al., 2022; Wunderling et al., 2022). Given the critical role of these ecosystems in the global carbon and water cycles, the collapse of tropical forest ecosystems would have potent effects on the whole Earth System, exacerbating current trends in climate change (Wunderling et al., 2024). Second, ground-based research remains scarce, and there remains a lack of knowledge to adequately understand science data from satellite missions from both current –e.g. **GEDI** (Global Ecosystem Dynamics Investigation), **EMIT** (Earth Surface Mineral dust source Investigation), **OCO-2/3** , and **ECOSTRESS** (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station), and future missions e.g., **NISAR***, **BIOMASS***, **EDGE***, and **SBG***. PANGEA will provide a unique opportunity to obtain ground-based measurements and airborne retrievals with coordinated, well-timed international efforts, to understand the signals from these missions, and to develop and calibrate data synthesis and data assimilation methods, and also drive and benchmark terrestrial biosphere and social-ecological system models. Failing to capitalize on these missions to coordinate them with ground-based measurements will miss a unique opportunity for reducing uncertainties in regions with the highest carbon stocks and major contribution to carbon, water, energy, and nutrient cycling amongst land ecosystems (Schimel et al., 2015; Schimel et al., 2019). Third, the risk of critical transitions in tropical forests differs across tropical forest biomes (Liu et al., 2017), with recent examples showing pronounced differences between Africa and the Americas (Hubau et al., 2020; Bennett et al., 2021; 2023). We are just beginning to understand the mechanisms behind these differences, along with the underlying structural and functional diversity of tropical forests. PANGEA will bridge critical knowledge gaps, enabling timely advances that directly support NASA's Carbon Cycle and Ecosystems Focus Area, in alignment with the Water and Energy Cycle and

Climate Variability and Change Focus Areas, the utility of missions including NISAR and SBG, as well as tools to implement and evaluate global climate and biodiversity commitments.

1.3 Role of Remote Sensing Observations

PANGEA will fill critical data and methods gaps to advance scaling between a multitude of ground-based measurements and satellite and airborne observations. We are in an unprecedented data-rich, model-rich, and computationally advanced moment. In recent years, spaceborne lidar, microwave radar, hyperspectral, altimeter, and other remote sensing capabilities have become operational at multiple scales. The satellite and airborne sensors allow more direct retrievals of atmospheric CO_2 and CH_4 concentrations, groundwater and surface water flows that can reveal lateral flows of carbon and nutrients, as well as structural, functional, and in some cases taxonomic diversity of forests. However, in tropical forest regions, ground-based measurements are scarce, limiting the global utility of satellite observations. Few tropical forest countries have regularly repeated, systematic forest and wildlife inventories, flux towers, or meteorological data, especially in tropical Africa. Even the limited number of research sites and ground measurements will, however, provide critical information on biogeochemical, ecological, and hydrological processes. The scarcity of these data makes it challenging to scale up measurements and analyses to regional, continental, or pantropical regions. PANGEA will conduct coordinated data collection and advance methods to scale more accurately among ground and tower measurements on the one hand and airborne and spaceborne observations on the other.

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

The constellation of international Earth Observing satellites in service today, those nearing launch, and those in the early stages of planning and implementation offer many dimensions of information not previously available nor widely used in tropical forest studies. The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) (Avissar et al., 2002; Davidson et al.; 2012; Keller et al., 2009), NASA's previous tropical forest project, began in 1998 before the launch of EOS Terra and Aqua satellites. Landsat was then the primary tool for monitoring deforestation (Skole and Tucker, 1993) and through the first decade of LBA research it was applied to estimate logging (Asner et al., 2005) and understory forest fires (Morton et al., 2011). Remote sensing information in early ecological models, such as the Carnegie-Ames-Stanford (CASA) biosphere model (Potter et al., 1993), originally incorporated normalized difference vegetation index (NDVI) data from polar-orbiting weather satellites (AVHRR) calibrated to net primary productivity. Understanding these data matching challenges motivated new linkages with more sophisticated remote sensing data. Interpreting MODIS data led to the observation that the Amazon region has a distinct seasonal signal of green-up and brown-down (Huete et al., 2006). LBA filled a void in knowledge, developing baseline understanding of the vulnerability of the Amazon to climate change. Moreover, LBA created a self-sustaining, vibrant research community that has thrived in Brazil and still influences all of South America. LBA was limited by the Amazon focal area, and the type and availability of both field observations and remote sensing data. The ongoing Next Generation Ecosystem Experiment in the Tropics project (NGEE-Tropics, https://ngee-tropics.lbl.gov) focuses on the predictability of tropical ecosystem processes at site-specific scales and increasing the ability to upscale these insights to continental and pantropical levels remains a critical challenge. PANGEA will address the limitations of previous efforts by harnessing more recent and future remote sensing data to scale ecosystem states and processes. This approach paves the way for a more comprehensive and predictive understanding of tropical ecosystems from local to pantropical scales. **New satellite sensor technologies are moving beyond assessing greenness,** (see *Section 5*) **and are providing much deeper insights into the function of tropical forests to enable more direct measurements of ecosystem fluxes, biodiversity, and responses to change.**

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

1.4 The Need for Coordinated Data Collection and Teamwork

Recognizing the deep imprint that colonialism has left on tropical forest research, along with parachute and flyover science (Culotta et al., 2024)**, PANGEA takes an interactive and interwoven approach to ensure equitable and ethical engagement with scientists, institutions and partners from governments, and Indigenous Peoples and Local Communities (IPLCs).** Several sections describe PANGEA's approach to community engagement (*Section 8*), an inclusive organizational structure (*Section 10.1*), Earth Science to Action (*Section 9*), training and education (*Section 7*), open science and data management (*Section 10.3*), and international agreements when conducting airborne campaigns (*Section 6.2.4*). PANGEA's approach is built upon the recognition that Earth system science is inherently multifaceted and complex. The NASA Terrestrial Ecology Program has promoted the multi-investigator model for decades of field campaigns that span the First ISLSCCP Field

Experiment (FIFE), the Boreal Ecosystem-Atmosphere Study (BOREAS), the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), and ABoVE. PANGEA will also foster close collaboration with key U.S. institutions, including **USDA**, **USFS**, **DOE**, **USGS**, the **Smithsonian**, leading universities, including **Penn State**, the **University of Oklahoma**, **UCLA**, and the **University of Maryland**, Indigenous communities, including the **Global Alliance of Territorial Communities (GATC)**, and international partners, including over 390 institutions, organizations and universities from tropical countries (**Figure 9**).

These partnerships span diverse research efforts, integrating expertise across disciplines to address critical knowledge gaps and the multiple drivers and interacting processes for

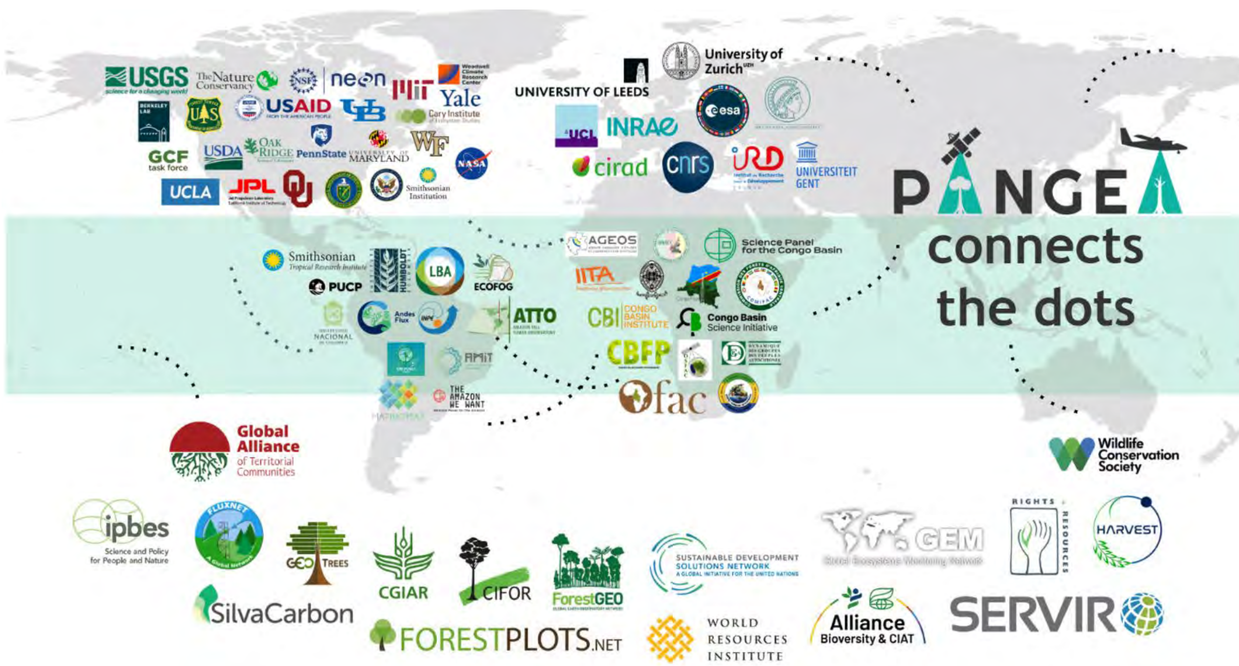

Figure 9. PANGEA connects the dots. PANGEA presents a unique opportunity to obtain ground and airborne data with coordinated, well-timed efforts, to maximize the value of current and next-generation satellite missions, through partnerships with institutions and organizations across the world and within the U.S. PANGEA will coordinate closely with current and forthcoming activities to fill remaining data, knowledge, and applications gaps.

understanding of tropical forests. Many variables require expert knowledge, ranging from the acquisition and use of satellite observations, and instruments such as a high-performance imaging spectrometer to the botanical identification of tree species or traditional knowledge of species interactions. No single individual or small group of individuals possesses all the knowledge and tools demanded by an Earth system science investigation. Fulfilling the needs of integrative analyses of the tropical biomes requires a large team of specialists working together. PANGEA requires strong collaboration to ensure that measurements are coordinated in time and space to maximize their value in interpretation and modeling. This can be achieved only through a cooperative, coordinated, transdisciplinary team. **To include, empower, and advance groups historically underrepresented in science, technology, engineering, and mathematics (STEM)—for example, people who identify as Black, Indigenous, Hispanic, women, or with disabilities—PANGEA will prioritize ethical and equitable engagement throughout.**

1.5 The PANGEA Terrestrial Ecology Field Campaign and Study Domain

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

PANGEA will include a **core** and an **extended** domain. The core domain is where the NASA-funded component of coordinated ground, tower, drone, and aircraft field campaigns will take place within multiple large (approximately 10,000 km^2) landscapes. *Section 6.2.2* outlines the Candidate Landscapes assessed during the scoping process that would be evaluated during the PANGEA Science Definition phase, prior to final selection. The extended domain will encompass pantropical moist forests and is the broader area of scientific interest, where additional projects can take place through partnerships, and where satellite and modeling analyses will be emphasized. *Box 1* describes a preliminary assessment of heterogeneity within key geographic landscapes in PANGEA's extended domain. The PANGEA domain (core + extended) covers tropical forest social-ecological systems and associated landscapes found in the humid tropics and the spatial scale required to address the primary questions (*Section 3*). Both the core and extended domains will encompass moist tropical forests, including flooded forests, wetlands, and peatlands.

PANGEA will leverage NASA's Terrestrial Ecology investment for its core resources. To account for a range of NASA funding scenarios to PANGEA, we have derived the **Baseline**, **Threshold**, and **Descope** levels of **Essential Scientific Measurements** from the PANGEA Science Objectives (see *Section 6.2.1* for details). The Essential Scientific Measurements will enable PANGEA to (1) understand differences in tropical carbon stocks and fluxes and the forces driving heterogeneity, (2) resolve scaling issues between field and satellite data by advancing process understanding and scaling methods, and (3) forecast varying tropical forest ecosystem responses to climate and land-use change. As noted above, PANGEA's core domain covers tropical moist forests in Africa and, depending on the Essential Scientific Measurement level, tropical moist forests in the Americas (**Figure 10**).

Here, we present an overview of the Strategy and Study Design, described in detail in *Section 6*. We will focus on PANGEA landscape campaigns and measurement activities at the start and end of the dry seasons. At the start of the dry season, measurements will capture system dynamics at a period of reduced stress, immediately following the heavy wet season. This time period enables coordinated multiscale measurements that are unachievable during peak wet season, when cloud cover limits optical remote sensing over the tropics. Measurement campaigns at the end of the dry season will capture times when tropical social-ecological systems are at their most stressed in terms of water and temperature. While we recognize that data collected only during the dry season risks biasing understanding of

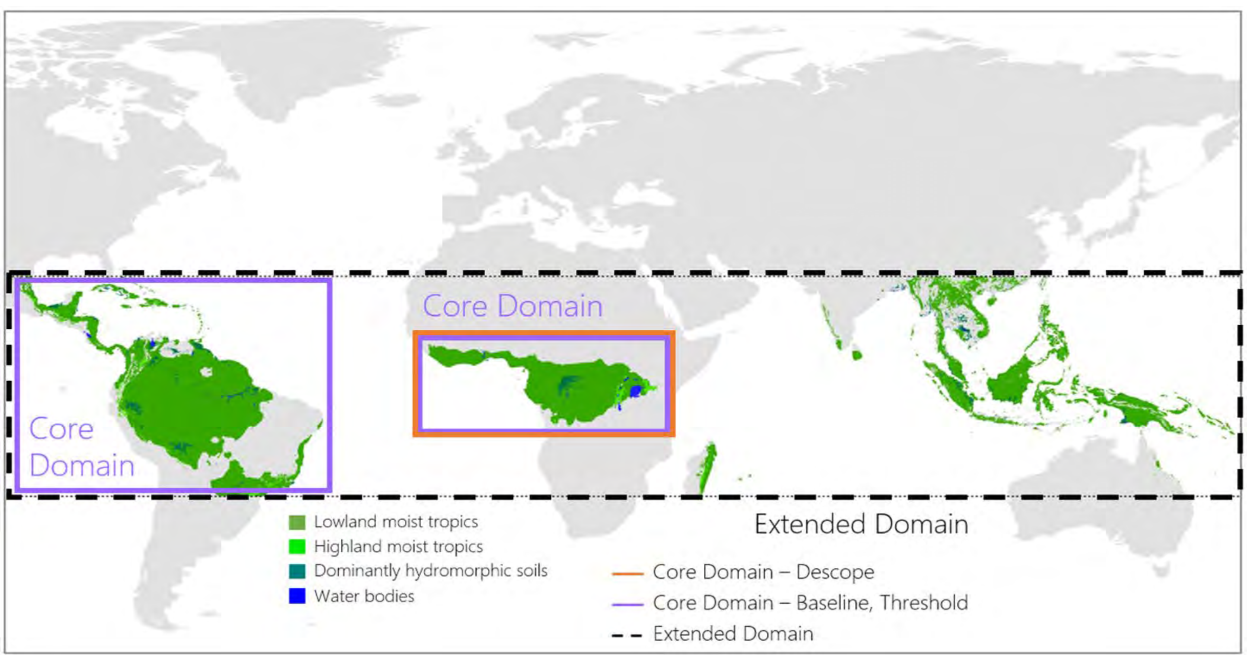

Figure 10. **PANGEA study domain.** PANGEA's core domain, under the Baseline and Threshold (solid purple lines) and Descope (solid orange line) levels of Essential Scientific Measurements, and extended domain (dotted black line). Boundaries were sourced from the following GAEZv4 agroecological zones: lowland humid tropics, highland humid tropics, dominantly hydromorphic soils, and land with severe soil/terrain limitations.

tropical forests given the strong seasonal differences in dynamics and processes, including carbon cycling, hydrodynamics, species interactions, and land-use activities (e.g., fire and clearing), the need to obtain concurrent terrestrial, airborne, and satellite measurements makes this a pragmatic decision. At the end of the wet season, most processes operating during peak wet season will still be present. For this reason, PANGEA will still be able to capture seasonal differences by focusing on the start and end of the dry season. To meet PANGEA's science and applications objectives, three potential strategies are presented:

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

The Baseline, Threshold, and Descope measurements detailed in *Section 6.2.1* represent stand-alone NASA-funded projects, without any dependency on non-NASA funds or synergistic efforts (**Table 1**). Intensive campaigns within these strategies are conceived to be implemented as stand-alone modules with limited dependencies so that the overall schedule and budget profile can be flexible. Given the urgency and importance of the topic, and such widespread interest from the community, there is strong potential to augment or even exceed NASA's contributions (see *Section 10.3* for more details). Unless otherwise noted, the core domain in the white paper refers to the one defined for the Baseline level of Essential Scientific Measurements.

Table 1. PANGEA achievables across the Baseline, Threshold, and Descope versions.

ACHIEVABLE	BASELINE	THRESHOLD	DESCOPE
VARIABILITY ACROSS CONTINENTS	Yes	Yes	No
VARIABILITY WITHIN CONTINENTS	Yes	Limited	Limited
TROPICAL FOREST FUNCTIONING ALONG ENVIRONMENTAL GRADIENTS	Multiple gradients. Intercontinental comparisons.	Single gradient. Indirect effects through intercontinental gradients.	Single gradient or co-linear.
ABILITY TO PROVIDE CALIBRATION DATA IN CRITICAL REGIONS	Very strong	Strong	Moderate
SUCCESS CONTINGENT ON EXTERNAL PARTNERSHIPS AND FUNDING	Not contingent	Somewhat contingent	Very contingent
ABILITY TO ANSWER PANGEA'S KEY SCIENTIFIC QUESTIONS	Fully	Mostly	Partially

The location of these primary research areas within the core domain will be based on (1) opportunities to conduct integrated research across science themes (*Section 2*); (2) the occurrence of key variability with respect to biotic, abiotic, and disturbance dynamics (**Figure 11**); and (3) the existence of ongoing or planned research funded by NASA, as well as relationships with and ongoing activities conducted by local and international collaborators and institutions. During the scoping study, an initial variability analysis across the extended domain was conducted to evaluate spatial heterogeneity (see **Box 1**).

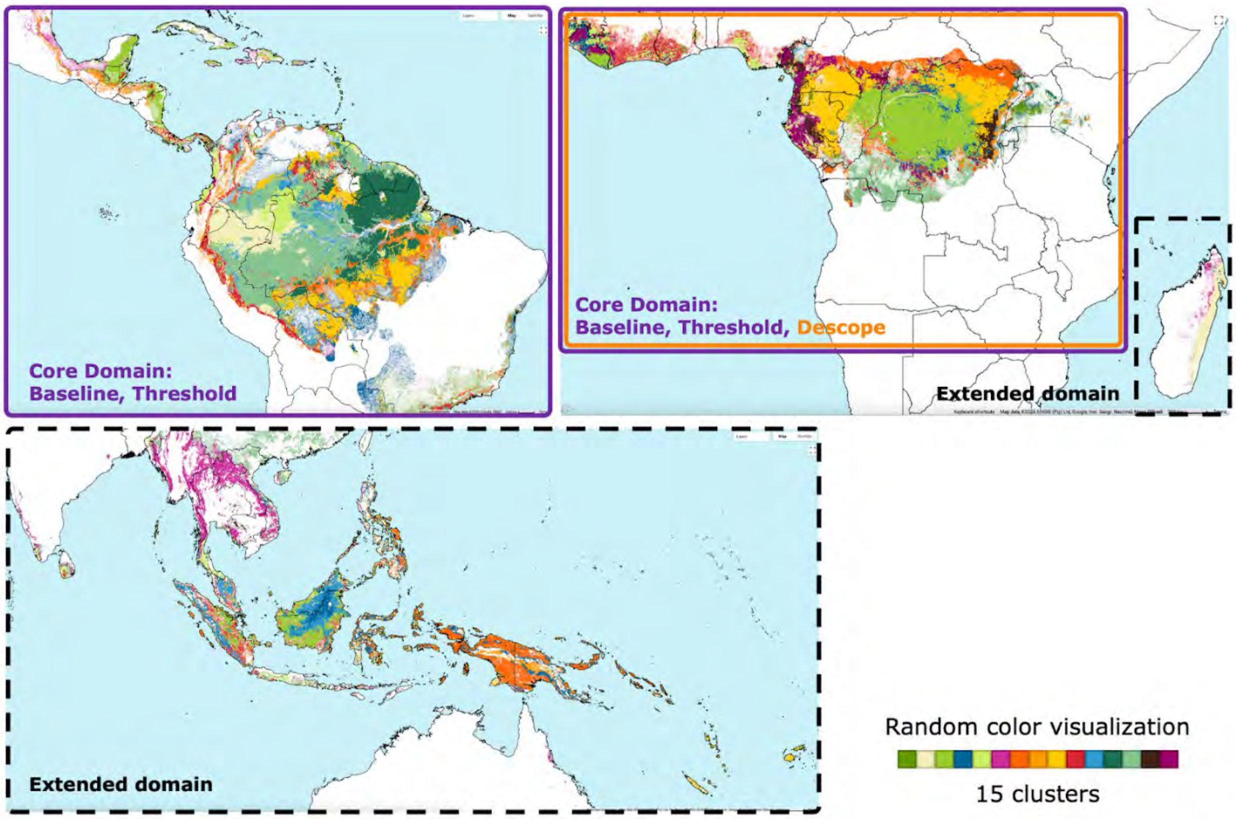

Figure 11. Variability analysis. Results from an initial variability analysis described in Box 1. For each continent, we defined 15 clusters describing the forest heterogeneity across landscapes, using climate, forest structure, composition and function, biodiversity, land-use, land cover, and disturbance history datasets. Clusters of each continent were defined independently and are shown in different random colors. The same color in different continents does not indicate correspondence of environmental conditions across continents.

Airborne campaigns will be a major component of the landscape-scale Baseline, Threshold, or Descope data acquisitions. These will include airborne flux observations data to measure CO_2, CH_4, sensible heat, and latent heat fluxes at high spatial resolution; hyperspectral reflectance and small-footprint lidar to measure canopy leaf traits and vegetation structure; synthetic aperture radar (SAR) data to measure wetlands, seasonally flooded systems, and disturbance dynamics; and small-footprint lidar to measure high-fidelity vertical and horizontal heterogeneity in ecosystem structure and plant area index. Ground-based measurements and knowledge are crucial to (1) validate both airborne and satellite

Box 1. Assessment of Heterogeneity within PANGEA's Extended Domain.

Tropical forest ecosystems are heterogeneous, and the patterns of forest structure, species composition, and function emerge from interactions between climate, geological history, soils, topography, biogeography, natural disturbance, biotic interactions, and land-use and land cover change. PANGEA's field campaigns will be designed to capture and sample forests that span multiple heterogeneous landscapes. To guide the selection of landscapes, the PANGEA team performed a cluster analysis of tropical forest ecosystems that accounted for multiple drivers of heterogeneity (Figure 11). This analysis was based on (1) forest structure from live biomass and net carbon fluxes (Harris et al., 2021) and canopy height (Lang et al, 2023); (2) biodiversity metrics from the species richness for non-plant taxa (e.g., IUCN, 2024); (3) solar-induced chlorophyll fluorescence (SIF) (Li and Xiao, 2019) as a proxy of gross primary productivity (GPP); (4) mean annual temperature and total precipitation from ERA5 (Hersbach et al., 2020) and long-term climatic water deficit (Chave et al 2014); (5) soil nitrogen and clay content from SoilGrids2.0 (Poggio et al., 2021); (6) topographic information from the height above nearest drainage (Donchyts et al 2016); and (7) a global human modification dataset (settlements, agriculture, transportation, mining, energy, and infrastructure) (Kennedy et al 2019). To ensure the landscapes were consistent with evolutionary history, each continent was analyzed separately, leading to 15 unique clusters for each region (tropical Americas, Africa, and Australasia). This initial assessment did not account for the uncertainty in the datasets, and did not seek to identify the most parsimonious number of clusters. PANGEA will refine this approach during the Science Definition phase and combine these results with the list of candidate landscapes (*Section 6.2.2*), regions dominating model and data synthesis uncertainty (*Section 6.3.1*), and the assessment of technical feasibility (*Section 10*) to define the priority landscapes in the Concise Experiment Plan (*Section 10.5*).

observations, (2) uncover ecological mechanisms, and (3) evaluate scale dependencies in tropical ecosystems. PANGEA addresses all three of these gaps in tropical forests through partnerships with local organizations and existing infrastructure to expand field observations and advance data and knowledge integration, including manual in situ data and TEK (e.g., floristic, faunal, and phylogenetic diversity, species interactions, disturbance dynamics, land-use activities); automated in situ data (e.g., sap flux measurements, camera traps, and bioacoustics sensors); eddy covariance flux and meteorological data; tower-based proximal remote sensing (e.g., SIF, thermal infrared radiation, VOD, and phenological cameras [PhenoCams]); and drone-based proximal remote sensing. A suite of models will be developed from the data and information collected, as well as synthesis products derived from the acquired datasets, which will be used to initialize, provide boundary conditions, and benchmark process-based models (*Section 6.3*). PANGEA's remote sensing and ground measurements for data-model integration will help generalize mapping capabilities across the tropics, and model carbon, water, and energy fluxes and their relationships with biodiversity to examine the stability of tropical forests under future climate projections.

1.6 Earth Science to Action

The Earth System with its interconnected geophysical, biological, and social systems is experiencing a particularly unique moment in its history. We must take the opportunity to benefit from the incredible advancements in modern tools, computing power (including AI), and research infrastructures. These advances will help people to take decisive action to conserve forests and biodiversity, mitigate and adapt to climate and land-use change, and improve food and water security and human health. Accelerating rates of change in the tropics drives the urgency to apply insights from the frontiers of NASA Earth Science. Since the inception of the Earth Science Enterprise Applications program in 2001 (ESE Strategic Plan) to the launch of the Earth Science to Action strategy in 2024 (St Germain, 2024 - ES2A Strategic Plan), NASA has innovated a systems approach to facilitate the collection of Earth Observations and predictions into decision and management support tools for diverse users and collaborators to advance their local initiatives that provide essential services to society. The 2017 Decadal Survey directs us to "pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observations and analysis to the nation and to the world in a way that delivers great value" (Decadal Survey, 2017).

PANGEA will build upon the strategic investments and international collaborations to bridge the gap between rapid advancements in science and technology, and society's ability to harness them for a more resilient world.

PANGEA's Earth Science to Action (ES2A) contributions to advance and integrate Earth science knowledge to empower humanity to create a more resilient world are described in Section 9 in detail. In short, PANGEA supports NASA's ES2A strategy by

- *Investigating the risks of crossing critical thresholds and the potential for cascading environmental and societal impacts.*
- *Supporting efforts to enhance Earth's resilience through the assessment of risks and contingencies and the development of mitigation and adaptation strategies to respond to global changes.*
- *Developing efficient, interactive end-to-end tools, models, and assessment systems with appropriate latencies, temporal and spatial scales, and uncertainty quantification to enable science-based actions for communities, policymakers, and action-takers.*

2 PANGEA Science Themes

Owing to the inherent complexity of tropical terrestrial ecosystems and their feedbacks with the Earth system, PANGEA takes an integrated, transdisciplinary approach across five science themes introduced in *Section 1.1*: Biogeochemical Cycles, Biodiversity, Climate Interactions and Feedbacks, Social-Ecological Systems, and Disturbance Dynamics. Understanding patterns and processes and constraining the uncertainty of future projections requires diverse expertise and coordinated collaboration. PANGEA bridges disciplines and ways of knowing to co-produce science that will address specific knowledge gaps and support urgently needed applications.

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

2.1 Biogeochemical Cycles

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

Tropical net biosphere exchange of carbon dioxide: Atmospheric carbon dioxide (CO_2) is a greenhouse gas (GHG) that has a major impact on the global climate system. The terrestrial biosphere is a large sink of atmospheric CO_2 with a present-day global net biosphere exchange (NBE) estimated at 3.3 Pg yr^{-1}, offsetting ~30% of the CO_2 emitted by fossil fuels annually (Friedlingstein et al., 2023). NBE refers to the total balance of CO_2 exchanged between an ecosystem and the atmosphere. Tropical terrestrial ecosystems contribute up to 0.6±0.4 PgC yr^{-1} of this sink (Friedlingstein et al., 2023) and contribute strongly to atmospheric global CO_2 interannual variability (Friedlingstein et al., 2023). Over the past three decades tropical deforestation has negated about two-thirds of the benefits derived from the global forest sink (2.2±0.5 Pg C yr−1, 1990-2019; Pan et al., 2024). Differences in the effectiveness of the tropical forest carbon sink within and between continents are evident. Previous research indicated that, from 2001 and 2019, the Amazon region (5.14 million km2) was a weak net carbon sink (−0.03 Pg C yr−1), with gross uptake (−0.4 Pg C yr−1) and gross emissions (0.3 Pg C yr−1). This is nearly one order of magnitude larger than the net sink. Brazilian Amazon live biomass alone was a net source of carbon (0.06 Pg C yr−1; Harris et al., 2021). In contrast, the smaller African Congo Basin (2.98 million km2) was a considerably stronger carbon sink (−0.17 Pg C yr−1) than Amazon forests despite having similar gross uptake rates (−0.3 Pg C yr−1). The magnitude of gross emissions in the Congo Basin (0.14 Pg C yr−1) was about half that of the emissions in the Amazon (Harris et al., 2021).

Understanding the mechanisms that drive the differences in carbon fluxes across tropical forest regions to quantify the spatial temporal distribution of carbon fluxes and their role in global carbon cycles, is a research priority.

Methane: Atmospheric methane (CH_4) is 25 times more potent as a GHG than CO_2 and contributes an estimated 30% of the increase in radiative forcing from anthropogenic emissions (Masson-Delmotte et al., 2021). The tropics contribute roughly 65% of total (anthropogenic + natural) global CH_4 emissions to the atmosphere (364 Tg CH_4 yr^{-1}) (Saunois et al., 2024). Around 40% of total CH_4 emissions from the tropics are from wetland, floodplains, and inland freshwater ecosystems sources (151 Tg CH_4 yr^{-1}), representing roughly 20% of the total global CH_4 budget and are responsible for interannual variability in the global atmospheric CH_4 growth rate (Feng et al., 2022; Saunois et al., 2024). Recent growth rates of CH_4 in the atmosphere have increased in ways inconsistent with our current understanding of global CH_4 sources and sinks (Turner et al., 2019). PANGEA will explore the CH_4 cycle across the tropics to develop improved models and understanding to contribute to management options.

Satellite-derived CO_2 and CH_4 measurements: The net biosphere exchange (NBE) over tropical South America demonstrated slower than expected carbon recovery following the 2015/2016 El Niño, possibly owing to heightened aridity and water deficits (Liu et al., 2024a). Signals from 2009 onwards indicate a persistent carbon sink in the Congo basin that contrasts with large sources of emissions in the western and eastern parts of tropical Africa (Palmer et al., 2019). Given the global impact of increasing GHGs and the uncertainties of recent measurements, PANGEA will use advanced sensors and the improved satellite derived column integrated CO_2 (XCO_2) and CH_4 (XCH_4) measurements used in inverse atmospheric models to constrain the tropical CO_2 and CH_4 budgets (e.g., Liu et al., 2016; Lunt et al., 2019; Crowell et al., 2019; Palmer et al., 2019; Yang et al., 2021a; Liu et al., 2020; Gaubert et al., 2023; Wang et al., 2023c; Liu et al., 2024a; Byrne et al., 2024). The recent OCO-2 model intercomparison project (MIP), based on 14 models, showed net carbon sources over the northeast Amazon and northern tropical Africa, contrasted with net carbon sinks over western Amazon and the Congo basin (Bryne et al., 2023). Tropical wetland emissions of CH_4 estimated using satellite retrievals of XCH_4 from GOSAT and TROPOMI (e.g., Parker et al., 2018; Ma et al., 2021; Feng et al., 2022; Yu et al., 2023) suggest that tropical wetland and aquatic emissions have been underestimated compared to ground-based CH_4 inventories (Yu et al., 2023), although cloud cover prevalence inhibits satellite retrievals (Ganesan et al., 2019; Melack et al., 2022). With rapidly advancing methane point source emissions detection capabilities using hyperspectral data now available (Hulley et al., 2016; Růžička et al., 2023), PANGEA will investigate the capacity to detect natural methane emissions using these or other higher fidelity sensors.

Validation needs: Satellite-based CO_2 inversion results are inconsistent in the tropics. For instance, GOSAT and OCO-2 atmospheric inversion results consistently showed a significant carbon source in northern tropical Africa (Palmer et al., 2019), driven by carbon releases during the dry season, when these satellites have more consistent cloud-free coverage of the region. On the other hand, a recent study combining four instances of aircraft CO_2 measurements with satellite-based inversions suggested that northern tropical Africa is close to carbon-neutral (Gaubert et al., 2023). These conflicting findings underscore the urgent need for additional research to resolve such discrepancies.

New insights from satellites: The OCO-2/3 and GOSAT satellite observations have provided new insights into the seasonal cycles and interannual variability of the tropical carbon cycle (Lei et al., 2024; Philip et al., 2022; Liu et al., 2017; 2024; Wang et al., 2023b). Interestingly, the seasonal cycle of NBE over the tropics, as inferred from OCO-2, exhibits a much larger amplitude than that simulated by state-of-the-art biogeochemical models. This result suggests that the tropical terrestrial biosphere responds to seasonal climate variations more dynamically than previously understood (Lei et al., 2024; Philip et al., 2020). Satellite observations have also greatly improved process-level understanding of the tropical carbon cycle's response to interannual climate variability (Liu et al., 2017; 2024; Wang et al., 2023b). For example, Wang et al. (2023b) showed that variability in total water storage drove the spatial heterogeneity of the Amazon's carbon cycle response to the 2015-2016 drought, while temperature played a more important role in influencing carbon flux variability across the entire tropical region. A recently published study (Stinecipher et al., 2022) showed that satellite observations of carbonyl sulfide (COS) provide a constraint on Amazon regional GPP consistent with other measures, suggesting that refined quantification of the fluxes of this gas at both local and regional scales may improve estimates of GPP (Berry et al., 2013).

Carbon in live plant biomass: Tropical forests store nearly 50% of the total above-ground plant biomass in terrestrial ecosystems (Santoro et al., 2021). The amount and processing of carbon in biomass is determined by net primary productivity, which balances the uptake of CO_2 and its emission from plants and some microorganisms (Bonan 2008). To understand the impact of climate and land use change in tropical forests it is essential to quantify the structure and function of tropical forests and interactions between plants and carbon in the atmosphere. Live biomass and productivity vary enormously in space and time across tropical forests (Sullivan et al., 2020; Xu et al., 2021a; Muller-Landau et al., 2021; Wang et al., 2023a, Sagang et al., 2024a). Regions with high rainfall typically support dense, evergreen forests with large carbon stocks and high productivity stocks, while areas with seasonal or lower rainfall harbor partially or fully deciduous forests with lower carbon stocks and productivity, and more seasonal variation in carbon fluxes (Malhi et al., 2002; Bonan 2008; Muller-Landau et al., 2021). Temperature also affects forest carbon cycling, both directly and through interactions with water availability (Taylor et al., 2017; Muller-Landau et al., 2021). Differences across the tropics and within tropical regions in geomorphology, climate, species composition, and phenology drive variations in rates of photosynthesis, woody productivity, respiration, tree mortality, and carbon flux across tropical forests (Sullivan et al., 2020; Muller-Landau et al., 2021; Wang et al., 2023a; Townsend et al., 2008; Quesada et al., 2010). Net primary productivity typically increases with soil fertility (Quesada et al., 2012), although there are no consistent relationships between soil fertility and live biomass, likely because turnover increases and woody residence time decreases with soil fertility (Muller Landau et al., 2021). Unfortunately, biomass and carbon dynamics studies based on ground measurements represent a miniscule fraction of tropical forest area a small and biased subset of tropical landscapes, prompting questions regarding the generalizability of these findings (Malhi et al., 2014; Marvin et al., 2014; Schimel et al., 2019; Hughes et al., 2021; Chapman et al., 2024). Disturbance regimes also play a crucial role in shaping tropical forest dynamics, influencing tree mortality, biomass turnover, and carbon cycling, detailed further in *Section 2.5*.

Tropical wetlands: A major contributor to the global carbon cycle are the large areas of tropical forests that are permanently or seasonally flooded wetlands, which include forested peatlands, swamps, and floodplains (Aselmann and Crutzen, 1989). For instance, Amazon River floodplain forests cover up to 250,000 km2 with most areas flooded six months of the year (Richey et al., 2002; Goulding et al., 2003). The Amazon floodplain represents the greatest natural CH_4 emission source in the tropics and rivals CH_4 sources from the Arctic (Pangala et al., 2017). In addition to the significant ebullitive CH_4 source from inundated soil, Amazon floodplain tree stems contribute CH_4 emissions which are estimated to be 200 times larger than from temperate wet forests (Pangala et al., 2017). The number of measurements and extent of coverage of CH_4 fluxes in the tropics are extremely limited compared to those in temperate and boreal regions (Johnson et al., 2022; Melack et al., 2022; Stanley et al., 2023). Tropical forest wetland CH_4 emissions are controlled by climate, hydrology, vegetation cover, disturbance dynamics, and land-use practices (Parker et al., 2018; Ma et al., 2021). The lack of carbon flux measurements in wetlands has led to poorly quantified tropical wetland and inland water system CH_4 emissions (Ganesan et al., 2019; Rosentreter et al., 2021). Existing mechanistic models have produced large differences in tropical CH_4 emissions (Melton et al., 2013; Bloom et al., 2017) and do not capture the observed CH_4 seasonality in tropical regions dominated by forested wetlands (Melack et al., 2022). Much of this difference is driven by the lack of fine-scale measurements detailing the drivers of wetland and aquatic emissions (Melack et al., 2022) and the threefold difference in wetland cover and inundation extents applied in individual models (Peng et al., 2022).

Tropical peatlands: Organic-rich tropical peatlands store the largest and highest-density carbon reserves that are irrecoverable on human decision-making timescales (Noon et al., 2021). Tropical peatlands store approximately 100 Pg C but there are large uncertainties in the spatial extent and associated carbon stocks of these peatlands. For example, the extensive peatland carbon stocks of the central Congo Basin and Pastaza-Marañón Foreland Basin in the Peruvian Amazon were recently mapped and account for more than a third of the carbon stored in tropical peat soils (Dargie et al., 2017; Crezee et al., 2022; Lahteenoja et al, 2012). Substantial undocumented peatland areas likely remain to be assessed (Hastie et al, 2024). Land-use change, through deforestation or drainage, and climate change threaten the carbon sink capacity of tropical peatlands (Page et al., 2022; Wang et al., 2018). In Southeast Asia extensive peatland drainage has turned peatlands of this region into a CO_2 source on par with regional fossil fuel emissions (Hoyt et al., 2020). Increasingly extensive and intense fires in peatlands, particularly in equatorial Asia and during El Niño years, have also become a major source of carbon, other trace gas emissions and particulate matter to the atmosphere (Page et al., 2009; Yokelson et al., 2022). As anthropogenic disturbances continue to threaten tropical peatlands (Hastie et al., 2022; Page et al, 2022), a better understanding of the distribution, carbon stock density, and emissions of tropical peatlands is needed (Roucoux et al, 2017; Deshmukh et al, 2021).

Nutrient cycling: Projecting the future productivity of tropical forests relies on understanding the interactions of nutrient availability from soils, plant functional composition and the impact of increasing temperature, CO_2 concentrations and extreme events. The typically low soil nutrient availability from highly weathered tropical soils is expected to constrain CO_2 fertilization as more nutrients are bound up in plant tissues (Fleischer and Terrer, 2022). Phosphorus will likely constrain the potential for higher forest growth rate responses to increased CO_2 by about half (Fleischer et al., 2019; Braghiere et al., 2022). While phosphorus is largely assumed to be the most limiting nutrient across lowland tropical forests (e.g. Cunha et al., 2022), recent observations reveal the heterogeneity of nutrient limitation across tropical forests, including limitation and co-limitation by nitrogen, phosphorus, potassium, and calcium (Davidson et al., 2004, Wright et al., 2011, Manu et al., 2022). Potassium plays a critical role in regulating plant responses to drought (Manu et al., 2024). Land-use change can further induce nutrient limitation by displacing large quantities of nutrients (Bauters et al., 2022; 2018; 2021, Kauffman et al., 1995), leading to local nutrient redistribution and losses. Remote sensing offers opportunities to capture the impact of available nutrient supplies and nutrient losses from disturbance events through observations of variations in foliar chemistry, functional traits, and canopy structure across large scales (Townsend et al., 2008, Chadwick and Asner 2016b; 2018, Martins et al., 2018).

2.2 Biodiversity

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

Tropical biodiversity: Biodiversity is the variability among all living organisms and ecosystems, including taxonomic, phylogenetic, functional, and genetic diversity within and among species, as well as within and among sites. Tropical forests are the most biodiverse biomes on Earth by all of these measures and are home to more than half of Earth's described species (Lewis et al., 2015; Barlow et al., 2018; Dinerstein et al., 2017; Pillay et al., 2022). The high total number of species found in tropical forests (high gamma diversity) reflects both extraordinary numbers of species within sites (alpha diversity), as well as substantial turnover of species among sites (beta diversity) (Condit et al., 2002; Basset et al., 2012; Jenkins et al., 2013; Slik et al., 2015). At small scales, among-site compositional variation in plant biodiversity largely reflects environmental filtering and stochasticity (Condit et al., 2002; Fyllas et al., 2009; Condit et al., 2013; Asner et al., 2014a; Chadwick and Asner 2018). The divergent evolutionary histories of different tropical continents have resulted in very different species assemblages and phylogenetic compositions (Slik et al., 2018; **Figure 12**). The high taxonomic and phylogenetic diversity of tropical forests is accompanied by high functional diversity, with species displaying a wide range of life history strategies, functional traits, and environmental responses (Fyllas et al., 2009; Condit et al., 2013; Slot and Winter 2017; Rüger et al., 2018; Homeier et al., 2021; Bialic-Murphy et al., 2024).

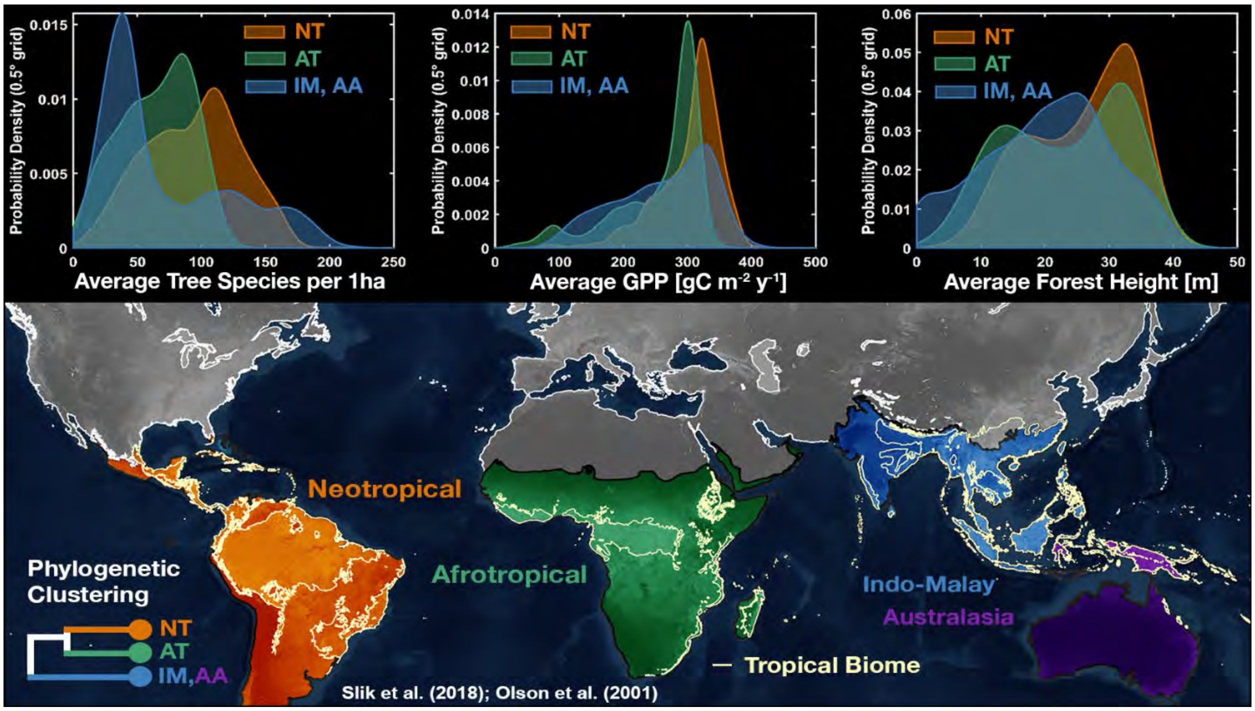

Figure 12. Tropical forests vary strongly in structure (height), function (GPP), and diversity within and among major floristic regions (mapped colors), shaping responses to climate and land-use change. The brightness of each color indicates mapped GPP. Source: Cavender-Bares et al. (2022).

Functional, structural, and species diversity: Tropical biodiversity is critically important to the functioning of tropical ecosystems and their feedbacks to the Earth system (Cardinale et al., 2012; Dirzo et al., 2014; Sakschewski et al., 2016; Berzaghi et al., 2018; Schmitt et al., 2020). Which species are present in an area, and their traits and abundances, affects forest structure, function, resilience, and interactions with local and global climate and social-ecological systems (e.g., Dirzo et al., 2014; Del-Claro and Dirzo 2021). The wide variation in ecosystem structure and function among tropical forests is closely linked to variation in biodiversity, reflecting not only the influences of abiotic environmental factors on biodiversity, structure, and function, but also their complex interactions (Muller-Landau et al., 2021). The species and functional composition of woody plants, which comprise the most aboveground biomass, is particularly important in shaping forest structure and function, which in turn affects microclimates, habitat, and food resources for animals and microbes. Understanding interactions among functional, structural, species diversity, and carbon cycle dynamics is critical given uncertainties surrounding whether or not tropical forests will survive and remain a carbon sink throughout the 21st century (Arora et al., 2020; Brienen et al., 2015; Hubau et al., 2020; Sabatini et al., 2019). High functional biodiversity creates greater ecosystem stability and resilience that may help mitigate negative effects of climate change (Sakschewski et al., 2016; Longo et al., 2018; Schmitt et al., 2020). Changing climate regimes could reduce biodiversity that might feedback on climate through lower carbon sequestration (Thomas et al., 2004; Cavanaugh et al., 2014). A review of 258 studies of naturally assembled communities, van der Plas (2019) found that, while most studies focused on the effects of taxonomic diversity, metrics of functional diversity were generally stronger predictors of ecosystem functioning. Although the tropics host immense botanical species diversity, the abundance of most species is low. Forest inventory plot data reveal that just 2% of species in the Americas (174 species), Africa (77 species), and Southeast Asia (172 species) account for 50% of the tropical trees on those continents (Cooper et al., 2024). Characterizing the functional diversity of these hyperdominant species and their interactions with other taxa is tractable and within the scope of PANGEA.

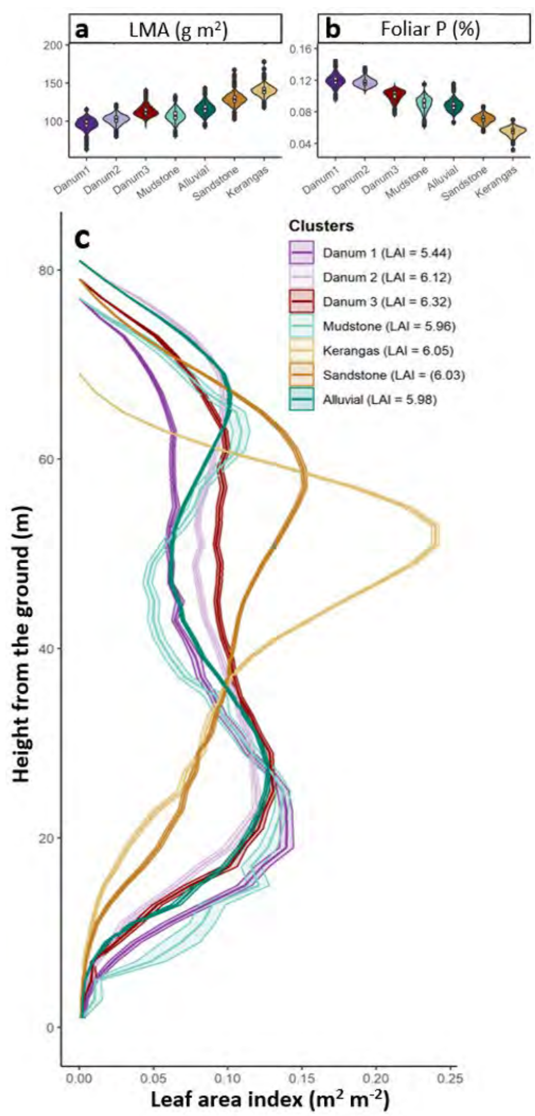

Figure 13. Variation in leaf mass per area (LMA), leaf phosphorus (P), and vertical leaf area index (LAI) in seven functionally distinct forest types mapped using airborne VSWIR and lidar data in Malaysian tropical forests (Ordway et al., 2022).

Woody plant trait variability and trade-offs: Woody plant functional trait distributions are an important manifestation of tropical biodiversity that affect forest structure and function (Li and Prentice, 2024). Important co-variations among traits include stature, the fast-slow axes of plant life history, and self-supporting versus climbing strategies to reach the canopy. Adult stature ranges from small shrubs to giant emergent trees above the main canopy (Rüger et al., 2018; Maynard et al., 2022). Vertical forest structure varies with ecosystem function even when vertically integrated metrics such as leaf area index (LAI) do not (**Figure 13**) (Ordway et al., 2022). The fast-slow axis refers to plant species with fast resource acquisition and processing (particularly

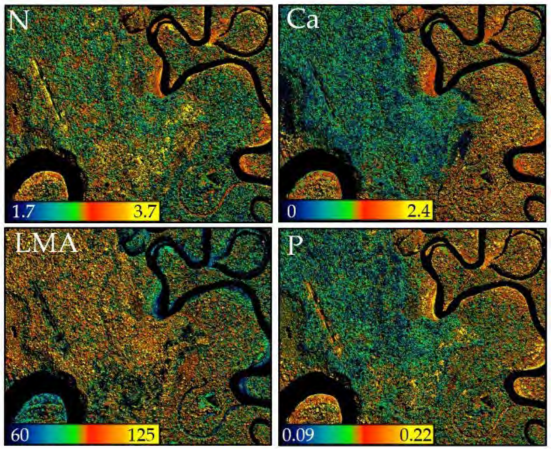

Figure 14. Landscape-scale variation in nitrogen (N), calcium (Ca), leaf mass per area (LMA), and phosphorus (P) in the Peruvian Amazon. Example of trait maps created from VSWIR imaging spectroscopy data from (Chadwick & Asner, 2016). No data of this type exist for Central Africa.

in terms of nutrient-use efficiency), fast growth, high resource needs, high mortality rates, and low shade-tolerance in contrast to species with slow resource acquisition and processing, slow growth, low resource needs, low mortality rates, and high shade-tolerance (Reich 2014; Rüger et al., 2018). Variation in functional composition among ecosystems thus relates to forest successional status, woody productivity, and woody residence time. Previous research has shown that trait distributions associated with wood, leaves and reproduction can be nearly orthogonal across tropical forest species (Baraloto et al., 2010; Fortunel et al., 2012). Nevertheless, the fast-slow axis still encompasses variation in leaf traits such as leaf mass per area (LMA) and leaf nutrient content (e.g., nitrogen, phosphorus, and calcium). Leaf nutrient content and LMA can be captured with hyperspectral remote sensing, enabling remote quantification of this dimension of plant functional composition (**Figure 14**) (Asner et al., 2017; Chadwick and Asner 2016a). Recent work has also explored functional diversity and redundancy trends across tropical forests using multispectral imagery (Aguirre-Gutiérrez et al., 2022).

Lianas, palms, and bamboos: Though much of the research in tropical forests is focused on trees, other plant life forms such as lianas, palms, and bamboos have a significant impact on ecosystem functioning, succession, and response to disturbances. For example, lianas (woody vines) are structural parasites that reduce tree growth and increase tree mortality via competition, and thereby alter forest structure and function, and carbon stocks (van der Heijden et al., 2013; Muller-Landau and Pacala 2020; Estrada-Villegas et al., 2022). Liana abundance varies widely among tropical forests in relation to climate, disturbance history, and other factors (Dewalt et al., 2015), and is increasing on average (Phillips et al., 2002; Schnitzer and Bongers 2011, Rueda-Trujillo et al., 2024). Previous research suggests that lianas may be vulnerable to droughts (Nepstad et al., 2007; Meunier et al., 2021) and they are favored by Increasing disturbance rates (Schnitzer and Bongers 2011, Schnitzer et al., 2021), while increasing tree growth has been linked to rising atmospheric CO_2 concentrations (Phillips et al., 2009, Brienen et al., 2015). Palms are an abundant clade in tropical moist forests (ter Steege et al., 2013), and several species are culturally and economically relevant (Laureto and Cianciaruso 2017). The distribution of palms across tropical forests is highly dependent on climate and edaphic conditions (Emilio et al., 2014; Muscarella et al., 2020). The high resistance of palms to wind damage in tropical storm affects the post-disturbance recovery of forests (Uriarte et al., 2019; Zhang et al., 2022). Intercontinental differences in palm abundance are marked, with tree-like palms being ubiquitous in the Americas, while being rare compared to understory and tree-climbing palms in Africa (Muscarella et al., 2020). Bamboos are tall grasses that occur in a broad range of habitats across the tropics (Fadrique et al., 2020). Their fast growth rates, combined with clonal reproduction, allow bamboos to dominate large extents of land, which can arrest forest succession and significantly decrease forest carbon accumulation (Griscom and Ashton 2003; Lima et al., 2012), and they may also become invasive where they are introduced (Montti et al., 2014). Bamboos are extensively harvested in tropical forests for economic reasons, which can impact local fauna dependent on bamboo forests for food (Sheil et al., 2012). Lianas, palms and bamboos differ from trees in their leaf traits and plant architecture, making it possible to quantify their abundance with multispectral, hyperspectral, and lidar remote sensing (de Carvalho et al., 2013; Dalagnol et al., 2022; van der Heijden et al., 2022).

Leaf phenology: Tropical plants display diverse leaf phenological strategies, from evergreen to deciduous, with variations in the duration, timing, completeness of deciduousness, and whether deciduousness is obligate or facultative (Borchert, 1994; Eamus, 1999; Kushwaha and Singh, 2005; Williams et al., 2008; Kearsley et al., 2024). The high carbon demand needed for flushing new leaves means that most drought-deciduous species in the tropics have thinner leaves to reduce construction costs, and high nutrient demand to increase photosynthetic capacity in shorter growing seasons (Eamus and Prior, 2001; Oliveira et al., 2021a). Leaf lifespan and the seasonal timing of leaf production are also important factors across evergreen and brevi-deciduous species, with implications for seasonal variation in leaf quality and photosynthetic capacity (Wu et al., 2016; Lopes et al., 2016; Wu et al., 2017a,b; Albert et al., 2018). The relative abundance of different phenological strategies varies systematically among tropical forests in relation to climate, geomorphology, soils, and other factors (Condit et al., 2000) and contributes importantly to strong stand-level variation in leaf and reproductive phenology among sites (Bohlman, 2010; Guan et al., 2015; Fisher et al., 2020; Fadrique et al., 2021; Yang et al., 2021b). Leaf phenology also varies substantially among years within sites, contributing to interannual variation in forest function (Pau et al., 2010; Detto et al., 2018; Lamjiak et al., 2021). Climate drivers of leaf phenology include water availability and light. Many tropical trees, species, and stands green-up at times of year when they receive the most light (fewer clouds), even when more light is accompanied by drier conditions (Wright and van Schaik, 1994; Lopes et al., 2016; Wagner et al., 2017; Li et al., 2021). Long-term changes in climate, especially in areas where dry seasons are lengthening, may increase the competitive advantage and abundance of drought-deciduous species (Vico et al., 2017; Aguirre-Gutiérrez, 2019).

Animals and microbes: Animals and microbes also drive ecosystem function and are influenced by global environmental change in consequential ways. Animals and microbes contribute to essential services such as pollination, seed dispersal, and nutrient cycling, and shape plant biodiversity, and forest structure and function, via these mutualistic interactions. Plant animal interactions may also be antagonistic such as through herbivory and disease (Dirzo et al., 2014). Megafauna like forest elephants (*Loxodonta cyclotis*)—found today in

Africa, but not in the Americas—have particularly important effects on forest structure and function due to browsing and physical disturbance. Elephants also assist the redistribution of nutrients and dispersal of large seeds, resulting in greater abundances of high-wood-density tree species across the landscape (Berzaghi et al., 2018; 2019; Campos-Arceiz and Blake, 2011). Experimental vertebrate exclosures have been shown to increase understory plant density and seedling abundance (Beck et al., 2013a; Camargo-Sanabria et al., 2015; Kurten and Carson, 2015). A large majority of tropical tree species and approximately half of liana (woody vine) species depend on vertebrates for seed dispersal, with most of the remaining species relying on the wind (Muller-Landau and Hardesty 2005). Defaunation of tropical forests by hunting and other human activities thus directly threatens plant regeneration, and may shift plant species composition and carbon cycle dynamics (Wunderly, 1997; Estrada-Villegas et al., 2023). Defaunation may ultimately lead to a shift towards lower forest carbon stocks (Brodie and Gibbs, 2009; Jansen et al., 2010; Bello et al., 2015; Osturi et al., 2016; Peres et al., 2016). Among sites in Panama, for example, increased defaunation was associated with species community compositional shifts in the seedling layer including more wind and water dispersed species and more lianas (Wright et al., 2007; Kurten et al., 2015).

2.3 Climate Interactions and Feedbacks

This PANGEA science theme will investigate the complex feedbacks and interactions between tropical forests and the climate system, as well as how changes in these processes will influence future tropical forest carbon sink/source dynamics.

Land-atmosphere interactions: Tropical forest land-atmosphere interactions modulate weather and climate both locally and regionally. Plants recycle precipitation through evapotranspiration and influence the onset and timing of rainy seasons (Wright et al., 2017; Sori et al., 2022; Worden et al., 2021a; van der Ent et al., 2010; Staal et al., 2018; Dirmeyer et al., 2009, Zemp et al., 2017; Nyasulu et al., 2024). Through the emission of biogenic volatile organic compounds plants affect cloud formation, albedo, and light availability for vegetation (Artaxo et al., 2022). Forest canopies also regulate albedo, and latent and sensible heat fluxes, and roughness, which drive biophysical climate feedbacks (Bonan, 2008; Chen et al., 2020; Lee et al., 2011). Furthermore, energy and water balances depend upon soil moisture, controlled by roots, soil texture, and geomorphology (Fan et al., 2017; Seneviratne et al., 2010; Zhou et al., 2021).

Weather and climate effects on tropical forests: Mesoscale convective systems deliver much of the precipitation in Central Africa and the Amazon (Andrews et al., 2024; Rehbein et al., 2017; Negron-Juarez et al., 2024). Storms, in turn, affect forest structure and tree mortality via windthrow (e.g., Negrón-Juárez et al., 2018; Feng et al., 2023a), and ecosystem functioning including processes that influence the prevalence of storm-resistant species (Uriarte et al., 2019; Liu et al., 2017). Lowland forests have adapted to submersion and waterlogging as precipitation causes flooding cycles (Alsdorf et al., 2016; Hawes and Peres 2016), which can lower oxygen availability, reduce photosynthesis, and decrease water conductance (Parolin et al., 2004; Parolin et al., 2016; Hawes and Peres 2016). Flooding also leads to increased production of CH_4 by microorganisms. Precipitation also affects nutrient cycles via wet deposition of nutrients such as nitrogen (Bauters et al., 2018, 2021), photosynthesis and reproduction through cloud cover and fog (Philippon et al., 2019; Pohl et al., 2021), and evapotranspiration via dew deposition (e.g., Gerlein-Safdi et al., 2018; Binks et al., 2019).

Drivers of climate interannual variability: Tropical climate is directly impacted by variation in sea surface temperature (SST), which controls the cross-equatorial energy transport (Cook and Vizy 2015; Zhou et al., 2019) and affects precipitation patterns via changes to the intertropical convergence zone (ITCZ; Schneider et al., 2014, Byrne et al., 2018), monsoons (Cook and Vizy 2019) and regional-scale dynamic systems (Cook and Vizy 2019; Creese et al., 2019; Montini et al., 2019). Phenomena like El Niño-Southern Oscillation (ENSO), the Madden-Julian Oscillation, the Indian Ocean Dipole, and Atlantic Meridional Overturning Circulation add to interannual variability in tropical convection (Raghavendra et al., 2020; Dias et al., 2017; Gu and Adler 2018). Different phases of these phenomena are strongly associated with droughts (Marengo et al., 2016; Ndehedehe et al., 2018; Jiménez-Muñoz et al., 2016), longer dry seasons (Jiang et al., 2019; Staal et al., 2020), and shifts in rainy season and storm intensification (Taylor et al., 2018; Rehbein and Ambrizzi, 2023; Balaguru et al., 2018). Responses to climate shifts vary across regions. African forests appear less vulnerable to droughts than Amazon forests (Tao et al., 2022; Asefi-Najafabady and Saatchi 2013; Saatchi et al., 2012; Bennett et al., 2021), and wetter tropical forests show resilience to climatic changes (Bennett et al., 2023), although the consequences of dryer or more variable conditions remains unknown.

Anthropogenic disturbance impacts on weather and climate: Human activities in the form of forest clearing, agriculture, cattle ranching, and fire, interact with climate change to exert significant feedbacks on terrestrial hydrological cycles (Li et al., 2022; Li et al., 2024). This includes changes at the surface such as river discharge and floods (Ndehedehe et al., 2022; Bogning et al., 2022; Oliveira et al., 2021b), as well as changes in convective development or atmospheric boundary layer dynamic and thermodynamic conditions (Taylor et al., 2022; Commar et al., 2023; Sierra et al., 2023; Wright et al., 2017; Leite-Filho et al., 2019; Jiang et al., 2019). Changes in these atmospheric dynamics lead to shifts in tropical storm activity, which has increased by 5–25% per decade over the past half century and seems likely to continue in the future (Taylor et al., 2018; Raghavendra et al., 2018; Lavigne et al., 2019; Harel and Price, 2020). Concurrent with increasing storm activity, tropical forests are experiencing longer dry seasons, greater atmospheric water stress, and more frequent droughts (Fang et al., 2022; Boiser et al., 2015; Duffy et al., 2015; Trenberth et al., 2014). Deforestation and forest degradation increase soil surface warming due to decreases in evaporative cooling (Devaraju et al., 2018; Li et al., 2015), with the magnitude of this effect influenced by the amount of forest cover lost (Alkama and Cescatti, 2016). Higher temperatures can subsequently increase tree respiration, which reduces NPP and changes how tropical forests cycle carbon (Choury et al., 2022; Das et al., 2023; Liu et al., 2017; Lloyd et al., 2023). Deforestation and degradation can increase streamflow and impact water quality due to sediment fluxes (Levy et al., 2018), as well as increase sensible heat flux and decrease evapotranspiration and infiltration (Costa et al., 2003; Souza-Filho et al., 2016; Longo et al., 2020; de Oliveira et al., 2021; Rangel-Pinagé et al., 2023). Land cover and land-use change can affect precipitation patterns by altering surface heterogeneity and influencing downstream moisture and heat fluxes (Mahmood et al., 2014; Snyder, 2010) and cross-continental nutrient cycles (Li et al., 2021; Barkley et al., 2019). In addition, biomass burning contributes aerosols, affecting cloud formation and dynamics (Liu et al., 2020; Zhang et al., 2008; Chaboureau et al., 2022; Tosca et al., 2015).

Climate-induced critical transitions of tropical forests: As new climate regimes are emerging, shifts of tropical forests to alternate, open-canopy ecosystems could occur (Hirota et al., 2011; Flores et al., 2024). However, vegetation sensitivity differs among tropical continents, and complex interactions with other changes, such as increased atmospheric CO_2, may alter vegetation response (Zhang et al., 2015; Bartlett et al., 2019). For example, African forests, particularly those in West Africa, are often exposed to higher temperatures compared to the relatively cooler, more humid tropical forests in Southeast Asia and therefore may be more adapted to heat stress (Malhi et al., 2013). However, this adaptation may come at the cost of West African forests operating closer to their critical temperature or hydraulic thresholds. Ultimately, exceeding historical climate thresholds in the tropics could lead to future shifts to alternative vegetation states that do not support contemporary tropical forest ecosystem services (Aguirre-Gutiérrez et al., 2020; Flores et al., 2024; Nobre et al., 2016; Scheffer et al., 2001).

Climate-biosphere feedback effects on freshwater resources: Tropical forests across the planet are also home to an extensive network of rivers and streams, which includes two of the largest river basins, the Amazon and the Congo (Dai and Trenberth, 2002). However, changes in temperature and precipitation regime, together with the expansion of deforestation and forest degradation are altering the hydrological cycles in both regions. While decreases in precipitation reduce the gross freshwater supply at the top of the canopies, deforestation and forest degradation may increase freshwater supply to rivers through the combination of higher throughfall precipitation and lower evapotranspiration (Davidson et al., 2012). In the case of the Amazon River basin, previous studies indicate that the net effect of climate change and deforestation is spatially heterogeneous, with river discharge reductions in sub-basins with strong precipitation declines or modest deforestation rates, and increases in areas heavily impacted by deforestation (Coe et al., 2011; Lima et al., 2014; Arias et al., 2018). Shifting hydrological cycles in freshwater systems also affects the extent and duration of seasonal floods across the river basins, which further impact fluxes of CO_2 and CH_4 (Hamilton, 2010; Alsdorf et al., 2016). Moreover, forest cover changes have significant impacts on water quality, such as changes in nitrogen and phosphorus concentration, water pH, oxygen availability and transparency (Neill et al., 2001; Ríos-Villamizar et al., 2017). These effects, combined with changes in temperature due to climate and canopy cover losses can significantly impact freshwater habitats and plant, algal, and animal riverine communities (Lorion and Kennedy, 2009; Castello and Macedo, 2016; Taniwaki et al., 2017; Zeni et al., 2019).

2.4 Social-Ecological Systems

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

Social-ecological systems: To fully understand the complexity of tropical forest social-ecological systems (SES) and how they are being impacted by global change, PANGEA takes a systems approach that centers the feedbacks and interactions that exist between people, climate and the environment (**Figure 15**). SES research has evolved over the past several decades to understand and model the relationships between and within social and ecological systems, spanning the sustainable livelihoods framework (Scoones 1998), SES subsystems and interactions (Ostrom 2009), SES resilience (Folke 2006), robustness in SES (Anderies et al., 2004), coupled human-nature systems (Liu et al., 2007), socionature (Swyngedouw 1999), ecosystem services (Costanza et al., 2017; Daily et al., 1997), nature's contributions to people (Díaz et al., 2018; Pascual et al., 2017), and social-ecological co-benefits (Levis et al., 2024). While these frameworks may differ in their definitions (Colding and Barthel 2019), they converge on key principles and variables that describe the social-

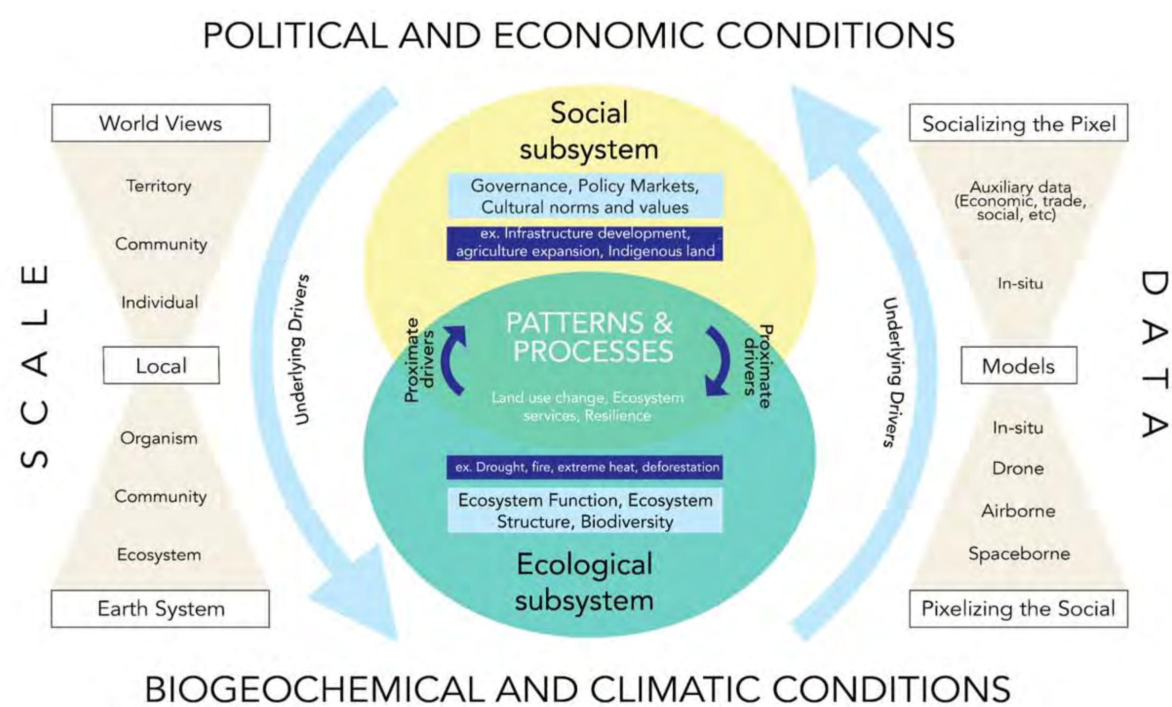

Figure 15. PANGEA's approach to SES will link proximate and underlying drivers of change in social and ecological systems across scales to understand how interactions in SES impact the vulnerability and resilience of tropical forests.

ecological system, including a central focus on the interactions and feedbacks that can facilitate or hinder change in SES. An SES perspective is particularly important in the tropics where land and forests are under high demand to meet food security and production needs, conservation and biodiversity goals, and support local livelihoods and development. Understanding the social and ecological impacts of these trade-offs and the feedbacks that shape them is required to develop a comprehensive understanding of the forces shaping tropical forest vulnerability and resilience and to guide effective and culturally sensitive adaptation and management strategies.

Patterns and drivers of land-use change: Across the tropics, regionally distinct drivers and patterns of land-use change, including deforestation, degradation, and forest regrowth, have the potential to impact the resilience of the tropical carbon sink (Saatchi et al., 2021; Hubau et al., 2020). In the Amazon and Southeast Asia, deforestation and degradation is primarily driven by the expansion of large-scale, commodity-based agriculture to meet demand from domestic and international markets (Curtis et al., 2018; Haddad et al., 2024). Specifically, in the Amazon land-use change is driven primarily by the expansion of pastureland for cattle and by industrial soybean production (Barlow et al., 2018; Londres et al., 2023). Soy farming and cattle ranching alter biogeochemical cycles (e.g., nitrogen and phosphorus), hydrologic and fire regimes, and are a leading cause of deforestation (MapBiomas, 2023). In Southeast Asia, where large-scale plantations are rapidly expanding at the expense of primary forest and peatlands, land-use change is driven largely by global demand for palm oil (Koh and Wilcove, 2008). In 2020, oil palm expansion was estimated to contribute 20% of the region's carbon emissions (Carlson et al., 2013). Improved smallholder livelihoods from oil palm expansion in Indonesia has been shown to yield direct tradeoffs with ecosystem function (Clough et al., 2016). Unlike the Amazon and Southeast Asia, the majority of land-use change in the Congo Basin is small-scale and driven by the expansion of subsistence and hyper local commodity crop agriculture (Tyukavina et al., 2018). Persistent demand for cocoa and timber continues to shape land-use change in tropical Africa, although small-scale and subsistence-based land-use change still plays an outsized role in driving land-use change (Hosonuma et al., 2012, Kamath et al., 2024; Fuller et al., 2019). For example, while commodity crops like oil palm have been expanding across tropical Africa since the 1990s, the expansion is linked to domestic demand and fulfilled by smallholders and informal market systems (Ordway et al., 2017a; Ordway et al., 2017b). The degree to which these different scales, intensity, and forms of land-use change among tropical continents impact distinct biodiversity and carbon cycle trajectories, however, remains poorly understood.

Feedback interactions: In tropical social-ecological systems, feedbacks between people and the Earth system plays a critical role in maintaining resilience and guiding the trajectory of these integrated systems (Dearing et al., 2010). Social-ecological systems dynamics in tropical forests involve feedbacks with a combination of proximate and underlying forces, including policy and/or market-based incentives, regulatory frameworks, access or barriers to information and resources, and long-standing connections between local communities, Indigenous peoples, and forest ecosystems (Geist and Lambin, 2002, Lambin et al., 2003).

These drivers not only shape ecological dynamics, including the carbon and water cycles, plant-animal interactions and weather and climate systems, but also in the social subsystem (**Figure 15**), including food security and local livelihoods (Sonwa et al., 2012; Flores et al., 2024). Moreover, drivers of change shape the feedbacks and interactions between the social and ecological subsystems, through changes, for example, in land use and cover, ecosystem resilience, and fire regimes (Whitfield et al., 2019; Gatti et al., 2023). The feedbacks between humans and tropical forests are tightly linked through the provisioning of ecosystem services and conservation and management activities, where, for example, the collection of non-timber forest products such as seeds, leaves, fruits, and roots can play an important role in supporting the livelihoods and cultures of tropical forest communities. While these interactions play out across the tropics, locally-specific political, economic, cultural, and management conditions influence the response, resilience, and adaptations of tropical forests and local communities to global change dynamics (Saatchi et al., 2021; Geist and Lambin, 2002; Turner, 2014).

Impacts on vulnerability and resilience: Human activities create complex feedbacks between social and ecological systems, resulting in a cascade of environmental and social impacts (Lambin & Meyfroidt, 2010). A better understanding of not only the feedbacks that amplify vulnerability, but also those that heighten the resilience of tropical forests is essential for developing place-based and culturally sensitive management plans that support both ecosystem resilience and community livelihoods. An example includes recent research focused on social-ecological 'hope spots'—defined as areas that can meaningfully impact social-ecological resilience, where local communities and public engagement can be strategically combined with science, engineering, and technology, including remote sensing, to provide the greatest impact for the conservation of vulnerable biodiversity (Levis, et al., 2024). The authors highlight the example of the Upper Xingu, located in the Brazilian Amazon's arc of deforestation, where Indigenous groups like the Kuikuro have enriched biodiversity through millennia of landscape management, including the creation of anthropogenic soils, domestication of diverse crops, and the cultivation of cultural forests, demonstrating cultural and management practices that promote forest resilience (Levis, et al., 2024). PANGEA offers an opportunity to expand similar research elsewhere in the tropics through equitable collaboration and co-production with Indigenous and local communities to identify practices that promote resilient systems that benefit both nature and people, including those that have the potential to be scaled. Far more work is needed to identify culturally appropriate methods and practices for integrating remote sensing and Indigenous science.

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

Global impacts of tropical forests: The impacts of tropical forests also extend far beyond the tropics. People in the U.S. and globally are impacted by tropical land-atmosphere interactions and are also agents of change for climate and tropical ecosystems, for example through consumption patterns, lifestyles and land use change. The Amazon plays a critical role in stabilizing climate systems across the Americas, and Amazon deforestation threatens rainfall patterns in the U.S that could lead to a 20% reduction in rainfall across the northwestern U.S. and a 50% decrease in the Sierra Nevada snowpack in California, which is the water source for agriculture and urban areas that the entire U.S. depend upon (Medvigy et al., 2013). If rainfall patterns in the U.S. Midwest, Northwest, and parts of the South are disrupted, this poses serious risks for U.S. agriculture and water resources (Lawrence and Vandecar, 2015). Amazon deforestation could lead to a 20% reduction in rainfall across the northwestern U.S. and a 50% decrease in the Sierra Nevada snowpack in California, which is the water source agriculture and urban areas that the entire U.S. depend upon (Medvigy et al., 2013). Such changes in precipitation, combined with shifts in atmospheric circulation, would strain water availability, diminish crop yields, and destabilize ecosystems from the U.S. Central Plains to the West Coast, with potential food security concerns. Amazon forest loss and degradation poses direct and serious threats to U.S. agriculture, water resources, and societal stability. In addition to the role tropical forests play in regulating global climate, many key commodity crops are grown primarily or entirely in the tropics, including cocoa, coffee, palm oil, and rubber. Numerous timber species are also only found in the tropics (Romero et al., 2017). PANGEA will assess the changing extent of land-use to support these crops and timber harvesting on tropical deforestation and climate change and consider tradeoffs, adaptation and mitigation strategies.

2.5 Disturbance Dynamics

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

Disturbance dynamics in the Tropics: There are two primary forest disturbance regimes: (1) direct human disturbance resulting from land cover and land use change, such as deforestation, degradation, agricultural development and human-ignited fire, and (2) natural disturbances that are largely associated with high temperatures, water stress, storms, biotic agents, and natural fire ignition, which are exacerbated indirectly by human actions that contribute to climate change. These two disturbance regimes contribute enormously to total forest turnover and carbon emissions from tropical forests (McDowell et al 2020, Qin et al., 2021), but have distinct spatial distributions, intensities, frequencies, and consequences for tropical regions. In Brazil's Arc of Deforestation, forest degradation through logging and fires caused more carbon loss than forest clearing from 2016-2018 (Csillik et al., 2024). The effect of windstorms on carbon loss was almost as great as fires, and larger than logging (Csillik et al., 2024; Urquiza-Muñoz et al. 2024; Esquivel-Muelber et al. 2020). The effects of changing drought and storm frequency and severity, rising temperatures, and deforestation and degradation are highly variable among ecosystems and can impact tree mortality, evapotranspiration, ecosystem respiration, species composition, and much more. Critically, interactions among disturbances can be multiplicative, rather than additive, meaning that we need to explicitly quantify their impact and interactions to understand their effects. Examples include drought amplifying the effects of fire (Brando et al., 2014), deforestation amplifying wind (Schwartz et al., 2017), and lianas amplifying lightning (Gora et al., 2023). PANGEA will quantify the effects of disturbance across biodiversity, climate, edaphic and land-use gradients to understand their individual and multiplicative consequences.

Direct human disturbance: Over the past several decades, direct human disturbance has posed the primary risk to tropical forest persistence and function. People clear vast tracts of tropical forest each year and cause degradation through selective logging, hunting, and fire. Direct human disturbances typically involve intense and enduring impacts, such as extensive biomass removal, defaunation, and conversion of land to non-forest ecosystems (Lewis 2015; Gibson et al., 2011, Wearn et al., 2012; Brodie et al., 2014; Silva Junior et al., 2020, Brando et al., 2014, Flores et al., 2024). Satellite remote sensing has revolutionized the rapid detection and quantification of direct human disturbance and enabled deeper understanding of the drivers (see *Section 2.4*). Deforestation and land cover change is now actively being mapped in high spatial resolution across the tropics and in association with specific sectors and practices driving these trends (Curtis et al., 2018; Maxwell et al., 2019; Qin et al., 2021; Harris et al., 2021; Lapola et al., 2023; McGregor et al., 2024; Csillik et al., 2024). With the advent of small-satellite arrays (e.g., PlanetScope), it is now also possible to quantify both deforestation and degradation in some systems within days-to-months (Welsink et al., 2023; Dalagnol et al., 2023). These advances have demonstrated that degradation contributes as much, or more, than deforestation to total tropical forest disturbance regimes (Maxwell et al., 2019; Qin et al., 2021), highlighting the importance of high-resolution and high-frequency data for understanding and monitoring these dynamics. Still, interactions between deforestation and degradation and factors such as hydrological cycling, micrometeorological conditions, species interactions, and biogeochemical cycling remain poorly understood, particularly in tropical Africa.

Fire: In moist tropical forests fire dynamics often interact with deforestation and degradation, where naturally ignited fires remain rare, and human-ignited fires are common (Uhl and Kaufmann, 1990; Cochrane, 2003; Brando et al., 2019a). From 2003-2018 in humid tropical forests, an estimated 41 ±14% of all forest loss was fire-related, although this varied considerably between continents (van Wees et al., 2021). Of all tropical fire-related forest loss during this period, 69% occurred in the tropical Americas, 22% in Southeast Asia, and only 8% in sub-Saharan Africa (van Wees et al., 2021). Although fires are associated with deforestation, the impacts of the decline in Amazonian deforestation, since 2005, on fire activity remains uncertain. Some studies showed a decoupling between fires and deforestation (Aragão et al., 2018) while others reported declines in fire activity (e.g., Andela et al., 2017; Libonati et al., 2021). In Africa there has been an increase in fire-related tropical forest loss, but the majority of fires in the region are likely going undetected (Wimberly et al., 2024). Human-ignited fires commonly spread into the understory of intact tropical forests where they cause tree mortality and make forests more susceptible to subsequent wind-driven disturbance (Barlow et al., 2003; Brando et al., 2014; Silvério et al., 2019; Berenguer et al., 2021b). Changes in forest structure associated with fires and forest fragmentation may increase the risk of subsequent fires both through the increased abundance of fuel loads like grasses and understory plants (Silvério et al., 2013, Sagang et al., 2024b) and higher solar radiation reaching the ground, which favors hotter and drier conditions near the surface (Brando et al., 2014; Longo et al., 2020; Nunes et al., 2022). Additionally, periodic droughts amplify the effects of fire by increasing fuel flammability, and thus climate-driven increases in severe droughts are expected to increase the effects of fire (Alencar et al., 2006; Brando et al., 2014, 2019a; Barbosa, 2024; Burton et al., 2024a,b; da Veiga et al., 2024; Jones, 2024). Fires transfer ecosystem nitrogen to the atmosphere through pyrodenitrification with the consequent effect of nitrogen impoverishment, leading to reduced rates of vegetation regeneration (Davidson et al., 2007). Satellite and ground measurements have revealed the widespread effects of fires and their major contributions to pantropical carbon cycling (Cochrane 2001; Berenguer et al., 2021a). Through coordinated, co-located ground measurements and advanced satellite and airborne observations PANGEA will significantly improve understanding of fire dynamics and their impacts.

Natural disturbance dynamics: Natural disturbances—primarily drought, storms, and biotic agents—present distinct challenges for detection, quantification, and attribution compared to direct human disturbances like deforestation and forest degradation–although defaunation remains essentially impossible to detect using remote sensing. Most natural disturbances occur at small spatiotemporal scales, with over 98% of biomass mortality from treefalls in the Amazon attributable to events less than 0.1 ha in area (Espírito-Santo et al., 2014). However, small disturbance events can collectively cause about 1.5-2% of biomass turnover annually, indicating that natural disturbances release the equivalent to the entire tropical forest carbon pool every 50-75 years (Galbraith et al., 2013; Espírito-Santo et al., 2014). Natural disturbances can also vary tremendously in space and time (Galbraith et al., 2013; Sullivan et al., 2020; Hubau et al., 2020; Dalagnol et al., 2021, Csillik et al., 2024, Negron-Juarez et al., 2023), with distinct drivers in different regions and strong evidence that natural disturbance regimes are shifting with climate change (Gloor et al., 2013; McDowell et al., 2018, Gora et al., 2020a; Sullivan et al., 2020; Gora and Esquivel-Muelbert 2021; Fang et al., 2022). Given their tremendous contributions to tropical forest carbon cycle dynamics–for example in the Brazilian Amazon, natural disturbances accounted for over 50% of total biomass carbon losses (Csilik et al., 2024)–even small changes in natural disturbance regimes will impact tropical forest function, biodiversity, and the global carbon budget.

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

Storms: Tropical storms (named hurricanes, cyclones, or typhoons depending upon their geographical location) are increasing in intensity and are a dominant form of disturbance in coastal tropical forests 10° north and south of the equator (Hoyos et al., 2006; Lugo 2008), although they play a limited role in pantropical disturbance regimes. In contrast, there is abundant evidence that wind and lightning associated with thunderstorms are dominant drivers of tree mortality and forest biomass dynamics (Chambers et al., 2013; Negrón-Juárez et al., 2018; Negron-Juarez et al., 2017, Negron-Juarez et al., 2023, Gora et al., 2020b; Gora and Esquivel-Muelbert, 2021). In the Amazon, tree mortality from storms has quadrupled since the 1980s (Urquiza-Muñoz et al., 2024), yet few studies in the Amazon have investigated storm drivers of forest dynamics and composition. Temporal variation in storm activity predicts canopy disturbance rates (Araujo et al., 2021) and spatial variation in storm activity is a strong correlate of spatial variation in forest biomass, biomass mortality rates, and species composition (Gora et al., 2020; Gorgens et al., 2021; de Lima et al., 2023; Feng et al., 2023a). For example, low storm activity is associated with high biomass in the Guiana Shield, whereas high storm frequency is associated with lower biomass and higher disturbance rates across the western Amazon (Gorgens et al., 2021). Storms likely play a similar role across other tropical forests, but storm disturbance analyses from the African and Indomalayan tropical forests are nearly non-existent. This knowledge gap is concerning because all existing data suggest that convective storms have increased in frequency by 5-25% per decade of the past century, and continued increases are expected (Taylor et al., 2018; Raghavendra et al., 2018; Lavigne et al., 2019; Harel and Price 2020).

Rising temperatures: Most lowland tropical forests experience high average temperatures throughout the year, with relatively low seasonal and interannual variability, which may make tropical forests uniquely vulnerable to shifts in temperature (Cunningham and Read, 2002). Climate projections indicate that tropical forests will increasingly experience no-analog mean annual temperatures and extreme heat events throughout the 21st century (Seneviratne et al., 2021). High temperatures can rapidly and non-linearly increase vapor pressure deficit (VPD) (Barkhordarian et al., 2019), which in turn negatively impacts primary productivity due to stomatal closure (Lloyd and Farquhar, 2008). Experiments have indicated that tropical tree species are able to sustain productivity up to 38°C if VPD does not increase (Smith et al., 2020). However, if average temperatures increase more than 4°C above current levels, tropical forest ecosystems may experience frequent periods of temperatures near 50°C, which could cause irreversible tissue damage and persistent loss of photosynthetic capacity (Doughty et al., 2023). The exact threshold at which temperature and VDP will cause permanent and extensive damage to tropical forests remains highly uncertain (Slot and Winter, 2016; Winter and Roelfsema, 2024).

3 Knowledge Gaps and Questions

In spite of the global importance of tropical forests, we do not fully understand the basic patterns and processes that underpin their survival, this limits our ability to effectively forecast their future role in the Earth system. Importantly, most of the current knowledge gaps are inherently transdisciplinary, and require advanced understanding of the processes and interactions among structurally, functionally, and socially diverse and heterogeneous tropical forest ecosystems, the effect of climate change, shifts in natural and anthropogenic disturbance regimes, and their combined impacts on biodiversity, biogeophysical and biogeochemical cycles. PANGEA science questions, therefore, cut across the five science themes described in *Section 2*. The questions addressing these themes–Biogeochemical Cycles, Biodiversity, Climate Interactions and Feedbacks, Social-Ecological Systems, and Disturbance Dynamics–are organized according to considerations of pattern (*Section 3.1*), process (*Section 3.2*), and projected future change (*Section 3.3*) to reflect their transdisciplinary nature. The measurements required to provide ecological, social, and geophysical data to address the science questions, will be obtained through ground-based, airborne, and satellite methods, and are described briefly in this section, with more detail in **Table 2** in *Section 6.2* and **Table E-1** in *Appendix E*. The range and variety of data collection for satellite, airborne, and ground-based measurements are shown in **Figure 16**.

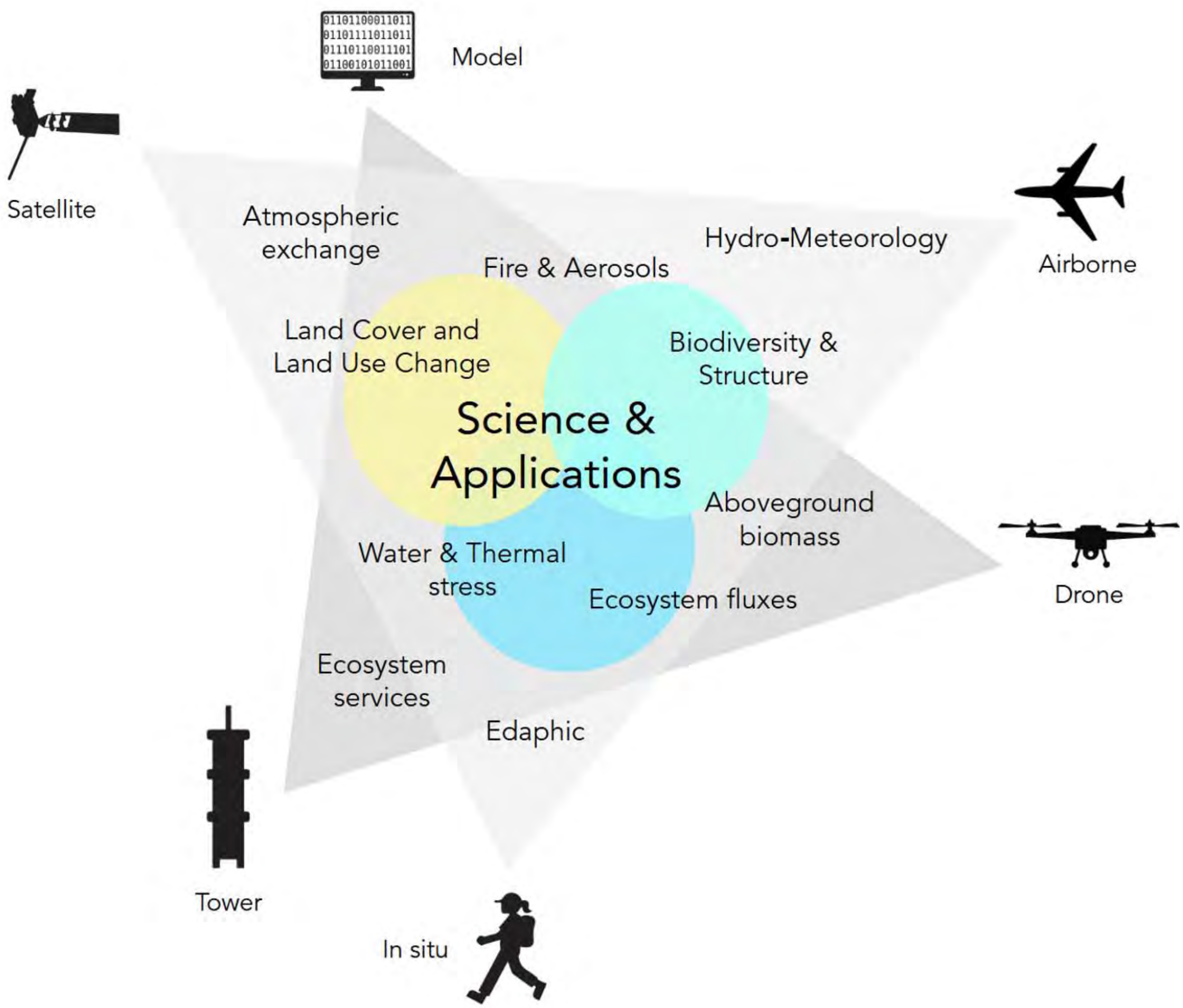

Figure 16. PANGEA's science and applications will reconcile scale mismatches through collocated in situ, tower, drone, aircraft, and satellite measurements in combination with advances in modeling and understanding of processes that underpin scaling theory.

3.1 Pattern

3.1.1 Pattern: Carbon Stocks and Fluxes

Current estimates of both carbon stocks and fluxes differ markedly across the tropics (Sullivan et al., 2020; Xu et al., 2021a; Muller-Landau et al., 2021; Wang et al., 2023a). Data from

Africa, albeit sparse and with a geographic bias and lack of representativeness, suggests that disturbance regimes and forest responses to disturbances are distinct from other continents (Hubau et al., 2020; Bennett et al., 2021; 2023), although this is still open to debate. In addition, across the tropics, the spatial and temporal patterns of disturbance dynamics are poorly characterized, which exacerbates the uncertainty about the future of the global carbon budget (Pugh et al., 2020). To fill in the knowledge gaps in our data and understanding of tropical carbon stocks and fluxes, PANGEA will address the following pattern-related questions to answer PANGEA's overarching question in *Section 1*:

- ***Q1.*** *How do forests across the tropics differ in carbon stocks and carbon dioxide, methane, and lateral fluxes, and how does their* ***spatial variation*** *within each forest relate to micro-climate, hydrological cycling, soils, geomorphology, and social-ecological interactions*
- ***Q2.*** *How do* ***temporal variations*** *in tropical forest fluxes relate to temporal variations in weather and how will these be affected by climate change?*
- ***Q3.*** *How do* ***disturbance types****, and gradients in* ***disturbance regimes*** *affect carbon stocks and fluxes, including carbon dioxide, methane, and lateral fluxes?*
- ***Q4.*** *How do geographic differences and spatial and temporal variations in tropical forest tree* ***phenology*** *vary with carbon stocks and fluxes, and is phenology changing in relation to shifts, including climate and land-use change, and disturbance regimes?*

To improve the **spatial characterization** of landscape-scale biomass (i.e., forest, croplands, pasturelands), and differences in biomass across the core and extended geographical domains, PANGEA will integrate forest inventory plot data and additional measurements at selected sites covering the landscape scale, with satellite and airborne lidar data. PANGEA will partner with GEO-TREES, a project that is coordinating ground measurements from forest inventories with terrestrial laser scanning, drone, and airborne lidar data collection. PANGEA will leverage information on tree allometry-based estimates of carbon stocks and will prioritize collocating landscapes with GEO-TREES forest sites to support upscaling efforts using **GEDI**, **NISAR**, **BIOMASS**, and **EDGE***. To advance the **temporal quantification** of ecosystem fluxes, PANGEA will integrate CO_2 and CH_4 data collected using existing eddy covariance flux measurements (Baldocchi 2020) and will also identify areas for implementing new towers to fill data and knowledge gaps across climatic, biodiversity, and disturbance gradients. Additional measurements of CO_2 and CH_4 will be made through strategic deployment of automated and manual chambers. To assess regional and pantropical constraints on CO_2 and CH_4 fluxes, PANGEA will employ airborne trace gas measurements, which played a key role in previous NASA field campaigns, such as the Manaus vertical profile measurements during LBA and the CARVE and Arctic-CAP airborne trace gas measurements during ABoVE (Sweeney et al., 2022). These will be used to validate satellite observations from sensors such as the **OCO-2 and -3**, **TROPOMI**, **Carbon Mapper**, and new products from geostationary satellites, including **GOES-R** (Crisp et al., 2017; Lorente et al., 2021; Khan et al., 2021; Ranjbar et al., 2023). **NISAR** and **BIOMASS** will be used to map tropical wetlands, which will be integrated with the Surface Water and Ocean Topography Mission (**SWOT**) surface water data to constrain the lateral carbon fluxes measurements.

PANGEA will collaborate with the Total Carbon Column Observing Network (TCCON) and COllaborative Carbon Column Observing Network (COCCON) to fill satellite observation validation gaps, especially in Africa, to resolve debates on continental source and sink estimates inferred from OCO-2 observations. The TCCON and COCCON are networks of ground-based Fourier Transform Spectrometers that are used to retrieve accurate and precise column-averaged abundance of CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO, providing an essential validation resource for **OCO-2/3**, **GOSAT** and **GOSAT-2**, **TROPOMI**, and other missions. These validation measurements are currently extremely scarce in the tropics, limiting the interpretation of the spatiotemporal flux patterns inferred from satellite CO_2 and CH_4 data. These measurements will also help to constrain models and quantify uncertainties of regional-scale estimates of CO_2 and CH_4 fluxes derived from inverse modeling (Beck et al., 2013b; Liu et al., 2016; Schuh et al., 2019) for landscapes across the PANGEA domain. Finally, PANGEA will quantify the impact of **canopy disturbance** from wind, lightning, and drought, and **tropical forest phenology** on carbon fluxes and stocks through a combination of field measurements, PhenoCams, and drones and satellite data to address knowledge gaps related to the different leaf phenological responses for individual species and functional types to climate and disturbance gradients across landscapes. PANGEA's datasets will complement existing efforts to expand geographic coverage of phenology using **Landsat, Sentinel-2** and **commercial satellite data** (Guan et al., 2015; Yang et al., 2021b; Wang et al., 2023a).

3.1.2 Pattern: Biodiversity and Functional Composition

Biodiversity varies markedly among tropical continents, not just due to climatic differences, but also as a result of their evolutionary past (Corlett and Primack 2006; Slik et al., 2018; Raven et al., 2020). Biodiversity is positively associated with higher net primary productivity in tropical forests (Durán et al., 2019). Understanding the mechanisms that support this relationship at regional to pantropical scales is a knowledge gap that PANGEA can help to fill. We lack detailed information on the functional diversity of tropical forest ecosystems. An initial assessment of tropical forest plant trait data abundance in the American tropics, based on TRY (Kattge et al., 2020); LT-Brazil (Mariano et al., 2021) and NGEE-Tropics (https://ngt-data.lbl.gov/dois/), reveals that a few sites in Central Panama and coastal French Guiana account for the bulk of forest tree species trait data, and most traits have limited information (**Figure 17**) especially for African tree species. By addressing these knowledge and data gaps, PANGEA will directly link ground measurements with airborne and satellite remote sensing to understand the distribution of canopy functional traits and functional diversity across the tropical forest biomes and will investigate the strength and scale-dependence of biodiversity controls on ecosystem function. PANGEA will answer the following questions to fill knowledge gaps in the understanding of biodiversity and functional composition across the tropics.

- ***Q5.*** *How does tropical forest structure and function differ geographically, and vary spatially with plant* ***biodiversity****?*
- ***Q6.*** *What are the plant* ***functional trait distributions in tropical forests*** *on different continents, and how do these differences reflect responses to disturbance and climatic gradients?*
- ***Q7.*** *To what degree are tropical carbon stocks and carbon cycle dynamics related to* ***plant functional trait composition****?*

To relate biodiversity metrics to structural and functional diversity, PANGEA will collect coincident ground measurements and airborne hyperspectral observations across species biodiversity and functional trait composition, and disturbance gradients. PANGEA will build on previous research that demonstrates how these approaches enable estimations of the functional composition and diversity of tropical forest ecosystems (Feret and Asner, 2013; Asner et al., 2014b; Asner et al., 2017; Chadwick and Asner 2020; Ordway et al., 2022). PANGEA will employ both airborne and satellite hyperspectral data, including from the **EMIT**; **PRISMA**; **DESIS**; Plankton, Aerosol, Cloud, ocean Ecosystem Mission (**PACE**), and **Planet Tanager** missions, and it will advance calibration and algorithm development to support PANGEA science and applications and the **SBG** mission. PANGEA will also characterize forest structural diversity using terrestrial and UAV-based, airborne, and spaceborne lidar (**GEDI**, **EDGE***) at individual-tree to ecosystem scales (e.g., Decuyper et al., 2018; Dubayah et al., 2020; Momo et al., 2020, Terryn et al., 2022; Schneider et al., 2019; Ferraz et al., 2016; Jucker et al., 2018a; Schneider et al., 2020; de Conto et al., 2024). To investigate the association between plant species composition and ecosystem functioning (Coverdale and Davies 2023), PANGEA will combine measurements on structural and functional diversity with in situ and remote sensing observations of CO_2, CH_4, water and energy fluxes and nutrient cycling, using time series of measurements and space-for-time sampling across the landscapes. To relate functional diversity with ecosystem responses to extreme

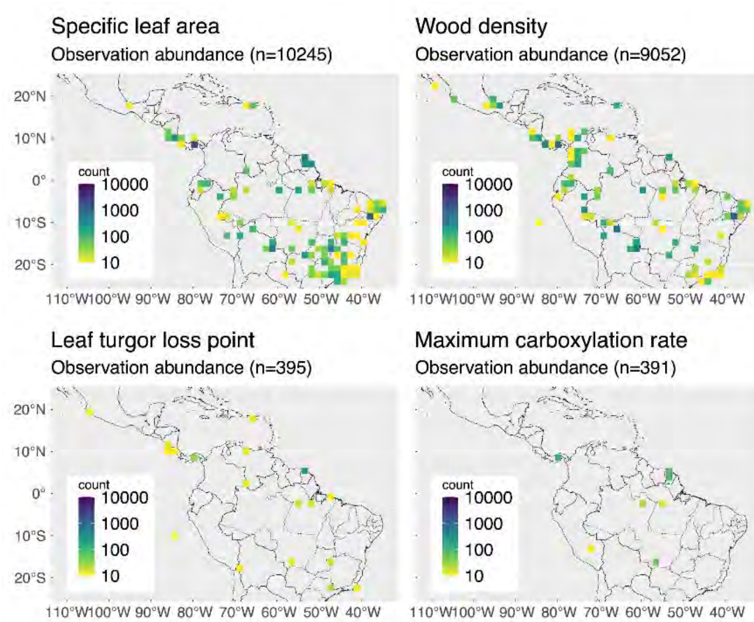

Figure 17. Number of observations for select traits across the American tropics, based on existing data bases–TRY (Kattge et al. 2020); LT-Brazil (Mariano et al. 2021, and references therein); and NGEE-Tropics (https://ngt-data.lbl.gov/dois/). For specific leaf area and maximum carboxylation rate, the tally includes only observations that were unequivocally taken from canopy or sun-exposed leaves.

events, PANGEA data collection will span landscapes that exhibited distinct responses to previous extreme events, for example the 2015 El Niño. We will use a space for time approach in the absence of extreme events during PANGEA. The detection of responses to extreme events, as well as the emergent relationships between functional diversity and ecosystem function will be used to scale datasets across the PANGEA domains and for process-based model benchmarking. *Section 3.2.1* presents additional PANGEA biodiversity-related questions that extend beyond botany to include non-plant taxa and species interactions. Based on conversations with Indigenous collaborators during the PANGEA scoping effort, addressing the questions in *Section 3.2.1* is more likely to benefit from the integration of Indigenous, Traditional, and Local Ecological Knowledge (IEK, TEK and LEK) with other forms of knowledge and data. We believe that IEK, TEK, and LEK have the potential to advance understanding of all PANGEA science questions in ways that will be explored through co-developed and equitable science.

3.1.3 Pattern: Land-Atmosphere Interactions and Thresholds

Despite advances in understanding the interactions and feedbacks between the biosphere and atmosphere in tropical regions from previous NASA projects and campaigns (Davidson et al., 2012), there remain substantial knowledge gaps on how these interactions vary within and across continents (Phillipon et al., 2019; Pohl et al., 2021; Martins et al., 2018; Chakraborty et al., 2019; Jonard et al., 2022). Hydroclimatic conditions in tropical forests vary significantly along disturbance gradients, from intact forests to heavily fragmented landscapes (Gutierrez-Cori et al., 2021), and there is evidence from modeling and remote sensing studies that widespread tropical forest degradation can alter energy and water fluxes (e.g., Longo et al., 2020; Rangel Pinagé et al., 2023), yet the effects of forest degradation on precipitation intensity and recycling remains unknown. The impacts of deforestation on the transport pathways for recycled atmospheric moisture are an increasing focus of research in the Amazon, but to a lesser extent in Central Africa (van der Ent et al., 2010; Zemp et al., 2017; Baker and Spracklen 2022; Te Wierik et al., 2022; Xu et al., 2022; Staal et al., 2023; Theeuwen et al., 2023; Flores et al., 2024; Nyasulu et al., 2024). This knowledge gap for Africa is a concern given recent evidence that suggests Central African tropical forests rely more heavily on moisture recycling to provide atmospheric moisture for rainfall than the Amazon (Worden et al., 2021b, 2024; Baker and Spracklen 2022). Moreover, land-use related fire activities can significantly change the aerosol concentration in the atmosphere and directly impact convective activities in tropical ecosystems (Andreae et al., 2004; Freire et al., 2020). To address knowledge gaps related to land-atmosphere interactions and hydroclimate thresholds, PANGEA will answer the following questions:

- ***Q8.*** *How do* ***land-atmosphere interactions****, including moisture recycling and carbon fluxes, vary with climate feedbacks, disturbances, carbon storage capacity, and resilience of tropical forests, under changing environmental conditions?*
- ***Q9.*** *How do* ***hydroclimatic thresholds****, such as critical soil moisture levels or thermal boundaries, vary within and among tropical continents?*

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

3.2 Process

3.2.1 Process: Species Interactions and Resilience

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

- ***Q10.*** *What is the role of* ***biodiversity*** *in driving the variations in tropical forest carbon stocks and fluxes at local, regional, and continental scales?*
- ***Q11.*** *How do* ***plant-animal interactions*** *mediate the vulnerability or resilience of tropical forest carbon stocks and fluxes?*
- ***Q12.*** *How vulnerable or resilient to climate and land-use change are the* ***species interactions*** *that underpin tropical forest function, including interactions among life habits (trees, lianas, palms, herbs/grasses and bamboos)?*
- ***Q13.*** *What* ***plant functional traits and structural attributes*** *confer carbon cycle resilience, and how do these vary across forest types, environmental gradients, and vertically within forests?*

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

3.2.2 Process: Disturbance-Ecosystem Function Feedbacks

Changing disturbance regimes, including drought, fires, storms, and land-use change, are reshaping tropical forests. Tropical regions across continents differ in their responses to similar disturbance events, such El Niño events (Liu et al., 2017). These continental differences may be associated with differences in forest resilience to both human action and climate change (Bennett et al., 2021; Saatchi et al., 2021), however, the mechanisms underlying the differences in forest vulnerability are elusive. Likewise, we lack quantification of the drivers of tree mortality over large scales, and the reasons for higher tree mortality on different continents (McDowell et al., 2018; Gora and Esquivel-Muelbert 2021). Part of this difficulty stems from scaling limitations. Although hurricanes, cyclones and typhoons produce large scale storm disturbances in coastal tropical forests they are not common in the core PANGEA sites of the Americas and Africa (Walsh et al. 2016). Most storm-related disturbances occur at very small scales (<0.1 ha) (Espírito-Santo et al., 2014; Negrón-Juárez et al., 2018; Negron-Juarez et al., 2023). Such small-scale disturbances are too small to be detected with contemporary satellite methods (Cushman et al., 2021). Large forest windthrows in the Amazon can span hundreds to thousands of hectares and are becoming increasingly common (Feng et al., 2023b; Urquiza-Muñoz et al., 2024). However, compared to small windthrow events, large windthrows are rare. Many small storm forest disturbances cannot reliably be attributed using traditional forest plot methods because of the typically long intervals between tree censuses (Arellano et al., 2021). Data describing the mechanisms underlying tree vulnerability to storm-associated winds and lightning are also limited (Gora et al., 2017; 2020b; Jackson et al., 2019; 2021a, 2021b; Feng et al., 2023a). More broadly, the relative influence of carbon starvation and hydraulic failure on tree mortality in the tropics, and the drivers and mechanisms for these influences, remain major knowledge gaps (Anderegg et al., 2016; McDowell et al., 2018; Bauman et al., 2022). Understanding time-varying carbon- and water-use efficiency of tropical forest ecosystems in relation to tree mortality trends and ecosystem-scale carbon uptake and respiration, particularly in response to extreme events, is critical to reconcile tropical forest source-sink dynamics (Chambers et al., 2004; Peñuelas et al., 2010; Adams et al., 2019). Advancing understanding of distinct ecosystem responses to mortality and disturbance events requires integrated data on tree mortality, carbon- and water-use efficiency, and post-disturbance recovery rates spanning disturbance regimes, patterns of functional composition, and land-use. PANGEA will answer the following questions:

- ***Q14.*** *How are changing disturbance regimes affecting the* ***carbon-use efficiency (CUE)*** *and* ***water-use efficiency (WUE)*** *of different tropical forests?*
- ***Q15.*** *How do* ***tree mortality*** *rates and patterns vary within and across tropical forests in response to shifts in forcing processes, including climate, land-use change, and disturbance regimes? How do temporal and spatial variability of mortality influence the heterogeneity of tropical carbon stocks and fluxes across tropical forests?*

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

3.2.3 Process: Recovery Dynamics and Management

As climate change increases the rate of recurrence of natural disturbances, the expansion of deforestation and forest degradation is further amplifying climatic disturbance regimes across tropical forests (Armenteras et al., 2006; Portela & Rademacher, 2001 Jusys 2018; Hosonuma et al., 2012). More frequent disturbances pose a threat to the resilience of tropical forests, with the potential to influence critical transitions to alternate states (Verbesselt et al., 2016; Whitfield et al., 2019; Falk et al., 2022). To assess such risks, however, it is imperative to thoroughly quantify how frequently disturbances occur, the ecosystem resistance to disturbances, and the recovery time following disturbance impacts (Cole et al., 2014; Longo et al., 2018). While much research has focused on the impacts of disturbances (e.g., McDowell et al., 2018; Brando et al., 2014), large uncertainties remain on recovery rates. Recovering tropical secondary and degraded forests now cover about 10% of the tropical forest area and have a large carbon sink potential (Heinrich et al., 2023). Previous field-based research indicated that post-disturbance restoration trajectory and rates of recovery, and time scales, vary considerably across the tropics and depend upon disturbance intensity and disturbance type (Poorter et al., 2016; Rutishauser et al., 2015). In addition to storms, the impact of geographic connectivity of changes in land management across different scales is also critical. For example, shifts from intensive cropping systems to agroforestry systems and restoration management (e.g., Indigenous stewardship), as well as interventions aimed at conservation, may result in local biodiversity and biomass restoration and increased resilience of systems that will support local livelihoods (e.g. Ebeling & Yasué 2008; Santika et al., 2017; Mills et al., 2019; Pienkowski et al., 2024). Tropical regions are playing an increasingly large role in global agriculture (Alexandratos and Bruinsma, 2012; Berenguer et al., 2021a) and there is immense pressure on tropical forests from agricultural expansion due to rising global demand for food, fiber, and biofuels (Erb et al., 2024; Pendrill et al., 2022). Agricultural intensification to support global demands and local livelihoods will greatly benefit from precision agriculture methods and biogeochemical cycle monitoring (e.g., phosphorus and nitrogen) to ensure sustainable solutions. On the other hand, agricultural intensification and efforts to improve sustainability may also lead to leakage and the displacement of disturbances to other geographies (Ewers and Rodrigues, 2008; Gan and McCarl, 2007; Henders and Ostwald, 2014, Meyfroidt et al., 2020; Hertel et al., 2019). To address knowledge gaps related to post-disturbance recovery and tropical forest resilience linked to land management practices, PANGEA will address the following questions:

- ***Q16.*** *How do disturbance type and intensity—including different land uses—influence the* ***post-disturbance recovery time and the trajectory*** *towards restored forest structure, species composition, and ecosystem function?*
- ***Q17.*** *Which* ***human activities and management practices*** *support the resilience of the tropical carbon sink, including the use of protected areas and other area-based conservation measures (OECMs) such as Indigenous and territorial community practices, agroforestry systems and selective logging practices?*

To quantify the post-disturbance recovery time scales, PANGEA will integrate data from field inventories in disturbance-impacted regions with age of disturbance information derived from long-term remote sensing (e.g., using **Landsat**) and more recent remote sensing of forest structure from lidar (airborne lidar, **GEDI**, **EDGE***, **NISAR*,** and **BIOMASS***), forest composition from hyperspectral imagery (airborne hyperspectral, **EMIT**, **PRISMA**, **DESIS**, **PACE**, and **Planet Tanager**), ecosystem function (**ECOSTRESS**, **TROPOMI**), and agricultural systems (**Landsat**, **EMIT**, **NISAR***, **Planet**) to build chronosequences in landscapes across environmental and management gradients. These chronosequences will be used to reduce uncertainties in process-based models that will then be used to attribute the role of environmental drivers and different disturbance characteristics on the recovery time scales across the PANGEA domain. By incorporating constraints on recovery into models, these could better simulate forest recovery and the complex interactions among species composition, forest structure, and environmental factors. This will enhance the ability of ecosystem models to project future shifts in carbon stocks under altered disturbance regimes and inform conservation and restoration efforts (Hérault and Piponiot, 2018; de Paula et al., 2015; Shi et al., 2024; Zhang et al., 2022).

Drawing on a variety of SES frameworks, PANGEA will adopt a systems perspective that centers the feedbacks between human systems (including governance, policy, markets, cultural norms, and values) and environmental processes, to better understand how human activities and management practices influence the resilience of tropical landscapes. PANGEA will leverage ongoing efforts from a variety of activities (e.g., **NASA Harvest**, **SERVIR**) to detect human activities and agroecosystems, that enable mapping and monitoring of natural resources (Meemken et al., 2024), and advances in crop type, yield, and disaster risk mapping (Jain et al., 2016; Azzari et al., 2017; Meza et al., 2020; Song et al., 2021) needed to enable livelihoods and enhance human well-being. To address the diversity of management practices across different actors in tropical systems, PANGEA will build on the existing global categorization of management regimes (Lesiv et al., 2022) together with specific local information on the diversity of implementation options for these different regimes. PANGEA will also explore recent approaches to extract socio-economic information from satellite data (Yeh et al., 2020). By using methods that integrate remote sensing data with in situ and other auxiliary information and knowledge, PANGEA will advance tropical social-ecological system measurables and investigate causality to examine whether SES feedbacks support the resilience of the tropical carbon sinks and other ecosystem processes.

3.2.4 Process: Hydrological Cycle Feedbacks

Tropical forests play a fundamental role in the water cycle (van der Ent et al., 2010; Spracklen et al., 2018), and climate projections from CMIP6 indicate increases of both extreme dryness and extreme wetness in different parts of the tropics (Vogel et al., 2020). Tropical forest deforestation has a marked impact on precipitation that depends upon the scale of deforestation (Spracklen et al., 2018). Widespread degradation-induced shifts in water and energy fluxes could also impact rainfall recycling across the tropics, but this hypothesis has not yet been tested. Forest degradation has a marked impact on evapotranspiration and sensible heat fluxes (Brando et al., 2019b; Jucker et al., 2018b; Longo et al., 2020; de Oliveira et al., 2021; Rangel Pinagé et al., 2023). Previous studies have found encouraging agreement in magnitude and seasonal variability of evapotranspiration between remote sensing estimates and eddy covariance towers in tropical forests (Melo et al., 2021; Salazar-Martínez et al., 2022), but they rely on a very limited number of sites. In reality, there is considerable spatial variation in magnitude and seasonality of ET at regional and continental scales (e.g., Baker et al., 2021; Weerasinghe et al., 2020). The combined effects of shifts in precipitation regimes, warmer temperatures and expansion of deforestation and forest degradation impact river discharges, freshwater habitats and water quality (Lima et al., 2014; Castello and Macedo, 2016); however, the predicted magnitude of these impacts is uncertain (Guimberteau et al., 2017; Farinosi et al., 2019). Understanding the net effects of the hydrological cycles on freshwater resources is also economically important, for many countries in the tropics rely on hydropower (Arias et al., 2020). Studies on tropical freshwater resources are concentrated in tropical South America and have rarely been studied across Africa and the Congo river basin (Fugère et al., 2016). Further, Earth System models have limited ability to map the spatial distribution of precipitation across the tropics because they are unable to represent extreme precipitation events (Negron-Juarez et al., 2024), and there are marked differences in how models represent rainfall recycling across continents (Baker and Spracklen 2022). Models also require accurate representations of ET and sensible heat flux to quantify rainfall recycling, and remote sensing products to benchmark ET at regional scales. To address these knowledge gaps, PANGEA will answer the following questions:

- ***Q18.*** *What are the direct and indirect* ***hydroclimate controls*** *on tropical forests' carbon (including* CO_2 *and* CH_4 *emissions), energy and water cycles?*
- ***Q19.*** *How does* ***precipitation recycling*** *influence the resilience or* ***vulnerability of forest carbon balance*** *with* ***shifting disturbance regimes****, land cover and land-use change, and rising atmospheric* CO_2*?*
- ***Q20.*** *How are climate and land-use changes altering* ***land surface biophysical properties*** *that influence the strength of land-atmosphere interactions?*
- ***Q21.*** *How do* ***deforestation****, forest* ***degradation****, and* ***forest regrowth*** *alter regional* ***hydrological cycles*** *in tropical regions, including precipitation regimes and freshwater resources?*

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

3.3 Projections

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

Future precipitation patterns across the tropics are uncertain, but Earth system model simulations suggest that tropical South America may see mean annual precipitation reductions, while mean annual precipitation in Central Africa may remain similar or even increase (Dobler et al., 2024). However, stability in the mean annual precipitation does not mean stability in the hydrological cycle. For example, rainfall seasonality may become more pronounced with stronger interannual variability (Gloor et al., 2013), and warming trends may increase atmospheric and soil dryness, even if precipitation remains similar to historical averages (Cook et al., 2020; Ukkola et al., 2020). The effects of atmospheric CO_2 on hydroclimate depend on multiple interacting factors and are uncertain. For example, high CO_2 may reduce leaf-level transpiration due to lower stomatal conductance (Sampaio et al., 2021), but changes in leaf area index and number of stomata will also affect the ecosystem-level response (Li et al., 2018). Deforestation and forest degradation across the Amazon (Spracklen et al., 2018; Baudena et al., 2021) could potentially impact rainfall through major impacts on evapotranspiration, canopy interception, runoff and water storage (Heerspink et al., 2020), although there is great uncertainty on the magnitude of this effect in modeling studies (e.g., Pires and Costa 2013; Swann et al., 2015).

Changes in hydroclimate, atmospheric CO_2, land cover and land-use change also interact with changes in the nutrient cycling, and understanding these feedbacks is critical. Phosphorus and potassium availability influence net primary productivity during droughts (Manu et al., 2024), and nitrogen can be an important limiting factor in secondary forests (Davidson et al., 2007). Research suggests that CO_2 fertilization effects can be greatly reduced when phosphorus is a limiting factor (Yang et al., 2016; Fleischer and Terrer 2022). However, our understanding of the feedbacks between nutrient cycling and other drivers (climate, CO_2 fertilization, and land cover and land use change) comes from small, localized manipulative experiments, making the scaling to highly heterogeneous landscapes and continental scales challenging (Townsend et al., 2008). By integrating coordinated measurements across landscapes and scales, PANGEA will address the following questions:

- ***Q22.*** *How will changes in precipitation patterns, increasing temperatures, and shifting disturbance dynamics in tropical forests alter the **terrestrial water balance** via changes in seasonal precipitation timing and duration, evapotranspiration, and soil moisture?*
- ***Q23.*** *How will **future changes in vegetation**, including deforestation, degradation, and regrowth, impact local, regional, and continental climate and hydrology?*
- ***Q24.*** *How will increasing temperatures, atmospheric CO_2, and extreme climate events impact **nutrient availability** and **soil-vegetation interactions**?*

Considering that these questions will explore simulations of future changes across the tropics, PANGEA will use process-based models (*Section 6.3*) that will be fully integrated with remote sensing (*Section 6.2*). For example, to initialize cohort- and individual-based mechanistic models with realistic, observed forest structure and composition across environmental gradients, PANGEA will integrate multispectral, hyperspectral, lidar, and radar data collected both through PANGEA airborne campaigns and from satellite measurements (**GEDI**, **EMIT**, **VIIRS**, **Sentinel-3**, **NISAR***, **SBG** visible to shortwave infrared [**VSWIR***] imaging). The emergent relationships based on remote sensing relating to forest structure, composition and function (*Section 3.1.2*) as well as remotely sensed hydroclimate and water stress variables (*Section 3.1.3*) will be used to assess and reduce model uncertainty. In addition, canopy nutrient concentrations estimated from hyperspectral remote sensing retrievals guided by lidar-derived geomorphological characteristics will be used to inform patterns and drivers of nutrient distributions across heterogeneous tropical forest landscapes. The optimized models will then be applied to a range of representative simulations to quantify and distinguish the roles of changes in climate, atmospheric CO_2, land cover and land use in driving changes in biogeophysical and biogeochemical cycles.

3.3.2 Projections: Heterogeneous Forest Resilience

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

- ***Q25.*** *In a changing climate, which* ***functionally distinct forest types*** *are most vulnerable to becoming net sources of carbon to the atmosphere, which forest types are resilient, and why?*
- ***Q26.*** *How will climate warming and shifting extreme events interact with land cover and land-use change to influence* ***shifting fire regimes*** *and their feedbacks with forest function and the climate?*
- ***Q27.*** *How will future changes in climate and extreme events impact carbon cycling within tropical forests, and what is the threshold when this will result in* ***large-scale transition*** *in functional composition and/or the regions becoming a net carbon source?*
- ***Q28.*** *How will climate and land-use change interact with the changing vulnerability of tropical forests, to influence the availability of ecosystem services and access to* ***social-ecological co-benefits****, including water availability, agricultural production, human health, disaster risk reduction, and cultural practices?*

Process-based and social-ecological system models (e.g., agent-based, bioeconomic, disequilibrium, or network modeling) will be used to quantify the impacts of changes in disturbance regimes on hyper-diverse tropical forests, and the consequences for ecosystem provisions and services that may impact economic activities and the livelihood of Indigenous Peoples and Local Communities. For process-based models, PANGEA will use the same approach described in *Section 3.3.1* to generate initial and boundary conditions. Likewise, emergent relationships between functional diversity and recovery rates will be derived using data from ground-based measurements and social-ecological research conducted with local researchers and communities, airborne campaigns combined with data streams from SIF (**TROPOMI**, **OCO-2/3**, **FLEX***), thermal infrared measurements (**ECOSTRESS**, **GOES-R**, **MTG-I**), and the chronosequences of ecosystem recovery based upon remote sensing (*Section 3.2.3*). To quantify the impacts of tropical forests on social-ecological co-benefits, PANGEA will conduct integrated social-ecological systems research to better understand the patterns and influence of land use and its change, including deforestation, degradation, forest restoration, drought and flooding, fire regimes, and extreme temperatures across tropical biomes. PANGEA will also study the feedbacks between social and ecological systems, spanning traditional, local, and Indigenous forest management to industrial systems, and how these systems affect ecosystem resilience and the provision of ecosystem services. PANGEA will integrate social and ecological data into existing models (e.g., Andersen et al., 2017; von Essen and Lambin, 2023) and develop new models to capture the feedbacks within social-ecological systems under different economic, cultural, environmental, and governance conditions.

4 Scientific and Technical Advancement from PANGEA

PANGEA will leverage decades of scientific efforts, including large projects such as LBA (Avissar et al., 2002; Davidson et al., 2012), international forest inventory plot networks (e.g., ForestPlots.net et al., 2021), and multiple model development efforts, including (but not restricted to) NASA's Global Modeling and Assimilation Office (GMAO), NASA's GISS BiomeE (Weng et al., 2022) and DOE-supported FATES model being developed as part of NGEE-Tropics (Koven et al., 2020; Huang et al., 2020; Xu et al., 2023; Knox et al., 2024; Shuman et al., 2024). Despite these efforts, attempts to assess the resilience of tropical forests to disturbance have garnered inconsistent results. Field studies suggest Central African forests may be more resilient to changing climatic conditions and may offer a longer-term carbon sink compared to other tropical forests (Hubau et al., 2020; Bennett et al., 2021). However, satellite remote sensing studies indicate that Central African forests are just as sensitive to climate anomalies as the Amazon and other tropical forest regions (Liu et al., 2017; Palmer et al., 2019). Inconsistencies between field measurements and satellite observations must be reconciled to predict the impact of climate change on the role of these forests in global carbon and water cycles. Several factors may explain these inconsistencies, including (1) changing rates of tree mortality, (2) different sensitivity of photosynthesis, respiration rates, and other ecosystem processes, (which alter net carbon and water fluxes), to natural and anthropogenic disturbances, (3) differing intensities and patterns of deforestation and degradation on ecosystem structure and function, (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), and (5) limited spatial and temporal data and incomplete or under developed models.

PANGEA will investigate the factors that might explain the differences in tropical forest responses on different continents, the inconsistencies (noted above), and other factors determined by the PANGEA community, by adding a pan-tropical view gaining new knowledge from enhanced multidimensional remote sensing measurements with collocated and coincident measurements and novel analyses. PANGEA emphasizes integration of ground measurements, and remote sensing datasets for tropical forests, supporting remote sensing algorithm and model development, and model-data integration. We foresee significant scientific advances from coordinated and collocated remote, ground measurements, and the use of stakeholder information including that from Indigenous, Traditional, and Local Ecological Knowledge embedded within a collaborative scientific effort that prioritizes transdisciplinarity. To advance scientific and technological capabilities and solutions, PANGEA will

- **Elucidate** the patterns of recent (5-30 years) and ongoing change in tropical forest landscapes, dynamics, and feedbacks, and their geographic differences with an emphasis on comparisons between the Americas and Africa.

- **Increase** understanding of processes that control heterogeneity and the vulnerability of tropical forest landscapes to structural and functional change.
- **Advance** remote sensing capabilities to measure, map, and monitor biodiversity, carbon cycle dynamics, and agricultural systems.
- **Provide** improved projections of future changes in tropical forest landscapes, which will encompass the feedbacks in local, regional, and global climates and social-ecological systems.

These scientific advances will be enabled by technical advances:

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

PANGEA will characterize ecosystem structure and function across multiple dimensions, from intact to degraded and high- to low-diversity tropical forest ecosystems. PANGEA will measure tree taxonomic and phylogenetic diversity, and vegetation demographic rates, using existing ground data from long-term forest inventory plots, and functional and structural diversity using remote sensing. Coincident remote sensing hyperspectral imagery and in situ leaf-trait measurements will map canopy traits and distinct functional communities, in addition to evaluating scalable models by leveraging satellite measurements. Using this output, we will characterize differences across abiotic, land-use, and biotic gradients. The resulting improvements in our understanding of trait distributions will improve our models of ecosystem fluxes under climate change and land-use change forcings and allow us to evaluate differences in ecosystem responses. With this combination of measurements and models, PANGEA will address how different tropical forest structure and function influences tropical forest stability in the face of land-use and climate change impacts.

The integration of ground-based and remote sensing data with model development and assessment is an integral part of PANGEA (*Section 6.3*). In situ and remote sensing (e.g., hyperspectral and lidar) measurements across critical gradients will be used to reduce parameter uncertainty and provide initial and boundary conditions for process-based models. PANGEA's teams will employ artificial intelligence and machine learning models to obtain synthesis datasets that scale measurements at intensive PANGEA sites and partner sites to the core and extended PANGEA domains using satellite remote sensing. These synthesis datasets will be used to parameterize and benchmark process-based models and social-ecological systems models at large scales and will provide boundary conditions for inverse models. Model and data integration will be fundamental for answering PANGEA's key questions (*Section 3*), which will serve as the basis for many studies that seek to (1) understand the role of structural and functional diversity in controlling tropical forest carbon, water, energy, and nutrient cycles; (2) investigate how increased CO_2 levels and rising temperatures specifically affect carbon sequestration rates in tropical forests; (3) quantify the impacts of extreme events, such as severe droughts, on forest health and CO_2 and CH_4 emission; (4) advance understanding of the consequences of deforestation and forest degradation on biodiversity, biogeophysical and biogeochemical cycles, ecosystem services and hydroclimate; (5) evaluate the effectiveness of restoration strategies on tropical forest resilience and climate change mitigation; and (6) characterize the risk of tropical forests reaching critical transitions to alternative states due climate change, deforestation, and forest degradation, and determine the role of biodiversity in mitigating such vulnerabilities.

5 Critical Role of NASA Remote Sensing

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

Identifying processes that result in tropical forest stability is paramount for constraining uncertainty in predictions of future terrestrial carbon-flux dynamics. To reconcile differences between ground and satellite datasets, to improve scaling strategies, to advance future monitoring, and to characterize how and why Central African and American tropical forests differ in their resistance to rapid climate change, we need coordinated airborne retrievals. For example, sufficiently high spatial resolution (~2–5 m) is needed to adequately scale organismal-level leaf and tree dynamics to landscapes, serving as an intermediary between field measurements and satellite observations (**Figure 14**). PANGEA builds directly upon the scaling developments and successes from NASA ABoVE in North America (e.g., Virkkala et al., 2021; Peltola et al., 2019; Braghiere et al., 2023), which shed new light on previously understudied Arctic systems.

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

Persistent cloud coverage is a significant issue when using space-based XCO_2 and XCH_4 to constrain tropical greenhouse gas fluxes (e.g., Rayner et al., 2002; Qu et al., 2021). Even at the higher spatial resolution of the current low-Earth-orbiting satellite sensors retrieving XCH_4 (e.g., **TROPOMI** [3.5 km × 7.0 km]) and XCO_2 (e.g., **OCO-2** [1.3 km × 2.2 km]), over 95% of retrieved information is filtered due to clouds in the tropics (Qu et al., 2021). Higher-spatial-resolution XCO_2 and XCH_4 satellite sensors such as the recently launched MethaneSat (100 m × 400 m) will greatly improve the ability to retrieve tropical flux through cloud gaps. Other point-source mapping satellite sensors (e.g., **EMIT**, **GHGSat**, **Carbon Mapper**, **PRISMA**) have been launched with very high spatial resolution (<100 m × 100 m). However, these target-mode observations will not provide the global coverage needed to constrain tropical greenhouse gas budgets. Cloud cover will likewise affect estimates of land surface temperature and evapotranspiration from thermal remote sensing, which will require bias-correction approaches (Van Niel et al., 2012).

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

6 Research Strategy and Study Design

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

6.1 Overall Study Approach

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

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

6.1.1 PANGEA's Science-to-Scale Strategy

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

PANGEA's science-to-scale strategy implements an integrated systems approach that encompasses complex landscape mosaics spanning forests to wetlands and peatlands, intact to disturbed forests, and agricultural and social-ecological systems. To ensure processes are captured across a broad diversity of environmental conditions and multiple data sources—ground, tower, drone, and aircraft sensors—PANGEA field and airborne projects will include sampling across gradients in ecosystem structure and function, climate, geomorphology and soils, nutrient availability, and disturbance regimes. Incorporating this variability is critical for regional and pan-tropical scaling and for informing models and ensuring that they can be assessed and benchmarked under different conditions, thus reducing the risk of equifinality–getting the right answers due to compensating for the wrong reasons. The choice of priority gradients will consider the current uncertainties in models, and novel processes that have not yet been assessed with remote sensing data at scale (e.g., temporal changes in canopy structure and composition, and their impacts on energy, water and carbon fluxes; plant hydraulic responses to climate variability).

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

Differences between the approximately 1 km footprint of tower-based eddy covariance fluxes and >2 km resolution satellite retrievals of gross primary productivity, methane fluxes, and ecosystem respiration require reconciliation (e.g., Li et al., 2018). Similarly, the retrieval of tree- and crown-level structural attributes from lidar is necessary to link organismal processes and dynamics to ecosystem responses observed at landscape scales. In addition, vertical variation in forest structure has been shown to vary with ecosystem function even when vertically integrated metrics such as leaf area index (LAI) does not (Ordway et al., 2022). Spaceborne lidar yields community-scale observations that, although incredibly valuable, remain insufficient to pair with tree-level in situ measurements. Because these spaceborne data exceed the dimensions of a tree crown, they do not support retrieval of crown- and tree-level metrics, or fine-scale ecosystem metrics like canopy gap detection and tree mortality.

Another example is the use of hyperspectral remote sensing data to estimate metrics of biodiversity. Hyperspectral retrievals of the top-of-the-canopy from EMIT, PACE, SBG, and CHIME have the potential to yield direct retrievals of plant spectral diversity (Cawse-Nicholson et al., 2021; Schimel et al., 2020), which can also be used to estimate ecosystem (Féret and Asner, 2014) and beta diversity (Schweiger and Laliberte, 2022), plant functional diversity (Cawse-Nicholson et al., 2021; Rocchini et al., 2022; Thompson et al., 2021), and in some cases plant taxonomic diversity (Schimel et al., 2020; Rossi and Gholizadeh, 2023). The fusion of these retrievals and metrics with data and knowledge on animal movement, plant-animal interactions, multi-taxa community assembly, and ecosystem structural variation from IEK, TEK, and LEK, as well as eDNA, bioacoustics, camera traps, and other remote sensing datasets (e.g., **GEDI**, **NISAR**, **SWOT**) has the potential to yield additional indirect biodiversity estimates and proxies. This integrative approach can, for instance, improve the implementation of carbon-based incentive programs (Castro-Magani et al., 2021), or improve national services, and maximizing societal benefits (Schiavon et al., 2023). However, calibration and validation data in the tropics, to test the generalizability of existing algorithms, are currently lacking. For instance, proper spectral resolution, pixel size, and the coexistence of multiple tree species in a given pixel, or the temporal resolution to quantify characteristic diurnal processes associated with those species needs to be properly addressed (Schimel et al., 2020; Rocchini et al., 2022). Endmember diversity is an approach to address some of these challenges (Rossi and Gholizadeh, 2023). Further, functional trait maps still require estimation using models calibrated to specific sites based on in situ leaf-trait measurements (e.g., Chadwick and Asner 2016a), and very limited work has been conducted to explore the fusion of disparate data types for developing process-based metrics or proxies (Mairota et al., 2015; Schimel et al., 2020; Ordway et al., 2022; Portillo-Quintero et al., 2022).

PANGEA will coordinate with existing scaling frameworks, facilitating the standardization of data collection methods.

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

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

PANGEA will improve our ability to push the limits of what we can infer with satellite sensors and better define the limitations, enabling the research community to focus efforts and resources where we need information to complement remote sensing research to gain greater understanding of tropical forest function.

Persistent cloud cover, for example, is an important limitation for optical sensors in tropical forests (e.g., Landsat, EMIT, OCO-2/3). Although aspects of the enormous biodiversity of tropical forests may be studied from space, it is unlikely that spaceborne observations will supplant species inventories from ground-based studies. Non-plant taxa are unlikely ever to be revealed by satellite-based investigations in tropical forests, though some aspects of non-plant biodiversity may be predictable from satellite data. The dense plant canopy of tropical forests also blocks our view of the soil and other belowground dynamics. Interrogating and clarifying the capabilities and limits of remote sensing of the tropics through methodological and computational advances and data fusion is urgently needed to guide ground-based research and implementation activities and targeted long-term multiscale monitoring efforts. See *Appendix D* for *Planned and Ongoing Research and Monitoring Activities* that stand to benefit from PANGEA.

6.1.2 Notional Project Timeline

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

6.2 Essential Scientific Components

Addressing data and knowledge gaps in the tropics requires coordinated ground and airborne projects spanning the two largest tropical forests in Africa and the Americas.

PANGEA leverages NASA's history of successful field and airborne campaigns in the tropics to measure ecosystem dynamics and status at the end of wet season and the end of dry season, when tropical forest systems are least and most stressed, revealing functional differences (Yang et al., 2021b), and heavy cloud cover limits remote sensing over the tropics during the wet season. Recent achievements that demonstrate feasibility include the highly successful AfriSAR-2 campaign that collected airborne L- and P-band UAVSAR data over Cameroon, the Democratic Republic of Congo (DRC), Gabon, Ghana, the Republic of Congo, and Sao Tome and Principe. Despite these successful campaigns there is still a critical need for collocated and coincident measurements across the highly variable tropical landscapes, particularly in Africa, where data gaps are the greatest, and process-based understanding is poorest. Measurements limited to the dry season risk biasing understanding of tropical forests, given strong seasonal differences in dynamics and processes (Cleveland et al., 2015), including carbon cycling, species interactions, land-use activities (e.g., fire and clearing), hydrological cycling, and more. PANGEA will fill important temporal gaps in remote sensing by coordinating suborbital retrievals timed during the end of the wet season and the end of the dry season with continuous and/or more frequent data acquisitions from flux towers, drones, and other sensors. Achieving PANGEA's objectives therefore requires flight campaigns that meet the measurement requirements described in *Section 6.2.1*, based out of multiple countries in Central Africa and the tropical Americas, to span the range of environments present in these systems. These observations will link high-resolution process measurements (forest plots, chamber measurements, flux towers, eDNA, animal movement data, agricultural data, TEK, IEK, and LEK) with extensive airborne and satellite remote sensing retrievals, providing a baseline for ongoing ground-based, airborne, and satellite datasets, and allowing comparison with past studies.

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

PANGEA will establish a network of coordinated field and airborne campaigns distributed across targeted tropical forest ecosystems to fill data gaps and enable scaling between field and remotely sensed datasets, as well as regional and pantropical scale modeling (**Table 2**). Using coordinated datasets, PANGEA will characterize differences across biotic, abiotic, and land-use gradients. PANGEA will then use these integrated measurements to model ecosystem structure, function, and fluxes under climate and land-use change scenarios to evaluate differences in ecosystem responses. In doing so, PANGEA addresses how varying tropical forest dynamics influence tropical forest stability in the face of climate and land-use change impacts.

6.2.1 Baseline, Threshold, and Descope Strategy

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

The **Baseline Investigation** fulfills all Science Objectives (*Section 1.1*) and all Science Questions (*Section 3*) at 3–6 American and 3–6 African tropical forest landscapes. To meet these Baseline Investigation Objectives, we establish the following requirements:

1. Collect airborne retrievals via wall-to-wall flightline mosaics and sampling transects over a minimum of three priority landscapes in Africa and three priority landscapes in the Americas, where landscapes cover hundreds of kilometers encompassing a variety of social-ecological systems—the ecosystems and the people who depend upon them (see *Sections 6.2.3* and *6.2.4* for details on landscape measurements).
    a. Airborne retrievals will include one successful capture at the end of the dry season and one successful capture at the end of the wet season at each landscape. End of the dry season (dry-to-wet) and wet season (wet-to-dry) captures occur in different months on different continents. Tropical forests can have unimodal seasonality (one dry and one wet season), or bimodal seasonality (two dry and two wet seasons). For this reason, retrieval schedules will be defined based on landscape-specific seasonality.

    b. Landscapes will be selected from candidate sites during the development of the Concise Experiment Plan.
    c. A variability analysis building on **Figure 11** and an analysis of model uncertainty will be used to inform important endmembers to capture and will contribute to landscape selection during the development of the Concise Experiment Plan.
2. Collect coincident and collocated ground measurements during airborne acquisitions for required measurements (e.g., chemical leaf traits, CO_2 and CH_4 chamber flux measurements).
3. Collect ongoing ground measurements at required temporal frequencies throughout the project (e.g., monthly drone- and ground-based tree mortality and phenology acquisitions, sub-hourly flux measurements).
4. Develop and apply data synthesis approaches to scale field and airborne observations to PANGEA's Core Domain, using satellite data to obtain constrained estimates (and uncertainties) of variables of interest.
5. Evaluate the transferability of data synthesis products across the Core Domain through cross-validation.
6. Model carbon, water, and energy fluxes, as well as vegetation dynamics, using terrestrial biosphere models initialized, parameterized, and benchmarked with the remote sensing based data synthesis products.
7. Apply optimized models to test tropical forest stability within and among all investigation landscapes and regionally based on terrestrial biosphere and social-ecological systems model results.
8. Model the relative role of climate, soils, and divergent evolutionary histories in determining variation in tropical forests' stability in the face of climate impacts.

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

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

Temporal revisit requirements: Two focused airborne campaigns with wall-to-wall mosaics and transects across multiple landscapes are necessary to capture seasonal variations and account for both within- and between-continental heterogeneity in a standardized way. The timing for surveys will account for the precipitation seasonality of each landscape. For landscapes where two dry seasons exist, PANGEA's campaigns will focus on the longest dry season. Airborne campaigns will capture necessary endmembers for scaling seasonal differences in fluxes, stocks, traits, plant-animal interactions, hydrodynamics, land-atmosphere interactions, and fire and agricultural land-use activities. The time elapsed between the two captures and between different landscapes will not affect the ability to capture these endmembers, allowing for a modular design and building in valuable airborne campaign flexibility. Within landscape-level subsections of these airborne acquisitions (e.g., 10–20 km^2), high-frequency (≤ monthly) drone retrievals of forest structure and spectra will allow for quantification of fine-scale temporal trends (e.g., mortality, phenology) and provide calibration and validation data for the development of satellite methods to monitor these dynamics. In addition, over a 6- to 9-year project, it is highly likely that extreme events, such as a major fire, drought, or an El Niño event, will occur, providing further opportunities for analysis.

Spatial variability requirements: Ecosystem structure, function, fluxes, and biodiversity are characterized across multi-dimensional gradients of intact to degraded, high- to low-diversity, and high- to low-carbon stock tropical forest systems. **PANGEA implements a sampling-to-scale approach, with a nested sampling design.** Ground and airborne measurements will span gradients within a landscape, and landscapes span climatic and biodiversity gradients within a continent (**Figure 11 and 18**). PANGEA data collection will be conducted at landscapes that encompass intact, disturbed, and degraded conditions across forests, peatland, and wetland ecosystems, as well as adjacent agro-ecosystems. Coordinated, coincident ground data collection on fluxes, foliar traits, forest structure, tree mortality, faunal diversity, species interactions, soil moisture, and more will be collected across these gradients within each landscape. For more information, see *Section 6.2.2, Candidate Landscapes,* and *Section 6.2.5, Field Observations and Studies*.

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

Table 2. Description of ecological and geophysical variables relevant to this project, with corresponding observing requirements and existing or forthcoming Earth Observation assets.

ARES: Airborne Research Facility for the Earth System. ET: evapotranspiration. LST: land surface temperature. SIF: solar-induced fluorescence. Purple text indicates satellites from non-U.S. federal agencies. * Indicates missions that have not yet launched and/or may still be under competitive consideration. ** Indicates recently ended missions. See **Table E-1** in *Appendix E* for a *Detailed PANGEA Measurements Table*.

Variable(s)	Science Questions	Ground Measurements	Observing Technologies	Earth Observation Assets	
				Satellite (Planned/Proposed)	Airborne (Drone/Aircraft)
Ecosystem Fluxes (GPP, ET, Ecosystem Respiration)	Q1–Q8, Q10, Q11, Q13-Q15, Q17, Q20–Q24	Flux towers, leaf-level spectra	Infrared Spectroscopy, Thermal	OCO-2/3, TROPOMI, GOES-R ABI, AHI, MTG-I, NASA GHG ESE*, Sentinel 5P/5*, FLEX*, CO2M*, GOSAT-2, GOSAT-GW*, Landsat, ECOSTRESS, SBG*, CHIME*, TRISHNA*, LSTM*, VIIRS, Sentinel-3, Commercial*, GEO weather satellites	NASA AVIRIS-NG/3 + HyTES, MASTER
Atmospheric Exchange (CO_2 & CH_4 Fluxes, Column CO_2/CH_4/CO)	Q1, Q2, Q4–Q8, Q10, Q11, Q13, Q14, Q20, Q21, Q24, Q27	Flux towers, chamber measurements, TCCON, COCCON, EM27/SUN Spectrometers	Hyperspectral, Airborne Eddy Covariance (AEC), Infrared Spectroscopy	EMIT, MethaneSat, SBG*, Carbon-i*, CarbonMapper*, OCO-2/3, NASA GHG ESE*, Sentinel 5P/5*, FLEX*, CO2M*, GOSAT-2, GOSAT-GW*	NASA AVIRIS-NG/3, CARAFE, CFIS (SIF), DLR CoMet (CO_2/CH_4), UZH ARES, NEON AOP, GAO
Aboveground Biomass & Structure (Canopy Height, Vertical Height Heterogeneity, Gap Dynamics, Tree Mortality)	Q1, Q2, Q4–Q13, Q15, Q17–Q21, Q23, Q25, Q28	Forest inventory plot data, terrestrial laser scanning, repeat census forest inventory plot data	Lidar, Radar, Multispectral	GEDI, Icesat-2, MOLI*, EDGE*, Sentinel-1, NISAR*, BIOMASS*, Landsat, Sentinel-1/2, Planet	NASA LVIS, UAVSAR, small-footprint lidar (aircraft), repeat drone RGB or Lidar
Diversity (Spectral, Functional, Canopy Foliar Traits, Faunal, Phenology)	Q2, Q4–Q7, Q10–Q15, Q20, Q24, Q25, Q28	Leaf-level spectra, taxonomic diversity; plant traits; IEK, TEK, LEK; camera traps; bioacoustics sensors; animal movement; eDNA; PhenoCams; long-term phenological observations	Hyperspectral, Lidar, Radar, Optical Radiometers (OR)	EMIT, PACE, PRISMA, EnMAP, Planet & Planet Tanager, SBG*, CHIME*, FLEX*, NISAR*, BIOMASS*, Landsat, Sentinel-2, OLCI	NASA AVIRIS-NG/3, UAVSAR, LVIS, UZH ARES, GAO, small-footprint lidar, repeat drone RGB

VARIABLE(S)	SCIENCE QUESTIONS	GROUND MEASUREMENTS	OBSERVING TECHNOLOGIES	EARTH OBSERVATION ASSETS	
				SATELLITE (PLANNED/PROPOSED)	AIRBORNE (DRONE/AIRCRAFT)
CRITICAL THRESHOLDS (Water Stress, Thermal Stress)	Q1-Q4, Q6-Q9, Q12-Q20, Q22, Q23, Q25	Soil moisture probes, Leaf water content, leaf/stem water potentials & conductance, tower-based VOD (L-band GNSS), FLIR cameras	Microwave radar/radiometry, GNSS-R/Signals of Opportunity, Hyperspectral	SMAP, SMOS, Sentinel-1, NISAR*, BIOMASS*, LSTM*, AMSR-E, EMIT, SBG VSWIR & TIR*, CHIME*, FLEX*, SNOOPI*, CYGNSS, Lemur-2, Landsat, ECOSTRESS, TRISHNA*, Commercial*	NASA UAVSAR, AVIRIS-NG/3 + HyTES, MASTER, AirMOSS
FIRE & AEROSOLS (Active Fire, Biomass Burning Aerosols)	Q3, Q4, Q6, Q7, Q9, Q12, Q13, Q19, Q21, Q26, Q28	Life fuel moisture, soil moisture, burn area, burn severity, IEK, TEK, LEK, fuel type, fuel density, aerosol measurements	Thermal, UV/Infrared, Photometers, Lidar	Landsat, VIIRS, Sentinel-3, SBG*, TRISHNA*, LSTM*, Commercial*, OMPS, EMIT, PACE, OLCI, NISAR*, BIOMASS*, CALIPSO-CALIOP**, AOS*	NASA HyTES, MASTER
LAND-USE & LAND COVER & ECOSYSTEM SERVICES: (Food, Freshwater, Medicine, Spiritual and Ceremonial Practices)	Q1, Q3, Q4, Q6, Q7, Q9, Q12-Q14, Q16, Q19, Q21, Q23, Q28	Agricultural activity, logging severity, fire practices, IEK, TEK, LEK, conservation management practices, cultural identifications, water quantity and quality	Optical Radiometers (OR), Hyperspectral, Lidar, Radar	Landsat, Sentinel-1/2, Planet, VIIRS, OLCI, EMIT, PACE, PRISMA, EnMAP, SWOT, SMAP, SMOS, GRACE-FO, SBG*, CHIME*, FLEX*, CarbonMapper*	NASA AVIRIS-NG/3, UAVSAR, LVIS, UZH ARES, GAO, small-footprint lidar
HYDRO-METEOROLOGY (Surface Water, Groundwater, Atmospheric Moisture, VPD, Wind)	Q1-Q4, Q6-Q9, Q14, Q16-Q19, Q22, Q23, Q25, Q28	Water-surface height, inundation extent, discharge characterization, well measurements, weather stations	Altimeter, Radar, Radiometer, Gravimetric, Microwave, Infrared Sounders, Imagers, Doppler wind lidar	SWOT, Sentinel-1, NISAR*, BIOMASS*, GRACE-FO, ATMS, GeoXO*, AOS*, Aeolus	NASA UAVSAR, radiosonde observations
EDAPHIC (Soil Nutrients and Texture, Topography, Geomorphology)	Q1, Q8, Q18, Q19, Q22-Q25, Q28	Soil samples	Hyperspectral, Lidar, Radar	EMIT, PACE, SBG*, CHIME*, SRTM, Copernicus GLO-30	NASA AVIRIS-NG/3, UAVSAR, LVIS, small-footprint lidar
				Note: PANGEA will explore correlative relationships with remotely sensed variables, not direct measurements.	

6.2.2 Candidate Landscapes

PANGEA will collaborate closely with in-country partner institutions to ensure the smooth execution of field and airborne activities across selected landscapes that will be roughly 10,000 km^2. **PANGEA's nested sampling design supports a sampling-to-scale approach** (**Figure 18**). Ground measurements will span gradients within a landscape, and landscapes will span climatic and biodiversity gradients within a continent (**Figure 11**). PANGEA will prioritize countries that encompass landscapes with a confluence of intact, disturbed, and degraded forest, peatland, and wetland ecosystems, with adjacent agro-ecosystems. Coordinated ground data collection will span these gradients within each landscape. **Table 3** summarizes candidate landscapes based on information provided by partners. PANGEA landscapes will prioritize locations where the data described at the beginning of *Section 6.2.4* are already being collected or where data collection can be extended under PANGEA.

Table 3. Candidate PANGEA landscapes. Colored circles indicate existing available data, by type. 🟡 = Ground data; 🟠 = Socioeconomic data; 🟢 = Tower data; 🔵 = Drone data; 🟣 = Aircraft data. Ⓝ = NASA aircraft data. * Indicates planned activities. ATTO: Amazon Tall Tower Observatory. Landscapes in **bold** are confirmed GEO-TREES sites. Landscapes in *italics* are confirmed One Forest Vision initiative sites.

LANDSCAPE	COUNTRY	AVAILABLE DATA
POTENTIAL AMERICAN TROPICAL FOREST LANDSCAPES		
KM34/ATTO (Manaus)	Brazil	🟡🟢🔵🟣
KM67 (Santarem)		🟡🟢🟣
Rebio Jaru		🟡🟢
Tanguro		🟡🟢🟣
Caxiuana		🟡🟢
Amacayacu	Colombia	🟡
Amazonas		🟡
La Planada		🟡Ⓝ
Santa Rosa	Costa Rica	🟡🟠🟢🔵Ⓝ
Turrialba		🟡🔵Ⓝ
Tiputini	Ecuador	🟡Ⓝ
Yasuní		🟡Ⓝ
Paracou	French Guiana	🟡🟢🔵Ⓝ
Agua Salud	Panama	🟡
BCI		🟡🔵Ⓝ*
Darien		🟡🟠
Iquitos	Peru	🟡
Huánuco		🟡🟢
Jenaro Herrera		🟡🟢
Los Amigos		🟡🟢
Madre de Dios		🟡
San Martin		🟡🟢
Tambopata		🟡🟢
Ucayali		🟡
Guanica	Puerto Rico	🟡🟢🟣
Luquillo		🟡🔵

LANDSCAPE	COUNTRY	AVAILABLE DATA
POTENTIAL AFRICAN TROPICAL FOREST LANDSCAPES		
Nalohou	Benin	🟡🟢
Bellefoungou		🟡🟢
La Lama		🟡🟢
Dja	Cameroon	🟡🟠🔵Ⓝ
Mbalmayo		🟡🔵Ⓝ
Korup		🟡
Campo Ma'an		🟡
Luki	Dem. Republic of Congo	🟡🔵
Mai Ndombe		🟡🟠🔵Ⓝ
Yangambi		🟡🟢🔵
Yoko Reserve		🟡🟠
Ankasa	Ghana	🟡🔵
Bia Tano		🟡🟢
Bobiri		🟡🔵
Kogyae		🟡🔵
Lopé	Gabon	🟡Ⓝ
Ipassa		🟡
Mondah		🟡Ⓝ
Mabounié		🟡Ⓝ
Rabi		🟡Ⓝ
Bokatola	Republic of Congo	🟡
Kolongomba		🟡
Lac Tele		🟡
Loundoungou		🟡🔵
Odzala-Kokoua		🟡🔵Ⓝ
Nyungwe	Rwanda	🟡
Volcanoes		🟡
Kibale	Uganda	🟡
Sebitoli		🟡

PANGEA will coordinate landscape selection closely with efforts that are actively in the process of selecting sites for complementary data collection and investment in infrastructure. These include GEO-TREES, the INPE-ESA Amazon campaign, the One Forest Vision Initiative, Moore Foundation and National Science Foundation (NSF) funded tropical methane and peatland field measurements, as well as multiple Schmidt Science Virtual Institute for the Carbon Cycle proposals focusing on the tropics. A landscape and site selection process will be formalized in the Concise Experiment Plan to ensure transparent selection and approval of landscapes and sites within landscapes for ground and airborne data collection. This process will build on ongoing discussions with local institutional partners and site managers that began during the scoping process and will include co-design with Indigenous Peoples and Local Communities (see *Section 8* for more information).

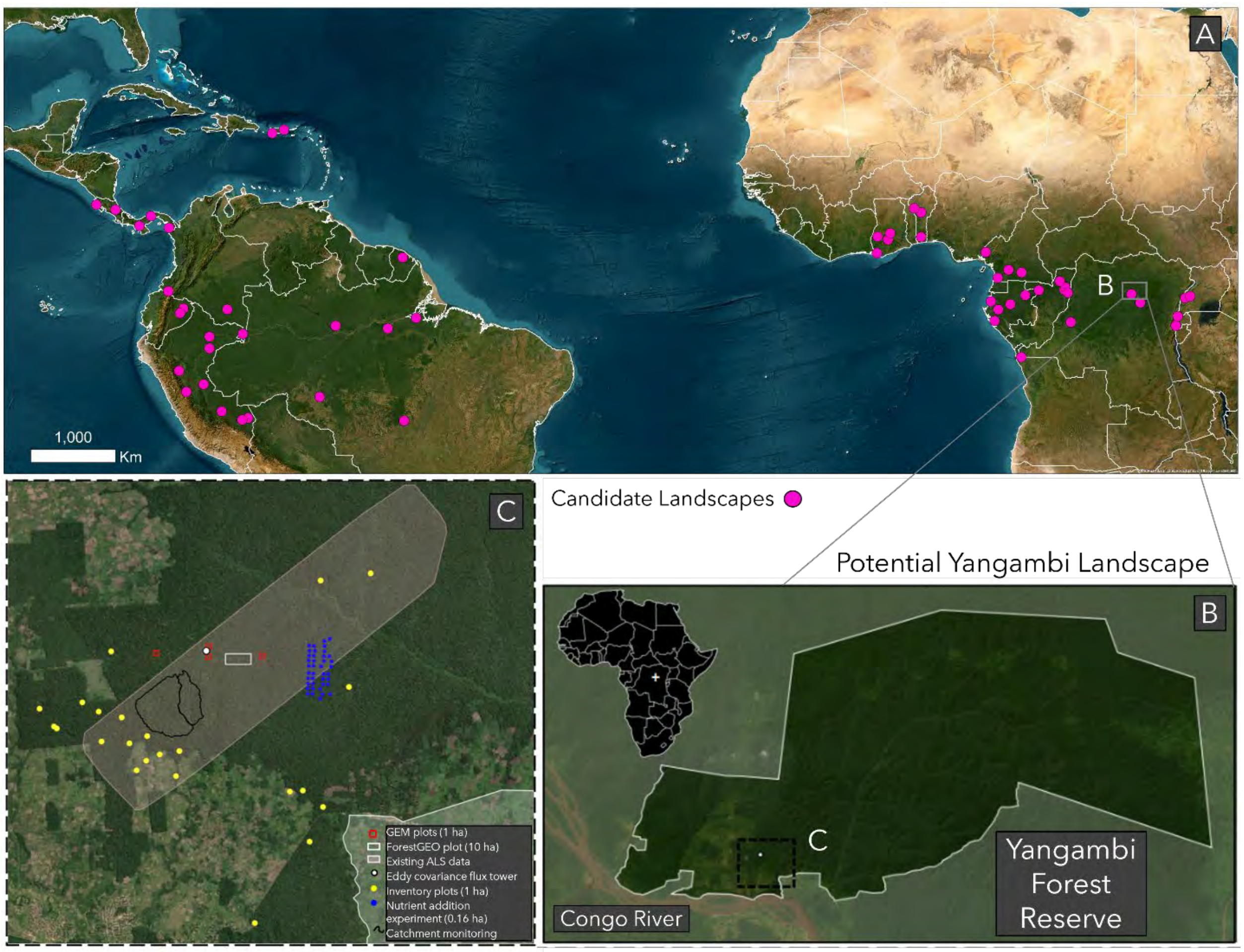

Figure 18. Potential candidate landscapes span the American and African tropics (A). Yangambi, one example of a potential candidate landscape, is illustrated in panel B, which has existing inventory plots, a flux tower, and aircraft data (C) that could be situated within a larger PANGEA landscape spanning agricultural, intact, and degraded ecosystems.

6.2.3 Satellite Remote Sensing Observations

There are a wealth of NASA satellite platforms that will contribute to the science and applications goals of PANGEA, as well as an ever-increasing ecosystem of sensors from other space agencies and nongovernmental organizations (NGOs) (**Tables 2** & **E-1**). PANGEA is well-poised to leverage the Earth Observing System (EOS) missions for understanding patterns of tropical ecosystem properties and their changes in the recent past, as well as to advance the way we use spaceborne sensors in the age of the Earth System Observatory (ESO) missions. PANGEA is also poised to contribute to the improvement and refinement of ESO algorithms to better represent tropical ecosystems and address user needs in these globally important regions. The in situ work carried out by PANGEA paired with satellite remote sensing observations will allow tropical forest biomes and the people living in these regions to become part of the Earth Science to Action virtuous cycle, ensuring their inclusion in the process.

Table 4. Examples of satellite remote sensing observations and advances.

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

Satellite Observations	Calibration, Validation, and Algorithm Advances from PANGEA
Sentinel-1, NISAR*, BIOMASS*	• Expand calibration/validation of biomass mapping along disturbance and climate gradients. • Support data product development from NISAR and BIOMASS in dense forests.
EMIT, CHIME*, SBG-VSWIR*	• Expand validation data for EMIT-derived product in tropical forests. • Support for improved L3 vegetation products from SBG VSWIR.
OCO-2/3, TROPOMI, MethaneSat, EMIT, CarbonMapper	• Obtain XCO_2 and XCH_4 cloud-free calibration samples in tropical regions. • Support data for L3 products, scaling between target-mode and broad spatial coverage data.
Carbon-I*	• Validation data of greenhouse gas fluxes from wetlands.
GEDI, ICESat-2, EDGE*	• High-accuracy forest structure data for improved L3 spaceborne lidar products. • Opportunities for calibration data for L4 biomass quantification products.
SMAP, SMOS	• Calibration data for soil moisture products in dense forests.
Geostationary: GOES-R ABI (Americas), MTG-I (Africa) & AHI (Asia)	• Calibration data for ecosystem function estimates at sub-daily time scales.
VIIRS, Sentinel-3	• Support development of L3 products of fire dynamics. • Calibration data for detection of small-scale fires.
ECOSTRESS, SBG-TIR, FLEX*	• Support data for deriving all-weather L3 and L4 ecosystem function estimates. • Calibration data for emergent relationships between forest structure and composition and ecosystem function.

In **Table 4**, we highlight a variety of operational and forthcoming NASA spaceborne sensors, their needs for advances in the tropics that PANGEA can address, and the science that the PANGEA team will be able to advance with the use of these sensors in concert with planned PANGEA activities. This table also includes some sensors that are operated by non-NASA space agencies where data are openly available. PANGEA will also explore commercial datasets available through NASA's Commercial SmallSat Data Acquisition (CSDA) program during the Science Definition and Implementation phases of the project.

6.2.4 Airborne Remote Sensing Observations

PANGEA airborne observations, including instrumented aircraft and drones, will be co-designed with local partners. All requests for country clearances and flight permissions will be coordinated by NASA and JPL airborne programs working with the NASA Office of International and Interagency Relations (OIIR) and the U.S. Department of State (see **Box 2**). When using NASA or NASA-contracted aircraft, all appropriate airworthiness processes and flight approval and releases will be coordinated at the PANGEA project level with the appropriate centers, NASA HQ, and JPL. Exact sensors and aircraft will be determined during the development of the Concise Experiment Plan.

PANGEA leverages and builds on NASA's history of successful international airborne campaigns, including many in Africa. Most recently, NASA executed the 2016 AfriSAR and

Box 2. International and Other Agreements

PANGEA international partners will be engaged at the outset and continuously to ensure strong relationships that will support the success of field and airborne campaigns. For each PANGEA landscape, formal agreements and/or permissions will be obtained from relevant governments and Indigenous community leaders. As soon as PANGEA is selected, the PANGEA Science Team will begin to engage institutional partners to support the development of formal discussions on the required diplomatic agreements that will be needed to conduct fieldwork and deploy aircraft in support of the NASA TE campaign. As pathways with each foreign government are established, the PANGEA Science Team will work with NASA SMD via the TE Program Manager to develop proper diplomatic arrangements for conducting fieldwork and airborne campaigns in each country. Diplomatic agreements (such as memoranda of understanding [MOUs], implementing agreements [IAs], and/or flight clearances) will need to be created between the U.S. Government and the given Foreign Nation as early as possible. When such documents are required between NASA and a Foreign Government, the PANGEA Science Team and the TE Program Manager, in collaboration with NASA's OIIR, SMD, NASA Centers including JPL, the CCE Support Office, and the U.S. State Department, will work through the proper diplomatic channels and protocols to establish the needed documents for a successful field and airborne campaigns. The PANGEA Science Team will also consult with NASA, the State Department, U.S. Forest Service (USFS) and U.S. Agency for International Development (USAID) to identify and pursue synergies between PANGEA activities and U.S. diplomatic objectives, including scientific cooperation and country-to-country ties. The PANGEA Science Team, TE Program, and CCE Support Office will work closely to guarantee that Indigenous land and sovereign territories are co-developers in any diplomatic approval processes. The current PANGEA Science Team's experience with numerous international field and airborne campaigns will facilitate establishing the proper international agreements for the PANGEA project.

2023/2024 AfriSAR-2 campaigns, where AfriSAR-2 expanded on the initial scope and successes of AfriSAR in Gabon to additionally collect data over Cameroon, the Democratic Republic of Congo (DRC), Ghana, the Republic of Congo, and Sao Tome and Principe. In 2023, the BioSCape campaign flew two NASA aircraft integrated with four airborne remote sensing instruments, acquiring contemporaneous observations from the UV through the VSWIR and thermal range as well as full waveform lidar data. This combination of instruments was accompanied by an extensive field observation campaign, executed by a diverse Science Team with ~50% local participation. AfriSAR and BioSCape's success and continued capacity building has served as an excellent example of science diplomacy and has positively influenced the public's perception of NASA and the United States in Africa.

A number of Earth Venture Suborbital (EVS) and other international NASA airborne campaigns have also demonstrated feasibility of NASA aircraft and NASA-contracted aircraft deploying internationally with in situ and remote sensing instruments in support of multi-year large-scale campaigns in the American tropics. In 2023, NASA JPL had a successful campaign with AVIRIS-NG collecting remote sensing data with a NASA-contracted aircraft over Chile, Colombia, and Ecuador for methane point-source observations in coordination with each country. This built on previous successful campaigns in the region, including, for example, UAVSAR flights in Colombia, Ecuador, Peru, and French Guiana; AVIRIS flights in Colombia, Ecuador, and Chile; with planned AVIRIS flights in Panama and Costa Rica; and LVIS flights in French Guiana. All of these campaigns represent decades of experience of NASA HQ and the centers (including JPL) working together with universities and international collaborators to successfully acquire airborne remote sensing and in situ data during global field campaigns.

As PANGEA develops its Concise Experiment Plan, it will continue to leverage the experience of team members from past international campaigns.

Importantly, PANGEA airborne data collection does not necessarily require NASA assets or NASA aircraft to be deployed. Commercial data-buys and flights on foreign and commercial aircraft are also viable options for PANGEA airborne acquisitions. NASA sensors can be flown on commercial aircraft. For example, AVIRIS sensors often fly both domestically and internationally on a Dynamic Aviation aircraft. The EVS Oceans Melting Greenland (OMG), Delta-X and Coral Reef Airborne Laboratory (CORAL) missions all successfully deployed NASA JPL contracted aircraft with JPL instruments and team members. Commercial data-buys will also greatly expand airborne capabilities. For example, U.S.-funded commercial lidar transects acquired with USAID support through Sustainable Landscapes Brazil span large areas of Brazil (dos Santos et al., 2019), and similar efforts allowed sampling over forests in the Democratic Republic of Congo (Xu et al., 2017), demonstrating feasibility in important PANGEA geographies. The Airborne Research Facility for the Earth System (ARES) from University of Zürich, is another important partner supporting PANGEA airborne acquisitions. ARES has successfully acquired data for collaborative NASA and ESA campaigns. Sensors onboard ARES include the AVIRIS-4 imaging spectrometer, a full waveform lidar, and a high-performance photogrammetric camera.

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

PANGEA will also leverage drone capabilities to supplement aircraft data collection and to make data acquisitions that require higher temporal frequency (e.g., tree mortality, phenology). PANGEA will use Technology Readiness Level (TRL) 9 lidar and RGB UAV instruments. Current commercial UAV-based hyperspectral offerings often present challenges and tend to cover the VNIR range only, losing the shortwave portion of the spectrum which is important for relevant ecosystem measurements. The PANGEA team will continue to track the availability and utility of these technologies and will build in protocols to employ them as appropriate to support science activities.

Some PANGEA data acquisitions will require nearly simultaneous field measurements and airborne observations enabled by advance planning of field campaigns; clear, reliable methods of communication between the flight and field teams; and plans that incorporate timing flexibility. In preparation for and during the campaigns, PANGEA will rely on near-real-time quick looks and flight-tracking tools, as used in BioSCape (Cardoso et al., 2024), to optimize airborne data collection, facilitate better field match-ups, and increase transparency.

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

6.2.5 Field Observations and Studies

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

- **Manual in situ data and knowledge** include all data that must be directly measured and/or gathered by individuals on-the-ground and cannot be easily automated. Examples include forest inventory plots, leaf and wood traits, terrestrial laser scanning, chamber flux measurements, species identification, eDNA, animal movement data, crop type and yield measurements, and Indigenous, traditional, and local ecological knowledge (IEK, TEK, and LEK). These data and knowledge bases are important for understanding the mechanistic relationships between pattern and process and for the validation of drone, aircraft, and satellite datasets.
- **Automated in situ data** include all ground measurements that support validation and understanding of ecologic processes but does not require frequent site visits and is more easily automated. Examples include dendrometer, sap-flux, and soil moisture measurements, and camera-trap and bioacoustics data. Similar to biological sampling, these measurements are important for developing and understanding processes and validating remote observations.
- **Flux and meteorological data** include all data collected at a flux tower or weather station, including carbon, water, and energy fluxes, air temperature, soil temperature, soil volumetric water content, relative humidity, and precipitation. The eddy-covariance technique uses scaffolding towers above the forest canopy and measures high-frequency wind and scalar (gas concentration, energy, momentum) data to estimate ecosystem water and carbon fluxes—where carbon refers to CO_2, CH_4, and lateral fluxes.
- **Tower-based proximal remote sensing** includes all data that can be collected from platforms mounted on towers. These measurements will supplement drone and aircraft remote sensing retrievals to more directly link ecosystem traits and fluxes with satellite observations. PANGEA tower-based proximal remote sensing measurements include hyperspectral reflectance, solar-induced fluorescence (SIF), thermal infrared radiation (TIR), microwave backscatter, lidar, VOD (L-band GNSS), and PhenoCams.
- **Drone-based proximal remote sensing** includes lidar, RGB images for both structure and spectra, multispectral data, and the potential development of a drone-based hyperspectral sensor. There are three key aspects of drone-based monitoring: (1) it

allows for high-frequency data collection and continuous monitoring of temporal trends in a manner that is not possible with aircraft; (2) it provides the ability to capture trends even during cloudy conditions, which are common in tropical forest regions; and (3) it can complement ground-based measurements that may miss the top of the canopy due in forest and agroforestry systems to occlusion. When paired with ground validation, drone-based acquisitions are critical to quantification of phenomena like tree mortality, carbon fluxes, phenology, and changes in functional traits with seasonal variation.

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

PANGEA will address these limitations by building lasting, mutually beneficial, collaborative partnerships with local tropical organizations to leverage, reinforce, and gap-fill existing infrastructure and efforts (**Table 5**). Partners have been engaged in the scoping process and will be involved throughout PANGEA, including during the development of the PANGEA Concise Experiment Plan. See *Section 8, Community Engagement Strategy*, for more information. PANGEA plans to build upon relationships with all of these partners to address the project's Science Objectives. We note in particular that flux sites, such as those in the global eddy covariance flux tower network (FLUXNET), typically have sufficient infrastructure and power supply to host additional support measurements such as proximal remote sensing. Because of this PANGEA will prioritize field measurements that are partnered with FLUXNET sites to make use of existing infrastructure and build collaborations. We also note that NGEE-Tropics will be sunsetting by the time PANGEA enters its most active phase. PANGEA will build directly on NGEE-Tropics data-collection efforts by extending similar measurements to Africa and collecting collocated remote sensing data, in addition to building on NGEE-Tropics modeling efforts (see *Section 6.3*).

Table 5. Partner organizations with ongoing field-based research and activities that are synergistic to PANGEA.

AMMA-CATCH: African Monsoon Multidisciplinary Analysis Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique. AndesFlux: Flux towers operated by PUCP. ForestGEO: Forest Global Earth Observatory. GEM: Global Ecosystems Monitoring network. PUCP: Pontifical Catholic University of Peru. RAINFOR: Amazon Forest Inventory Network.

ORGANIZATIONS	POTENTIAL CONTRIBUTIONS
Alliance for Tropical Forest Science (ATFS)	• 11 research networks (e.g., AfriTRON, ForestGEO, GEM, RAINFOR). • 11,656 forest inventory plots in 56 countries. • Strong leadership in capacity building.
Amazon Tall Tower Observatory (ATTO)	• Joint German-Brazilian project. • Three flux towers (including a 325-m one). • Ancillary data (biogeophysical/biogeochemical cycles and weather).
AndesFlux	• 6 eddy flux towers and permanent plots in western Amazon. • Sites spanning a dry-season length gradient (0–6 months).
Congo Basin Institute (CBI)	• 2 biological field stations in Cameroon. • Organizational networks across the Congo Basin. • CBI School for Indigenous and Local Knowledge (SILK).
Congo Basin Science Initiative	• Scientist-led platform for long-term scientific investment. • Efforts on building local scientific capacity. • Sustainable development initiatives.
CongoFlux	• Tropical research station in Yangambi (Democratic Republic of Congo). • Eddy covariance fluxes (CO_2, N_2O, CH_4, H_2O, sensible heat). • Additional data to characterize carbon cycling.
FLUXNET	• International network of networks (e.g., Americas' eddy-covariance Flux tower network [AmeriFlux], Integrated Carbon Observation System [ICOS]). • Consolidated and standardized eddy covariance flux data.
GEO-TREES	• Network of networks (e.g, AfriTRON, ForestGEO, GEM, RAINFOR). • Coordinated forest inventory plots and airborne remote sensing. • Data for calibrating carbon stock estimates from space.
Global Alliance of Territorial Communities (GATC)	• Network of Indigenous Peoples and Local Communities. • Represent 35 million people in 24 countries (Africa, Americas, Asia). • Capacity building for sustainable management and cultural protection.
Guyafor and Guyaflux	• Guyafor: Network of 54 long-term plots across 17 sites in French Guiana. • Guyaflux: Long-term (21 years) eddy covariance tower in French Guiana.
LBA	• Permanent Program of the Brazilian government. • Platform for infrastructure and research collaboration support in the Amazon.
NGEE-Tropics	• Decadal, multi-institutional project by the U.S. Department of Energy (DOE). • Intensive sites in Australia, Brazil, Malaysia, Panama, and Puerto Rico. • Data collection aimed at improving modeling of diverse forests.
West Africa Flux Network	• 3 eddy flux towers: 2 forest (Bellefoungou and La Lama), 1 mixed crop (Nalohou) • Bellefoungou and Nalohou: Long-term (16 years) eddy covariance and weather measurements, surface water (AMMA-CATCH network), and soil samples that span topography and geomorphology gradients. • La Lama: Species survey available in GBIF

6.3 Modeling, Data Synthesis, and Integrative Analyses

6.3.1 Modeling and Data Integration Approach

Modeling and data syntheses are fundamental components of PANGEA. Modeling and data synthesis activities will cut across all Science Themes (*Section 2*) and be instrumental for answering PANGEA's key scientific questions (*Section 3*). Throughout the project, PANGEA will prioritize ground and airborne datasets that can be synthesized across multiple scales and integrated by models, whether for initialization, boundary conditions, or assessment. This approach has been successfully implemented in previous model and data-integration projects (e.g., ABoVE and NGEE-Tropics), and we plan to build on these projects. The modeling and data synthesis goals are to

- Identify key processes that are poorly represented and regions within the PANGEA domain that drive uncertainty of key variables and processes in existing models.
- Develop activities akin to Observing System Simulation Experiments (OSSEs) that will help inform the best locations and gradients needed to maximize the representativeness of the intensive sites within the PANGEA domain.
- Synthesize and scale measurements from landscapes to the Core and Extended PANGEA domains using remote sensing and modeling.
- Implement new processes and techniques, as well as improve existing ones that leverage remote sensing data-model integration and apply them to answer PANGEA's scientific questions.

Over the past decades, terrestrial biosphere models have expanded scope and incorporated many new processes that could not be addressed during LBA (**Figure 19**). For example, processed-based models now resolve structural and functional diversity, a broad variety of natural and anthropogenic disturbance dynamics, and strong coupling with biogeochemical cycles (Fisher et al., 2018; Fisher and Koven, 2020; Negron-Juarez et al., 2020). We are now in a time in which ecological processes in diverse ecosystems driving energy, water, carbon and nutrient cycling on Earth must be accounted for (Bonan et al., 2024). Likewise, several classes of models have been increasingly leveraging the broad range of remote sensing observations, and throughout PANGEA we will have participation of a broad range of models that can use remote sensing for initialization, uncertainty quantification, and data assimilation (**Table 6**). Moreover, new technologies such as artificial intelligence can advance both model calibration (Li et al., 2023) and become integral parts of predictive modeling (Schneider et al., 2017; Reichstein et al., 2019; Eyring et al., 2024). Nonetheless, as models evolve, addressing future challenges such as acclimation, nutrient limitation, shifts in functional composition, accounting for methane emissions, and carbon allocation partitioning between above and belowground biomass will be increasingly important for maintaining model accuracy.

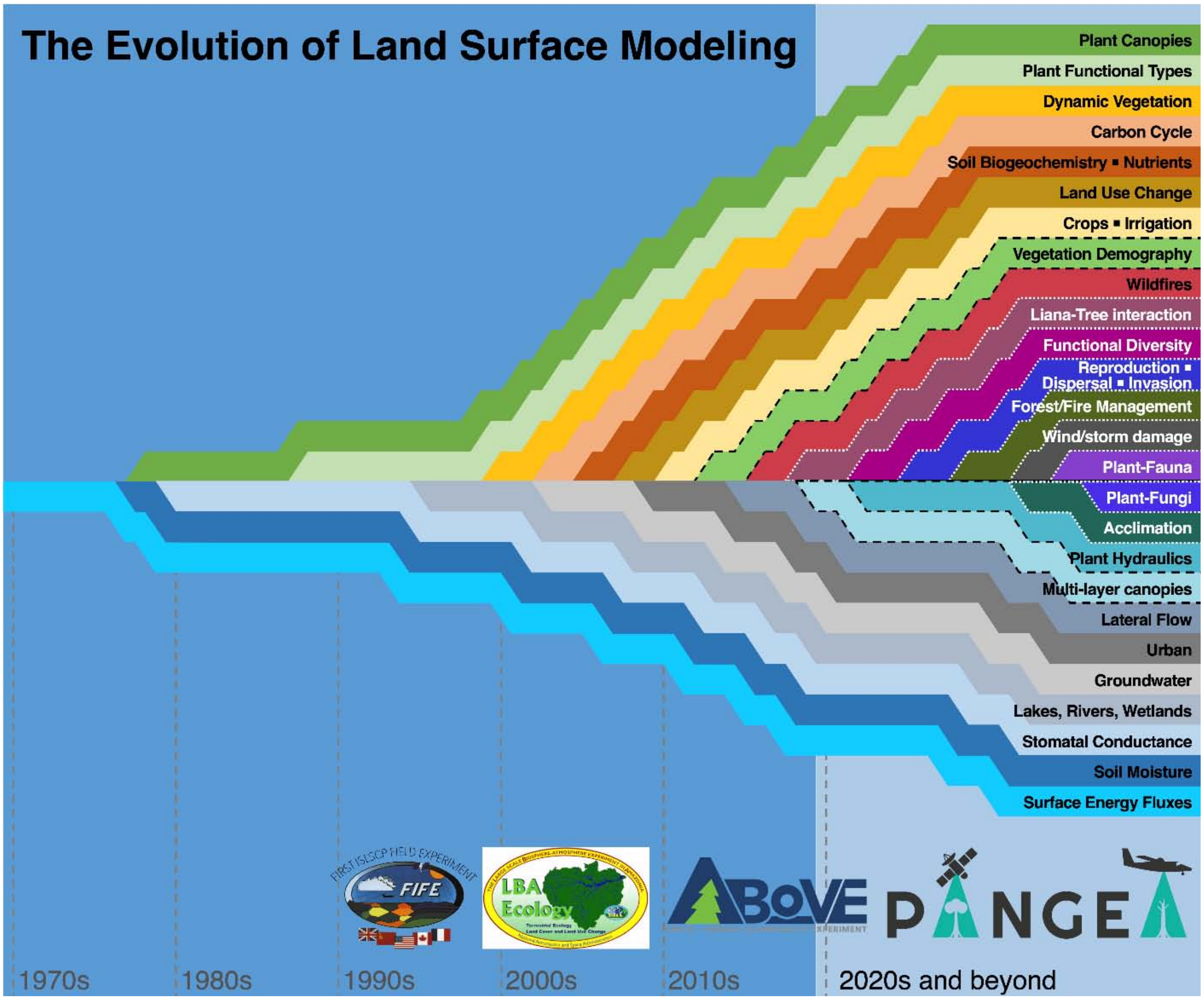

Figure 19. Change in processes solved by terrestrial biosphere models over the decades, along with prior NASA Terrestrial Ecology campaigns. Black dashed lines: implemented processes, still under significant development. White dotted lines: processes that are starting to emerge and are expected to emerge in the upcoming years. Source for original figure: Fisher and Koven (2020).

Projecting the future trajectory of tropical ecosystems presents a significant challenge to ESMs, as these models must accurately represent complex physical, biogeochemical, and ecosystem dynamics. Model intercomparison projects such as CMIPs (Taylor et al., 2012; Eyring et al., 2016) and TRENDY (Friedlingstein et al., 2023; Sitch et al., 2024) are crucial for tracking the development of process-based models and identifying areas that need to be improved (Arora et al., 2020). While the benchmarking and validation of ESMs have become more common in recent years (Fisher et al., 2018), it is still rare to systematically evaluate the performance of carbon cycle models after they have been updated (Fer et al., 2021). However, such comparisons with observational datasets are essential for testing hypotheses and evaluating predictive accuracy (Negron-Juarez et al 2015, Fisher et al., 2018). The ILAMB project provides tools to track and compare model performance using a comprehensive skill score method and incorporates multiple observational datasets to account for model uncertainty (Hoffman et al., 2017; Collier et al., 2018; Braghiere et al., 2023). Improved agreement between historical simulations and observations may indicate that model components can be refined to better represent processes, thereby increasing confidence in future projections. In addition to representing processes accurately, the model performance can be significantly influenced by the quality and representativeness of the initial and boundary conditions (Hurtt et al., 2004; Antonarakis, 2014; de Frenne et al., 2021). Data collected through PANGEA will be used to expand benchmarking tools using integration of ground-based observation and remote sensing data, and to provide initial and boundary conditions that are representative of the actual state of tropical forest ecosystems.

Table 6. Non-exhaustive list of models that can integrate PANGEA data and help answer science questions and test PANGEA hypotheses. Classes of model: PBM, process-based terrestrial biosphere models; HM, data-driven hybrid models; TDM, top-down models; AI/ML, models based on artificial intelligence machine learning; and ABM, agent-based models. Subclasses of PBM models: IBM, individual-based models; CBM, cohort-based models; DGVM, dynamic global vegetation models (excluding IBMs and CBMs). CLiMA: Climate Modeling Alliance.

<table>
<tr><th colspan="5">MODELS</th><th colspan="2">EXAMPLES OF DATA-MODEL INTEGRATION OPPORTUNITIES</th><th rowspan="2">SCIENCE QUESTIONS ADDRESSED</th></tr>
<tr><th>CLASS</th><th>SUBCLASS</th><th>EXAMPLES</th><th>REFERENCES</th><th>EXAMPLES OF PROCESSES OF INTEREST</th><th>AIRBORNE/SPACEBORNE REMOTE SENSING</th><th>FIELD MEASUREMENTS</th></tr>
<tr><td rowspan="3">PBM</td><td>IBM</td><td>FORMIND
TROLL</td><td>Fischer et al. (2016)
Maréchaux & Chave (2017)</td><td>• Carbon stocks and fluxes
• Structural/Functional diversity
• Demographic rates
• Disturbance rates</td><td rowspan="4">FOREST STRUCTURE/CARBON STOCKS:
• Airborne lidar
• GEDI, EDGE*, NISAR*, BIOMASS*
• Landsat, Sentinel-1, Sentinel-2
FOREST COMPOSITION:
• Airborne hyperspectral
• DESIS, EMIT, PACE, PRISMA, SBG*
OTHER:
• Water/energy fluxes: ECOSTRESS
• C fluxes: FLEX, OCO-2/3, TROPOMI
• Soil water: SMAP, SMOS, SWOT
• Canopy water content: AMSR-E, EMIT
• Phenology: Landsat; Sentinel-2; drone RGB
• Cloud/precipitation: GOES-R, GPM
• Land cover: Landsat; Sentinel-2
• Burned area: Landsat, Sentinel-2, VIIRS</td><td rowspan="4">• Forest inventory plots
• Litter/coarse woody debris
• Terrestrial laser scanning
• Plant functional traits
• Meteorological data
• Eddy covariance fluxes
• COS/Isotopes
• Sapflow
• Soil moisture/temperature
• Soil flux chambers
• Tower-based GNSS data
• PhenoCams</td><td rowspan="3">Q1–Q27</td></tr>
<tr><td>VDM</td><td>BiomeE
ED/ED3
ED2
Ent TBM
FATES
LPJ-GUESS</td><td>Weng et al. (2022)
Ma et al. (2023)
Longo et al. (2019)
Kim et al. (2015)
Koven et al. (2020)
Hickler et al. (2012)</td><td>• Carbon stocks and fluxes
• Structural/Functional diversity
• Demographic rates
• Disturbance rates
• Water/energy cycling
• Nutrient cycling
• Land-cover/land-use change
• Burned area/fire emissions</td></tr>
<tr><td>DGVM</td><td>CLM
ELM
JSBACH
JULES
LPJ
ORCHIDEE</td><td>Lawrence et al. (2019)
Ricciuto et al. (2018)
Reick et al. (2021)
Harper et al. (2018)
Sitch et al. (2008)
Krinner et al. (2005)</td><td>• Carbon stocks and fluxes
• Disturbance rates
• Water/energy cycling
• Nutrient cycling
• Land-cover/land-use change
• Burned area/fire emissions</td></tr>
<tr><td colspan="2">HM</td><td>CARDAMOM
CliMA
NASA-CASA</td><td>Bloom et al. (2016)
Braghiere et al. (2023)
Potter et al. (2012)</td><td>• Carbon stocks and fluxes
• Water/energy cycling
• Land-cover/land-use change
• Burned area/fire emissions</td><td>Q1–Q4; Q6; Q8; Q9; Q14–Q16; Q18; Q22–Q27</td></tr>
<tr><td colspan="2">TDM</td><td>CarbonTracker
CMS-Flux
HYSPLIT
STILT-VPRM</td><td>Peters et al. (2007)
Liu et al. (2020)
Stein et al. (2015)
Dayalu et al. (2024)</td><td>• Carbon fluxes
• Water/energy cycling
• Burned area/fire emissions</td><td>• C fluxes: FLEX, OCO-2/3, TROPOMI
• Water/energy fluxes: ECOSTRESS
• Burned area: Landsat, Sentinel-2, VIIRS</td><td>• Eddy covariance fluxes
• Meteorological data
• COS/isotopes
• Soil flux chambers
• PhenoCams</td><td>Q1–Q2; Q4; Q6; Q9; Q14; Q17</td></tr>
</table>

MODELS					EXAMPLES OF DATA-MODEL INTEGRATION OPPORTUNITIES		SCIENCE QUESTIONS ADDRESSED
CLASS	SUBCLASS	EXAMPLES	REFERENCES	EXAMPLES OF PROCESSES OF INTEREST	AIRBORNE/SPACEBORNE REMOTE SENSING	FIELD MEASUREMENTS	
AIML		MapBiomas Fire MetaFlux	Alencar et al. (2022) Nathaniel et al. (2023)	• Carbon stocks and fluxes • Water/energy cycling • Burned area/fire emissions	**CARBON STOCKS:** • Airborne lidar/hyperspectral • GEDI, EDGE*, NISAR*, BIOMASS* • Landsat, Sentinel-1 and -2 **OTHER:** • **Water/energy fluxes:** ECOSTRESS • **C fluxes:** FLEX, OCO-2/3, TROPOMI • **Burned area:** Landsat, Sentinel-2, VIIRS	• Plant functional traits • Meteorological data • Eddy covariance fluxes • COS/isotopes • Soil flux chambers • Tower-based GNSS data • PhenoCams	Q1–Q2; Q4; Q6; Q9; Q14; Q17
ABM		ABSOLUG SimPachamama RepastSimphony	von Essen & Lambin (2023) Andersen et al. (2017) North et al. (2013)	• Land cover/land-use change • Household state/dynamics • Bioeconomics metrics • Cattle reproduction rate	**CARBON STOCKS:** • Airborne lidar/ hyperspectral • GEDI, EDGE*, NISAR*, BIOMASS* • DESIS, EMIT, PACE, PRISMA, SBG* • Landsat, Sentinel-1 and -2 **OTHER:** • **Land Cover:** Landsat; Sentinel-2 • **Burned Area:** Landsat, Sentinel-2, VIIRS	• Forest inventory plots • Forest management data • Crop/timber yields • Cattle dynamics data • Territory boundaries • Human census data • Survey data • Choice experiment data	Q21; Q28

Box 3. Example of PANGEA Modeling and Remote Sensing Data Integration Approach

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

PANGEA data synthesis activities will facilitate the upscaling of landscape ground measurements and airborne observations described in *Sections 6.2.4* and *6.2.5* to regional and pantropical scales. By synthesizing key variables using airborne remote sensing datasets paired with ground measurements (e.g., soil moisture, plant functional traits, fluxes), we can establish robust empirical relationships using statistical models to interpolate wall-to-wall variations in critical variables. As an example, ground measurements on biomass carbon losses due to droughts across multiple sites can be used to develop statistical models that predict biomass changes in response to varying soil moisture, VPD, drought frequency, and plant functional groups. The derived product can then be used to map pantropical impacts on forest biomass following specific drought scenarios, enhancing our understanding of ecosystem responses to environmental stressors across diverse tropical landscapes. Moreover, the combination of multiple data synthesis products can be used for exploring the emergent relationships of the tropical forest ecosystems. For example, canopy height maps before droughts can be contrasted with evaporative stress indices during drought conditions. These datasets can be then applied as additional constraints and benchmarks for process-based models.

PANGEA will leverage artificial intelligence and machine learning (AI/ML) models for data synthesis due to their robustness in handling non-linearities and interactions among multi-factorial processes and predictors. AI/ML can be further used to emulate process-based models (Swaminathan et al., 2024) and more efficiently explore models' parametric space or run short/long-term forecasting (Li et al., 2023; Meunier et al., 2024). To improve the interpretability and insights into the underlying ecological processes of AI/ML models, PANGEA will implement techniques such as (1) Feature Importance Analysis, which quantifies and highlights the most influential factors driving the model's predictions; and (2) Partial Dependence Plots, which can be employed to visualize how changes in specific variables impact predicted outcomes. Additionally, PANGEA will employ non-AI techniques including causal inference (Venelli Pyles et al., 2022), time series analysis (Bullock et al., 2020) including Breaks For Additive Season and Trend Monitor (BFAST; DeVries et al., 2015; Verbesselt et al., 2012), and Bayesian statistics (Goulamoussène et al., 2017), which yield insights into cause-and-effect relationships, uncover temporal patterns, and quantify uncertainty in predictions and analyses. These strategies will also provide valuable insights and effective workflows that can be integrated into process-based models for reducing parameter uncertainty and increasing prediction accuracy (Dietze et al., 2013; Meunier et al., 2021).

One significant challenge in understanding tropical forest dynamics across large scales is the relatively short time series of most data products related to forest structure, composition, carbon stocks, and function. To overcome this challenge and obtain long-term, high-resolution forest biomass regrowth data, previous work used a space-for-time substitution approach, which calculates recovery rates of variables of interest (e.g., biomass, canopy height) from a reference time in areas that experienced disturbance in different (and known) years (Heinrich et al., 2021; Rappaport et al., 2018). This approach, coupled with AI/ML models and traditional data synthesis techniques, ensures that PANGEA can robustly assess and predict tropical forest dynamics across various scales and timeframes, supporting use of long-term satellite records as a result of PANGEA data acquisitions and methodological advances. Chronosequences have been used to constrain process-based models that characterize distributions of age since last disturbance (Ma et al., 2017).

6.3.2 Coordination with Other Modeling and Data Integration Communities

Coordination with established modeling, data synthesis, and data integration communities will be crucial to extend the impact of PANGEA beyond providing field and satellite observations. For example, the TRENDY project (Sitch et al., 2024), which coordinates global carbon cycle simulations, represents another potentially important partnership. PANGEA's detailed site-specific data for tropical forests will be critical for improving the parameterization and performance of TRENDY models, particularly for regional carbon dynamics and fluxes in tropical biomes. Likewise, the CMIP (Eyring et al., 2016), a global leader in climate modeling, will benefit from PANGEA's observations, especially in the context of improving the representation of tropical ecosystems. These datasets will be highly valuable for evaluating and improving models used in global efforts, including the CMIP land components. This partnership will enhance the representation of tropical ecosystems in Earth system models by providing benchmarks specifically tailored to tropical forests, helping global models achieve higher accuracy in their predictions.

PANGEA will ensure that its data and findings contribute to ongoing efforts to enhance land model performance and reduce uncertainties in global projections as a result of tropical forest responses to climate and land-use change. For instance, one important partner of PANGEA is the ILAMB project (Collier at al., 2018). Data collected through PANGEA and derived products developed through data synthesis can become new benchmarks on processes that currently show high uncertainty among datasets (e.g., gross primary productivity) or are absent in ILAMB (e.g., vegetation demography, plant hydraulics). Similarly, PANGEA will collaborate with PEcAn (Predictive Ecosystem Analyzer; LeBauer et al., 2013), which focuses on leveraging field and satellite datasets to optimize model parameters and improve carbon and water flux predictions (Dokoohaki et al., 2022; Meunier et al., 2021). PANGEA will collaborate with process-based model communities that successfully integrated remote sensing observations of vegetation demography, such as the Ecosystem Demography Model (ED2; Antonarakis et al., 2014; Longo et al., 2020). Another key partner is NGEE-Tropics, which, while scheduled to end around the time PANGEA enters its most active phase, provides a rich foundation of modeling tools including the FATES model (Functionally Assembled Terrestrial Ecosystem Simulator; Koven et al., 2020), and extensive experience in designing and executing field campaigns to collect data aiming at reducing model uncertainty. PANGEA can also count on partnership with a transdisciplinary team of scientists and technologists, recently funded by NASA's Advanced Information Systems Technology (AIST) program that will develop an Earth System Digital Twin (ESDT) titled "Central Africa Carbon Storage and Biodiversity Corridors." This ESDT integrates extensive advanced remote sensing data on carbon and biodiversity, socio-economic data, and animal movement models into Earth system models. Its purpose is to assess the current and projected status of forest carbon stocks and biodiversity, evaluate the effectiveness of conservation strategies, and analyze the potential impacts of global actions such as the Paris Agreement and REDD+ on Central Africa's ecosystems. Finally, the Global Modeling and Assimilation Office (GMAO) can complement PANGEA's efforts with advanced data assimilation techniques that can be used for benchmarks and boundary conditions for predictive models of tropical forest dynamics. Examples of products include the SMAP Level-4 products on soil temperature and soil moisture in the rooting zone (Reichle et al., 2019) and the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2, Gelaro et al., 2017).

In addition to the communities developing process-based models, data synthesis products, and benchmarking workflows, PANGEA aims to collaborate with initiatives that directly assimilate remote sensing data into model predictions. For example, inverse modeling will play a critical role in PANGEA's coordination strategy, offering a framework for reconciling discrepancies between observed and simulated ecosystem fluxes. This technique will help assimilate large-scale satellite-derived datasets with field measurements, allowing for refined predictions of carbon and water dynamics in tropical biomes (Liu et al., 2016). PANGEA also aims to collaborate with innovative modeling efforts such as the NASA-CASA (NASA Carnegie-Ames-Stanford ecosystem model; Potter et al., 1993; 2012) and CARDAMOM

(CARbon DAta-MOdel fraMework; Bloom et al., 2020), which combine satellite and ground-based acquisitions for carbon cycle data assimilation and modeling and have been effectively applied in OSSEs (Philip et al., 2019). Finally, collaboration with CliMA (Climate Modeling Alliance; Schneider et al., 2017), which is developing a cutting-edge Earth system model that integrates machine learning and data assimilation techniques, will enhance PANGEA's ability to scale tropical forest observations. These collaborations will help bridge the gap between field data collection and predictive modeling, driving new insights into the functioning of tropical ecosystems and their role in the Earth system.

6.3.3 Modeling and Data Integration Activities

Modeling and data synthesis activities will occur throughout PANGEA. However, such tasks will shift focus as the project progresses. Once a Science Team is selected for PANGEA, a Modeling and Data Synthesis Working Group (SWG) will be established. This group will identify key areas and processes that currently drive uncertainty in process-based models related to carbon, water, energy, and nutrient cycles, as well as biodiversity and human interactions in tropical moist forests. The group will develop model intercomparison efforts using established benchmarking (e.g., TRENDY, FLUXCOM) and tools (e.g., ILAMB) to inform the project design. The SWG will also seek rapid responses through the use of approaches based on Observing System Simulation Experiments (OSSEs) using existing models and drivers to provide a first assessment of key areas of uncertainty and areas that lack representativeness in existing observations.

After initial evaluations and OSSE efforts, SWG focus will shift to multiple, complementary goals. Activities linked to process-based models will focus on implementing key missing mechanisms identified during Phase 1, which will advance understanding of the drivers of observed patterns on carbon, water, energy, and nutrient cycles in the field campaigns. Activities linked to synthesis will enable the upscaling of findings from local and regional to the global scales. Data synthesis research will focus on using PANGEA datasets to generate products at scales that can be assimilated by inverse and hybrid models, as well as used for benchmarking of process-based models. Synthesis approaches will include, but will not be limited to, artificial intelligence, machine learning, and space-for-time substitution. Group members working with inverse and hybrid models will use PANGEA datasets and derived synthesis products for quantifying uncertainty in scaled quantification of state variables and fluxes. Efforts will not focus on a single set of models and techniques, but rather bring together methods that allow for scaling of space- and time-limited measurements to the entire pantropical region along with robust estimates of uncertainty.

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

7 Capacity Building, Training, and Education

Strengthening capacity for U.S. and tropical country participants through investing in training, education, and knowledge exchange is fundamental for the success of PANGEA, and critical for preparing the next generation of scientists with the necessary expertise and tools to fully leverage NASA's Earth Observing System (EOS), and knowledge of social-ecological systems, and scientific methods and data management and analyses and scientific model development. PANGEA capacity building, training, and education will engage with U.S.-based research and workforce communities, and local and national communities in tropical forest countries partnering with PANGEA. Experience gained during prior TE field projects, especially LBA, demonstrated that capacity building built in longevity to the projects and justified the projects to host countries. PANGEA will partner with existing NASA programs, as well as with local and international collaborating institutions, to plan and engage in knowledge exchange, capacity building, training, and educational activities that are appropriate for a range of potential participants, including students, early career scientists, the broader workforce, Indigenous Peoples and Local Communities (IPLCs), and scientists. Capacity building, training, and education will focus on encouraging the participation of IPLCs, the broader workforce, and a cohort of undergraduate and graduate students.

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

7.1 Workforce Development

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

7.2 Educating a Cohort of Graduate Students

PANGEA will provide a unique opportunity for a generation of undergraduate and graduate students from across the United States and the host tropical countries to develop highly integrative and transdisciplinary research. PANGEA's scientific goals will allow students to understand tropical ecosystems and their importance for the planet, appreciate social ecological systems and carry out data-intensive research projects using both field observations and remote sensing datasets, and to develop critical skills in data synthesis (including artificial intelligence, machine learning and data assimilation) as well as process-based modeling. Equipping students with the skills to understand the importance of and promote the conservation and sustainable management of tropical forest landscapes, managing "big data," artificial intelligence, and computationally intensive modeling, will prepare students for multiple career opportunities in academia, government and industry. In addition, the implementation of the PANGEA project will be inherently collaborative, and will bring together scientists from multiple institutions and universities, both within the U.S. and internationally. By participating in fieldwork activities and scientific events, undergraduate and graduate students will directly interact and collaborate with researchers based at NASA and other U.S. agencies (e.g., DOE, USFS, USGS). This will open possibilities for students to pursue long-term careers at these agencies and pursue private sector and entrepreneurial activities in related sectors. PANGEA will enable students to develop the collaborative critical thinking skills required for multi-institutional and international partnerships.

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

PANGEA's biggest opportunity for capacity building and training is within the Science Team. Following LBA and BioSCape models, NASA can encourage or require that proposals be co-developed with local researchers. These requirements ensured that about 50% of the BioSCape science team was from South African institutions. Likewise, PANGEA funding announcements can require or strongly encourage training, education, and capacity building as part of the proposed activities, similar to what was achieved during LBA. PANGEA can work directly with existing initiatives like the Amazon Institute of Technology (AmIT), the LBA Phase 3 team, the Congo Basin Science Initiative (CBSI), Central African Forest Research Network (R2FAC), and the Applied Research in Ecology and Social Sciences program (RESSAC) to achieve this objective.

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

Another important goal of PANGEA's capacity building strategy is to strengthen and grow the NASA Earth data user community in the tropics, including Indigenous peoples and local communities. PANGEA's airborne activities will generate a lot of excitement around the potential of remote sensing for many applications, including applications focused on climate change mitigation and carbon monitoring, biodiversity conservation, sustainable agriculture and disaster risk prevention and monitoring. The diverse user group will benefit greatly from PANGEA's methodological advances for using NASA's satellite assets. PANGEA will use the momentum created by the airborne campaigns to catalyze and promote broader application of NASA spaceborne datasets, particularly those that are well suited for examination alongside the airborne data products, e.g., EMIT, PACE, ECOSTRESS, GEDI, and in the future NISAR and SBG. Working with regional partners, PANGEA will collaborate with host countries on the development of national data banks so that the emerging knowledge from PANGEA can be integrated with and applied to regional and national demands for socio-economic promotion and policy development. PANGEA's approach to capacity building intends to build NASA Early Adopter user groups in the tropics - particularly for NISAR and SBG, as well as for ESA missions like BIOMASS, CHIME, and FLEX. PANGEA will draw upon NASA's Earth Science to Action strategy to "build capacity through an extensive and diverse set of partnerships, both traditional and new" (St Germain, 2024 - ES2A Strategic Plan). PANGEA's partners will include "national and international governmental agencies, academia, nongovernmental and international organizations, the private sector, and philanthropies," consistent with that strategy. PANGEA will partner with existing NASA programs and training efforts led by partners, in line with the goal of "leveraging existing value-amplifying initiatives" that "could be national or international" to "achieve both depth and wide breadth in our impact and support to humanity while being cost effective" (St Germain, 2024 - ES2A Strategic Plan). Examples are included in **Table 7**.

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

8 Community Engagement Strategy

PANGEA will engage with diverse communities to address science questions, identify synergies with local research priorities, and implement PANGEA in a manner that is beneficial in the landscapes and countries that will participate in this research, and that establishes and strengthens long-term partnerships between U.S.-based and international institutions. The strategy draws upon the knowledge, expertise, and experiences shared throughout PANGEA's scoping study, which engaged with over 800 individuals and 300 organizations from 42 countries across 5 continents through (a) consultative workshops, (b) outreach events, (c) working group discussions, (d) bilateral meetings, and (e) web surveys. Within the U.S., PANGEA has engaged with more than 110 federal agencies and U.S. institutions across 30 states and Washington, DC. A more detailed description of engagement methods used during the scoping study is provided in *Appendix C*. Here, we present a list of the communities prioritized for engagement in PANGEA, the principles that underpin PANGEA's engagement efforts, and PANGEA's strategy for engaging local communities and cultivating a long-term, positive legacy during and beyond the project.

Table 7. Potential partners and providers that could collaborate with PANGEA for training and capacity building activities.

PARTNER	ACTIVITY	TARGET AUDIENCE
AI4ESP	Work with AI4ESP (Artificial Intelligence for Earth System Predictability) to integrate AI with ES models to improve predictive capabilities, tackle scientific challenges, and improve data integration and observation techniques.	Researchers and students, decision-makers
AIMS	Postgraduate training, research, and public engagement in math, science, and machine learning. The AIMS network has 5 centers of excellence teaching African Masters in Machine Intelligence (AMMI), including in Cameroon, Ghana, and Rwanda. The AIMS network has over 2,400 alumni from 44 African countries of which 33% are women.	African students
ARSET	Multipart training webinar series, building on the in-person training model trialed during BioSCape.	Decision-makers, academics, scientists
ATBC	Trainings, workshops, and networking among researchers pantropically with the Association for Tropical Biology and Conservation (ATBC) who promotes research, education, and communication on tropical biology and conservation. ATBC has ~1,000 members from 70 countries and supports capacity building and hosts international meetings.	ATBC members from over 70 countries
DAACs	Training notebooks and workshops modeled on those already presented at conferences (e.g., AGU, ESA, ATBC) facilitating access to NASA EOS.	Researchers at all career stages
DEVELOP	Partner with decision makers who are interested in using NASA Earth data to support their work. Each partner would have a DEVELOP team of 4-5 people work with them over 10 weeks (renewable) to develop capacity to use NASA Earth data to address their needs.	Decision makers and the broader workforce
FLUXNET	Training and tools to use/analyze eddy covariance flux tower data, including in multiple languages (currently in Spanish & English). PANGEA will work with FLUXNET to extend translation to French and Portuguese and develop new training materials that integrate remote sensing and flux-tower data.	Researchers and students
GLOBE	Locally tailored educational activities for K-12 students, teachers, and citizens including train-the-trainer elements allowing multiplication. Opportunity to channel excitement of airborne campaigns and Earth Observation data.	K-12 students, teachers, and citizens
INDIGENOUS PEOPLES INITIATIVE	Collaborate with Indigenous communities to enhance the use of EOS for informed decision-making. PANGEA developed partnerships with Indigenous alliance organizations in the tropics, including the GATC and RRI, and will coordinate with NASA's Indigenous Peoples Initiative to extend efforts to co-develop trainings, support Indigenous-led projects, strengthen relationships, and create opportunities for Indigenous inclusion in NASA's ESD.	Indigenous communities
NSF RISE	Foster transdisciplinary collaborations that engage the broader geosciences community to drive discoveries and innovations in workforce development.	Researchers and students
SELPER	Identify partnership opportunities with SELPER, the Latin American Society for Remote Sensing and Space Information Systems to develop remote sensing training and research activities across Latin American countries. SELPER promotes these activities at workshops, symposia, and short courses, often with partnership with the broader international community.	SELPER members and participants of scientific meetings
SERVIR	Coordinate with SERVIR hubs to develop custom services for the specific decision-making needs of local partner organizations, building on SERVIR's Planning Toolkit to provide regionally targeted instruction on how to assess and deliver impactful agriculture, forest restoration, and other interventions.	SERVIR hubs, implementing partners (local and national governments, NGOs)

8.1 PANGEA Co-Development and Partners

PANGEA research on tropical forests will complement and expand upon many existing efforts. Data acquired during the PANGEA field campaigns will be used for initializing, assessing, and constraining predictions of multiple process-based terrestrial ecosystem models and Earth System Models across tropical forests. Examples of models include FATES, a model whose development is supported by DOE through NGEE-Tropics, as well as multiple models with current and previous support by NASA, such as BiomeE (NASA-GISS), ED2 (led by Harvard University), ED3 (University of Maryland), CliMA's land component (California Institute of Technology and JPL), and CARDAMOM (JPL) (*Section 6.3*). PANGEA will enhance SilvaCarbon's efforts by incorporating a broader range of field sites and remote sensing data, offering deeper insights into carbon dynamics and forest processes at regional and global scales while strengthening its monitoring, reporting, and verification (MRV) analyses. Improved understanding and analyses of carbon dynamics and ecosystem functions will be key elements to inform USDA USFS International Program to develop forest management and conservation strategies with international organizations. Some of these efforts are limited to small geographical areas or represent networks of individual sites. Others, such as the One Forest Vision initiative (OFVi) and GEO-TREES, have pantropical ambitions like PANGEA. The range of partnership opportunities is illustrated with examples in **Table 5** and **Table B-1**. *Appendix B* describes in greater detail the communities with which PANGEA will engage, lists the current PANGEA partners according to community type, and discusses more specific engagement considerations for each.

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

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

8.2 Diversity, Equity, and Inclusion Principles

PANGEA will prioritize diversity, equity, and inclusion (DEI) across all of its activities, such as PANGEA project management, access to resources and training opportunities, and during community engagement, by ensuring accessibility, requiring DEI and cultural awareness training, and establishing feedback mechanisms to ensure that DEI policies are being adhered to. PANGEA developed **Community Guidelines** and a **Code of Conduct** for the scoping study will serve as foundational material for a project Code of Conduct. A starting point will be the policies implemented by NASA's Office of Diversity and Equal Opportunity (ODEO, https://www.nasa.gov/odeo/). Organizations such as the Association for Tropical Biology and Conservation (ATBC) have established specific standards for the tropical research community, which spans many languages, cultures, customs, and norms. Upon selection, PANGEA will implement a Code of Conduct considering existing precedents, make it publicly available, and ensure that research groups are aware of and agree with the code upon joining the project. The Code of Conduct will include clear mechanisms for reporting and dealing with deviations from the code of conduct and a professional in DEI support will be appointed to manage this for PANGEA. PANGEA is also committed to gender balance and will implement proactive efforts to ensure inclusivity, such as promoting leadership roles for females and historically underrepresented groups and providing mentorship opportunities. PANGEA aims to make significant strides by fostering gender-responsive practices and tracking over time key performance indicators such as gender representation in leadership and participation. PANGEA will also engage Indigenous peoples and local Communities. In doing so, PANGEA will implement and build on principles adapted from the Collective Benefit, Authority to Control, Responsibility, and Ethics (CARE) Principles for Indigenous Data Governance to conduct ecology and biodiversity research based on work by Jennings et al. (2023) and Carroll et al. (2020). **Table 8** outlines PANGEA's principles of engagement based on CARE. See *Section 10.3* for the integration of these principles with PANGEA's Open Science strategy.

Table 8. PANGEA principles of engagement based on CARE.

Adapted from Jennings et al. (2023) and Carroll et al. (2020). IPLCs: Indigenous Peoples and Local Communities.

CARE Principles	Issues	PANGEA Strategy
Collective Benefit	Research that benefits communities	Prior to research, explain and demonstrate how research and potential results are relevant and are of value to the interests of the community and individual members; PANGEA research will work to support community-led initiatives and help secure funding for long-term investments in the community.
	Data grounded in community values, aspirations and well-being	PANGEA will co-develop and/or link to Indigenous Peoples and Local Communities (IPLC) data classification and analysis frameworks that reflect community values, needs and aspirations; local community experts will be included in research teams.
	Data for self-determined development	PANGEA will collect and code data using categories that identify information and individuals using community norms; Where possible, data will be disaggregated, especially from global or large geospatial datasets, to increase relevance for IPLCs
	Compensate local experts	PANGEA will work hard to locate funding sources to be able to compensate community experts throughout the research process, including research proposal development, data collection, manuscript writing and community review of prepublication manuscripts.
Authority to Control	Recognize IPLC's rights to and interests in their knowledges and data	Principles and protocols for research development, data management and publication that support IPLC's Data Sovereignty will be co-developed; These will include metadata fields available for disclosure of Indigenous rights and interests.
	Recognize the rights of IPLCs to free, prior and informed consent	PANGEA will ensure data use is consistent with individual and community consent provisions and ensure ongoing consent processes, including the ability to refuse, withdraw and reconsent.
	Data available for IPLC governance	PANGEA will ensure IPLCs, and the appropriate tribal authorities, have access to data, metadata about their people, communities and non-human relations in a usable format.
	Develop and enact IPLC Data Governance protocols	IPLC partners will co-develop data and data protocols, and will use and/or incorporate IPLC frameworks and principles to inform data management protocols and processes; IPLC guidance will influence how, what, who and where research is conducted and data is managed, as well as publication standards, which will document community support, participation and approval for publishing data and authorship.

CARE Principles	Issues	PANGEA Strategy
Responsibility	Enable capability and capacity sharing for research design and digital infrastructure	PANGEA will create and expand opportunities for community capacity through (1) participatory methodologies including planning and design, knowledge management and data workforce capacity building, and (2) initiatives to enable the design, collection, management, storage, security, governance, collective privacy and application of data.
	Respect reciprocity, trust and mutual understanding with those to whom data relate	PANGEA will record Traditional Knowledge and biocultural labels in metadata and will establish a system to ensure local review of draft publications before dissemination; PANGEA will also identify and address sensitive data, including privacy issues for individuals and communities.
	Data-generating resources for languages, worldviews and lived experiences	PANGEA will work hard to use the local and Indigenous languages, link research to community worldviews, and upload data with appropriate metadata labels in culturally accessible formats (digital storytelling, seasonal calendars, visual art forms, etc.).
	Community-defined benefit sharing	PANGEA will conduct research that is of mutual benefit, consent driven, inclusive and relevant to the needs of IPLCs and individuals.
Ethics	Align with Indigenous and local ethical frameworks	Indigenous ethical frameworks will be used in the co-development process and community-defined review process will be developed for activities delineated in data management plans.
	Maximize benefits from the perspectives of IPLCs	PANGEA researchers will include IPLCs and PANGEA researchers will explain benefits to IPLCs, including identifying and contributing to community-defined benefits. Potential financial gain will be disclosed and benefits will be shared with communities from research outputs and/or economic value of data.
	Minimize harms from the perspectives of IPLCs	PANGEA's community-defined code of conduct will be accessible and incorporate IPLC ethical frameworks; Data-access protocols will consider the potential for community harm, which will be remedied through sharing data; ensuring ongoing consent.
	Data governance accounts for potential future use	Community protocols will be applied for infrastructure, metadata and secondary use; Traditional Knowledge and biocultural labels will be included in metadata fields, as will community and/or tribal affiliation; Community guidelines will be established for the use and reuse of data; Provenance will be recorded and recognized.

8.3 Engagement Strategy

PANGEA activities will coordinate with existing and future projects from other agencies and other nations. Building on lessons learned from the Brazil-led LBA program, PANGEA will promote an international scientific steering committee (SSC). The SSC will reinforce and coordinate with existing organizations, alliances, and activities to ensure that PANGEA supports the development of a long-term network of networks that will enhance and sustain the accessibility, usability, transferability and benefits of the data, methods, models, and knowledge about tropical ecosystems. PANGEA's SSC will co-develop strategies to ensure that scientists, local institutions, and communities work together throughout the PANGEA project to effectively collaborate in diverse geographic and cultural contexts. During LBA, the SSC met twice annually and served as a clearinghouse for information across national projects. This committee had a number of attributions including the recommendation of projects for inclusion in LBA based on criteria such as subject matter, adequacy of counterpart arrangements, and capacity building plans. The SSC shouldered much of the burden that may have otherwise fallen to national agency managers. Existing organizations such as the Congo Basin Science Initiative and the extant Brazilian LBA are primed to serve as partners for coordination of PANGEA scientific studies. Similarly, PANGEA established relationships with the GATC during the scoping process. The GATC, built over 10 years by tropical Indigenous communities, represents 24 countries and over 35 million people who occupy over 958 million hectares of land. The partnership with GATC will support PANGEA's ability to engage Indigenous communities in a meaningful and mutually beneficial way.

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

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

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

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

PANGEA's applications also have strong potential to engage the private sector, including, but not limited to (a) agribusinesses and cooperatives cultivating and/or harvesting agricultural, timber and forest non-timber products; (b) extractive industries; (c) energy companies; (d) big data companies; (e) conglomerates and financing institutions that invest in, buy, and/or sell any of the aforementioned types of companies; and (f) companies involved in ecotourism. The profile of companies present in each landscape where PANGEA is implemented will vary ranging from corporations to small and medium-size enterprises, cooperatives, and associations.

9 Enabling Earth Science to Action

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

Achieving PANGEA's science and measurement objectives will advance monitoring capabilities in tropical forest biomes in ways that address direct end-user needs, where data and knowledge gaps otherwise limit the utility of new and forthcoming satellite sensors. This section presents the ways PANGEA will enable Earth Science to Action (ES2A) in critical fields like climate change and carbon monitoring, biodiversity conservation, and sustainable agriculture and livelihoods. Uptake of research products requires meaningful end user engagement, so this section also details the current and future processes that the project employs to ensure uptake of research outputs by users. PANGEA's early, intensive, and diverse engagement of partners during the scoping phase for co-design is foundational to ensure the uptake and use of data products. Engagement of potential end users at a diverse range of fora like Biodiversity COP 16 in Colombia have demonstrated interest in PANGEA's products from a wide variety of potential end users, including private sector, government, NGO, and academic actors. Based on feedback from the scoping phase (see *Appendices C and F*), PANGEA data products will be highly accessible and user-friendly, and will include information on scaling approaches, offer educational materials, and continue a bidirectional dialog that raises awareness about PANGEA and its products while collecting feedback on user needs. PANGEA plans to advance methodologies to weave local, traditional, and ecological knowledge with remote sensing data, which offers both opportunities for improved scientific understanding, and unearths novel routes to put PANGEA products in the hands of decision makers and action takers.

9.1 Applications of PANGEA Research Outputs

9.1.1 Carbon Sequestration Stability and Methane Fluxes

Table 9. PANGEA research applications for carbon sequestration stability and methane fluxes.
GCF-TF: Governors' Climate and Forests Task Force. OSFAC: Satellite Observatory of Central African Forests.

Science Questions	Research Application	Potential Partners and/or Outlets for Impact
Q1, Q2, Q3, Q8, Q15, Q16, Q18–Q20, Q25, Q27	Mapping and quantifying **carbon sequestration long-term stability** (i.e., permanence in carbon markets)	U.S. GHG Center, GEO-TREES, CTrees, Land and Carbon Lab (WRI), OSFAC, GCF-TF, Woodwell, SilvaCarbon, IPCC
Q1, Q2, Q3, Q18, Q27	Mapping and quantifying tropical **methane flux predictions**	U.S. GHG Center, SERVIR, WRI

Mapping and monitoring tropical carbon stocks and fluxes: These activities are critical for closing the global carbon budget, constraining climate projections, and for improving measurement, reporting, and validation (MRV) of carbon credits. This requires improving climate projections by decreasing uncertainty around carbon fluxes of tropical forests, tropical land-use changes, and tropical forest responses to climate shifts. Results from PANGEA can improve our understanding of the carbon budget, support carbon markets, and improve understanding of CH_4 emissions. PANGEA will coordinate with the U.S. Greenhouse Gas Center activity to determine areas of alignment and opportunities for PANGEA to contribute data and understanding that meet stakeholder needs (National GHG MMIS Strategy, 2023).

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

Improving the carbon finance market: Carbon financing approaches have gained popularity across tropical communities and involve polluting entities transferring payments to local governments and communities for various carbon emission remediations including forest protection, reforestation, enhanced forest management, and the establishment of forest plantations (Anderegg et al., 2020; Morita & Matsumoto, 2023). However, carbon markets are constrained by a lack of confidence in methods, high monitoring costs, and increasing concerns related to their long-term viability (Anderegg et al., 2020; Pan et al., 2024). PANGEA's advancements of process-based understanding, tropical carbon stocks and flux mapping, and constrained spatially explicit model predictions of the future tropical land sink can directly support tools for mapping and quantifying the long-term stability of tropical forest carbon sequestration including

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

Mapping and quantifying methane flux predictions: Uncertainty in predicting future methane emissions from the tropics could lead to inaccurate global climate predictions, making it difficult to assess the full scope of climate change impacts. By improving our understanding of tropical methane fluxes, we can refine global carbon budgets, better anticipate future climate shifts, and inform more effective mitigation strategies to curb greenhouse gas emissions. PANGEA will advance natural and anthropogenic tropical methane flux monitoring capabilities using satellite remote sensing in alignment with needs and activities emerging from the U.S. Greenhouse Gas Center. These efforts will be carried out in collaboration with partners like SERVIR regional hubs and the Land and Carbon Lab led by the World Resources Institute to advance capabilities from local technical expertise to global mapping and monitoring applications.

9.1.2 Biodiversity Conservation

Table 10. PANGEA research applications for biodiversity conservation.

Science Questions	Research Application	Potential Partners and/or Outlets for Impact
Q5, Q6, Q7, Q10, Q11, Q12, Q13, Q17	Biodiversity mapping to support **landscape connectivity** and **corridor implementation** and **tropical forest restoration** (in alignment with Ecosystem Atlas)	Alexander von Humboldt Biological Resources Research Institute, Alliance Bioversity CIAT, OSFAC, Conservation International, European Space Agency, IUCN Regional Offices, AFR100
Q5, Q6, Q10, Q11, Q12, Q13, Q17, Q23-24, Q26, Q28,	Empowering and elevating Indigenous, local, and traditional communities through the **integration of IEK, LEK, and TEK with remote sensing**	NASA Indigenous Peoples Initiative, Global Alliance of Territorial Communities, Rights & Resources Initiative, Congo Basin Institute School for Indigenous and Local Knowledge, MapBiomas, Woodwell Climate Research Center

The first Global Biodiversity Framework 2030 target is to "Plan and Manage all Areas To Reduce Biodiversity Loss" while respecting the rights of Indigenous peoples and local communities (CBD, 2030). Doing so requires a project on the scale of PANGEA. Targets 2 and 3 are to restore 30% of all degraded ecosystems, and conserve 30% of all land, water, and sea. However, data scarcity and quality concerns have limited the ability to even assess progress against these targets (Forest Declaration Assessment, 2024). PANGEA will support biodiversity conservation in three ways:

Improved understanding of biodiversity: PANGEA will advance understanding of biodiversity across a range of scales. The Group on Earth Observations (GEO) Global Ecosystems Atlas effort, supported by the Convention on Biological Diversity (CBD) and United Nations Framework Convention on Climate Change (UNFCCC), is working to unite high-quality global, regional, and national ecosystem maps into a single, open, online resource. The Global Ecosystem Atlas is prioritizing mapping "structure and function of the world's ecosystems in unprecedented detail." **PANGEA will fill major calibration and validation data gaps in Earth's most diverse biome and will directly support this effort in collaboration with the U.S. Geological Survey (USGS), European Space Agency (ESA), International Union for Conservation of Nature (IUCN), Environmental Systems Research**

Institute, Inc. (ESRI), and others. Likewise, PANGEA will catalyze NASA remote sensing of Essential Biodiversity Variables (EBVs) like the biological effects of fire and irregular inundation to address high-priority data gaps identified by the Group on Earth Observations Biodiversity Observation Network (GEO BON; Skidmore et al., 2021). PANGEA understands that weaving diverse knowledge sources improves overall understanding and will specifically prioritize engagement with Indigenous Peoples and Local Community alliances and organizations to empower and elevate Indigenous, local, and traditional communities through the **integration of Indigenous, local, and traditional knowledge (IEK, LEK, TEK) with remote sensing**. PANGEA will support efforts initiated and led by the Global Alliance of Territorial Communities (GATC), whose women's movement is already conducting drone data-collection training, and the Rights and Resources Initiative (RRI), who has partnered with Woodwell in the past to quantify and estimate the carbon stored in Indigenous, Afro-descendent, and local community lands (Policy Brief, Research Report). There is strong interest in similar initiatives emphasizing biodiversity.

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

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

9.1.3 Sustainable Agriculture and Livelihoods

Table 11. PANGEA research applications for sustainable agriculture and livelihoods.

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

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

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

Increased sustainability and capacity for adaptation: Agriculture under climate change will require farmers to grow more food under increasingly unpredictable circumstances, including shifting precipitation regimes and periods of intense heat. As a major contributor to climate change, there is also a movement to make agriculture more sustainable, through decreased use of fertilizers and pesticides, curtailed water use, and increased efforts to control erosion based on remote sensing of crop needs. Such "precision agriculture" is already commonplace in the U.S. but is lacking in much of the tropics because the underlying data and methods are incomplete. PANGEA will work with colleagues from the International Institute for Tropical Agriculture (IITA), Alliance Bioversity-CIAT, and the International Water Management Institute (IWMI) to develop and deploy techniques like spatially explicit farm-scale crop health monitoring that will allow these organizations to identify threats to food security quickly and respond with mitigating measures.

Improved traceability: There is globally increasing demand to link agricultural commodities with the exact farm where they were grown, driven by both consumer demand and regulatory pressure from new policy regimes like the European Union Deforestation Free Commodities Regulations (EUDR) and a similar bill under consideration in the U.S. PANGEA will allow for the use of new sensors like NISAR, BIOMASS, and SBG to detect multiple forms of agricultural expansion into tropical forests, which will make it easier for agricultural commodities companies to assess the land-use change impact of their value chains. Companies like Satelligence will use data from PANGEA to demonstrate EUDR compliance for some of the largest food companies in the world. Methodological improvements from PANGEA's data acquisition may also improve our ability to use remote sensing tools to distinguish between complex agroforestry and secondary forests, currently a major gap that undermines the ability to recognize and map coffee and cocoa farms that use more sustainable shading methods. PANGEA will work with partners like Alliance Bioversity CIAT to apply these improvements to help farmers and farmer cooperatives demonstrate compliance and market high-value products. These activities also position PANGEA to impact other livelihood sectors, like payments for ecosystem services, bioeconomies, and non-timber forest products.

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

To deliver on potential gains for food security and livelihoods, PANGEA has engaged agricultural research partners like NASA Harvest, SERVIR, the Consultative Group for International Agricultural Research (CGIAR), including IITA and partners working at the nexus of forests and agriculture, including the CIAT, World Resources Institute and Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF). Information shared by these partners during the PANGEA scoping process directly informed PANGEA's science questions to potentiate Earth Action outcomes. Partners such as IITA and CIAT specialize in translation of findings from research into practice and build on decades of experience with private sector and government partners.

9.2 Process to Enable Earth Science to Action

9.2.1 User Engagement

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

- **Amplify impact through partnerships:** PANGEA's investment in community engagement has attracted a diverse array of partners, including international governments, donors, and local communities (see *Section 8* for details about community engagement). These partners include potential users, data contributors, and potential funders for applications—the last of which will help make PANGEA's work cost effective by supplementing NASA's Earth Science resources with funds to support capacity building, community engagement, and research translation (see *Section 10.2, Co-Funding Opportunities,* for additional information). PANGEA also brings extensive international partnerships, ranging from national space agencies that could provide complementary data to tropical communities who will participate in data collection and potentially in use and action. PANGEA engaged these partners early in the process to increase their investment and their input in co-development of potential end products.
- **Engage a diverse workforce and broader Earth Science community:** PANGEA's transdisciplinary goals are supported by a diverse team that ranges from data scientists to economists and hail from NASA, academia, non-profit organizations, other federal agencies, and governments from around the world. PANGEA's extensive international engagement also offers opportunities to work with and recruit the best minds globally to NASA's Earth Science efforts, while the capacity building and training efforts (see *Section 7*) help ready the next generation of scientists.

During the Scoping Phase, PANGEA led extensive outreach to potential users (see *Appendix B*), and engaged with potential users about what questions and data are most valuable to them. As a result, PANGEA has worked since its inception to bridge the difficult gap between what science questions are being asked and what end users need for decision making. Community engagement is central to PANGEA's ES2A strategy (see *Section 8* for details on how PANGEA will engage the community). We are aware that community engagement comes with the risk of creating expectations that cannot be met by the project, largely because the airborne data being collected are spatiotemporally limited in scope and will be more episodic than needed to meet many user applications and decision-making needs. PANGEA will make every effort to repeatedly and clearly convey the limitations of project data, which are necessarily limited spatially and temporally. PANGEA will also endeavor to leverage the momentum created by a brief but intense project period to create, grow, and strengthen a new and more diverse user community for NASA Earth data. The depth and reach of PANGEA's engagement will be contingent on funding and is a priority in co-funding opportunities.

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

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

9.2.2 Supporting Application of PANGEA Research

PANGEA will harness its existing and planned partner engagement to integrate ES2A holistically into the project. This includes conducting a user needs assessment as part of the Concise Experiment Plan and conducting an environmental scan to identify existing tools that could integrate data. This is particularly important because integration into existing tools usually increases the likelihood of uptake, use, and maintenance in the long term. **Figure 20** demonstrates PANGEA's approach to advancing results through NASA's Application Readiness Levels (ARLs), which will hinge on combining strong subject matter alignment with thoughtful, early, and inclusive partner engagement. While the example is displayed as a linear process using NASA's ARL framework, PANGEA expects our ES2A activities to be iterative, and at times non-linear, which is representative of the complexities that define real-world policy and decision making.

NASA, along with other domestic and international agencies, are increasingly playing a leading role in the development and implementation of decision support systems. These systems are designed to incorporate the results from research activities within a modeling framework in order to provide information to land managers, subnational and national governments, among others who require information in a specific context. The PANGEA Information Portal (PIP) will provide a platform to conduct further research on the use of

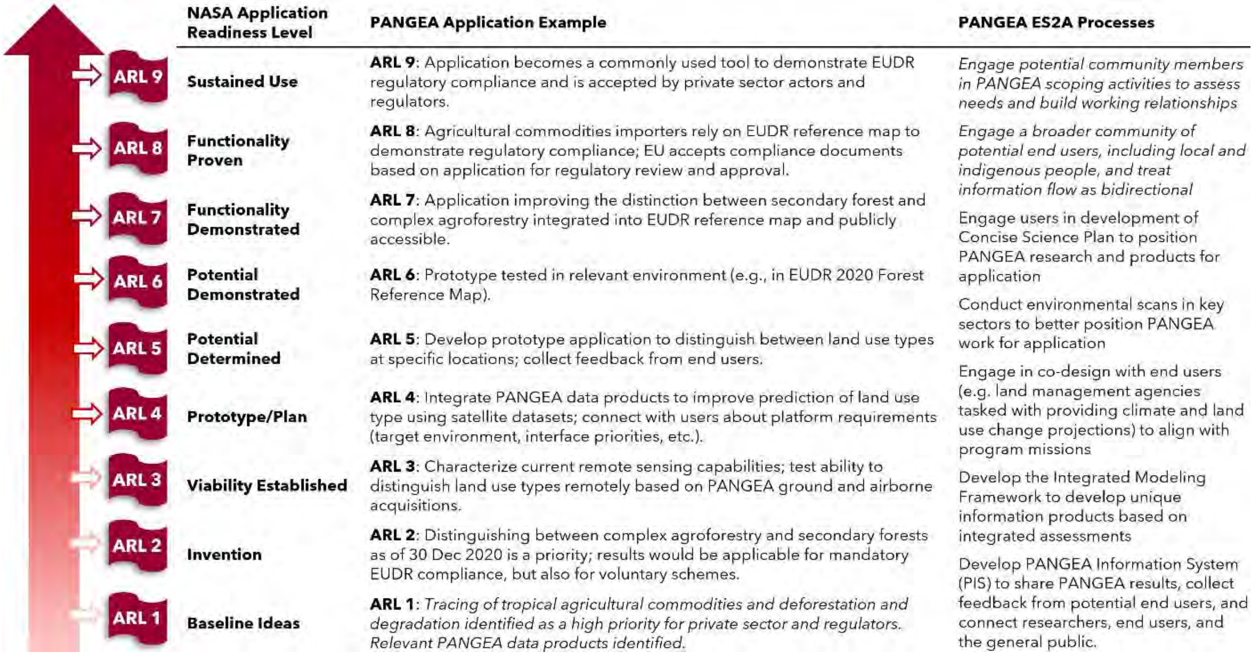

Figure 20. Example Application Readiness Level strategy for PANGEA focused on support for the European Union Deforestation Regulation (EUDR). Similar regulation is under consideration in the U.S.

satellite information products to support decision making. It will be a critical platform for PANGEA researchers to interact at multiple levels with scientists and managers at agencies who are responsible for assessing the impacts of climate change in tropical regions, as well as the media and general public. PANGEA's Integrated Modeling Framework will provide another scaffold for ES2A activities by creating unique information products based upon integrated assessments.

There is increasing recognition by NASA and other U.S. and international agencies of the need to co-develop decision support systems to exchange information and analysis with land managers, governments, and other policy and decision makers. PANGEA will co-develop products with these partners who are responsible for the provision of data required for climate and land cover change monitoring. The process-driven models that will be the focus of research in PANGEA align well with the missions of these offices. Researchers from these offices were involved in the PANGEA scoping process, and their input has informed research questions and seeded ideas for research application of PANGEA's results.

PANGEA also offers the opportunity to engage in transdisciplinary work and application, particularly given the interrelated nature of climate change, biodiversity conservation, and agricultural production, which are some of the main applications for PANGEA products. **Figure 21** demonstrates the potential overlap in these topics and highlights a small selection of the partners who are already engaged in work at the intersection of the different subject matter.

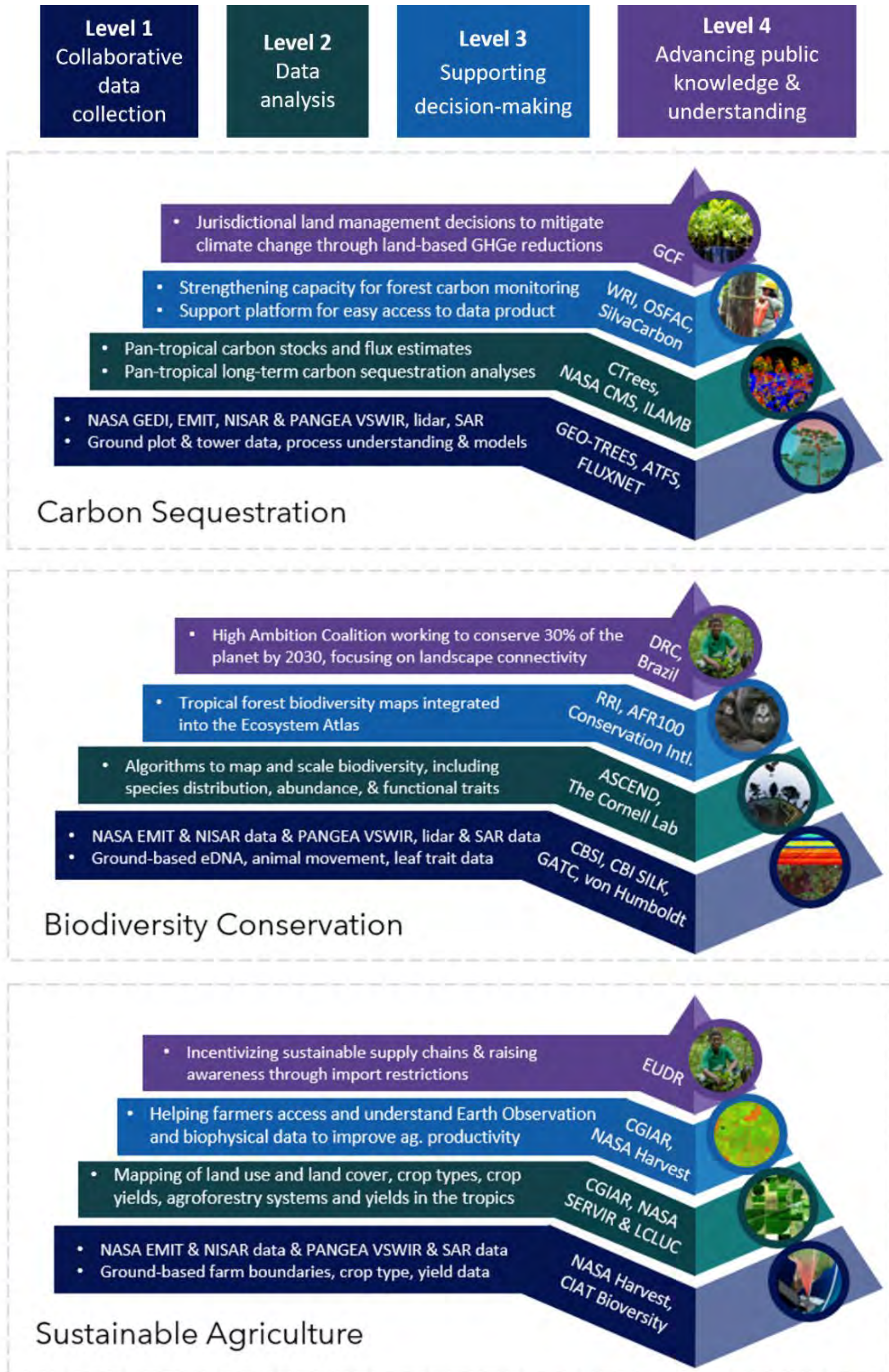

Figure 21. Example PANGEA Earth Science to Action strategy implementation, with a focus on carbon sequestration, biodiversity conservation, and sustainable agriculture and examples of partners already engaging in related activities.

10 Technical and Logistical Feasibility

PANGEA will leverage NASA's history of successful international field and airborne campaigns, including recent campaigns in the Americas, Africa, and Asia. A number of Earth Venture Suborbital (EVS) and other international NASA airborne campaigns have also demonstrated feasibility of NASA aircraft and NASA-contracted aircraft deploying internationally with in situ and remote sensing instruments in support of multi-year large-scale campaigns in the American tropics. In 2023, NASA JPL had a successful campaign with AVIRIS-NG collecting remote sensing data with a NASA contracted aircraft over Chile, Colombia, and Ecuador for methane point-source retrievals in coordination with each country. This built on previous successful campaigns in the region, including, for example, UAVSAR flights in Colombia, Ecuador, Peru, and French Guiana; AVIRIS flights in Colombia, Ecuador, and Chile; and LVIS in French Guiana. NASA has also planned AVIRIS flights in Panama and Costa Rica for 2025. In addition, NASA has done extensive research in Africa, including SAFARI, AfriSAR-1, AfriSAR-2, and BioSCape. There are also immense investments in Africa currently that will support important feasibility elements of PANGEA, including the Congo Basin Science Initiative (CBSI), CongoFlux, One Forest Vision, the Science Panel for the Congo, African Masters of Machine Intelligence (AMMI) via the African Institute for Mathematical Sciences (AIMS), existing NASA collaboration with the Gabonese Space Agency (AGEOS) and Satellite Observatory of Central African Forests (OSFAC), and GEO-TREES. The PANGEA team has been in contact with the U.S. State Department's Bureau of Oceans and International Environmental and Scientific Affairs, which is enthusiastically supportive of PANGEA and the benefits it would have for environmental and scientific diplomacy.

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

In cases where NASA aircraft cannot obtain overflight permission or acquire data using its own instrumentation, PANGEA will deploy commercial or other assets, such as commercial

ALS, commercial UAV-based instrumentation, or local instruments and aircraft to acquire the required airborne datasets. This is particularly important in Brazil, where NASA has historically encountered restrictions for ground observations using non-Brazilian instruments and aircraft. PANGEA will build on precedents employed by NASA and the U.S. government of using commercial airborne data providers to collect the required datasets (see *Section 6.2.4, Airborne Remote Sensing Observations*).

10.1 Organization and Management

The organization and coordination of PANGEA will be determined by NASA Program Management. We present a concept for organization and management that reflects a successful model used in ABoVE and LBA-ECO (**Figure 22**). This structure will enable the organization and management of a long-term project with significant investment from transdisciplinary partnerships and collaborations at the national and international scale.

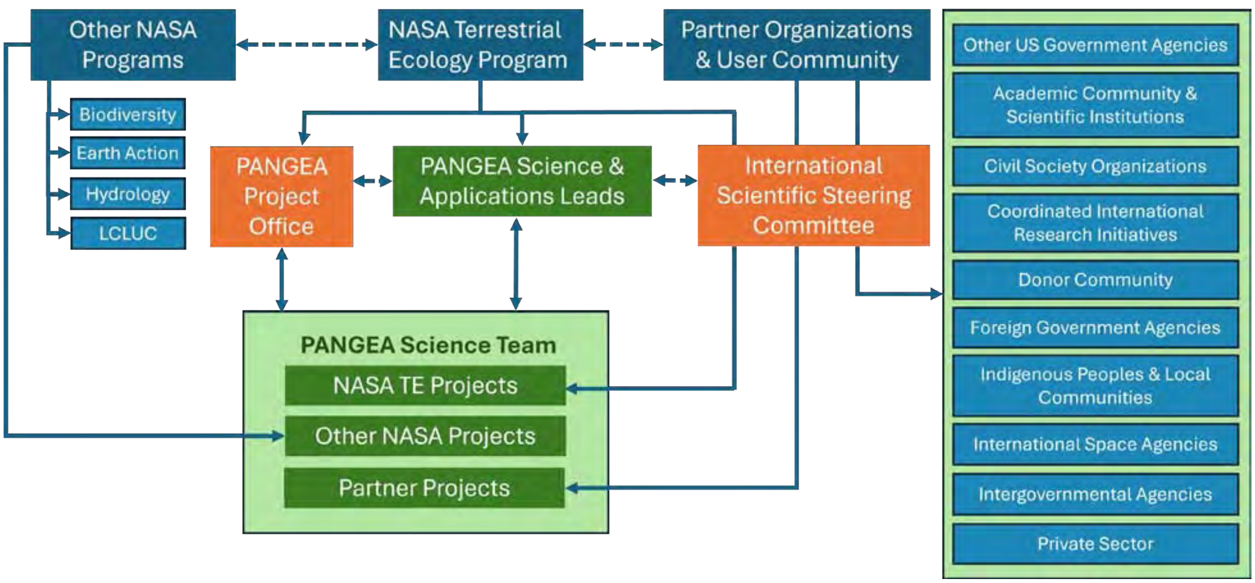

Figure 22. Proposed PANGEA organizational structure.

10.1.1 Program Management

The NASA Terrestrial Ecology *Program Management* will organize and oversee PANGEA with the support of the PANGEA *Project Office*. They will work within the NASA Earth Science Division to select and fund research projects conducted by the PANGEA *Science Team* for participation in PANGEA and to allocate resources to the PANGEA *Project Office* including the PANGEA *Project Scientist and Deputy Project Scientist* (jointly the *Scientific Leadership [SL])*, who are also selected by Program Management. Program Management will be responsible for representing PANGEA activities within NASA, including other NASA

Programs that may support PANGEA activities. Program management will coordinate PANGEA activities with other research partners from domestic and foreign agencies.

10.1.2 Project Office

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

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

10.1.3 Science Definition

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

10.1.4 Project Implementation

The PANGEA project will be implemented by the selected PANGEA Science Team supported by the Project Office over a nominal period of six to nine years as called for in the NASA announcement A.4 of 2022. A Project *Implementation Plan* will be elaborated based on the Concise Experiment Plan. The Project Office shall be responsible for the Implementation Plan including regular updates, the frequency of which will be determined in consultation with the Science Team and Program Management. The implementation plan shall detail the research activities to be conducted and specify roles and responsibilities for investigators involved in those activities during the execution of PANGEA. A notional timetable for project implementation is presented in *Section 10.4* (**Table 14**). At the outset of the project, approximately one year will be spent preparing for field and airborne data collection activities. The main period of data collection will extend from three to six years depending upon the overall project duration and scope. Analysis of the data collected will be continuous throughout the project. We expect data collection to draw gradually to a close one to three years prior to the conclusion of the project to allow time for data analysis, integration, and synthesis. PANGEA will leave a legacy of data and open science that will support future scientific investigations that will respond to the PANGEA science questions and to new science themes.

10.1.5 Science Team and Science Leadership

The *Science Team*, led by a Project Scientist and a Deputy Project Scientist, will be composed of Principal Investigators (PIs) and Co-Investigators (Co-Is) of selected investigations, as well as scientists recruited by those PIs and Co-Is, including postdoctoral scientists and students. In close coordination with the PANGEA Science Team, the Project Office, and Program Management the Project Scientist and Deputy will call and organize the agendas for regular PANGEA Science Team meetings. The Science Team will meet regularly, nominally with one in-person meeting annually. For virtual meetings, PANGEA will endeavor to arrange meetings considerate to the time zones of people represented. These meetings will advance Science Team planning, exchange of early results, and greatly facilitate interactions among project participants. The meetings are a particularly important opportunity for students and postdoctoral scientists to meet with the senior scientists from other projects. The meeting venues will be selected to facilitate travel and to minimize complications related to obtaining visas. The Project Scientist and Deputy will meet with Program Management and the Project Office management, at a minimum, quarterly, to review progress, resolve issues, and discuss implementation next steps.

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

PANGEA science investigations will be managed by the Science leadership and carried out by the Science Team. As noted, membership of the Science Team will include investigators selected by NASA and investigators who are recruited by Science Team PIs and Co-Is. PANGEA investigations will concern a number of countries throughout the tropics. Based on NASA experience in the LBA, we recommend that *all* investigations have counter-part investigators in humid tropical forest countries and endeavor to train early career scientists and technicians from countries where PANGEA research is active and other countries of the humid tropics. This should apply even to investigations that have no field component. During LBA, NASA learned that this approach had many benefits. Practically, it offered an incentive for host countries to support the work of NASA in-country, because of the capacity being built by the researchers. Researchers found that host countries often provided significant leverage for their research projects through in-kind and funded contributions, especially student fellowships. Decades after the NASA presence in South America for LBA concluded, NASA still has a large network of friendly collaborators in the South American scientific community. The impact of those investigators on science in their home countries has been vast. For more information, see *Section 7, Capacity Building, Training, and Education*.

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

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

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

with local collaborators and cultural diversity and extra care taken to uphold NASA's reputation internationally.

Leadership and engagement during the PANGEA scoping process demonstrated exceptional support for the project and the diversity of participants with the capacity and interest to contribute to PANGEA.

During the scoping process, PANGEA's Thematic Working Co-Leads included 22 people from the global North and South. The following demographics illustrate several axes of diversity represented by PANGEA's leadership team and working group co-leads:

- 42% female (n = 14 of 33)
- 60% non-white (n = 20 of 33)
- 30% from the global South (n = 10 of 33)
- 27% early career (n = 9 of 33)

It is important to note that the PANGEA scoping team worked to achieve greater representation from the global South on our leadership. Owing to limited resources that can be allocated to directly support participants from the global South, we were restricted. Many highly qualified people from the global South were overstretched and unable to help lead the scoping effort without compensation. However, well over 50% of the people engaged in the scoping effort through workshops, meetings, Town Halls, and symposia were from global South countries. Lessons learned during the scoping process informed co-funding pursuits for the PANGEA project. The scoping effort also exemplified PANGEA's ability to implement scientific diplomacy internationally.

10.1.6 Disciplinary Skills Required

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

10.2 Co-Funding Opportunities

The Baseline, Threshold, and Descope levels of measurement defined in *Section 6.2.1* represent stand-alone NASA projects with no dependencies. However, given the urgency and importance of the topic, there is strong potential to augment or even exceed NASA's contributions. During the scoping effort, the PANGEA leadership team has made significant strides towards securing diverse sources of funding to build on a NASA investment. Multiple U.S. government agencies, private foundations, international governments, and philanthropies have expressed interest in supporting PANGEA-related activities that are both within and outside of NASA's scope, including direct support for international partners and implementation of Earth Science to Action. Opportunities to leverage additional support from partners interested in teaming up with NASA include example partners listed in **Table 12**. For further details, see *Appendix A*, *Letters of Support*.

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

Table 12. PANGEA potential co-funding and in-kind support opportunities.

USFS-IP: U.S. Forest Service International Programs. ONACC: National Observatory on Climate Change (Cameroon).

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

10.3 Open Science—Data Management and Sharing

PANGEA will facilitate open-source science, promote collaboration, and maximize the value of PANGEA data broadly and for the long term, in alignment with NASA's Strategy for Open Science (Strategy for Data Management and Computing for Groundbreaking Science 2019–2024). This strategy will adhere to community principles and practices and keep ethical guidelines and cultural sensitivity in mind. PANGEA will also coordinate closely with Indigenous partners to ensure data sovereignty, specifically including Indigenous Data Sovereignty (IDS). PANGEA will build on the success from past field projects and leverage new advances in open science and data management concepts and technologies.

PANGEA will integrate data streams from multiple data-acquisition systems, partners, countries, and paradigms (e.g., Western science paradigm, Indigenous ecological knowledge, traditional ecological knowledge) (see **Table 13**). PANGEA data management will adhere to the Findable, Accessible, Interoperable, and Reusable (FAIR) guiding principles to improve data discoverability and accessibility, promote data interoperability and integration, and enhance data reusability and reproducibility (Wilkinson et al., 2016). PANGEA data collection, management, and use will also align with the CARE principles, which emphasize the importance of considering the rights and interests of Indigenous Peoples and Local Communities when managing data related to their communities, lands, and resources. The CARE principles for Indigenous Data Governance complement the FAIR principles by focusing on the ethical, cultural, and social dimensions of data management, and reflecting the crucial role of data in advancing Indigenous innovation and self-determination (Caroll et al., 2020).

PANGEA data collection, management, and use also acknowledges the importance of data sovereignty, which requires active partnerships with Indigenous Peoples and Local Communities. Data sovereignty is the management of information in a way that is consistent with the laws, practices, and customs of the nation-state in which it is located. Indigenous data sovereignty is the "right of Indigenous Peoples and Nations to govern the collection, ownership, and application of their own data, deriving from the inherent right of Indigenous Nations to govern their peoples, lands, and resources," and is positioned as a collective right within international Indigenous rights frameworks (Cannon et al., 2024). Indigenous knowledge-holders retain culturally sensitive information and data. To ensure that PANGEA's data collection and management efforts are ethical and respect the rights of Indigenous Peoples and Local Communities, PANGEA will work with partners and Indigenous Peoples and Local Communities following CARE principles as described in **Table 8**.

Participation in the PANGEA Science Team will require a commitment to provide free, open, and transparent access to all data that are acquired as part of PANGEA in accordance with FAIR and CARE principles. In collaboration with NASA Program Management, the PANGEA Science Team, led by a PANGEA Open Science Coordinating Group, will work with government agencies, foreign government partners, and Indigenous partners to establish data and information gathering, sharing, and handling agreements and workflows at the national, international agency, and territorial level to outline data ownership, usage rights, and storage plans compliant with Open Science, FAIR, and CARE principles. PANGEA will prioritize first-authored publications by early- and mid-career researchers from the tropics and advancing Indigenous-led research.

Table 13. Examples of coordinated data management and sharing activities with partners.

PARTNER(S)	DATA MANAGEMENT AND SHARING ACTIVITY
LBA	LBA and PANGEA will work together to harmonize protocols for multiple data types including forest inventory, tower-based fluxes, and acquisitions from UAVs. The recently adopted (June 2024) revised LBA data policy is based on Open Science principles and guidelines, fair use and fair dealing, in compliance with the FAIR data principles. LBA data will adopt the Creative Commons Attribution 4.0 International license (CC-BY-4.0; https://creativecommons.org/licenses/by/4.0/). To expand the scientific community's access to and collaboration with the program's data. These new LBA data policies should make LBA and NASA PANGEA data and open science policies highly compatible.
ALLIANCE FOR TROPICAL FOREST SCIENCE (ATFS)	Coordinate with ATFS tropical forest plot network partners to ensure that ground and drone data collection and management follow existing standards and protocols.
INDIGENOUS AND LOCAL COMMUNITY PARTNERS (E.G., GATC, RRI)	Engage with IPLC partners during the development of the Concise Experiment Plan, well before data are collected. Determine who is responsible for granting permission for external parties to access data and/or Indigenous territories for research. Create steps or policies for researchers and/or IPLCs for data sharing and/or requesting permission to access data or IPLC territories. Establish a plan for data collection and/or monitoring. Build capacity and work with partners, including IPLCs to secure funding for IPLC-led storing and managing of Indigenous data. Provide training to create tools for IPLCs that would support data collection, management, and dissemination.
NEON, SBG & NISAR SCIENCE TEAMS	Harmonize protocols across research communities to support scaling. Examples of existing initiatives that PANGEA will engage with include the SBG VSWIR Terrestrial Vegetation algorithm team and the NISAR cal/val network. PANGEA will contribute to developing data collection protocols, airborne data extraction and processing strategies, and database structures that will allow community generated joint airborne-field data collection to be more easily integrated into the model training datasets needed to improve algorithms for underrepresented ecosystems.

PANGEA will follow guidelines from the NASA Earth Science Data Preservation Content Specification[2] to prepare and preserve data as well as associated information beyond the life of a project. This will enable future users to understand how the data were used for deriving information, knowledge, and policy recommendations, and to ensure reproducibility to ascertain the validity and possible limitations of conclusions reached in the past, and to provide confidence in long-term trends that depended on data from multiple projects. The Preservation Content Implementation Guidance document[3] provides guidelines and

[2] https://www.earthdata.nasa.gov/esdis/esco/standards-and-practices/preservation-content-spec
[3] https://www.earthdata.nasa.gov/s3fs-public/2022-07/ESDS-RFC-042VERSION1.pdf)

checklists to address the PCS needs for different types of Earth science research projects, including airborne and field investigations.

In collaboration with partners, the PANGEA Project Office will develop a publicly accessible **PANGEA Information Portal (PIP)**. This Information Portal will outline PANGEA's data management and sharing strategy, provide direct links to data, models, and information on the planned and ongoing activities of PANGEA investigators and collaborators, including inventories of the location, timing, and types of data collected. The PANGEA Science Team and Project Office will work closely with data owners when collating and linking to existing data sources to ensure data sharing is collaborative and ethical, and respects the rights and ownership of data already collected in concordance with FAIR and CARE principles. The PIP will provide easy discovery and access to data collected by PANGEA and also existing data useful for PANGEA research.

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

Data provenance and reproducibility are important aspects of open-source science. Sampling protocols, metadata, data cleaning, codes, algorithms, and workflows associated with data creation, processing, and validation for PANGEA will be made openly available. PANGEA will establish consistent formats and practices for data and metadata and optimization for cloud-based access and analysis, especially for emerging types of data, like drone-based datasets. These activities will work with, rather than attempt to replicate, existing data- and discipline-specific efforts. Existing networks and programs such as FLUXNET, NEON, ICOS, OzFlux, TERN, and SAEON have invested in the definition of standards in the processing and data distribution and are moving toward the FAIR implementation. The Regional Networks have also activities in tropical areas; for example, ICOS is coordinating the KADI project (Knowledge and climate services from an African observation and Data research Infrastructure, https://kadi-project.eu/) that has the aim of design and move toward a pan-African climate observation system.

Conversations to ensure alignment with these efforts have already begun. Coordination will deepen upon selection to ensure ground data, flux tower data, drone data, camera trap data, bioacoustics data, Indigenous and Traditional Ecological Knowledge, and more are collected, stored, and shared appropriately and according to the best available practices. PANGEA will leverage and integrate with existing and emerging capabilities and systems offered by NASA Earth Science Data Systems as much as possible. These include the Distributed Active Archive Centers (DAACs) for airborne data, DAAC tools and services to make airborne and orbital data easier to use for terrestrial ecology research, NASA's

Visualization, Exploration, and Data Analysis (VEDA) platform (https://www.earthdata.nasa.gov/esds/veda), and ongoing efforts to coordinate data standardization and protocols.

PANGEA will also adopt an open-source approach for models. Models participating in PANGEA-related activities and projects will be expected to have the source code openly available through collaborative platforms (e.g., GitHub), and released with permissive licenses consistent with the Science Mission Directorate (SMD) Open-Source Science Guidance. PANGEA will promote model governance for community engagement including a code of conduct, technical notes and user's guides, active forum for discussing code issues, and pathways for contributions with model development from the broad scientific community. To comply with PANGEA's open science principles, projects part of PANGEA will deposit the exact version of published models in long-term repositories with a DOI along with parameter and data information needed to reproduce results.

PANGEA will develop an open **cloud-based data analysis platform** for PANGEA investigators to support open and collaborative research. PANGEA's data analysis platform will be based on successful science clouds implemented by ABoVE, SHIFT, BioSCape, and NASA's Multi-Mission Algorithm and Analysis Platform (MAAP, https://www.earthdata.nasa.gov/esds/maap). These efforts demonstrate successful international data collaboration, including between NASA and ESA (MAAP), and by leveraging Amazon Web Services' Social Responsibility Program (BioSCape). PANGEA's cloud-based computing platform will lower barriers to entry, especially for international partners who are likely to be limited in bandwidth, data storage capacity, and computing power. The cloud computing platform will also allow PANGEA Science Team members to easily share early versions of data products (before they are ready for archiving) and troubleshoot data analysis problems communally. Additionally, capacity building materials, especially coding notebooks, can be developed specifically for the cloud computing environment, allowing anyone anywhere in the world to run them and apply similar approaches. The importance of a cloud computing environment was demonstrated during BioSCape, whose South African science team members would otherwise have been severely limited in their ability to access, analyze, and apply the campaign's data.

PANGEA will provide open-source science and data management capacity building throughout the project, including through trainings and workshops on data management in collaboration with the DAACs, FLUXNET, LBA, Indigenous and local community partner organizations like the Global Alliance of Territorial Communities, ATFS, and more. Many of these partners have existing training programs that will be leveraged. PANGEA will prioritize trainings and workshops with partners to support independent and coordinated data management efforts, which (1) enhances the capacity of Indigenous peoples, local communities, and tropical institutions; and (2) ensures international alignment that will serve as a foundation for datasets and collaboration to continue beyond the PANGEA project. Co-funding is being sought to support the investment in infrastructure needed to ensure that open-source science can be carried out equitably across PANGEA landscapes, including funding to support local electricity and internet infrastructure.

10.4 Timetable

The PANGEA team has used virtual and hybrid meetings for early engagement of a diverse science scoping team. We have time-saving approaches that can greatly reduce the timeline needed to develop the Concise Experiment Plan and move on to the Implementation phase. **Table 14** outlines the proposed timeline, assuming PANGEA's next activities begin in Fiscal Year 2025.

Table 14. Proposed PANGEA timetable.

SDT: Science Definition Team. TE: Terrestrial Ecology. CEP: Concise Experiment Plan. PAC: PANGEA Airborne Campaign. SATSM: Science and Applications Team and Stakeholder Meeting.

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

10.5 Risk Assessment

PANGEA will use proactive risk management to mitigate all risks for all project activities, including such things as travel, fieldwork, equipment use, and airborne and field operations across the wide tropical study range required to deliver high-impact science. The Project Office will compile a comprehensive list of project risks, assess them with a standard Risk Assessment Matrix, provide these risk assessments to participants, and monitor compliance. The project will also coordinate with the health and safety requirements of each partner institution. For high- and medium-risk cases, the project will develop and implement a mitigation plan, which will be reviewed with the NASA Program Office. PANGEA expects most risks will fall into three categories: (1) health and safety; (2) meeting science objectives; and (3) meeting community engagement and applications objectives.

Health and safety: The project will follow health and travel safety guidelines issued by the U.S. Department of State Bureau of Consular Affairs and individuals will follow the specific project risk assessments devised by the PANGEA project office. PANGEA will also engage with local U.S. Embassies, Consulates and their Regional Security Offices for guidance. Given the remote nature of many of the study sites, the project will develop plans for safe transportation to the field study sites, whether by off-road vehicle, boat, or other methods. The project will also develop plans for the safety of the airborne crew and instrument operators during the campaigns, following NASA guidelines for aircraft operations and on the ground. Some potential study regions include risks for malaria, yellow fever, and other diseases; the project will ensure participants are advised on relevant vaccines and other prophylaxis prior to field visits.

Meeting science objectives: The Project Office will work proactively to engage institutional partners and develop formal MOU's, with the help of NASA's OIIR office, ESPO, and the U.S. State Department. International airborne campaigns have been repeatedly plagued by slow landing clearances and associated bureaucracy, and much of this can be avoided by beginning the formal MOU process early. While using NASA aircraft for airborne observations has benefits, use of these aircraft requires diplomatic clearance both in study area countries and during transit. Diplomatic clearance can sometimes be obtained only near its need-by date, so portions of campaigns or entire campaigns may be canceled on short notice. In addition, because NASA aircraft are operated by U.S. civil servants, there is a demonstrated risk of a U.S. government shutdown delaying or canceling science flights, especially in the October–December timeframe. The PANGEA Project Office will consider these and other risks and may consider using commercial aircraft to mitigate these risks.

Weather is also an important consideration in successful field and airborne data acquisitions for PANGEA, especially for optical observations that require cloud-free conditions. During the Science Definition phase, PANGEA will run a climate analysis to determine the best time of year for airborne observations. During the airborne campaigns, PANGEA will work with local weather forecasters who understand the local climate to facilitate successful airborne retrievals and field measurements.

Fieldwork presents multiple risks. For those who do not work in tropical forests, risks such as venomous snakes and poisonous spiders come to mind. While these biological risks are real, PANGEA can manage them by establishing and enforcing safety guidelines and educating participants. The greatest risk to project participants is often during transportation to and from the field sites. Travel by truck and by boat was the greatest risk during LBA. PANGEA can mitigate this risk by ensuring that drivers are trained and that vehicles are properly maintained. Other risks in the field include disease and loss of equipment through theft and violence. Medical prophylaxis can mitigate endemic diseases, such as malaria, and violence can be avoided through good community relations, situational awareness, and communications. PANGEA will mitigate all of these risks by conducting locally specific field safety and cultural awareness training and establishing good relations with local communities.

Meeting community engagement and applications objectives: Engaging with local communities and developing science and applications outcomes that will be useful to a wide variety of people requires coordination and genuine effort. A risk to PANGEA is that engagement efforts are not successful and/or applications are not useful. PANGEA will take several actions to mitigate these risks. PANGEA will co-produce engagement plans for each landscape during the Concise Experiment Plan development that includes milestones, objectives, and metrics to evaluate success regularly throughout the project. PANGEA will embrace inclusivity and will actively work to develop and promote inclusive and co-developed practices throughout. Co-developing projects and working equitably with all partners, including Indigenous peoples and local communities can take a long time. PANGEA will continue to work hard to build on long-standing relationships. However, given the limited duration for PANGEA fieldwork in each location, there is a risk that the project will not meet these goals. PANGEA will work with partners to develop plans for continued support beyond the duration of the project. PANGEA will work to maintain relationships with community partners throughout the project and will work with international and industrial partners to secure additional funding to support these efforts in order to increase the depth and meaningfulness of these relationships.

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13 Glossary

Bioeconomy: An economic system driven by research and innovation in life sciences and biotechnology, encompassing transformative biobased and bio-enabled applications in areas such as energy, chemicals, advanced materials, environmental remediation, agriculture, electronics, and health. It is enabled by technological advances in engineering, computing, and information sciences (Schmidt Futures, 2022).

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

Biogeochemical cycles: Biogeochemical cycles encompass the movement and transformation of essential elements (e.g., carbon, nitrogen, and phosphorus) through Earth's biosphere, atmosphere, hydrosphere, and lithosphere. In tropical forests, these cycles are highly dynamic, with rapid nutrient and biomass turnover; nonetheless tropical forests play a significant role in global carbon storage.

Carbon stocks and fluxes: Carbon stocks refer to the total amount of carbon stored in a system (e.g., in vegetation, soils, or oceans), while carbon fluxes represent the movement of carbon into and out of these stocks through processes such as photosynthesis, respiration, and decomposition, and include fluxes of carbon dioxide (CO_2), methane (CH_4), and lateral flows of carbon.

Climate interactions and feedbacks: Bidirectional interactions between climate systems and ecosystems. Tropical forests directly regulate carbon, water and energy cycles. Climate changes (like temperature and rainfall shifts) and land use and land cover changes (like fires and forest degradation) can alter forest ecosystem dynamics, creating feedback loops that affect global climate stability.

Co-benefits: Joint positive contributions of biodiversity and cultural diversity for humans and other species. These contributions are associated with the concepts of nature's contributions to people and people's contributions to nature (Levis et al, 2024).

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

Disturbance dynamics: Disturbance dynamics vary by type, intensity, and frequency, and involve natural or human-induced events, such as fires, storms, drought, and logging, that disrupt ecosystems and affect their structure and function. In tropical forests, these disturbances can lead to shifts in biogeochemical cycling, biodiversity, and feedbacks to climate and to social-ecological systems.

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

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

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

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

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

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

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

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

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

Social-ecological systems: Interconnected systems of humans and nature, where ecological and social components interact and influence each other. In tropical forests, these systems are shaped by the livelihoods, cultural practices, and resource-use of local- to global-communities, while ecological changes impact social well-being, creating complex feedbacks between human activities and ecosystem stability.

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

Vulnerability: The propensity of social and ecological systems and their practices to be adversely affected by changes, encompassing their sensitivity to such changes and their ability to adapt. Adapted from (FAO 2013).

14 Acronyms and Abbreviations

AboVE	Arctic Boreal Vulnerability Experiment
ABSOLUG	Agent-Based Simulator of Land Use Governance
AGEOS	Agency for Space Studies and Observations (Gabon)
AGU	American Geophysical Union
AI	Artificial intelligence
AI/ML	Artificial Intelligence and Machine Learning
AI4ESP	Artificial Intelligence for Earth System Predictability
AmeriFlux	Americas' eddy-covariance Flux tower network
AmIT	Amazon Institute of Technology
AMMA-CATCH	African Monsoon Multidisciplinary Analysis Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique
AMMI	African Masters of Machine Intelligence
AMSR-E	Advanced Microwave Scanning Radiometer for EOS Mission
AndesFlux	Flux towers operated by PUCP
ARES	Airborne Research Facility for the Earth System
ARL	Application Readiness Level
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATBC	Association for Tropical Biology and Conservation
ATFS	Alliance for Tropical Forest Science
ATTO	Amazon Tall Tower Observatory (Presidente Figueiredo, Brazil)
BiomeE	A NASA-GISS demographic vegetation model
BioSCape	Biodiversity Survey of the Cape
BOREAS	Boreal Ecosystem–Atmosphere Study
CARAFE	Carbon Airborne Flux Experiment

CarbonTracker	Data assimilation system for CO_2 tracking
CARDAMOM	Carbon Data Modeling Framework
CARE	Collective Benefit, Authority to Control, Responsibility, and Ethics
CBFP	Congo Basin Forest Partnership
CBI	Congo Basin Institute
CBSI	Congo Basin Science Initiative
CCE	Carbon Cycle and Ecosystems (NASA office)
CENAREST	National Center for Scientific and Technological Research (Gabon)
CEOS	Committee on Earth Observation Satellites
CEP	Concise Experiment Plan
CFIS	Chlorophyll Fluorescence Imaging Spectrometer
CGIAR	Consultative Group for International Agricultural Research
CH_4	Methane
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment
CIAT	International Center for Tropical Agriculture
CIFOR-ICRAF	Center for International Forestry Research and World Agroforestry
CliMA	Climate Modeling Alliance
CLM	Community Land Model
CMIP	Coupled Model Intercomparison Project
CMIP5	CMIP—Phase 5
CMIP6	CMIP—Phase 6
CMS-Flux	Carbon Monitoring System Flux inversion system
CNES	French National Space Agency
CO_2	Carbon dioxide
COCCON	COllaborative Carbon Column Observing Network
Co-I	Co-Investigator

COMIFAC	COMIFAC
CongoFlux	Eddy covariance flux tower in the Congo Basin
COS	Carbonyl sulfide
CSDA	Commercial SmallSat Data Acquisition
CUE	Carbon use efficiency
DEI	Diversity, equity, and inclusion
DGVM	Dynamic Global Vegetation Model
DLR	German Aerospace Center
DOE	Department of Energy
DRC	Democratic Republic of Congo
E3SM	Energy Exascale Earth System Model
EBV	Essential Biodiversity Variable
ECOSTRESS	Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station
ED	Ecosystem Demography
ED2	Ecosystem Demography Model version 2
ED3	Ecosystem Demography Model version 3
EDGE	Earth Dynamics Geodetic Explorer
eDNA	Environment deoxyribonucleic acid
ELM	E3SM Land Model
EMIT	Earth Surface Mineral Dust Source Investigation
ENSO	El Niño Southern Oscillation
Ent TBM	Ent Terrestrial Biosphere Model
EOS	Earth Observing System
ES2A	NASA's Earth Science to Action Strategy
ESA	Ecological Society of America
ESA	European Space Agency

ESM	Earth System Model
ESRI	Environmental Systems Research Institute, Inc.
ET	Evapotranspiration
EUDR	European Union Deforestation Free Commodities Regulations
FAIR	Findable, accessible, interoperable, and reusable
FAO	Food and Agriculture Organization (United Nations)
FAPESP	São Paulo Research Foundation
FATES	Functionally Assembled Terrestrial Ecosystem Simulator
FIFE	First ISLSCP Field Experiment
FLEX	Fluorescence Explorer Mission
FLUXNET	Global eddy covariance flux tower network
ForestGEO	Forest Global Earth Observatory
ForestPlots	Network for measuring, monitoring, and understanding the world's forests
FORMIND	Forest Model Individual-based model
FTAC	Fast Track Action Committee (on Climate Services)
GAO	Global Airborne Observatory
GATC	Global Alliance of Territorial Communities
GCF-TF	Governors' Climate and Forests Task Force
GEDI	Global Ecosystem Dynamics Investigation
GEM	Global Ecosystems Monitoring network
GEO BON	Group on Earth Observations Biodiversity Observation Network
GEO	Group on Earth Observations
GEO-TREES	Group on Earth Observations–Trees
GHG	Greenhouse gas
GIS	Geographic Information System
GISS	Goddard Institute for Space Studies (NASA)

GLOBE	Global Learning and Observations to Benefit the Environment
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellites
GOSAT	Greenhouse Gases Observing Satellite
GPM	Global Precipitation Measurement
GPP	Gross primary productivity
GPS	Global Positioning System
GPU	Graphics processing unit
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On mission
GSFC	Goddard Space Flight Center
Guyaflux	Eddy covariance flux tower at the Paracou Field Station (Sinnamary, French Guiana)
Guyafor	Network of 54 long-term plots across 17 sites in French Guiana
H_2O	Water
HBCUs	Historically Black Colleges and Universities
HiLDEN	High-Latitude Drone Ecology Network
HQ	Headquarters
HYSPLIT	A NOAA atmospheric transport and dispersion model
HyTES	Hyperspectral Thermal Emission Spectrometer
IA	Implementing agreement
ICCN	Congolese Institute for Nature Conservation
ICOS	Integrated Carbon Observation System
IEK	Indigenous ecological knowledge
IITA	International Institute for Tropical Agriculture
ILAMB	International Land Model Benchmarking project

INPA	National Institute of Amazonian Research (Brazil)
INPE	National Institute for Space Research (Brazil)
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPLCs	Indigenous Peoples and Local Communities
IRD	Research Institute for Development (France)
ISLSCP	International Satellite Land–Surface Climatology Project
ISRO	Indian Space Research Organisation
ITCZ	Intertropical Convergence Zone
IUCN	International Union for Conservation of Nature
JAXA	Japan Aerospace Exploration Agency
JSBACH	Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg model
JULES	Joint United Kingdom Land Environment Simulation
K34	Kilometer 34 eddy covariance tower (Manaus, Brazil)
K67	Kilometer 67 eddy covariance tower (Belterra, Brazil)
LAI	Leaf Area Index
LBA	Large-Scale Biosphere-Atmosphere Experiment in Amazonia
LBA-ECO	The NASA Terrestrial Ecology Program contribution to the first phase of LBA
LBNL	Lawrence Berkeley National Laboratory
LCLUC	Land-Cover and Land-Use Change (NASA)
LEK	Local ecological knowledge
LPJ	Lund-Potsdam-Jena dynamic global vegetation model
LPJ-GUESS	LPJ General Ecosystem Simulator
LST	Land surface temperature

LUH2	Land-Use Harmonization project, version 2
LVIS	Land, Vegetation, and Ice Sensor
MAAP	Multi-Mission Algorithm and Analysis Platform
MapBiomas	Biome Mapper initiative
MASTER	MODIS/ASTER Spaceborne Thermal Emission and Reflection Radiomete
MetaFlux	Meta-learning framework for climate sciences
MINFOF	Ministry of Forests and Fauna, Cameroon
ML	Machine learning
ModEX	Model-Experimentation
MODIS	Moderate Resolution Imaging Spectroradiometer
MOU	Memorandum of understanding
MRV	Monitoring, reporting, and verification
MSI	Minority Serving Institution
N_2O	Nitrous oxide
NASA	National Aeronautics and Space Administration
NASA-CASA	NASA Carnegie-Ames-Stanford ecosystem model
NBE	Net biosphere exchange
NDVI	Normalized Difference Vegetation Index
NEON	National Ecological Observatory Network
NGEE-Tropics	Next Generation Ecosystem Experiments–Tropics
NGO	Nongovernmental organization
NISAR	NASA-ISRO SAR Mission
NOAA	National Oceanic and Atmospheric Administration
NOANET	Northwest Open Access Network
NPP	Net primary productivity
NSB	National Science Board

NSC	Nonstructural carbohydrate
NSF	National Science Foundation
NSTC	National Science and Technology Council
OCO-2/3	Orbiting Carbon Observatory–2 or –3
OECMs	Other Effective Conservation Measures
OFVi	One Forest Vision Initiative
OIIR	NASA Office of International and Interagency Relations
ONACC	National Observatory on Climate Change (Cameroon)
ORCHIDEE	Organising Carbon and Hydrology in Dynamic Ecosystems
ORNL	Oak Ridge National Laboratory
OSFAC	Satellite Observatory of Central African Forests
OSSE	Observing System Simulation Experiment
PAC	Pangea Airborne Campaign
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem Mission
PANGEA	PAN tropical investigation of bioGeochemistry and Ecological Adaptation
PecAn	Predictive Ecosystem Analyzer
PFT	Plant functional type
PhenoCam	Phenological Camera
PI	Principal Investigator
PIP	PANGEA Information Portal
PUCP	Pontifical Catholic University of Peru
QA/QC	Quality assessment and quality control
R2FAC	Central African Forest Research Network
RAINFOR	Amazon Forest Inventory Network
RepastSimphony	Recursive Porous Agent Simulation Toolkit with Symphony Java interface
RESSAC	Applied Research in Ecology and Social Sciences program

RGB	Red green blue
RRI	Rights and Resources Initiative
RUBISCO	Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation
SATSM	Science and Applications Team and Stakeholder Meeting
SBG	Surface Biology and Geology Mission
SDT	Science Definition Team
SERVIR	SERVIR is a NASA and USAID partnership that supports locally led efforts to strengthen climate resilience, food and water security, forest and carbon management, and air quality.
SES	Social-ecological systems
SHIFT	SBG High-Frequency Time Series
SIF	Solar-induced (chlorophyll) fluorescence
SILK	School for Indigenous and Local Knowledge
SimPachamama	Hybrid simulation model for socio-environmental trade-offs
SL	Science Leadership
SLA	Specific leaf area
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SPUN	Society for the Protection of Underground Networks
SSC	Scientific Steering Committee
SSP	Shared Socioeconomic Pathways
SST	Sea surface temperature
STEM	Science, technology, engineering, and mathematics
STILT	Stochastic Time-Inverted Lagrangian Transport model
STRI	Smithsonian Tropical Research Institute
SWOT	Surface Water and Ocean Topography Mission

Tallo	A global tree allometry and crown architecture database
TBD	To be determined
TCCON	Total Carbon Column Observing Network
TE	Terrestrial Ecology
TEK	Traditional ecological knowledge
TERN	Terrestrial Ecosystem Research Network
TIR	Thermal infrared radiation
TIRS	Thermal Infrared Sensor
TmFO	Tropical managed Forests Observatory
TRISHNA	Thermal infraRed Imaging Satellite for High-resolution Natural Resource Assessment
TRL	Technology Readiness Level
TROLL	Tree Representation Of Landscape Level model
TROPOMI	Tropospheric Monitoring Instrument
TRY	Plant Trait Database
U.S.	United States of America
UAV	Uncrewed aerial vehicle
UCLA	University of California, Los Angeles
UNFCCC	United Nations Framework Convention on Climate Change
UN-SDSN	United Nations Sustainable Development Solutions Network
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VEDA	Visualization, Exploration, and Data Analysis
VIIRS	Visible Infrared Imaging Radiometer Suite

VOC	Volatile organic compound
VOD	Vegetation optical depth
VPD	Vapor pressure deficit
VPRM	Vegetation Photosynthesis and Respiration Model
VSWIR	Visible to shortwave infrared
WRI	World Resources Institute
WUE	Water-use efficiency

15 Appendices

A. Letters of Support

B. PANGEA Partners & Engagement Activities

C. Engagement During the Scoping Study

D. Planned and Ongoing Research and Monitoring Activities

E. Detailed PANGEA Measurements Table

F. Responses to Feedback

G. Topics beyond the Scope of PANGEA

Model Tables

Table X. Table Caption PANGEA.

Table Note PANGEA.

Table Heading C PANGEA Standard Column Heading Fill: 198/224/220	Table Heading C PANGEA Alternative Grey Subheading Fill: 210/210/210	Table Heading C PANGEA manually reduced to 8 pt Alternative Blue Heading Fill of Same Shade as Green: 194/225/241
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Figure in Figure PANGEA Word style.

Figure X. Caption in Figure Caption PANGEA Word style (with figure # manually bolded).

A. Letters of Support

Alexander von Humboldt Institute (Instituto Humboldt); https://www.humboldt.org.co/

Alliance Bioversity & International Center for Tropical Agriculture (CIAT); https://alliancebioversityciat.org/

AmeriFlux–Americas' eddy-covariance flux tower network; https://ameriflux.lbl.gov/

Amazon Institute of Technology (AmIT); https://amit.institute/

Amazon Tall Tower Observatory (ATTO); https://www.attoproject.org/

AndesFlux–flux towers operated by the Pontifical Catholic University of the Peru (PUCP)

Airborne Research Facility for the Earth System (ARES); https://www.uzhfoundation.ch/en/projects/sustainability/ares-airborne-research-facility-for-the-earth-system-1

Batelle National Ecological Observatory Network (NEON); https://www.neonscience.org/

Biodiversity Survey of the Cape (BioSCape); https://www.bioscape.io/

BiomeE–NASA Goddard Institute for Space Studies (GISS) demographic vegetation model; https://ntrs.nasa.gov/citations/20220017198

Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF); https://www.cifor-icraf.org/

Center for Sustainable Amazonia Studies (CEAS); https://ceas.usp.br/

Climate Modeling Alliance (CLiMA); https://clima.caltech.edu/

Congo Basin Science Initiative (CBSI); https://congobasinscience.net/

CongoFlux–eddy covariance flux tower in the Congo Basin–Ghent University team; https://www.congo-biogeochem.com/congoflux

CongoPeat–peatlands measuring and sampling research program; https://congopeat.net/

Ecosystem Demography modeling community (ED2); https://github.com/EDmodel/ED2

Embrapa (Brazilian Agricultural Research Corporation) Acre; https://www.embrapa.br/en/international

Embrapa Florestas; https://www.embrapa.br/en/international

Environmental Systems Research Institute, Inc. (ESRI); https://www.esri.com/en-us/home

FLUXNET CH4–initiative to compile a global database of eddy covariance methane flux measurements; https://fluxnet.org/data/fluxnet-ch4-community-product/

Food and Agriculture Organization (FAO); https://www.fao.org/fao-office-climate-change-biodiversity-environment/en

ForestGEO; https://forestgeo.si.edu/

ForestPlots–network for measuring, monitoring, and understanding the world's forests; https://forestplots.net/

Gabonese Agency for Space Studies and Observations (AGEOS); http://spaceinafrica.com/2019/02/26/all-about-ageos-gabon-space-program/

Group on Earth Observations–Trees (GEO-TREES); https://geo-trees.org/

Global Land Analysis & Discovery (GLAD); https://glad.umd.edu/

Governors' Climate and Forests Task Force (GCF-TF); https://www.gcftf.org/

Guyaflux–eddy covariance tower at the Paracou Field Station (Sinnamary, French Guiana); https://paracou.cirad.fr/website/experimental-design/guyaflux-tower

Guyafor–network of 54 long-term plots across 17 sites in French Guiana; https://paracou.cirad.fr/website/experimental-design/guyafor-network

Integrated Carbon Observation System (ICOS); https://www.icos-cp.eu/

International Institute for Tropical Agriculture (IITA); https://meta.icos-cp.eu/resources/stations/ES_GF-Guy

Mancomunidad Regional Amazónica (MRA)–Amazon Regional Commonwealth

MapBiomas–Biome Mapper initiative; https://brasil.mapbiomas.org/en/

NASA Harvest; https://www.nasaharvest.org/

National Center for Scientific and Technological Research, Gabon (CENAREST); https://www.cenarest-gabon.org/?p=accueil

National Institute for Space Research, Brazil (INPE); https://www.inpe.br/crc/

National Observatory on Climate Change, Cameroon (ONACC); https://onacc.cm/

Next Generation Ecosystem Experiments (NGEE)-Tropics; https://ngee-tropics.lbl.gov/

One Forest Vision Initiative (OFVi); https://www.oneforestvision.org/

Predictive Ecosystem Analyzer (PecAn); https://pecanproject.github.io/

Pennsylvania State University, Department of Meteorology and Atmospheric Science; https://www.met.psu.edu/

Rainforest Foundation Norway; https://www.regnskog.no/en/

Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation (RUBISCO); https://climatemodeling.science.energy.gov/projects/reducing-uncertainty-biogeochemical-interactions-through-synthesis-and-computation-rubisco

Research Institute for Development, France (IRD); https://en.ird.fr/

Satellite Observatory of Central African Forests (OSFAC); https://www.osfac.net/

Society for the Protection of Underground Networks (SPUN); https://www.spun.earth/

UN Sustainable Development Solutions Network (UN-SDSN); https://www.unsdsn.org/

Universidad Nacional del Altiplano (UNAP) Peru; https://www.portal.unap.edu.pe/
Letter in Spanish, followed by English translation of letter

Universidad Nacional de Piura Peru (UNP)—Agronomy Department; https://www.gob.pe/unp

Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Peru (UNTRM) (https://www.untrm.edu.pe/portal/en/)

Université catholique de Louvain, Belgium—Earth and Life Institute; https://uclouvain.be/en/research-institutes/eli

University of California, Los Angeles (UCLA) Vice Chancellors Office for Research and Creative Activities; https://www3.research.ucla.edu/

University of Energy and Natural Resources (UENR) Ghana, Office of the Vice Chancellor; https://uenr.edu.gh/

US Forest Service International Program (USFS-IP); https://www.fs.usda.gov/about-agency/international-programs

West Africa Flux Network

Wildlife Conservation Society (WCS); https://www.wcs.org/

Woodwell Climate and Research Center; https://www.woodwellclimate.org/

World Resources Institute (WRI); https://www.wri.org/

December 4th 2024

NASA Earth Science Division
NASA Headquarters
300 E Street SW
Washington, D.C. 20546

Dear Members of the NASA Earth Science Division,

On behalf of the Alexander von Humboldt Institute, I am writing to express our strong support for the PAN-Tropical Investigation of BioGeochemistry and Ecological Adaptation (PANGEA) initiative. We are eager to collaborate in advancing PANGEA's scientific objectives in Colombia, and to contribute to the broader goal of understanding tropical forest resilience to climate change and land-use dynamics.

The Humboldt Institute's mission is to conduct basic and applied research on Colombia's biodiversity, including the creation of a national inventory of the country's biotic, hydrobiological, and genetic resources. This mission aligns perfectly with PANGEA's goal to investigate tropical forests and their responses to environmental change. We have a significant expertise in conducting biodiversity monitoring using a variety of tools, including forest inventory plots, plant trait measurements, bioacoustic monitoring, camera traps, and eDNA collection. We also specialize in integrating field-based data with advanced remote sensing, such as hyperspectral and lidar technologies, making us a strong partner for PANGEA's goal of scaling biodiversity measurements across tropical landscapes. Our ongoing research in the Colombian Amazon, Andean regions, and other tropical ecosystems positions us well to support PANGEA's efforts, particularly in enhancing our understanding of the impacts of climate change and land-use on biodiversity and ecosystem function.

A key objective of PANGEA is to prepare the next generation of scientists from tropical countries, particularly from regions like the Amazon and Congo Basins, who will carry the work forward. The Humboldt Institute is deeply committed to fostering capacity building for effective biodiversity conservation and its sustainable use, particularly among local and Indigenous communities. We have a strong record of engaging postdocs, and undergraduates in field research, as well as facilitating exchanges with global researchers. We therefore look forward to contributing to PANGEA's training efforts by offering research opportunities and mentoring to students and early-career scientists from Colombia and the broader tropical regions. By collaborating on workshops and field-based training, the Humboldt Institute can help ensure that PANGEA's activities are aligned with local research priorities and the knowledge needs of tropical nations.

Ultimately, our primary goal is to ensure that biodiversity knowledge is transformed into actionable solutions for conservation and sustainable development. To reach this objective, we work hand-in-hand with local communities, decision-makers, and the private sector to implement science-based solutions for biodiversity conservation, land-use planning, and climate adaptation. These efforts directly support PANGEA's objective of using science to inform decision-making and guide actions for climate change mitigation, biodiversity conservation, and sustainable land use.

In sum, the Humboldt Institute is well-positioned to support PANGEA's goal of developing tools for monitoring environmental changes, such as fire risks, biodiversity trends, and carbon sequestration. Our expertise in biodiversity monitoring, our commitment to capacity building, and our experience translating scientific research into actionable knowledge make us a valuable partner for PANGEA. Together, we can contribute to more resilient, sustainable, and informed management of tropical forests and the biodiversity they support.

Sincerely,

Jose Manuel Ochoa
Centro de Estudios Socioecológicos y Cambio Global
Alexander von Humboldt Institute
Bogotá, Colombia

RM-CJ-209-2024
August 21, 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

Thank you for the invitation to collaborate on the PAN Tropical Investigation of BioGeochemistry and Ecological Adaptation (PANGEA) Scoping Campaign. The Internatoonal Center for Tropical Agriculture (CIAT) is happy to support the PANGEA program once NASA funding is confirmed.

CIAT is a non-fo-profit, non-governmental research organization established in 1967, with headquarters in Palmira-Colombia and various regional offices worldwide. Our goal is to deliver research-based solutions that harness agricultural biodiversity and sustainably transform food systems to improve people's lives in a climate crisis. To achieve our objectives, we currently conduct research on crop improvement, agrobiodiversity conservation, and climate-smart agriculture in regions including Latin America, Africa, and Asia.

PANGEA aims to improve the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions. The new findings are necessary to determine the resilience and vulnerability of tropical forest ecosystems. Therefore, the PANGEA research agenda is closely aligned with our research priorities. We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the Tropics to advance scientific understanding, strengthen capacity for ecological research, and support the application of scientific results to governance and sustainable land management practices.

Should PANGEA be funded, CIAT can provide cost-shared funding in the form of in-kind support. This includes staff time, as well as evidence-based data and information derived from our collaborations with national and regional governments, other CGIAR Centers and private sector actors. These partners play a critical role in advancing agricultural and ecological research in their respective regions and are essential in achieving sustainable land management practices. Engaging with these partners is beneficial for PANGEA as they bring local knowledge, research expertise, and strong connections with farming communities that are directly affected by climate change. Our expertise spans sustainable and zero-deforestation business and investment models, bioeconomy, biodiversity monitoring, and climate services, integrating comprehensive crop and soil data.

We conduct various initiatives and projects in the Amazon Basin within the tropical rainforest ecosystem because it is a critical region for global biodiversity and carbon storage. This site is of strategic importance to PANGEA due to its high biodiversity and the significant impact of deforestation and land-use change on global climate patterns. CIAT has been working in this location for over 40 years and can facilitate PANGEA's implementation by helping with local stakeholder engagement, data collection, and capacity-building activities.

While our organization excels at harnessing agricultural biodiversity to drive sustainable food systems and improve livelihoods, particularly through our expertise in community engagement, the integration of crop and soil data, and biodiversity monitoring, we seek to engage with PANGEA to enhance our work in Central Africa and Southeast Asia along the Amazon rainforest. Specifically, PANGEA can support us by providing advanced Earth observation tools and methodologies that will complement our on-the-ground research. This collaboration will help us improve our understanding of ecosystem dynamics, monitor deforestation impacts, and strengthen our ability to develop climate-smart strategies. By integrating PANGEA's insights with our existing data, we can enhance our efforts in biodiversity conservation and sustainable land management in this critical region.

PANGEA offers a unique opportunity to explore novel research hypotheses that are crucial for understanding tropical forest systems in the face of rapid environmental changes. We are excited to collaborate on this groundbreaking research and contribute to advancing our collective knowledge of these vital ecosystems. We look forward to engaging in new research endeavors under the PANGEA initiative and leveraging its insights to enhance our efforts in Central Africa and Southeast Asia along the Amazon rainforest.

Javier Mateo-Vega

Javier Mateo-Vega

Global Director Partnerships & Communications

,

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Jena, December 5, 2024

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter attests my strong support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If funded, PANGEA will significantly advance data and methods gaps related to the measurement, understanding, and scaling of carbon, water, and energy fluxes in tropical forests and their interactions with biodiversity, climate change, and human activities. The field campaign will make a major contribution towards understanding how tropical forests across the world are responding to changes in climate, land cover and land use. PANGEA's main goals are very aligned with activities conducted by the Amazon Tall Tower Observatory.

The Amazon Tall Tower Observatory (ATTO; www.attoproject.org) is a Brazilian-German collaborative project funded primarily by the Brazilian Ministry for Science Technology and Innovation (MCTI), the German Ministry for Education and Research (BMBF), and the Max Planck Society. ATTO, the Amazon Tall Tower Observatory, is a unique scientific platform in the central Amazon, 150 km northeast of Manaus. The overall goal of ATTO is to provide a site for long-term research on the changing role of Amazon forests in the Earth system. Research at ATTO seeks to improve fundamental understanding of the complex physical, chemical and biological interactions between the world's largest expanse of tropical forest and the atmosphere. It includes multidisciplinary studies with over 200 collaborating researchers using the single site to study the balance of energy, water and trace gases, the importance of forests in atmospheric chemistry and aerosol formation, clouds and convection, and the processes underlying seasonal and interannual variations in atmosphere-forest exchange for the diverse ecosystems found in the footprints of ATTO's 80-m and 325-m tall towers.

Max Planck Institute for Biogeochemistry
Hans-Knöll-Str. 10, 07745 Jena
Postfach 10 01 64, 07701 Jena
Germany
www.bgc-jena.mpg.de

Susan Trumbore, Director
Department of Biogeochemical Processes
Phone: +49 3641 576110
trumbore@bgc-jena.mpg.de

MAX PLANCK INSTITUTE
FOR BIOGEOCHEMISTRY

,

It is clear that the goals of ATTO and PANGEA are inherently synergistic. For example, both PANGEA and ATTO will seek to link remotely sensed (aircraft and satellite) characteristics with ground observations. Likewise, ATTO is integrating observations across multiple scales with mechanistic models to gain process-understanding of the main drivers of changes in forests, which complements PANGEA's overall objectives.

Should PANGEA be selected, the ATTO project will be open to opportunities for collaboration. ATTO already involves ~200 collaborating researchers from a range of institutions and disciplines. We have a process for integrating new projects that involves a proposal by potential new investigators, a search for synergies with ongoing research, an assessment of resources needed to support implementation, and an ultimate decision about the integration of the proposed research through our Science Steering Committee. We imagine there are many ways that ATTO can find synergies with PANGEA, and also that PANGEA help can put ATTO measurements into the broader context of other tropical forests.

PANGEA is an exciting project that will significantly advance our understanding of how forests are changing in response to shifts in climate and disturbance regime. As the co-coordinator of ATTO from the German side oft he project, I confirm our interest in and support for the PANGEA Terrestrial Ecology Field Campaign, and look forward to exploring opportunities for collaboration between ATTO and PANGEA.

Sincerely,

Prof. Susan Trumbore, PhD

Dept. Biogeochemical Processes

Max Planck Institute for Biogeochemistry
Hans-Knöll-Str. 10, 07745 Jena
Postfach 10 01 64, 07701 Jena
Germany
www.bgc-jena.mpg.de

Susan Trumbore, Director
Department of Biogeochemical Processes
Phone: +49 3641 576110
trumbore@bgc-jena.mpg.de

Lawrence Berkeley National Laboratory

EARTH & ENVIRONMENTAL SCIENCES

Dr. Margaret S. Torn
Senior Scientist & Senior Program Advisor
Climate & Ecosystem Sciences Division, Lawrence Berkeley National Laboratory
mstorn@lbl.gov

Oct 20, 2024

Dear Dr. Elsa Ordway and PANGEA Team,

I am writing on behalf of the AmeriFlux Management Project to express our support for the NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA), and to signify our intent to collaborate with PANGEA to produce actionable science on tropical forests around the world.

I lead the AmeriFlux Management Project (AMP), which serves the AmeriFlux Network of 674 field sites and teams measuring land-atmosphere fluxes of carbon, water, and energy using the eddy covariance technique. The U.S. DOE established AMP at Berkeley Lab in 2012 to support the AmeriFlux community and AmeriFlux sites, through activities like data quality assurance and control (QA/QC), technical support, and outreach. AmeriFlux site teams across the Americas, from Chile to Alaska, share their data with the network and we make data openly available at ameriflux.lbl.gov. The network also encompasses the global community of scientists and stakeholders who use the data for myriad applications. AmeriFlux datasets, and the understanding derived from them, provide crucial linkages between terrestrial ecosystem processes and climate-relevant responses at landscape, regional, and continental scales.

AmeriFlux has a long history of working with NASA and providing validation data for NASA missions. In fact, we have just convened a Theme Year of Remote Sensing, which emphasized the value of combining remotely sensed and ground-based observations, and increased collaborations with NASA partners. If PANGEA is selected for funding, we will coordinate with the project to advance these capabilities further.

Tropical forests are important ecosystems of interest for the AmeriFlux community. If PANGEA is selected for funding, we will work with the project and make AmeriFlux resources available in a number of ways.

- The AmeriFlux data archive, with over 3500 site-years of downloadable data, will be available to PANGEA researchers. It would be highly beneficial to expand the set of observations in tropical forests, specifically.
- AMP maintains a set of eddy-flux instrument packages which we loan for up to three years (rapid response systems); PANGEA-affiliated scientists would be able to apply to deploy these systems in tropical forests.
- We will coordinate with PANGEA on joint events, such as workshops and training opportunities.
- We will invite PANGEA researchers to participate in our active research community and events. AmeriFlux regularly comes together in community events, and forms working groups to address new challenges and harness opportunities. The PANGEA project would be invited to host sessions at the AmeriFlux Annual Meeting, give updates at the AmeriFlux AGU Town Hall, and other participation.
- Should new eddy covariance sites for measuring carbon fluxes be established for PANGEA, we will assist in registering them in AmeriFlux, offer technical advice, and provide data QA/QC, processing, and publication.

Sincerely,

Margaret Torn

Margaret Torn

November 7th, 2024.

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

I am writing to express our strong support for NASA's Terrestrial Ecology Field Campaign proposal: PAN-tropical Investigation of Biogeochemistry and Ecological Adaptation (PANGEA). If selected, this campaign will address gaps in data, methods, and applications related to measuring, understanding, and scaling carbon, water, and energy fluxes in tropical forests, as well as their interactions with biodiversity, climate change, and human activities. PANGEA has the potential to support and enhance the Sustainable Development and Local Resource Exploration; Education and Scientific Training; and International Research and Innovation Networks activities led and conducted by AmIT in the Pan-Amazon region.

The Amazonian Institute of Technology (AmIT) is a non-profit initiative established in 2022 in Brazil (https://amit.institute/). Our mission is to contribute to the socioeconomic development and improved quality of life of the Amazonian population, in synergy with the conservation and valorization of forests and rivers, by transforming scientific and traditional knowledge into technological innovation serving the Amazon and the world. To achieve our objectives, we plan to operate in the countries of the Amazon basin. Currently, we are in contact with Peru and Colombia to develop activities involving: Advanced Technologies for the Amazon; Human Development for the Amazon; Sustainability for the Amazon Biome; Amazonian Environmental Services; and Applied Biological Sciences for the Development of the Amazon.

We recognize alignment between the efforts and objectives of AmIT and PANGEA, particularly in Sustainable Development and Local Resource Exploration; Education and Scientific Training; and Formation of International Research and Innovation Networks. We are eager to support PANGEA's efforts to leverage Earth observation with multidisciplinary methods to conduct research. AmIT is enthusiastic about the prospect of engaging diverse communities in the tropics to promote scientific understanding, strengthen research and monitoring capacity, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

We seek initiatives with local communities and institutions in partner with Amazonian countries. We are undertaking this initiative in the Amazon due to our strategic geographic position and the region's importance to PANGEA, considering the risks the Amazon faces. AmIT proposes the socioeconomic

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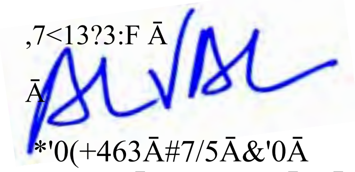

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INTE 050-2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Lima, 22 October, 2024

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing to express my strong support for the proposed NASA Terrestrial Ecology Field Campaign: PANtropical Investigation of bioGeochemistry and Ecological Adaptation (PANGEA). If selected, this campaign will fill critical gaps in our understanding of biogeochemical cycles in tropical forests and their feedbacks with climate, biodiversity, and human activities. PANGEA will also complement and reinforce national and international activities led by NASA and DOE, aligning with ongoing collaborations with AndesFlux, a network led by the Pontifical Catholic University of Peru.

The synergies between AndesFlux and PANGEA are evident, particularly in the measurement and analysis of biogeochemical gases (CO_2, H_2O, CH_4), using eddy flux towers, and forest dynamics, using inventory plots. For years, AndesFlux has been at the forefront of monitoring these processes across five sites spanning the climatic gradient of the western Amazon. Our goal is to elucidate the drivers of biogeochemical gas fluxes and forest dynamics in one of the most understudied regions of the Amazon basin.

We are enthusiastic about PANGEA's vision to leverage Earth observation data and multidisciplinary approaches to advance tropical ecology. The campaign's commitment to engaging diverse communities across the tropics resonates with our own objectives of advancing scientific understanding, building capacity for research and monitoring, and applying results to inform climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

The western Amazon holds strategic importance for achieving PANGEA's objectives. The data we are collecting here are critical for developing a comprehensive understanding of Amazonian ecosystems. Should PANGEA be funded, AndesFlux can offer logistical support across our five sites to validate and improve satellite-derived measurements. We also envision using our existing data to collaborate on PANGEA-related studies, which would benefit from dedicated research funding.

As a longstanding leader in measuring biogeochemical gases and forest dynamics in the Western Amazon, the Pontifical Catholic University of Peru is equally committed to capacity building. Through PANGEA, we aim to expand opportunities for Peruvian scientists by supporting their participation in Master's and Ph.D. programs that utilize AndesFlux data. This will ensure a pipeline of skilled researchers equipped to tackle critical ecological questions.

PANGEA represents an unparalleled opportunity to enhance our collective understanding of Earth systems. As professors and principal investigators of AndesFlux, we express our unwavering support for this campaign and are optimistic that NASA's backing will enable us to pursue these shared research goals.

Founded in 1917, the Pontifical Catholic University of Peru is a leading private research institution based in Lima. Our mission is to advance knowledge and innovation through rigorous research, academic excellence, and community engagement. To achieve these objectives, we operate projects in diverse ecosystems, including tropical forests, coastal zones, and Andean environments, where we focus on ecological monitoring, capacity building, and sustainable development initiatives.

We look forward to the potential of contributing to PANGEA and are confident that this partnership will yield transformative scientific and societal impacts.

Eric G. Cosio, Ph.D.
Director, INTE-PUCP
Professor
Science Department

Norma Salinas, Ph.D.
Senior Research Scientist, INTE-PUCP
Associate Professor
Science Department

Universität Zürich[UZH]

President

University of Zurich
President's Services
Rämistrasse 71
8001 Zürich
www.del.uzh.ch

UZH, President's Services, Rämistrasse 71, 8001 Zurich

Prof. Dr. Michael Schaepman
Professor of Remote Sensing
University of Zurich
Switzerland

Prof. Dr. Elsa M. Ordway
University of California, Los Angeles
USA

09 November 2024

Letter of Support for PANGEA

Dear Dr. Ordway

This letter of support refers to your white paper of PANGEA («The PAN tropical of bioGeochemistry and Ecological Adaptation») discussing the scoping of a NASA-sponsored field campaign.

The above white paper provides in depth information on the scientific rationale, a study design concept for a field campaign, addressing the key science questions of PANGEA, and its rationale and implementation. We have read with great interest the white paper and we are pleased to fully support its goals within the possibilities of the University of Zurich.

More specifically, the University of Zurich acts as Principal Investigator for an airborne observatory named ARES (Airborne Research Facility for the Earth System) with the imaging spectrometer AVIRIS–4 serving as core instrument. AVIRIS–4 is an instrument jointly developed between NASA JPL and the University of Zurich and in operation since 2024.

The ARES team and infrastructure is glad to support PANGEA with airborne acquisitions. The scientific content of PANGEA is of utmost importance and relevance; therefore, the University of Zurich expresses its willingness to provide some in-kind financing for the deployment of ARES for PANGEA.

We are looking forward to a continued excellent collaboration!

Kind regards,

Prof. Dr. Michael Schaepman
President, Professor of Remote Sensing

[Click or type here to enter the enclosures.]

November 20, 2024

Dr. Elsa Ordway
Forest Ecosystems & Global Change Lab
Department of Ecology and Evolutionary Biology
University of California Los Angeles
elsaordway@ucla.edu

Dear Dr. Ordway,

On behalf of Battelle and the NEON program, I am writing regarding your research proposal entitled, “PANGEA (PAN tropical investigation of and Ecological Adaptation) - A Scoping Study for the NASA Tropical Terrestrial Ecology Campaign” being submitted to NASA’s Terrestrial Ecology Program.

If PANGEA is funded, Battelle will work together with you on the proposed effort as we would for any appropriately related NASA-funded project, subject to availability of resources and alignment of the proposed activities with NEON's mission.

PANGEA is a proposed, decade-long campaign that employs satellite and airborne remote sensing paired with ground and flux tower measurements to characterize how heterogeneous tropical forests within and among continents vary in response to anthropogenic pressures to understand and predict their vulnerability or resiliency to future change. If selected, PANGEA will establish a network of centrally coordinated field and airborne campaigns that are distributed across targeted tropical forest ecosystems to fill data gaps and enable scaling between field and remotely sensed datasets, as well as regional and pan-tropical scale modeling.

The National Ecological Observatory Network (NEON), funded by the U.S. National Science Foundation and operated by Battelle, offers open, high-quality, continental-scale ecological data and samples. These resources are freely accessible, enabling researchers to understand and predict ecological responses to environmental changes. NEON operates 47 terrestrial and 34 aquatic sites across the U.S., including Alaska, Hawaii, and Puerto Rico. In coordination with in-situ observational and instrumented systems (e.g., eddy covariance flux towers), NEON conducts airborne remote sensing surveys, with the Airborne Observation Platform (AOP), to gather regional-scale landscape data during peak greenness, providing insights into land cover, ecological changes, and the impact of invasive species. All NEON data and resources are freely accessible for download, sharing, and analysis via the NEON Data Portal or the NEON Data API.

We are closely integrated with the environmental and ecological research community through collaboration, standardized practices, data usage, and research support services. NEON also provides educational and training resources to foster the next generation of students and scientists and aims to broaden and diversify the community for effective utilization of NEON data, samples, and technology.

Battelle promotes a safe and inclusive working environment on the NEON Program that complies with the NSF requirement for Safe and Inclusive Working Environments for Off-Campus or Off-Site Research. It is expected that any individuals working with NEON staff will adhere to the NEON Code of Conduct to create a safe and positive community experience for all.

We are actively collaborating with the NASA EMIT team to develop scaling workflows between NEON and satellite data in preparation for NASA's upcoming Surface Biology and Geology (SBG) mission, and PANGEA could strengthen collaboration and engage a broader research community. There will be strong synergies between NEON and PANGEA in methods optimization and advancement, data collection and processing standards, algorithm development, scaling approaches, training, validation of satellite analyses and large-scale synthesis studies using NEON-like data across global ecological gradients. The NEON Program would benefit from collaboration with PANGEA, given NEON's sites in Hawaii and Puerto Rico fall within PANGEA's extended pan-tropical domain.

PANGEA will be crucial for assessing the resilience and vulnerability of tropical forests to climate change, and provide guiding data in biodiversity conservation, climate change adaptation, and mitigation.

Sincerely,

Paula Mabee, Ph.D.

Chief Scientist and Observatory Director
National Ecological Observatory Network (NEON)
Battelle
Boulder, CO USA
mabee@battelleecology.org

BioSCape: The Biodiversity Survey of the Cape
% Adam Wilson
Department of Geography
University at Buffalo
Buffalo
NY, 14261, USA

Dear Review Panel,

It is our pleasure to recommend the PANGEA project and to offer the experience and expertise of BioSCape as a resource for its success. BioSCape is a biodiversity-focused airborne and field campaign funded by NASA's Biodiversity and Ecological Conservation Program. The project aims to enhance our understanding of terrestrial and aquatic ecosystems in South Africa through advanced imaging spectroscopy, thermal, and lidar data collection. The ultimate goal of BioSCape has been to advance our capability to measure biodiversity from space, shedding light on ecosystem structure, function, and composition.

The BioSCape campaign presented an exceptionally complex Concept of Operations. The science team included 19 PI-led research teams with unique objectives and distinct geographic regions of interest. The campaign required near-simultaneous data collection of target areas by four NASA instruments aboard two separate aircraft—an orchestration made even more challenging by varying environmental conditions and science requirements. Moreover, the BioSCape team was intentionally international, with over 150 members, nearly half of whom were affiliated with institutions outside the U.S. While this diversity brought tremendous value, it also presented challenges in equitable funding due to restrictions on direct U.S. federal funding for non-U.S. affiliates. Additionally, the science team was diverse in scientific discipline, proximity to end-users, field experience, local knowledge, technical capacity, and culture. Consequently, BioSCape was vulnerable to parachute science. Being aware of this risk, BioSCape made a concerted effort to prevent parachute science through co-developing research with end-users in mind and demonstrating a commitment to Open Science, capacity building, and outreach.

BioSCape was a huge success, and we hope to share the lessons we learned with PANGEA and support them in executing high-quality, inclusive international NASA science. Specifically, the BioSCape leadership team will support PANGEA by offering advice on:

- Executing a complex airborne and field campaign in a middle-income country with a diverse set of science team objectives.
- Making progress in best practices for preventing parachute science through co-developing research with end-users in mind and demonstrating a commitment to Open Science, capacity building, and outreach.
- Running an inclusive international campaign and cultivating an ethical and high-trust team dynamic.
- Garnering support and participation from multiple local, regional, and national agencies and institutions on the ground in Africa.

The BioSCape team strongly supports the goals of PANGEA and is committed to contributing to its success. We look forward to the possibility of collaborating with the PANGEA team and seeing their accomplishments in advancing NASA's research objectives.

Sincerely,

Adam M. Wilson

Adam Wilson (PI) on behalf of the BioSCape leadership team: Erin Hestir (Co-PI), Jasper Slingsby (South African PI), and Anabelle Cardoso (Science Team Manager)

Center for Climate Systems Research,
Columbia University
NASA Goddard Institute for Space Studies

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095, USA

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter is to confirm our support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If the field campaign as proposed is selected, PANGEA will fill a fundamental gap on the data needs related to the measurement, understanding, and scaling of carbon, water, and energy fluxes in tropical forests and their interactions with climate change and human activities, contributing towards an improved understanding of how tropical forests are responding to the rapid global changes. PANGEA's overarching goals are closely aligned to the endeavor of modeling global vegetation dynamics and land surface fluxes at NASA Goddard Institute for Space Studies (GISS) in its earth system model, ModelE.

Demographic vegetation modeling (BiomeE) is a model development project within GISS ModelE that has been supported by the NASA Modeling, Analysis, and Prediction (MAP) program since 2020 (https://map.nasa.gov/research/ROSES20/). This project's main objective is to model global vegetation dynamics and its feedback to climate systems. Tropical forest ecosystems are a major component in this modeling effort.

We foresee the synergistic activities and opportunities for collaboration between the land modeling group at GISS and PANGEA. Both projects aim at improving the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions. The new findings will improve the predictive skills of terrestrial biosphere models and quantify the resilience and vulnerability of tropical forest ecosystems. We have submitted a proposal to NASA MAP 2024 on integrating observations across multiple scales with NASA GISS's demographic vegetation model (BiomeE) based on data assimilation and machine learning approaches to gain process-understanding of the main drivers of forest-savanna ecosystem state shifts in the tropical regions of South America and Africa. This topic is also an important objective for PANGEA.

We will look for possible ways for direct involvement with PANGEA should the field campaign be selected for improving the modeling of tropical forest ecosystem in GISS ModelE. We will look for calls for proposals and funding opportunities from PANGEA and other programs (e.g., MAP, Carbon Science, and Biological Diversity & Ecological Conservation), and seek contributions that are related to the goals of PANGEA.

PANGEA is a critically important project that would significantly advance our scientific knowledge of the ecosystems that are still poorly represented in Earth system models. As the developer of the terrestrial ecosystem module in GISS ModelE, we would like to offer our enthusiastic support for the PANGEA Terrestrial Ecology Field Campaign, and look forward to exploring opportunities for collaboration with PANGEA.

Sincerely yours,

Ensheng Weng
Associate Research Scientist
Center for Climate Systems Research, Columbia University
NASA Goddard Institute for Space Studies
2880 Broadway, New York, NY 10025, USA
Email: ew2560@columbia.edu, ensheng.weng@nasa.gov
Office: 212-678-5585
http://www.giss.nasa.gov/staff/eweng.html

Benjamin Cook
Research Physical Scientist
NASA Goddard Institute for Space Studies
2880 Broadway, New York, NY 10025, USA
Email: benjamin.i.cook@nasa.gov
Office: 212-678-5669
https://www.giss.nasa.gov/staff/bcook.html

Prof. Paulo Artaxo

Centro de Estudos Amazônia Sustentável
Universidade de São Paulo

ceas
Centro de Estudos
Amazônia Sustentável

Phone: +[55] (11) 3091 7016 +55-11-991158970 e-mail: artaxo@if.usp.br

São Paulo, November 9, 2024

To whom it may concern

PANGEA letter of support

The Center for Sustainable Amazonia Studies (CEAS) from the University of São Paulo (USP) is pleased to support the PANGEA proposal fully. This innovative approach will help us better understand the critical role that tropical forests play in the global climate. The Brazilian scientific community is eager to join PANGEA's efforts. We are running LBA, ATTO, FACE, and many large-scale experiments that are closely related to the PANGEA scientific agenda.

The University of São Paulo has recently set up a Center for Sustainable Amazonia Studies, which has more than 200 USP researchers from several areas. Our multidisciplinary approach is online with PANGEA, and we will be happy to help and support PANGEA activities.

The FAPESP Global Change Program, of which I am one of the coordinators, will also be happy to join forces. CEAS is already running several FAPESP Thematic projects, and integrating these different initiatives will benefit all of us.

We fully support PANGEA and are ready to help with the implementation plan, integrating our activities with this critical scientific agenda.

Sincerely,

Prof. Paulo Artaxo

Director, CEAS – Center for Sustainable Amazonia Studies

Elsa Ordway, PhD
Forest Ecosystems & Global Change Lab
Department of Ecology and Evolutionary Biology
Congo Basin Institute | Center for Tropical Research
UCLA

05 December 2024.

Support Letter for PANGEA (PAN Tropical Investigation of bioGeochemistry and Ecological Adaptation)

We are writing to convey our enthusiastic support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, the PANGEA program will greatly enhance research activities in forest monitoring, climate change, and capacity building under the leadership of the Centre for International Forestry Research and the World Agroforestry Centre (CIFOR-ICRAF).

CIFOR-ICRAF is an international research organization focused on global issues, namely climate change, biodiversity, food, value chains, and equity. It is dedicated to producing research information to support decision-makers worldwide in improving well-being. Our scientists bring the latest research findings and analysis on forests, trees, and agroforestry to major global forums. CIFOR-ICRAF has offices in 26 countries and works on all six continents.

PANGEA's goals align closely with our ongoing efforts, addressing global challenges like deforestation and biodiversity loss, the climate crisis, inequity, unsustainable supply and value chains, and dysfunctional food systems. We are applicants for supporting PANGEA's use of Earth observation and multidisciplinary approaches in researching tropical forests, peatlands, and coastal ecosystems.

If PANGEA is selected, CIFOR-ICRAF can offer in-kind support through its extensive network and logistical structure in the three tropical basins. There is also the possibility to initiate resource mobilization from other sources to support joint activities with PANGEA, as it represents a project with significant potential impact.

As Chief Executive Officer at CIFOR-ICRAF, I fully support the PANGEA campaign and hope that NASA's endorsement will facilitate this valuable partnership, advancing our shared goals in climate mitigation, adaptation, and conservation, with a particular emphasis on forest ecosystems.

Sincerely,

Dr. Eliane Ubalijoro

CEO of CIFOR-ICRAF

Caltech Linde Center for Global Environmental Science
Division of Geological and Planetary Sciences

Mail Code 131-24
Pasadena, CA 91125
(626) 395-6143
tapio@caltech.edu
www.clima.caltech.edu

10 September 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
Los Angeles, CA, 90095

Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway:

I am writing to express the Climate Modeling Alliance's (CliMA) strong interest in the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA) Scoping Campaign. We are excited by the potential of PANGEA to advance our understanding of tropical forest ecosystems and their response to climate and anthropogenic changes. The alignment between PANGEA's research objectives and CliMA's mission makes this an excellent opportunity for future collaboration and mutual benefit.

At CliMA, our core mission is to deliver actionable climate predictions to empower effective climate adaptation and mitigation planning. We are developing a next-generation Earth system model that leverages machine learning, data assimilation, and extensive ground and space-based observations. Our goal is to predict changes in critical climate phenomena such as droughts, heat waves, and extreme rainfall events, with a focus on providing accurate, localized information.

PANGEA's focus on assessing the impact of global changes on tropical biogeochemical cycles and forest structure aligns with our research interests. We see tremendous potential in integrating high-resolution simulations from our Earth system model with on-the-ground and satellite data collected by PANGEA. This synergy can enable us to quantify uncertainties, offer novel insights into ecosystem responses, and contribute to addressing PANGEA's Science Question 1 regarding the similarities and differences in tropical forest biogeochemistry and structure.

Furthermore, the Earth observations gathered by PANGEA would be invaluable for refining CliMA's models and improving our predictions of ecosystems under future climate scenarios. The opportunity to access data from underexplored tropical forest regions would be particularly beneficial in enhancing our understanding of and capabilities to model these critical ecosystems.

We are also enthusiastic about PANGEA's commitment to open science and capacity building in the Global South. CliMA shares these values and is dedicated to making our scalable, open-source modeling platform accessible to a wide range of stakeholders through cloud resources. We believe that fostering collaboration and providing user-friendly tools for real-world decision-making are essential for addressing the complex challenges posed by climate change.

We eagerly anticipate the outcomes of the PANGEA Scoping Campaign and are optimistic about the potential for future collaboration. Should the PANGEA program secure NASA funding, we would be keen to explore opportunities to leverage CliMA's modeling capabilities in support of PANGEA's research objectives.

Thank you for considering our perspective. We look forward to staying engaged with the PANGEA initiative and contributing to its success in the future.

Sincerely,

Tapio Schneider
Theodore Y. Wu Professor of Environmental Science and Engineering
Principal Investigator, CliMA

Dr. Renato K. Braghiere
Research Scientist
Land Modeling Lead, CliMA

Congo Basin Science Initiative

c/o Congo Basin Water Resources Research Center
Department of Natural Resources Management
University of Kinshasa
Bâtiment FOGRN BC
Kinshasa
Democratic Republic of Congo

Email: info@congobasinscience.net

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

26 November 2024

Dear Dr. Ordway,

RE: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

This letter attests our strong support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If funded, PANGEA will significantly advance scaling of carbon, water, and energy fluxes in tropical forests and/or their interactions with biodiversity, climate change, human activities, via new data, methods, and techniques. The field campaigns will make a major contribution towards understanding how tropical forests across the world are responding to changes in climate, land cover and land use. We co-chair the Congo Basin Science Initiative, which is closely aligned to PANGEA's main goals.

The Congo Basin Science Initiative (CBSI) is a large network of scientists, led by those from the region, to understand the Congo Basin as a changing regional entity, train a new generation of scientists from the region, and deliver this new data and knowledge to policy makers and civil society. Our main source of funds is from the UK government, to implement the CBSI Science and Capacity Plan, which includes distributed data collection across the region including climate, hydrology, vegetation and biogeochemistry, biodiversity, land cover and land use change, and socio-ecological data, to understand the full climate-water-forest-society system.

CBSI and PANGEA are inherently synergistic. For example, both PANGEA and CBSI are working at the large-scale, but with complementary methods, PANGEA focused more on airborne and spaceborne sensors and CBSI more ground-based and process-oriented data collection. Likewise, the ultimate aim of both endeavours is integrating observations across multiple scales with mechanistic models to gain process-understanding of the main drivers of changes in forests.

Should PANGEA be selected, CBSI will seek opportunities for close collaboration with PANGEA. For instance, we will look for funding opportunities that are related to joint PANGEA and CBSI goals.

We will also look to maximize the exposure of our cohort of PhD and MSc students from the region to NASA and wider US science.

PANGEA is an exciting and much needed project, and will significantly advance our understanding of how forests are changing in response to shifts in climate and disturbance regime. As co-chairs of CBSI, we confirm our full support for the PANGEA Terrestrial Ecology Field Campaign, and look forward to exploring opportunities for collaboration between CBSI and PANGEA in the hopefully near future.

Sincerely,

Prof. Raphael Tshimanga
Co-chair, Congo Basin Science Initiative
Professor
University of Kinshasa, DRC

Professor Simon L Lewis FRS
Co-chair, Congo Basin Science Initiative
Chair of Global Change Science
University of Leeds, UK

Rik Van de Walle
Rector

E rector@ugent.be
T +32 9 264 30 01

Campus Ufo, Rectorate
Sint-Pietersnieuwstraat 25
BE-9000 Ghent
Belgium

www.ugent.be

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095

DATE	PAGE	OUR REFERENCE
06 November 2024	1/3	2024/RVDW/ddb/068

Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

I am writing to express strong support of Ghent University for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical data and fundamental research gaps related to the understanding and scaling of CO2 (and other greenhouse gasses) and water fluxes in tropical forests, especially in Central Africa. PANGEA will support and reinforce the data collection, modelling and more generally many of the research activities led and carried out at Ghent University by multiple colleagues, including Prof. P. Boeckx, Prof. M. Bauters, Prof. H. Verbeeck, Prof. W. Hubau and Dr. F. Meunier.

Furthermore, Ghent University is interested to become a member of the science planning team of PANGEA. Ghent University is an internationally renowned public higher education institution of around 50,000 students and 16,000 employees. Our 11 faculties offer over 200 programs and conduct in-depth research in a wide range of scientific fields. Our credo is "Dare to Think", which encourages everyone to question conventional views and dare to take a nuanced position. We are a pluralistic university open to all, whatever their ideological, political, cultural or social background. Ghent University is also the first European university to start a campus on Incheon Global Campus in Korea. We are a Dutch-speaking university, but English is widely spoken by students and staff, and international students can choose from a wide variety of courses and programs in English.

We see several aligned efforts and complementarities between Ghent University's activities in Central Africa and PANGEA, especially in relation to our unique activities in Yangambi, DR Congo, since 2010. In Yangambi we operate since 2020 the first eddy covariance flux tower (CongoFlux) for the Congo basin. CongoFlux follows ICOS protocols and is an associated tower to the ICOS network. We also coordinate a ground-based network of permanent 1 ha inventory plots as well as ForestGeo (1), GEM (4) and regrowth plots (5 chronosequences), ecosystem monitoring, terrestrial and airborne laser scanning, in Yangambi and in multiple other locations in DR Congo and other rainforest countries in Central Africa. We also have specific experience with dynamic vegetation models applied to the tropics, in particular to Central Africa. In addition, we have added tropospheric ozone and black carbon analyzers, FTIR for total column measurements of CO2, CH4 and CO as well as solar induced fluorescence (SIF) sensors.

We and some organizations to which our colleagues are related (e.g., CongoFlux, the Congo Biogeochemical Observatory, the Congo Basin center of Excellence, and the center of excellence for the African Great Lakes' Natural Capital) look forward to supporting PANGEA's efforts to leverage Earth observations and multidisciplinary data collection and methods to conduct research. We are particularly excited to strengthen via PANGEA the remote sensing component (e.g., LIDAR and hyperspectral data) at the CongoFlux site to allow scaling our observations. Hence, we look forward to the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen local capacity (both technicians and researchers) for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

We have already pursued various sensitizing and capacity building initiatives with local communities, the National Institute for Agronomic Study and Research (INERA) in Yangambi, the Universities of Kisangani, Lubumbashi and Bukavu and Mountains of the Moon, as well as various national parks (Kahuzi-Bièga, Salonga, Rwenzori). Ghent University has been working in Yangambi for 15 years and can facilitate PANGEA's implementation by helping with e.g., logistics for new data collection, the synthesis of ancillary data and the modeling of the ecosystems. We have a team of ca. 25 PhDs, 4 local professors and 5 technical staff in the Kisangani-Yangambi landscape.

Should PANGEA be funded, Ghent University can provide in-kind support in the form of data, local networks, logistics, and many other types of support that can be useful. Our team will also consider developing research proposals to seek funding to support participation in PANGEA-related studies.

In conclusion, our institution is one of the few international organizations actively collecting ground-based data in central Africa. We excel at collecting and analyzing different types of ground-based data, including eddy covariance data, plot inventories, wood and leaf trait data, at strengthening capacity of local universities and government officials, and at engaging with local population via various sensitizing activities. We seek to further strengthen our capacities to link vegetation models, ground based, eddy covariance and remote sensing data to improve our understanding of pantropical carbon accounting and ecosystem functioning.

We believe that this is an important project with the potential for high impact. As Rector of Ghent University, I express my utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue these common interest and efforts.

Kind regards,

Rik Van de Walle
Rector

School of Geography

University of Leeds
Leeds
LS2 9JT

UNIVERSITY OF LEEDS

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

7 November 2024

Dear Dr. Ordway,

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

I am writing to express strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of and Ecological Adaptation (PANGEA). If selected, PANGEA will fill critical data, methodological, and training gaps and needs related to the measurement, understanding, and scaling of carbon cycle dynamics in tropical peatlands and their interactions more broadly with biogeochemical cycles, biodiversity, climate change and disturbance dynamics, human activities. PANGEA will also support and reinforce future mapping activities particularly combining ground and Earth Observation data analysis led and carried out by CongoPeat.

CongoPeat is a collaboration between five UK Universities, Marien Ngouabi University in Republic of the Congo and the universities of Kisangani and Kinshasa in the Democratic Republic of the Congo, first established in 2012. Our goal is to understand the past, present and future function of the central Congo peatlands, and supply new knowledge to policy makers and civil society to enhance their long-term protection. To achieve our objectives, we have previously conducted diverse fieldwork across the 16.7 million hectare peatland region, published landmark studies (Dargie et al. 2017, Nature; Garcin et al. 2023 Nature; Hawthorne et al. Quaternary Science Reviews, Young et al. 2024 Global Change Biology), and assisted the establishment of a new law in Republic of the Congo protecting the peatlands from industrial use.

We currently have long-term activities in Ekolongouma (Republic of the Congo), Ossendo and Ossango (Republic of the Congo) and Lokolama (DRC) where we are installing a flux tower and other instrumentation with partners at University of Kisangani, University of Ghent, and University of Kinshasa. We are training a new generation of students in diverse aspects of peatland and wetland science, including 12 current students from Republic of Congo and DRC.

We see several aligned efforts and general aims between CongoPeat and PANGEA, in particular in combining ground data and Earth Observation data to produce better maps of the peatlands; understanding the carbon balance of the peatlands; understanding methane fluxes from the peatlands, and modelling how these might change in the future.

We look forward to working together with PANGEA and its efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics on peatland and wetland research to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

Should PANGEA be funded, CongoPeat will try to align our research activities and assist PANGEA to understand how we can gain additional scientific insights from this. There will be no in-kind benefits from the Republic of Congo and DRC Universities or staff, as we do not have spare capacity or resources. The UK universities may provide in kind support depending on the details of the research programs to be determined, or we will consider developing research proposals where the Republic of Congo and DRC partners co-lead collaborations for win-win research in the Global South and Global North.

We believe that PANGEA is a very important project with the potential for high impact. As founder and Co-lead of CongoPeat, I express my utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue this common effort to understand the world's largest tropical peatland complex, and protect its 29 billion tonnes of stored carbon and world's highest densities of lowlands gorillas and forests elephants for the long-term.

Yours sincerely

Professor Simon L. Lewis FRS
Chair in Global Change Science
School of Geography
University of Leeds
Leeds. LS2 9JT. UK.
Tel: +44 (0)113 343 3337
Email: s.l.lewis@leeds.ac.uk

CONGO PEAT

HARVARD
Faculty of Arts and Sciences
ORGANISMIC AND EVOLUTIONARY BIOLOGY

November 29, 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing in support of the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If selected, PANGEA will address important knowledge gaps regarding the role of structurally and functionally diverse tropical moist forests on carbon, energy, water, and nutrient cycles. The proposed field campaigns will advance our knowledge on the risks of different tropical forest regions undergoing critical, potentially irreversible, transitions due to intensification of climate extremes and expansion of deforestation and forest degradation.

PANGEA's main objectives and vision are closely aligned to the modeling and model-data integration activities conducted by the Ecosystem Demography Model (ED2) team. The ED2 model is a process-based land-surface model that accounts for the dynamic, heterogeneous nature of forest structure and composition, and the resulting impacts of this heterogeneity on ecosystem function. ED2 has been used in multiple studies to answer scientific questions relating to the role of diverse forests in the Earth System, at scales ranging from a single site to entire continents. ED2 can provide mechanistic understanding and quantification of the role of tropical forest functional diversity on increasing the resilience of tropical forests to global change, which is one of the key PANGEA's overarching questions. Importantly, with respect to PANGEA's goals, ED2 has been extensively applied to: (i) study the dynamics of terrestrial carbon, water and energy cycles in tropical regions; (ii) determine and quantify the impacts of using new forms of terrestrial remote sensing observations – including, lidar and radar measurements of forest structure, imaging spectrometry-based measurements of forest composition, and microwave measurements of canopy and soil moisture – to constrain predictions of long-term, large-scale terrestrial ecosystem dynamics; and (iii) bench-marking predictions of terrestrial ecosystem dynamics, including several assessments in tropical regions.

The development and application of the ED2 modelling framework has been supported by multiple United States funding agencies over the past two decades. While NASA has been the primary supporting agency, the National Science Foundation and the Department of Energy have also provided support. Should PANGEA be selected for funding, the ED2 modeling group will seek out opportunities to directly engage with PANGEA activities, including submitting proposals to funding opportunities from the above US agencies that are related to PANGEA's overarching goals. We will also seek opportunities for contributing to capacity building and training of students on land-surface terrestrial ecosystem modeling, both within the US and in the tropics.

PANGEA is a timely and critically important project that will advance our current understanding of the resilience of tropical forests to on-going global environmental change. We enthusiastically support the PANGEA Terrestrial Ecology Field Campaign and look forward to exploring opportunities for collaboration between ED2 and PANGEA.

Sincerely,
The ED2 model development team

Paul R. Moorcroft
Harvard University
Professor of Organismic and Evolutionary Biology
Faculty Affiliate, Environmental Science and Engineering Program, Harvard University
Cambridge, MA 02138

Marcos Longo
Research Scientist
Lawrence Berkeley National Laboratory
Climate and Ecosystem Sciences Division
Berkeley, CA 94720

Ryan Knox
Ecosystem Modeler
Lawrence Berkeley National Laboratory
Climate and Ecosystem Sciences Division
Berkeley, CA 94720

David Medvigy
Associate Professor
University of Notre Dame

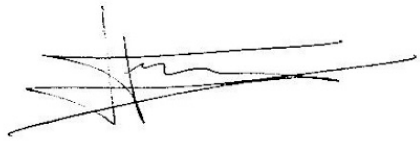
Department of Biological Sciences
Notre Dame, IN 46556

Michael C. Dietze
Professor
Boston University
Department of Earth & Environment
Boston, MA 02215

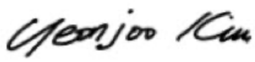
Naomi M. Levine
Professor
University of Southern California
College of Letters, Arts and Sciences
Los Angeles, CA 90089

Abigail Swann
Professor
University of Washington
Department of Atmospheric and Climate Science
Seattle, WA 98195

Xiangtao Xu
Assistant Professor
Cornell University
Dept. of Ecology and Evolutionary Biology
Ithaca, NY 14853



Hans Verbeeck
Associate Professor
Ghent University
Department of Environment
B-9000 Gent, Belgium



Yeonjoo Kim
Professor
Department of Civil and Environmental Engineering
Yonsei University
Seoul, Korea.

Empresa Brasileira de Pesquisa Agropecuária
Ministério da Agricultura e Pecuária
Embrapa Acre
Rodovia BR-364, km 14, Caixa Postal 321
CEP 69900-97 - Rio Branco-AC
Telefone: (68) 3212-3200
www.embrapa.br

Carta nº 109/2024-CPAF-AC/CHGE

Rio Branco, 04 de dezembro de 2024.

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Assunto: **Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)**

Dear Dr. Ordway,

This letter attests our strong support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If funded, PANGEA will significantly advance with data, methods, applications, training gaps/needs related to the measurement, understanding, and scaling of carbon fluxes in tropical forests and/or their interactions with climate change and human activities. The field campaign will make a major contribution towards understanding how tropical forests across the world are responding to changes in climate, land cover and land use. PANGEA's main goals are very aligned with similar activities conducted by Embrapa Acre/C-arouNd in Western Brazilian Amazon.

Refining Soil Conservation and Regenerative Practices to Enhance Carbon Sequestration and Reduce Greenhouse Gas Emissions - C-arouNd is a EJP that has been supported by Embrapa and international institutions since 2023 (https://ejpsoil.eu/soil-research/second-external-call-international-call/c-around). C-arouNd's goals include to investigate how short and long-term agricultural management practices affect SOM persistence in the soil profile and contribute to inclusion of the effects in national inventories to inform policy to reduce net greenhouse gas emissions and mitigate global change. We are currently investigating this persistence in tropical soil of Acre, Western of Brazilian Amazon at Rio Branco and Mâncio Lima, a regional scale.

Refining Soil Conservation and Regenerative Practices to Enhance Carbon Sequestration and Reduce Greenhouse Gas Emissions and PANGEA are inherently synergistic. For example, both PANGEA and C-arouNd are interesting in tropical areas. Likewise, C-arouNd is producing field data that can used to integrate observations across multiple scales with models to gain process-understanding of the main drivers of changes in forests and also agroecosystems, which complements PANGEA's overall objectives.

Should PANGEA be selected, the C-arouNd group will seek opportunities for close collaboration with PANGEA. For instance, We will look for funding opportunities that are related to PANGEA's goals.

PANGEA is an exciting and much needed project, and will significantly advance our understanding of how forests are changing in response to shifts in climate and disturbance regime. We confirm our intention to support for the PANGEA Terrestrial Ecology Field Campaign, and look forward to exploring opportunities for collaboration between Refining Soil Conservation and Regenerative Practices to Enhance Carbon Sequestration and Reduce Greenhouse Gas Emissions and PANGEA.

Sincerely,

Dr. BRUNO PENA CARVALHO
Chefe-Geral da Embrapa Acre

Embrapa
Florestas

Colombo, December 2[nd], 2024.

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter attests my strong support for the proposed NASA Terrestrial Ecology Field Campaign entitled PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). If funded, PANGEA will significantly advance on data, training gaps/needs related to the greenhouse gases measurement in tropical forests, climate change and human activities. The field campaign will make a major contribution towards understanding how tropical forests across the world are responding to changes in climate, land cover and land use. PANGEA's main goals are very aligned with to samples collection and greenhouse gases (CH_4 and CO_2) analysis, using chromatographs activities conducted by Embrapa Florestas.

I am interested in exchanging experience and learning about modeling with your team, also I can see future connections with my projects with alternative biomasses for energy, that can mitigate deforestation. Also, in a Project to produce gold bioextrator produced with leaves from an Amazon native tree that can be used also for mining forest recuperation areas. These projects are related with PANGEA, once it can provide regional changes that that can have global impacts on carbon cycle dynamics and biodiversity loss.

PANGEA is an exciting and much needed project, and will significantly advance our understanding of how forests are changing in response to shifts in climate and disturbance regime. I confirm my utmost support for the PANGEA Terrestrial Ecology Field Campaign, and look forward to exploring opportunities for.

Sincerely,

gov.br Documento assinado digitalmente
MARINA MOURA MORALES
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Marina Moura Morales
Embrapa Florestas
Researcher Sustainable systems
marina.morales@embrapa.br
+55 41 3675 5705 / +55 41 992087182

Marcelo Francia Arco-Verde
Embrapa Florestas
Main head
cnpf.chgeral@embrapa.br
+55 41 3675 5610

Subject: Esri Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing to express our strong support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will significantly advance the application of existing and emerging geospatial technologies developed by Esri towards both social and environmental outcomes. PANGEA's focus on advancing carbon, biodiversity, and agricultural remote-sensing capabilities in the tropics perfectly aligns with Esri's demonstrated commitment to sustainable development initiatives and the conservation of biodiversity.

The Environmental Systems Research Institute, Esri Inc. is a global leader in Geographic Information Systems committed to advancing the understanding or our world through geographic technologies. Esri serves over 650K organizations worldwide who leverage our technology across a wide variety of industries. Our mission is to develop best of class technology, serve the communities using these tools and advance greater efficiencies, understanding and positive impacts for society and the environment.

Esri's primary technology framework, ArcGIS, provides considerable imagery and remote sensing management and analysis capabilities increasingly including emerging hyperspectral capabilities. A close partnership with PANGEA, if selected, would provide Esri an opportunity to exercise these existing and emerging capabilities for positive environmental and social impact. Esri provides complimentary and low-cost access to its technology for Education, Conservation, Humanitarian, and Disaster Response initiatives through formal programs serving tens of thousands of organizations globally. Alignment with PANGEA presents an opportunity for demonstrating the potential of emerging technologies and data sources to communities who can substantially benefit from a new class of geospatial information products and decision support solutions.

We are eager to work with PANGEA to practically apply and improve ArcGIS to further advance Earth observation capabilities. We strongly endorse PANGEA's collaborative and multidisciplinary approach to understanding tropical forest, peatland, and wetland responses to global environmental change to support the development of innovative and effective solutions.

If PANGEA is selected, ESRI can provide in-kind support through the access of Esri technology for key stakeholders including nonprofits, academic institutions and Local and Indigenous

Communities. Our team is also prepared to explore funding opportunities to formally participate in PANGEA-related research and applications activities through support from Esri Professional Services and our global network of partner organizations.

We believe PANGEA represents a project with high potential impact. As the Director of Conservation Solutions at ESRI, I offer my full support for the PANGEA campaign and hope that NASA's endorsement of PANGEA will facilitate this valuable partnership and further our impact towards sustainable development, climate and biodiversity conservation goals.

David Gadsden

Director, Conservation Solutions
Esri Inc.
380 New York Street
Redlands, California

STANFORD UNIVERSITY

Robert B. Jackson, Douglas Provostial Professor
Department of Earth System Science
School of Earth, Energy & Environmental Sciences
Stanford, California 94305-4216

Phone: (650) 497-5841
Fax: (650) 498-5099
jacksonlab.stanford.edu

Dr. Elsa Ordway
Department of Ecology and Evolutionary Biology
UCLA

4 December 2024

Re: PANGEA Application

Dear Dr. Ordway and the PANGEA Team,

We are writing in support of your project "PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)" and to express our intent to collaborate with you on the project. We established and coordinate the FLUXNET-CH_4 network and we are currently establishing a network of new methane flux towers across the Amazon and into Africa, in collaboration with researchers in these regions. This includes eddy flux measurements in Brazil, Peru, French Guiana, and Botswana, as well as synthesis of data from flux towers across the South America, Africa and Southeast Asia. The tropics are a large and growing source of methane emissions, but measurements of these fluxes remain extremely limited. PANGEA's proposed work will fill this gap by providing new measurements locations and a platform to scale these findings with remote sensing.

We would welcome the chance to collaborate with you on PANGEA. We see many synergies between our efforts and PANGEA's proposed work. For example, one of our major goals is synthesis of existing *in situ* methane flux data from tropical ecosystems. This will complement PANGEA's airborne campaigns and provide a valuable foundation to target new field measurements. Additionally, we have developed virtual training materials on methane flux data processing to improve data quality from tropical sites. A collaboration with PANGEA would offer a platform to disseminate these resources more widely. In summary, if PANGEA is selected for funding, we see many opportunities to align our research and training efforts to improve our understanding of tropical methane emissions.

Sincerely,

Robert B. Jackson
Douglas Provostial Professor
Department of Earth System Science
Stanford University
Stanford, CA 94305
(650) 497-5841 (Ph)
rob.jackson@stanford.edu

Alison M. Hoyt
Assistant Professor
Department of Earth System Science
Stanford University
Stanford, CA 94305
(650) 283-9862
ahoyt@stanford.edu

Viale delle Terme di Caracalla, 00153 Rome, IT www.fao.org

Rome, Italy 24 September 2024

Dr Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for PAN tropical investigation of biogeochemistry and Ecological Adaptation (PANGEA)

Dear Dr Ordway,

I am writing to express my strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of biogeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical data, methods, applications, training gaps and needs related to the measurement of carbon, water, and energy fluxes in tropical forests and/or their interactions with biodiversity, climate change, human activities. PANGEA will also support and reinforce several activities led and carried out by the Climate Change, Biodiversity and Environment Office of the United Nation Food and Agriculture Organization (FAO).

We see several aligned efforts and general aims between FAO and PANGEA, in particular, improving our understanding of the tropical forest biomes and all the land use change processes that are occurring in these regions. We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

Should PANGEA be funded, FAO can provide in-kind support in the form of data exchange, cooperation and direct/indirect participation to many projects occurring in the tropical regions. Our team will also consider supporting participation in PANGEA-related studies.

While our organization excels at strength (e.g. community engagement, collecting and analysing ground-based data, strengthening capacity of local government officials, etc.), we seek to engage in research activities such as, "leveraging satellite imagery to improve carbon cycle assessment".

We believe that this is an important project with the potential for high impact. As leader of the Climate Action Support Team in the Office of Climate Change, Biodiversity and Environment (OCB), I express my utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue this common effort.

Martial Bernoux
Senior Natural Resources Officer
Climate Action Support Team
Office of Climate Change, Biodiversity and Environment (OCB)
Food and Agriculture Organization of the United Nations (FAO)
Viale delle Terme di Caracalla, 00153 Rome, Italy

Forest Global Earth Observatory
Smithsonian Tropical Research Institute

6 December 2024

To: Dr. Elsa Orway
PANGEA Lead, Forest Ecosystems & Global Change Lab
Department of Ecology and Evolutionary Biology
Congo Basin Institute | Center for Tropical Research
UCLA

RE: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

I am pleased to provide my strong support for your NASA proposal entitled *"PAN-tropical bioGeochemistry Airborne Experiment in Africa and the Americas (PANGEA)."* This is an extremely important initiative that will lead to a huge leap in understanding of how tropical forests are and will respond to the combined effects of climate and land-use change.

As Director of the Forest Global Earth Observatory (ForestGEO) at the Smithsonian Institution, I am excited to contribute to this research effort through ForestGEO activities across the tropics. Leveraging the long-term site-based monitoring of tropical forests by ForestGEO partners over the past 40 years, will advance the goals of PANGEA and will be hugely beneficial to ForestGEO's goals of tropical forest science and capacity sharing and strengthening.

Please feel free to contact me if you require any further information.

Yours sincerely,

Stuart Davies

Stuart J. Davies
Frank H. Levinson Chair in Global Forest Science
Director, Forest Global Earth Observatory (ForestGEO)
Smithsonian Institution
www.forestgeo.si.edu
daviess@si.edu

School of Geography
University of Leeds
Leeds LS2 9JT
U.K.

+44 (0) 113 34 36832 (direct)
Email: o.phillips@leeds.ac.uk

UNIVERSITY OF LEEDS

FORESTPLOTS.NET

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

21st November 2024

Dear Dr. Ordway,

I write to express my enthusiastic support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will significantly enhance the understanding of Earth's most precious ecosystems. It will also help support the work of many tropical partners of ForestPlots.net, connecting them better to the remote-sensing community.

ForestPlots.net is a global collaboration of many networks and almost 3,000 scientists engaged in measuring, monitoring and analysing the world's tropical forests. Our primary aims are to connect people measuring forests on the ground, to fund fieldwork in tropical countries, and to support our tropical partners so they can manage their data effectively and engage equitably in global science.

Several of PANGEA's goals align closely with ongoing efforts at ForestPlots.net, perhaps especially in central Africa where we have received new funding recently from the Central African Forest Initiative (CAFI) to support AfriTRON partners in their long-term forest measurements. We are eager to support PANGEA's collaboration with the forest plot community to advance equitable collaboration, integrate of field measurements and knowledge with Earth observation, and develop a multidisciplinary approach to research in tropical forests, peatlands, and wetlands.

ForestPlots.net partner scientists are interested in diverse themes, such as tree mortality and its drivers, pan-tropical biodiversity and ecosystem function patterns and processes, and forest resilience to climate change. Our contributing networks are grounded in local partnerships, and especially active in Amazonia and tropical Africa. These partnerships and the deep knowledge of tropical forest ecosystems embedded in the ForestPlots.net community will facilitate PANGEA's objectives as this expertise and ForestPlots.net's longstanding regional experience will provide strong local support for PANGEA's implementation across the tropics.

If PANGEA is selected, we are interested to explore funding opportunities so our partners can directly participate in PANGEA-related research and applications activities. We see opportunities in PANGEA's focus on advancing remote-sensing capabilities in the tropics to further our goals, connecting our partners' work to help them collaborate with this community, and generating new sources of funding to support the vital fieldwork which underpins the calibration and validation of remote-sensors and their products.

I strongly believe that PANGEA represents a project with high potential impact. As Coordinator of the global ForestPlots.net initiative and the RAINFOR network in Amazonia, and Chair in Tropical Ecology at the University of Leeds, I therefore offer my full support for the PANGEA campaign. I hope that NASA's endorsement of PANGEA will facilitate this valuable partnership and further our shared goals on climate mitigation and adaptation goals and globally-equitable science, with a particular emphasis on resilient forests and locally led solutions.

Yours sincerely

Professor Oliver Phillips
Chair in Tropical Ecology
University of Leeds
School of Geography
Leeds, UK
(44) 113-343-6832
www.rainfor.org
www.ForestPlots.net
o.phillips@leeds.ac.uk

AGEOS
AGENCE GABONAISE D'ETUDES
ET D'OBSERVATIONS SPATIALES

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

I am writing to express my strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical data, methods, applications, training gaps/needs related to the measurement, understanding, and scaling of carbon, water, and energy fluxes in tropical forests and/or their interactions with biodiversity, climate change, human activities. PANGEA will also support and reinforce Gabonese national forest characterization and monitoring activities already led and carried out by AGEOS.

AGEOS is a governement agency that was established in 2010 in Gabon (http://ageos.ga/). Our goal is to Involve in the implementation of the Government's policy on the acquisition, analysis and availability of data from space observation of the national land for the sustainable management of the environment, natural resources, land use, regional planning, research and innovation. To achieve our objectives, we develop a national strategy for space observation activities ; manage the space infrastructure ; ensure the monitoring and evaluation of the implementation of public policies (roads, housing, energy, natural resources, etc.) ; provide data related to climate change and promote training, research and capacity building in earth observation tools.

We see several aligned efforts and general aims between AGEOS and PANGEA, in particular in biogeochemical cycles and carbon dynamics, ecosystem structure, function and biodiversity and climate feedbacks and interactions.

We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

While our organization/institution excels at analyzing remote sensing datas and collecting ground-based data, we seek to engage in leveraging satellite imagery (data), data collect method and capacity building (advanced level) planned in PANGEA framework to improve carbon accounting.

We believe that this is an important project with the potential for high impact. As [General Director of AGEOS, I exprcss my utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue this common interest/activity/effort.

AGENCE GABONAISE D'ETUDES D'OBSERVATIONS SPATIALES
RÉPUBLIQUE GABONAISE
UNION-TRAVAIL-JUSTICE
LE DIRECTEUR GÉNÉRAL

Aboubakar MAMBIMBA NDJOUNGUI
General Director
AGEOS
NKOK Special Economic Zone (ZES) - Plot R27- PK27
Gabon

2 December 2024

To: Dr. Elsa Orway
PANGEA Lead
Forest Ecosystems & Global Change Lab
Department of Ecology and Evolutionary Biology
Congo Basin Institute | Center for Tropical Research
UCLA

RE: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing to express our enthusiastic support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will significantly advance understanding of the role of tropical forests in the earth system. It will also benefit and be synergistic with the recently established GEO-TREES initiative.

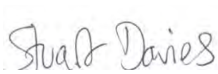
GEO-TREES is a ground-based reference system for the calibration and validation of earth observation satellite estimates of forest carbon. GEO-TREES is working with hundreds of partners across the world's forests to establish a representative network of permanent reference sites. This involves ground plots, terrestrial laser scanning, and airborne laser scanning at each site, and is underpinned by significant investments in training and capacity sharing. Our initial goal is to establish 100 core reference sites globally, with at least 60 sites in tropical forests.

Several of PANGEA's goals align closely with ongoing efforts at GEO-TREES, particularly in understanding current and future changes in tropical forest dynamics and functioning. We are eager to support PANGEA's use of Earth observation and multidisciplinary approaches in research in tropical forests, peatlands, and wetlands that span intact to disturbed forests. We see a particular opportunity for PANGEA's focus on advancing remote-sensing capabilities in the tropics to further GEO-TREES goals through the incorporation of biodiversity monitoring in tropical forests.

If PANGEA is selected, GEO-TREES will endeavor to support PANGEA research and training initiatives at sites across the tropics. We would also welcome the opportunity to explore funding opportunities to participate in PANGEA-related research and applications activities. The longstanding experience of the GEO-TREES leadership team and partner sites and networks across the tropics will be of strategic importance to PANGEA's objectives.

On behalf of the GEO-TREES Executive Board, we offer our full support to the PANGEA campaign. We believe PANGEA represents a project with high potential impact, and hope that NASA's endorsement of PANGEA will facilitate this valuable partnership and further our shared climate mitigation and adaptation goals.

Yours sincerely,



Stuart J. Davies
Frank H. Levinson Chair in Global Forest Science
Director, Forest Global Earth Observatory (ForestGEO)
Smithsonian Institution
www.forestgeo.si.edu

Jérôme Chave, CNRS
UMR5300 Centre de Recherche sur la Biodiversité et l'Environnement,
CNRS, INPT, IRD, Université de Toulouse, France
https://jeromechave.github.io/

UNIVERSITY OF MARYLAND
DEPARTMENT OF GEOGRAPHICAL SCIENCES

December 4, 2024

Re: PANGEA letter of support

To whom it may concern:

I am writing in support of the PANGEA research campaign and its goals of discovering the impacts of climate and land-use change on the world's humid tropical forests, focusing on the Americas and Africa. Our GLAD (Global Land Analysis and Discovery - glad.umd.edu) laboratory at the University of Maryland generates the annual global forest loss maps that are the core data set of the Global Forest Watch (globalforestwatch.org) program, and much of our work is focused on humid tropical forests. By definition, primary humid tropical forests are a finite resource. Our data show an increasing rate of loss for this invaluable, and non-renewable, environmental asset. The outcomes of deforestation are well documented, including carbon emissions, biodiversity loss, and local and global downstream climate impacts. Change in humid tropical forests used to be predominantly mechanical extraction/clearing. Increasingly, we see fires consuming rainforests. Whether accidental or intentional, practically all rainforest fires are human set and track with climate anomalies. What is clear is that land use and climate change have made the rainforests more likely to burn, and we are in critical need of understanding and mitigating this dynamic. The list of interventions is long, but must be informed by science. Without such action, per the concept of the tipping point, humid tropical climate systems may change states and lead to the conversion of rainforests without any direct human action.

All of this is to say that PANGEA fits the need and call for action. The proposed field campaign will help us understand the differences and commonalities between rainforests, building a data-driven framework that advances our monitoring, modeling, and possible mitigation of the effects of large-scale climate and land use change on rainforests.

Our work at GLAD is a ready input to this effort. While we work pan-tropically, we also partner with national governments, NGOs and universities. Our capacity building efforts advancing land remote sensing in the tropics, whether supporting national reporting with the forestry agencies of the Democratic Republic of the Congo and Republic of Congo, or in a scientific advisory capacity with MapBiomas in Brazil, constitute a host of in place partnerships ready to synergize with PANGEA.

Please, use this letter as evidence of my unqualified and enthusiastic support for PANGEA and its comprehensive and ambitious plan to advance our understanding of current rainforest dynamics in helping to mitigate future rainforest loss.

Sincerely,

Matthew Hansen
mhansen@umd.edu
University of Maryland, Professor

November 20, 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

On behalf of the Governors' Climate and Forests Task Force (GCF Task Force), we are writing to express our ongoing support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical needs in terms of data, capacity building, and improved understanding of carbon, water, and energy fluxes in tropical forests and their interactions with biodiversity, climate change, and human activities. PANGEA also has significant potential to support and reinforce forest protection and land use governance efforts led and carried out by member jurisdictions of the GCF Task Force.

Established in 2009, the GCF Task Force is a unique coalition of 43 states and provinces from 11 countries working to establish and enhance jurisdiction-wide approaches to reducing deforestation and promoting sustainable land use. We work directly with the Governors, Secretaries, and civil servants in our member states and provinces as well as with their partners from civil society, Indigenous and local communities, academia, and the private sector to develop innovative, collaborative approaches to the problems of deforestation and climate change.

We see several aligned efforts and general aims between the GCF Task Force and PANGEA, particularly helping to ensure close collaboration between researchers, data scientists, and land use decisionmakers. To that end, we were pleased to co-sponsor a PANGEA scoping workshop in Lima, Peru in June 2024. Technical civil servants from GCF Task Force member jurisdictions in Bolivia, Colombia, Ecuador, and Peru, together with academic researchers from these same countries, convened to learn about PANGEA and to provide insight into how improved data, methods, and applications from this field campaign could support both scientific and forest governance advancements on the ground.

The GCF Task Force was an early advocate for the proposal to design the PANGEA scoping study (see attached support letter), and we look forward to continuing to support PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. Should PANGEA be funded, we are particularly excited at the prospect of increasing the engagement of diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices. We hope to leverage our network of policymakers, technical staff, and partners from across our 43 member states and provinces to use PANGEA products and participate in capacity building activities.

We believe this is an important project with the potential for high impact. We look forward to working with you and your team and hope that NASA's support of PANGEA will enable us to pursue this common effort together.

Sincerely,

William Boyd
Project Lead

Jason Gray
Project Director

Attachment: Support Letter for Scoping Studies

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter is to affirm my support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If the PANGEA field campaign is selected for funding, it will fill important knowledge gaps on how biodiverse tropical moist forests impact the energy, water and carbon cycling at local, regional, and global scales. It will also obtain calibration data for the new generation of satellite sensors at historically undersampled areas, and provide a unique opportunity to train and build research capacity in tropical regions. PANGEA will also be synergistic to Guyaflux activities led and carried out by INRAE in French Guiana.

Guyaflux (GF-Guy), located at the Paracou field station in French Guiana, is a long-term research program led by INRAE and funded by INRAE and various European contracts since 2003 (https://paracou.cirad.fr/website/experimental-design/guyaflux-tower). Guyaflux aims at analyzing the impact of environmental conditions, particularly climate change, on greenhouse gas fluxes between the tropical rainforest ecosystem and the atmosphere. The Guyaflux site has power (solar panels) and wooden houses that may facilitate collaborations with PANGEA. Participants of PANGEA will also have access to labs located at INRAE's research center at Kourou (45-min drive from Paracou field station).

There are multiple highly aligned goals between Guyaflux and PANGEA. For example, both projects seek to understand the impacts of climate variability and climate extremes on the resilience of tropical moist forests. We also share the same vision on the need of integrative approaches that combine field observations, remote sensing and models to better understand how tropical forests are responding to climate change.

Should PANGEA be selected, the Guyaflux team will consider applying for funding opportunities that are synergistic with PANGEA, to advance direct collaboration with PANGEA and expand international partnerships.

PANGEA will be an extremely important project for filling critical knowledge gaps in highly biodiverse yet vulnerable tropical moist forests, and for building a long-lasting local research capacity in the tropics. As the PI and scientific head of the Guyaflux site, I express my support for the PANGEA Terrestrial Ecology Field Campaign and hope that NASA's support of PANGEA will unlock several opportunities for a strong partnership with Guyaflux.

Dr. BONAL Damien

Senior Scientist

INRAE

UMR SILVA, 54180 Champenoux, France

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter is to affirm my support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If the PANGEA field campaign is selected for funding, it will fill important knowledge gaps on how biodiverse tropical moist forests impact the energy, water and carbon cycling at local, regional, and global scales. It will also obtain calibration data for the new generation of satellite sensors at historically undersampled areas, and provide a unique opportunity to train and build research capacity in tropical regions. PANGEA will also be synergistic to Guyafor activities led and carried out by Cirad in French Guyana.

Guyafor network (GF-Guy) is a long-time survey program of experimental forest plots led by Cirad and funded by Cirad and various French and European fundings since 1984 (https://paracou.cirad.fr/). Guyafor network aims at assessing the response of guyanese forests dynamics, structure and functioning to climatic variability and logging practices. We currently integrate regular forest inventories, botanical identification, environmental data and remote sensing data at the scale of experimental stations across the territory and at regional scale in french guyana. Within the Guyafor network, Paracou station has power and wooden houses that may facilitate collaborations with PANGEA, and the UMR EcoFoG labs are accessible in Kourou (45-min drive from the Paracou station).

There are multiple highly aligned goals between Guyafor and PANGEA. For example, both projects seek to understand the impacts of climate variability and climate extremes on the resilience of tropical moist forests. We also share the same vision on the need of integrative approaches that combine field observations, remote sensing and models to better understand how tropical forests are responding to climate change.

Should PANGEA be selected, the Guyafor team will consider applying for funding opportunities that are synergistic with PANGEA, to advance direct collaboration with PANGEA and expand international partnerships.

PANGEA will be an extremely important project for filling critical knowledge gaps in highly biodiverse yet vulnerable tropical moist forests, and for building a long-lasting local research capacity in the tropics. As the PI of Paracou station and among scientific coordinators of Guyafor network, I express my support for the PANGEA Terrestrial Ecology Field Campaign and hope that NASA's support of PANGEA will unlock several opportunities for a strong partnership with Guyafor.

Dr. MIRABEL Ariane
Researcher
Cirad
UMR EcoFoG, 97310 Kourou, France

ICOS Integrated Carbon Observation System

To
Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Dr. habil. Werner Leo Kutsch
Director General
Integrated Carbon Observation System (ICOS ERIC)
Email: werner.kutsch@icos-ri.eu

Helsinki, 15 November 2024

Dear Dr. Ordway,

Subject: Letter of Support for the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

I am writing to express my strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical data and methods gaps related to the measurement, understanding, and scaling of carbon, water, and energy fluxes in tropical forests. PANGEA will also support and reinforce international research, training, and data collation activities led and carried out by ICOS.

The Integrated Carbon Observation System (ICOS) is a distributed Research Infrastructure to generate high-precision data and integrate knowledge on the carbon cycle and greenhouse gas (GHG) budgets and of their perturbations. ICOS conducts long-term observations in three networks – atmosphere, ecosystems, and oceans – as required to understand the present state and extrapolate to the future behaviour of the global carbon cycle and GHG fluxes. ICOS has an increasing role in scientific support of climate policy.

ICOS has a number of activities ongoing in Africa, in particular with one Ecosystem Associate station (Yangambi in the Democratic Republic of Congo) and the Atmospheric station in La Réunion, and in French Guiana with the Associated Ecosystem station GuyaFlux. In addition, ICOS coordinates an EU project that has the aim to design an environmental Research Infrastructure in Africa (https://kadi-project.eu/).

We see a number of aligned efforts and general aims between ICOS and PANGEA, in particular in advancing research that leverages satellite imagery to advance methods to scale fluxes, and to validate and calibrate remote sensing products using the data collected at the flux towers. The ICOS Ecosystem stations have long histories of data being used for Cal/Val and model benchmarking, and a set of standardized tower-based remote sensing data are being implemented in the ICOS network, including FAPAR, canopy thermal measurements and imaging, phenology cameras and spectral data. PANGEA would help to fill spatial gaps thanks to the extensive use of remote sensing data (including the European satellites) and help to build a consistent and robust link between local scale field measurements and large scale continental and global products.

The collaboration between ICOS and PANGEA will improve accessibility to high quality carbon cycle data and can develop common or coordinated training initiatives and material for the next generation of scientist, in particular on the scalability of in situ measurements using high quality remotely sensed data. The plan of PANGEA in extending training material and activities in Portuguese and French languages would make the training more effective and accessible in the target areas of Africa and South America.

Should PANGEA be funded, ICOS will be excited to coordinate activities, and support PANGEA through the ICOS stations in tropical regions, the ICOS Ecosystem Thematic Centre and the ICOS Head Office and Carbon Portal. Among the activities, ICOS will continue to perform rigorous eddy covariance data processing and distribution services, including for possible new sites in Africa, and evaluate the extension of measurements and products as funding availability allows. ICOS will also consider developing research proposals to seek funding to support participation in PANGEA-related scientific and training activities.

We recognize the mutual benefits in coordinating with PANGEA and sharing efforts, research methods (e.g., numerical models), datasets, resources, and experiences to advance understanding of tropical terrestrial ecosystems and better leverage Earth observation datasets to support our Research Infrastructure goals. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for the research and understanding in the carbon cycle, and support the application of scientific results to governance and sustainable land management practices.

We believe that this is an important project with the potential for high impact. As the Director General of ICOS, I express my utmost support on behalf of the PANGEA campaign scoping team and hope that NASA's support of PANGEA will enable us to pursue this common research interest.

Yours sincerely,

Werner Kutsch

Dr. habil. Werner Leo Kutsch

IITA Transforming African Agriculture CGIAR

International mailing address
IITA Ltd, Suite 32
5th floor, AMP House
Dingwall Road
Croydon
CR0 2LX

Headquarters
PMB 5320, Oyo Road, Idi-Oshe
Ibadan, Nigeria
Tel.: +1 201 6336094
+234 700 800 4482
Fax.: +44 (208) 711 3786 (via UK)

14 November 2024

Co-Director,
Centre for Tropical Research and Congo Basin Institute
Department of Ecology and Evolutionary Biology
410K Botany Building
University of California
Los Angeles, CA 90095.

Dear Dr. Ordway,

RE: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

I am writing to express the support of the International Institute of Tropical Agriculture (IITA) for the proposed National Aeronautics and Space Administration (NASA) Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical data, methods, applications, and training gaps and needs related to the measurement, understanding, and scaling of remote sensing data in tropical forest regions. This aligns well with IITA's mission to offer a leading research partnership that facilitates agricultural solutions to hunger, poverty, and natural resource degradation throughout sub-Saharan Africa.

IITA leads the One CGIAR's African continental agenda and operates in twenty-one (21) research stations in Africa covering sixteen (16) countries, including multiple stations in the Congo Basin covering Burundi, Cameroon, Central African Republic, Chad, Republic of Congo, DR Congo (DRC), Equatorial Guinea, Gabon, Rwanda, and São Tomé and Príncipe. IITA's operations focus on Research for Development (R4D) and Partnerships for Delivery (P4D), a structure designed to bridge the gap between research and its deployment in Africa. Through partnerships with governments, development partners, and communities, IITA deploys successful technologies and methods to sustainably advance food security in Africa.

As a leading organization focused on conducting research and deploying advances to address food insecurity, we anticipate partnering to use data and methodological improvements from PANGEA through an Earth Science to Action (ES2A) framework. Specifically, improved remote sensing data from the tropics could be leveraged as part of the One CGIAR Sustainable Farming program, a multi-institutional initiative on sustainable food production, with a focus on sub-Saharan Africa. Specifically, the PANGEA initiative aligns perfectly with IITA's programs on breeding for resilient crops under the genetic innovation research area, plant health, natural resource management and mixed crop agronomy under the resilient farming systems research area, as well as the climate adaptation under the system transformation research area. Methodological improvements from PANGEA offer opportunities to remotely track the impact of agronomy interventions on crop yields, significantly increasing our ability to measure the uptake and impact of new agronomic inputs and methods. We also anticipate using findings from PANGEA to advance climate-smart agriculture, and better understand the impacts of climate change on crop productivity.

Transforming African Agriculture CGIAR

International mailing address
IITA Ltd, Suite 32
5th floor, AMP House
Dingwall Road
Croydon
CR0 2LX

Headquarters
PMB 5320, Oyo Road, Idi-Oshe
Ibadan, Nigeria
Tel.: +1 201 6336094
+234 700 800 4482
Fax.: +44 (208) 711 3786 (via UK)

Remote sensing is a particularly powerful tool in a region like Central Africa, where the vast majority of farmers are smallholders, many of whom live in relatively remote areas. Improved remote sensing capabilities, and in particular improved resolution that allows remote research on parcels of less than 1 ha, offer significant promise to improve our ability to understand and improve food production in the region. Improved resolution on multiple scales is also needed to understand the interrelation between smallholder farms and forest loss and to reliably track land use changes at scale in the region.

PANGEA initiative is led by the University of California, Los Angeles (UCLA) with which IITA has established an initiative named Congo Basin Institute (CBI) that aims to integrate the dual goals of biodiversity and forest conservation while improving local community livelihoods. Since 2015, CBI has developed various initiatives aiming at connecting agricultural improvement activities with biodiversity and forest conservation to achieve more efficient traits that will maintain yield under heterogeneous environments. The PANGEA initiative will then be a unique opportunity for this partnership to further produce an impact on the needs to feed the growing population while conserving forest cover and biodiversity in the Congo Basin region that harbors the second-largest rainforest in the world, representing 30% of the global forest area, and that faces accelerated degradation due to multiple pressures among which poorly practised agriculture alone contributes up to 84% of the forest cover loss.

If selected, we look forward to supporting PANGEA's efforts to leverage earth observation and multidisciplinary data and methods in ways that align with these IITA efforts. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for improved food security, climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

Should PANGEA be funded, IITA expects to use the resulting data and methodologies to inform our research to sustainably improve food security in Africa and to monitor the deployment of those technologies. Our team also plans to develop research proposals to seek funding to apply PANGEA's data and methodologies to improve food security in Central Africa.

We believe this is an important project with the potential for high impact. As the Deputy Director General, Partnership for Delivery of IITA, I express my utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to collaboratively pursue these common interests.

Yours Sincerely,

Signed by:
Dr. Kenton Dashiell
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Dr. Kenton Dashiell
Deputy Director General Partnerships for Delivery

“Año del Bicentenario, de la consolidación de nuestra Independencia, y de la conmemoración de las heroicas batallas de Junín y Ayacucho”

Pucallpa, 10 de setiembre de 2024

CARTA No. 149-2024-MRA-PMRA

Señores
ADMINISTRACIÓN NACIONAL DE AERONÁUTICA Y EL ESPACIO – NASA
Presente. -

ASUNTO: APOYO A LA INICIATIVA PANGEA

Por medio de la presente, me complace dirigirme a ustedes a fin de saludar la posibilidad de impulsar la iniciativa PANGEA por parte de la NASA, la misma que permitiría realizar una campaña de investigación de campo de largo a nivel de la Amazonía.

En el Perú, los gobiernos subnacionales de la Amazonía hemos conformado la Mancomunidad Regional Amazónica – MRA y pertenecemos a la plataforma de los Gobernadores por el Clima y los Bosques – GCF Task Force (por sus siglas en inglés) que agrupa a 43 gobiernos subnacionales a nivel global, incluyendo a los gobiernos subnacionales de Pastaza, Morona Santiago y Zamora Chinchipe de Ecuador; Caquetá en Colombia; Pando, Santa Cruz y Tarija de Bolivia; Maranhão, Amapá, Tocantins, Pará, Roraima, Mato Grosso, Amazonas, Rondonia y Acre de Brasil; y Amazonas, Huánuco, Loreto, Madre de Dios, Piura, San Martín y Ucayali del Perú.

Actualmente en mi calidad de Gobernador Regional de Ucayali en Perú, soy Presidente de la Mancomunidad Regional Amazónica del Perú, representando 7 gobiernos subnacionales peruanos y presido actualmente también la plataforma del GCF Task Force, representando a 43 gobiernos subnacionales, de los cuales 22 pertenecen a la Amazonía en 5 de los países amazónicos.

Los gobiernos subnacionales, especialmente los de la Amazonía somos conscientes de que los bosques tropicales están experimentando cambios climáticos dramáticos, se ha incrementado la pérdida de biodiversidad y hay cada vez mayor presión por cambios en el uso de la tierra, sin que contemos con las capacidades y la información necesaria para hacer frente a estos desafíos.

Los cambios en la dinámica del flujo de carbono, el ciclo del agua, los eventos climáticos extremos y las migraciones de las especies están generando cambios importantes que afectan la vida y la producción de alimentos, lo cual pone en riesgo la seguridad alimentaria de nuestras poblaciones, especialmente de pueblos indígenas que habitan nuestra Amazonía.

“Año del Bicentenario, de la consolidación de nuestra Independencia, y de la conmemoración de las heroicas batallas de Junín y Ayacucho”

La Amazonía es reconocida en el mundo entero por ser megadiversa y por ello altamente vulnerable al cambio climático y aunque los ecosistemas de bosques tropicales están mostrando evidencia de respuestas de adaptación frente al mismo, no conocemos a profundidad que esta sucediendo y cómo podríamos contribuir con este proceso de forma más eficiente y urgente.

Consideramos que la iniciativa PANGEA nos serviría para impulsar mejoras continuas en la ciencia de la teledetección, la recopilación de datos y la aplicación de esta ciencia para mejorar la gobernanza forestal, la planificación territorial, los esfuerzos de comando y control, la lucha contra incendios, combate a las economías ilegales y otras acciones críticas en el territorio.

Estamos comprometidos con la iniciativa PANGEA para mejorar la comprensión a través de sus tres pilares:

- *Utilizando la ciencia para avanzar en la comprensión de cómo las regiones de bosques tropicales responderán de manera diferente al cambio global*.
- *Desarrollando capacidades en nuestros científicos de las regiones amazónicas para que puedan liderar estos esfuerzos científicos*.
- *Actuando con mejores capacidades de teledetección satelital para mapear y monitorear el carbono, la biodiversidad y la agricultura*.

Esperamos que la NASA tenga a bien seleccionar la iniciativa PANGEA y esperamos poder contribuir desde nuestros gobiernos subnacionales en el trabajo de campo que pueda ser realizado, estamos seguros de que la recopilación de datos de sensores remotos aéreos, el uso de sensores remotos satelitales y modelos para comprender mejor la dinámica de los bosques tropicales contribuirán a una mejor gestión de los bosques brindándonos evidencia científica para tomar mejores decisiones de política pública.

Atentamente,

Manuel Gambini Rupay
Presidente de la Mancomunidad Regional Amazónica del Perú
Presidente del Grupo de Gobernadores por el Clima y los Bosques

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

15.11.2024

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter indicates my support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). PANGEA will significantly advance the science and data to understand and scaling of carbon, water, and energy fluxes in tropical forests and/or their interactions with biodiversity, climate change, human activities. Combined with land use change mapping initiatives such as the ones produced by the MapBiomas Network, this may be a major contribution towards understanding how tropical forests across the world are responding to changes in climate, land cover and land use.

I see a lot of potential for synergies with lots of positive feedback when MapBiomas and PANGEA spreads across Latina America, Congo Basin and Southeast Asia. It is especially important for ensuring local capacity across the board to generate timely, accurate and relevant information about the tropics.

I look forward to the collaboration and generation of lots of fruits!

Sincerely,

Tasso Azevedo
General Coordinator
MapBiomas Network

HARVEST EARTH DATA FOR INFORMED AGRICULTURAL DECISIONS

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing to express our strong support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will significantly enhance/advance/benefit several NASA Harvest-led initiatives including: agricultural climate risk assessments, environmental health research, agricultural insurance for sustainable farming transitions, and climate finance frameworks.

NASA Harvest is NASA's Global Food Security & Agriculture program, established in 2017, and led and implemented by the University of Maryland, College Park. Harvest is committed to advancing Earth observations for agricultural decision-making and food security. Our network of over 45 leaders in agriculture and Earth observation works across public, private, NGO, and humanitarian sectors. Our team pursues objectives that include improving crop yield forecasting, enhancing early warning systems for food security, and advancing satellite-based agricultural monitoring through active projects in Africa, Southeast Asia, and Latin America.

Several of PANGEA's objectives directly align with NASA Harvest's priorities, particularly in mapping and monitoring agricultural expansion and intensification in tropical forest regions, advancing methods to track carbon stocks and fluxes in agricultural-forest landscapes, improving crop type, yield, and condition monitoring capabilities using new satellite sensors, and supporting agricultural adaptation to climate change through enhanced monitoring.

NASA Harvest can provide valuable support through our ground validation data from agricultural monitoring sites, local logistics and community engagement through regional partners, technical expertise in agricultural remote sensing and machine learning, and access to our global network of food security stakeholders. The integration of PANGEA's forest measurements with agricultural observations will be transformative for understanding tropical land-use dynamics.

The integration of PANGEA's forest measurements with agricultural observations will be transformative for understanding tropical land-use dynamics. As NASA Harvest's Director, I enthusiastically support PANGEA and believe it will significantly advance our shared goals of sustainable agriculture and food security.

We believe PANGEA represents a project with high potential impact. As Director at NASA Harvest, we offer our full support for the PANGEA campaign and hope that endorsement of PANGEA will facilitate this valuable partnership and further our shared food security and climate mitigation and adaptation goals.

Sincerely,

Inbal Becker-Reshef
NASA Harvest, Director
University of Maryland
2181 Lefrak Hall, College Park, MD 20742

MINISTERE DE L'ENSEIGNEMENT SUPERIEUR, DE LA RECHERCHE SCIENTIFIQUE ET DE L'INNOVATION TECHNOLOGIQUES

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE ET TECHNOLOGIQUE

COMMISSARIAT GENERAL

REPUBLIQUE GABONAISE
Union-Travail-Justice

Professor Elsa Ordway
618 Charles E. Young Drive S.
Los Angeles, CA 90095

21[h] November, 2024

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are pleased to express our strong support for NASA's proposed Terrestrial Ecology Field Campaign, the PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA has the potential to significantly advance our understanding of tropical forest resilience, climate impacts, and biodiversity conservation, with Gabon serving as a pivotal region, as led by the Centre National de la Recherche Scientifique et Technologique (CENAREST).

Established in 1976, CENAREST is Gabon's national center for scientific and technological research, committed to fostering innovative research for sustainable resource management and poverty reduction. Gabon, known for its high carbon storage and low forest degradation within the Congo Basin, offers an exceptional environment for these efforts. CENAREST's work focuses on understanding the impacts of land use and climate change on biodiversity, ecosystem services, and the socio-economic aspects of conservation. CENAREST collaborates extensively on tropical ecology and global environmental change through active partnerships with regional and international organizations across the Congo Basin.

PANGEA's objectives align closely with CENAREST's mission, particularly in the integration of satellite data with ground and airborne measurements. These tools are critical for improving predictions of tropical forest responses to climate and land-use changes, enabling the development of robust, science-based strategies for mitigation and adaptation. We are excited about PANGEA's emphasis on Earth observation technologies and its multidisciplinary approach to studying tropical forests, peatlands, and wetlands, which are essential for addressing complex ecological challenges.

CENAREST actively partners with key Gabonese institutions, such as the Agence Nationale des Parcs Nationaux (ANPN), the Agence d'Etude et d'Observation Spatiale (AGEOS), the National Climate Council (CNC), and the Gabonese Ministry of Water and Forests. These established partnerships, combined with our in-depth regional expertise, position CENAREST to provide robust local support for PANGEA's implementation in Gabon. If PANGEA is selected, CENAREST is prepared to offer in-kind support, including data sharing, assistance with local logistics, facilitation of research permits, and community engagement. Furthermore, we are committed to exploring funding opportunities to actively contribute to PANGEA's research and application activities.

We are confident that PANGEA's focus on advancing remote-sensing capabilities will complement and enhance our own efforts, including improved carbon stock assessments, deeper understanding of land-use changes, and strengthened biodiversity conservation strategies.

As Commissaire General (Executive Director) of CENAREST and African Senior scientist on tropical and global ecology, I strongly believe that PANGEA represents an exceptional opportunity to tackle some of the most pressing global challenges. We are proud to offer our full support for this groundbreaking campaign and are optimistic that NASA's endorsement will help bring this valuable partnership to fruition, furthering our shared objectives of climate mitigation and biodiversity conservation.

Sincerely yours,

Professor Alfred NGOMANDA

São José dos Campos, November 11, 2024

PANGEA letter of support

To whom it may concern:

The Strategic Projects Division of the National Institute for Space Research is pleased to support the PANGEA proposal. I foresee that the innovative approach in PANGEA will help to advance the understanding of the critical role that tropical forests play in the global climate, ecosystem services and relevance to local communities. Several projects developed by the Brazilian scientific community (e.g., LBA, ATTO, AMAZONFACE, ADAPTABRASIL, to name a few) are closely related to the PANGEA scientific agenda.

The team of scientists linked to the Strategic Project and the Impact, Adaptation and Vulnerability Divisions (where I also work) are eager to fully support PANGEA and are ready to help with the implementation plan, integrating our activities with its critical scientific agenda.

Jean Pierre Ometto
Senior Researcher
Head of the Strategic Project Division

REPUBLIQUE DU CAMEROUN **Paix-Travail-Patrie** ----------- OBSERVATOIRE NATIONAL SUR LES CHANGEMENTS CLIMATIQUES ----------------- DIRECTION GENERALE	ONACC-NOCC	**REPUBLIC OF CAMEROON** **Peace-Work-Fatherland** ----------- NATIONAL OBSERVATORY ON CLIMATE CHANGE ----------------- DIRECTORATE GENERAL

N° 000148 /L/ONACC/DG **Yaoundé, le 26 NOV 2024**

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing to express our strong support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will significantly contribute to enhance relevant initiatives currently carried out by the National Observatory on Climate Change for Cameroon (ONACC).

ONACC is a State autonomous Scientific and Technical Institution created by a Presidential Decree and placed under the Technical supervisory authority of the Cameroon Ministry of Environment. ONACC has as main mission to monitor and assess the socioeconomic and environmental impacts of climate change and to propose prevention, mitigation and/or adaptation measures to fight the adverse effects and risks associated with these changes. To this end, it shall in particular:

- define relevant climate indicators for monitoring the environmental policy;
- conduct prospective studies to propose a vision on the evolution of climate in the short, medium and long terms;
- monitor the evolution of climate, provide weather and climate data/information to all sectors of human activity concerned and produce the annual climate report for Cameroon;
- initiate and promote studies on the identification of indicators, impacts and risks related to climate change;
- collect, analyze and make available to policy makers, private as well as various national and international organizations, reference information on climate change in Cameroon.
- initiate activities to promote awareness and information on the prevention of climate change;
- serve as operational tool to all other activities aimed at reducing greenhouse gases;
- carry out greenhouse inventories and produce annual Carbon balance of all socioeconomic development sectors;
- propose to the Government preventive measures for the reduction of greenhouse gas emissions, as well as mitigation and/or adaptation to the adverse effects and risks associated with climate change;
- serve as an instrument of cooperation with other regional or international observatories operating in the climate sector;

ONACC's primary focus is on several key action areas: the production of robust and precise climate services and forecasting, vulnerability studies, assessment of the economic cost of climate variability on the one hand and on the other, GHG emission inventory and production of annual carbon balance of the various socioeconomic development sectors including but not limited to agriculture, forestry and other land-uses. ONACC uses GIS and remote sensing tools to monitor forest cover change (losses and gains). She also uses climate modelling for forecasting weather and climate dynamics.

It is important to state here that PANGEA's goals align closely with ongoing efforts at ONACC. We are eager to support PANGEA's use of Earth observation and multidisciplinary approaches in research in tropical forests, peatlands, wetlands and agricultural systems.

ONACC currently works on specific domains such as assessing the economic costs of climate change in the agricultural sector, disaster risk prediction and monitoring, and supporting farmers in climate adaptation efforts with partners including FAO, WFP, FIDA, GIZ, WWF, IUCN, ACF, USFS. Our shared expertise and ONACC's longstanding regional experience will provide strong local support for PANGEA's implementation in Cameroon and the Central African Sub region.

If PANGEA is selected, ONACC can provide in-kind support through local logistics, regionally relevant translation of science to action, and coordination with government ministries. Our team is also prepared to explore funding opportunities to participate in PANGEA-related research and application activities.

We see an opportunity for PANGEA's focus on advancing remote-sensing capabilities in the tropics to further our goals, such as desired collaboration to enhance fire risk monitoring capabilities and develop fire monitoring tools to guide farmer land-use practices to support low-emissions agriculture, improve local and regional weather and climate predictions and improve local and regional early warning systems, and assess the economic cost of extreme weather events in the various socioeconomic development sectors.

We believe PANGEA represents a project with high potential impact. As Director General at ONACC, we offer our full support for the PANGEA campaign and hope that NASA's endorsement of PANGEA will facilitate this valuable partnership and further our shared climate mitigation and adaptation goals, with a particular emphasis on resilient and sustainable development based on scientific evidence and local knowledge.

Prof. AMOUGOU Joseph Armathé
Director General
National Observatory on Climate Change, Cameroon
Email: info@onacc.cm, josepharmathe@yahoo.fr
Website: www.onacc.cm
App. onacc.alerte downloadable from Google playstore

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter confirms our strong support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). Should the proposed field campaign be selected, PANGEA will provide critical data on the dynamics of tropical forests across the tropics, train a new generation of scientists domestically and internationally, and foster collaborative international research that will help advance pressing scientific needs on the future of tropical forests under global change. Importantly, PANGEA will be synergistic to the Next Generation Ecosystem Experiments (NGEE-Tropics) activities led and carried out by Lawrence Berkeley National Lab and our partner institutions.

NGEE-Tropics is a long-term, multi-institutional project that has been supported by the Department of Energy since 2015 (https://ngee-tropics.lbl.gov). NGEE-Tropics aims at development and testing of a process-rich ecosystem model that can be used to project the future of tropical forests under global change. To this end, we currently are developing and testing the ELM-FATES model, which represents plant demography and a broad set of tropical forest processes, as well as field activities to measure plant physiology, forest demography, soil hydrology and biogeochemistry, and ecosystem carbon and water cycling, at multiple field sites, including in Panama, Brazil, and Malaysia.

There are multiple highly aligned goals between NGEE-Tropics and PANGEA, as both projects aim to improve the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions. The new findings are necessary to determine the resilience and vulnerability of tropical forest ecosystems. For example, both projects seek to understand the processes that govern forest carbon and water cycling, and growth and mortality dynamics of tropical forest trees. We also share the same vision on integrating observations across multiple scales with mechanistic models to gain process-understanding of the main drivers of changes in forests. There are also key areas of complementarity between the projects, for example PANGEA's focus on African tropical forests, which NGEE-Tropics was not able to investigate as fully as forests in the Americas and Asia.

If PANGEA is selected, our team will also seek opportunities for direct collaboration with PANGEA, for example, through the development of proposals for funding opportunities aligned with PANGEA's goals.

PANGEA is a much-needed project that has the potential to greatly expand the scientific knowledge of critical yet under-studied ecosystems. Being the lead PI of NGEE-Tropics, I express my utmost support for the PANGEA Terrestrial Ecology Field Campaign and hope that NASA's support of PANGEA will unlock several opportunities for a strong partnership with NGEE-Tropics.

Charlie Koven
Senior Scientist
Climate and Ecosystem Sciences Division
Lawrence Berkeley National Lab

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing on behalf of the One Forest Vision Initiative (OFVi) to express our strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical data, methods, applications, and training gaps related to the measurement, understanding, and scaling of carbon, water, and energy fluxes in tropical forests and their interactions with biodiversity, climate change, human activities. PANGEA will also support and reinforce international scientific cooperation and data collection activities led and carried out by OFVi.

OFVi is a scientific initiative that was initiated in 2023 in France by the coalition of 6 French research institutions: CEA, CIRAD, CNRS, INRAE, IRD and MNHN, (for further details, please refer to our website: https://www.oneforestvision.org/eng). Our goal is to provide scientific support to countries within tropical basins with a specific focus on preserving their environmental integrity, particularly regarding the biodiversity and carbon stocks contained in tropical forests and wetlands. To achieve our objectives, we currently (i) increase and disseminate scientific knowledge on biodiversity and carbon; (ii) strengthen the skills and autonomy of researchers and managers in the Congo Basin; (iii) develop and disseminate biodiversity and carbon monitoring tools in the Congo Basin, more specifically in Congo, DRC and Gabon.

We see several aligned efforts and general aims between One Forest Vision and PANGEA, in particular in the measurement and monitoring of forest composition, structure and biogeochemical cycling. We are keen to support PANGEA in leveraging Earth observation techniques and multidisciplinary datasets to conduct impactful research. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

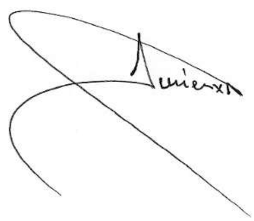
We pursue scientific activities and collaboration with local institutions from Congo, DRC, Gabon, Cameroon and Uganda. We are conducting field activities in 8 "super-sites" in these countries (link to the super-sites map : https://www.oneforestvision.org/eng/scientific-productions/pillar-1). These locations may be of strategic importance to PANGEA because of their habitat type and long-term data. Members of One Forest Vision have been working in some of these locations for years and can facilitate PANGEA's implementation by helping with local expertise and the access to crucial data.

Should PANGEA be funded, One Forest Vision can provide aligned activities in the form of workshop and event expenses. While our initiative aims to assess the state of animal biodiversity in relation to plant biodiversity and the structure and functioning of the forest habitat ; to develop new approaches to enable multi-year monitoring at high spatial resolution of the structure, above-ground biomass and functional composition of tropical forests ; to build capacity building for local researchers and managers in the Congo Basin, we seek to ensure our activities are synchronized and complementary to other similar efforts carried out in the region. We already participate to monthly meetings with the PANGEA scoping team and the ongoing Congo Basin Science Initiative team.

We believe that PANGEA is an important project with the potential for high impact. As co-coordinators at One Forest Vision initiative, we express our utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue this common activity.

The 24th September 2024:

Jean-François Soussana
Co-coordinator for One Forest Vision initiative
Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE)
147 rue de l'Université, 75338 Paris, France



Laurent Durieux
Co-coordinator for One Forest Vision initiative
Institut national de Recherche pour le Développement (IRD)
44 boulevard de Dunkerque 13572 Marseille, France

Alain Billand
Co-coordinator for One Forest Vision initiative
Centre de coopération internationale en recherche agronomique pour le développement (CIRAD)
42, rue Scheffer, 75116 Paris France

Boston University
Department of Earth and Environment
685 Commonwealth Ave, Rm 130
Boston, MA 02215

November 20, 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter attests our strong support for the proposed NASA Terrestrial Ecology Field Campaign entitled *PAN tropical investigation of bioGeochemistry and Ecological Adaptation* (PANGEA). If funded, PANGEA will significantly advance the measurement and modeling of tropical ecosystem processes, biogeochemistry, and greenhouse gas dynamics and their interactions with climate and human activities. The field campaign will make a major contribution towards understanding how tropical forests across the world are responding to changes in climate, land cover and land use. PANGEA's main goals are very aligned with the model-data fusion activities conducted by the PEcAn (Predictive Ecosystem Analyzer) project.

PEcAn is a community cyberinfrastructure project that has been supported by a wide range of funding agencies (NASA, NSF, DOE, DoD SERDP, ARPA-E) and tech partners (Google, Amazon, Red Hat) since 2009 (https://pecanproject.org/). PEcAn's vision is to see ecosystem science, policy, and management informed by the best available data and models. We aim to achieve this through our mission to develop and promote open, accessible tools for reproducible ecosystem modeling and forecasting. This includes interoperable support for running >20 land models and analyzing them through a wide range of tools for data ingest, uncertainty propagation and partitioning, model calibration, validation, visualization, and iterative data assimilation. In particular, PEcAn is currently focused on developing continental-scale carbon cycle reanalysis products that fuse numerous bottom-up and remotely-sensed data constraints with process-based models to produce harmonized carbon budgets with sophisticated uncertainty accounting across space, time, and pools/fluxes. We are working with a number of international, federal, and state agencies to integrate these products into carbon inventories, with an aim to expand to a global scale over the next few years.

PEcAn and PANGEA are inherently synergistic. For example, both PANGEA and PEcAn are focused on uncertainty quantification, field campaigns inspired by modeling needs and uncertainties, and better connecting science to policy, management, and decision making (e.g., national C inventories, REDD, voluntary markets). Likewise, PEcAn is deeply interested in integrating observations across multiple scales with mechanistic models to gain process-understanding of the main drivers of changes in forests, which complements PANGEA’s overall objectives.

Should PANGEA be selected, the PEcAn group will seek opportunities for close collaboration with PANGEA. For instance, we will look for funding opportunities that are related to PANGEA's goals, and will make PEcAn tools and training available to PANGEA scientists, including but not limited to working to add additional PANGEA-prioritized models to PEcAn and extending existing workflows to PANGEA sites and regional domains.

PANGEA is an exciting and much needed project, and will significantly advance our understanding of how forests are changing in response to shifts in climate and disturbance regime. As the PEcAn project lead, I confirm our utmost support for the PANGEA Terrestrial Ecology Field Campaign, and look forward to exploring opportunities for collaboration between PEcAn and PANGEA.

Sincerely,

Michael C. Dietze
Professor, Boston University
PEcAn project lead
Director, Ecological Forecasting Initiative

PennState

Department of Meteorology
and Atmospheric Science
The Pennsylvania State University
502 Walker Building
University Park, PA 16802

814-865-0478
meteodept@meteo.psu.edu
met.psu.edu

Dr. Elsa Ordway
Department of Ecology and Evolutionary Biology
University of California, Los Angeles
410K Botany Building, Los Angeles, CA, 90095

Re: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We thank you for your leadership in developing the science plan of the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA) Scoping Campaign. We, the undersigned at The Pennsylvania State University, enthusiastically support the PANGEA program as it calls for novel and urgently needed research to advance the current understanding of the structure and function of the iconic tropical rainforests, which are undergoing major degradation in response to the influences of a rapidly changing global climate and land use changes.

Penn State University has several academic units and research groups, which have active interdisciplinary research programs related to the processes and activities that PANGEA will address over the next few years. In addition, we have strong graduate programs in Ecology, Ecosystem Science and Management, and Geography that grant Master of Science and Doctoral degrees. The academic program in Climate Science provides outstanding academic training in emerging research areas such as numerical modeling, data assimilation, machine learning, and artificial intelligence. At Penn State University, one key strength of academic training and research activities relates to climate change investigations and climate solutions, as evidenced by the Earth and Environmental Systems Institute, the Institute of Energy and Environment, and our new Penn State Climate Consortium (climate.psu.edu). Our pioneering strategies of engaging traditionally underrepresented groups in science and engineering will advance the community engagement component of the PANGEA imitative.

We wish to contribute to PANGEA's goals to improve the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions. New findings are necessary to determine the resilience and vulnerability of tropical forest ecosystems and the people that depend upon them. Therefore, the PANGEA research agenda is closely aligned with our research and academic priorities. We look forward to supporting PANGEA's efforts to leverage Earth observations and generate multidisciplinary data sets and methods to conduct ecological research. We are particularly excited to engage with diverse partners, including Indigenous communities, throughout the Tropics such that we can develop and advance scientific understanding, strengthen capacity for ecological research, and support governance and sustainable land management practices.

Should PANGEA be funded, at Penn State University, we can provide cost-shared funding in the form of in-kind support contributed through the availability of research infrastructure such as laboratories equipped with contemporary technologies, and climate and ecological numerical models, and academic tuition or stipend support, commensurate with our university commitment to supporting graduate and undergraduate education. In addition, the Penn State University team will develop research proposals to seek funding to support participation in PANGEA-related studies. Our research proposals would draw from our current research interests and expertise that are closely related to PANGEA science questions: "**How do ongoing and projected changing climate impacts influence the resilience of the tropical carbon sink?" and "How does the weakening of the carbon sink influence additional feedbacks on the Earth's climate?"**

Our interest in PANGEA stems from previous experiences and partnerships that we have pursued in the Amazon rainforest. We have established long-term collaborations with diverse colleagues from academic institutions and government agencies in South America. Such partners will participate in PANGEA-related activities and play key roles in developing new research aimed at addressing regional and national land management practices. The Amazon rainforest plays critical roles not only in terms of water and carbon cycling but also in influencing the Earth's climate. Therefore, the Amazon is a strategic region to be investigated as part of the PANGEA initiative. Given our previous research in the Amazon during the last two decades, we can help facilitate PANGEA's implementation by assisting with ground-validation studies, numerical modeling, and community engagement. We will contribute analysis tools that identify causal feedback processes related to water and carbon cycling that lead to improved understanding of the nonlinear processes within the climate dynamics. In that context, one specific goal is to develop process-based numerical models to estimate the magnitude of feedbacks that can then be employed to perform targeted ground-based observations and thus enhance the fidelity of the data collection process. Our expertise with Earth System Modeling will be critical for identifying pathways that will inform ways to collect observational data that can inform causal inference estimates of tropical forest structure and function, and provide validation of remote sensing information. Our research community has existing and growing research interests working directly with Indigenous communities in the tropics, including in tropical South America and Africa. This work engages directly on issues related to climate resilience, socio-ecological systems, and Indigenous knowledge systems, providing ample opportunities for bridging Earth system modeling through a co-design framework.

We recognize the mutual benefits in sharing efforts, research methods (e.g., numerical models), data sets, resources, and experiences to advance understanding of terrestrial ecology and better leverage Earth observation to support our organization's goal. PANGEA will certainly provide the unique venue to achieve a common set of novel research hypotheses that would create needed knowledge of tropical forest systems in a rapidly changing environment. We, therefore, are enthusiastic to join in the pursuit of new research endeavors under the auspices of PANGEA.

Sincerely,

Erica A.H. Smithwick

Erica Smithwick
Distinguished Professor of Geography, Walker Building, 302 North Burrowes Street, University Park, PA 16802; Director, Earth and Environmental Systems Institute; Associate Director, Institute of Energy and the Environment; The Pennsylvania State University, University Park, PA USA; Email: smithwick@psu.edu

Chris E Forest

Chris E Forest
Professor of Climate Dynamics, Department of Meteorology and Atmospheric Science, 507 Walker Building, University Park, PA 16802; Email: ceforest@psu.edu

Jose D Fuentes
Professor of Atmosphere Science, Department of Meteorology and Atmospheric Science, 508 Walker Building, University Park, PA 16802; Email: jdfuentes@psu.edu

Letter of support to the PANGEA research project lead by Elsa Ordway

I am writing to offer my strong support for the research project PANGEA that aims to explore how climate change and land-use changes are influencing the vulnerability and resilience of tropical rainforests, particularly those in Central Africa and the Amazon, and explores the degree to which these rainforests are impacted in similar or divergent ways. By examining both regions in tandem, this study has the potential to provide invaluable insights into how different rainforest ecosystems respond to similar climate and land use stressors and to identify the unique challenges each region faces.

The comparative nature of the research will offer new perspectives on the resilience of these ecosystems and inform conservation strategies that are tailored to the specific needs of each region. Furthermore, the findings could provide important guidance for policymakers and conservation organizations working to mitigate the impacts of climate change on biodiversity and forest health.

The research methodology outlined in the white paper demonstrates a robust approach to understanding the complex interactions between climate change and rainforest ecosystems. The project's interdisciplinary approach promises to yield results that are scientifically sound and of practical importance to global environmental sustainability efforts.

Sincerely,

Tørris Jæger
Secretary General

Rainforest Foundation
Norway

PO Box 2008
Oak Ridge, TN 37831-6036
(865) 576-7680 | hoffmanfm@ornl.gov
https://www.climatemodeling.org/∼forrest

November 4, 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, California 90095
USA

Dear Dr. Elsa Ordway:

Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

This letter is to provide my strong support for the proposed NASA Terrestrial Ecology Field Campaign entitled PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). If this field campaign is selected, it will provide critical measurements needed for advancing understanding of Earth's largest store of living carbon and will inform the scaling of carbon, water, and energy fluxes in tropical forests required for constraining Earth system models and projecting impacts and feedbacks of climate change. The goals and deliverables of PANGEA are well aligned with the simulation and analysis of global biogeochemical cycles conducted in the Reconciling Uncertainties in Biogeochemical Interactions through Synthesis and Computation (RUBISCO) Science Focus Area.

RUBISCO is a project supported by the US Department of Energy that investigates terrestrial and marine biogeochemical cycles by combining observations and models to understand feedbacks of climate change. One of the key products emerging from the project is the open source International Land Model Benchmarking (ILAMB) package, which assesses the fidelity of land carbon cycle models through comparison with best-available observations. PANGEA shares strong synergy with the RUBISCO project for the incorporation of new multi-scale reference (observational) data sets into ILAMB and the creation of new tropical ecosystem-relevant metrics for evaluating mechanistic models of tropical forests.

Should PANGEA be funded, the RUBISCO project team will collaborate directly with PANGEA on constraining models of tropical ecosystems and will seek collaborative funding opportunities to propose additional projects that are synergistic with PANGEA's main goals.

PANGEA has a unique potential to significantly advance understanding and reducing uncertainties on the impacts of global change on tropical forests. Therefore, as the Laboratory Research Manager, I express my utmost support for the PANGEA Terrestrial Ecology Field Campaign and hope that NASA's support of PANGEA will enable multiple collaboration opportunities with the RUBISCO project.

If I can provide any additional information in support of PANGEA and potential collaborations with the RUBISCO SFA, please contact my at your earliest convenience.

Sincerely,

Forrest M. Hoffman
Distinguished Computational Earth System Scientist
Group Leader, ORNL Integrated Computational Earth Sciences (ICES) Group
Laboratory Research Manager, Reconciling Uncertainties in Biogeochemical Interactions
through Synthesis and Computation (RUBISCO) Science Focus Area

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

Institut de Recherche pour le Développement
FRANCE

911 avenue Agropolis – BP 64501
34394 MONTPELLIER Cedex 5 - FRANCE
TEL : +33 (0) 4 67 41 51 71
ecobio@ird.fr

Le directeur du département ECOBIO

Montpellier, le 5 décembre 2024

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing on behalf of IRD, the French Institute for Sustainable Development, to express our support to project PANGEA (PAN tropical investigation of bioGeochemistry and Ecological Adaptation) submitted to NASA Terrestrial Ecology Field Campaign. If selected, this project will complement the efforts of IRD teams and researchers to collect critical data, develop methods and applications, and build capacities for the monitoring, understanding, and scaling of carbon, water, and energy fluxes in tropical forests and their interactions with biodiversity, climate change, human activities.

PANGEA will more specifically complement IRD research efforts in the Congo Basin forests, where we support for years international scientific cooperation. We see several aligned efforts and general aims between IRD research programs and PANGEA, in particular with activities conducted by our Laboratoire Mixte International DycoFac (Dynamics of Continental Ecostystems in Central Africa (https://www.lmi-dycofac.org/), which contributes, with local partners, to the monitoring of forest composition, structure and biogeochemical cycling. We are keen to support PANGEA in leveraging Earth observation techniques and multidisciplinanary datasets to conduct impactful research. We are particularly excited at the prospects of engaging with diverse communities throughout the topics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

We believe that PANGEA is an important project with the potential for high impact and we express our utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue this common activity.

Jean-Christophe AVARRE

I.R.D. INSTITUT DE RECHERCHE POUR LE DÉVELOPPEMENT

Directeur du département ECOBIO

OSFAC
Observatoire Satellital des Forêts d'Afrique Centrale

Kinshasa November, 22, 2024

N/Réf : OSFAC-HQ/22112024

Dr. Elsa Ordway
Department of Ecology and Evolutionary Biology
University of California, Los Angeles
410K Botany Building, Los Angeles, CA, 90095

Concern: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr Elsa Ordway,

We are delighted to know that you are submitting a proposal for the implementation of a major international project called "***The PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)***" which will address several themes. This excellent initiative will provide a lot of scientific knowledge on tropical ecosystems.

The objectives of PANGEA are in line with the vision of the Satellite Observatory of Forests of Central Africa (**OSFAC**) which is a Non-Governmental Organization (NGO) with a regional vocation and also representative in Central Africa of the international network Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD). Indeed, OSFAC's vision is that Central Africa has reliable and relevant data to guide decision-making. With this in mind, OSFAC and its partners in Africa and Northern countries work to provide users and decision-makers with reliable and regularly updated information. This information relates to the state of forests, their dynamics (extent of forest cover, deforestation, dégradation, forest fires, restoration of forest landscapes, etc.), the drivers that guide this dynamic, the quantification of biomass, carbon and greenhouse gas emissions, climate change etc.

We are confident that the implementation of the PANGEA Project will be a good opportunity to better understand the composition and functioning of tropical ecosystems, as well as the immense role they play in the living conditions of populations but also on several questions of interest the world today, among other things, climate change. In addition, considering all the teams that could participate in this project, PANGEA will be a place for multicultural meetings, a laboratory of ideas and proposals for innovative solutions.

The methods, tools (satellites, drones, planes) and data (in-situ, optics, Radar, Lidar, etc.) that the PANGEA Project plans to use will make it possible to generate results that will be used to resolve a large part of the environmental problems of the tropical world and contribute to improving the well-being of populations in this region.

It is for this reason that the Satellite Observatory of Central African Forests (OSFAC) of which I am the Director fully supports the PANGEA Project and wishes its funding.

Sincerely,

DIRECTOR OF OSFAC

Observatoire Satellital des Forêts d'Afrique Centrale
OSFAC
14 Av. Sergent Moke, Kinshasa, RDC

Dr. Landing MANE

SPUN | SOCIETY FOR THE PROTECTION OF UNDERGROUND NETWORKS

Society for the Protection of Underground Networks
3500 South DuPont Highway, Suite EI-101
Dover, DE 19901

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

6, September, 2024

RE: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

Thank you for the invitation to collaborate on the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA) Scoping Campaign. The Society for the Protection of Underground Networks (SPUN) is happy to support the PANGEA program once NASA funding is confirmed.

SPUN is a scientific research NGO that was established in 2021 (www.spun.earth) with a mission is to map, protect, and harness the mycorrhizal fungal networks that regulate Earth's climate and ecosystems. Mycorrhizal fungi form root symbioses with more than 90% of all plant species, creating underground networks that draw down carbon and provide essential nutrients to plants. These fungi help soil ecosystems store 75% of all terrestrial carbon, but mycorrhizal fungi are overlooked in Natural Climate Solution (NCS) goals. SPUN is developing high-resolution global and regional datasets of mycorrhizal fungal diversity and functioning to advocate for their protection and inclusion in NCS strategies.

PANGEA's aims to improve the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions. The new findings are necessary to determine the resilience and vulnerability of tropical forest ecosystems. Therefore, the PANGEA research agenda is closely aligned with our research priorities of pinpointing degraded ecosystems with underperforming fungal networks and identifying keystone mycorrhizal species associated with the recovery of threatened ecosystems. We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the Tropics to advance scientific understanding, strengthen capacity for ecological research, and support the application of scientific results to governance and sustainable land management practices.

Should PANGEA be funded, SPUN can provide cost-shared funding in the form of in-kind support contributed through the availability of SPUN's research infrastructure (e.g., computation resources for fungal bioinformatics, ecological modeling, and geospatial analysis), staff time, and relevant travel costs related to two of SPUN's ongoing project areas:

1) integrating remote sensing tools with *in-situ* mycorrhizal fungal measurements and 2) SPUN's Underground Explorers Grant program. These projects are closely related to PANGEA Science Question 1 (*Examine similarities and differences in forest composition, structure and biogeochemical cycling across tropical regions*), and PANGEA broader impact goals of advancing scientific capacity for researchers in the Global South.

Monitoring changes in mycorrhizal biodiversity is time and resource intensive with on-the-ground measurements. We need a dynamic way to estimate underground network responses in real-time, at scale. Remote sensing technologies offer the ability to observe plant biodiversity and ecosystem functioning with high spatial and temporal resolution, but so far its applications are limited to aboveground ecosystems. SPUN has partnered with Caltech and the 11th Hour Project at the University Chicago Data Science Institute to explore whether remote sensing data can be used to detect changes in mycorrhizal fungal diversity and abundance. Our goal is to identify mycorrhizal signatures in the immense volume of remotely-sensed spectral data from US National Ecological Observatory Network sites. However, these data do not cover tropical forests or tropical mycorrhizal fungi, meaning that any spectral biology models we develop to estimate mycorrhizal fungi will be incomplete and likely unapplicable for tropical systems. Working with PANGEA, SPUN will leverage our capacity to generate extensive *in-situ* mycorrhizal fungal data paired with the specific flight campaigns of this tropical focused NASA Terrestrial Ecology program. These novel datasets will 1) provide critical insights for understanding the role of mycorrhizal fungi in shaping biogeochemical variation across different tropical forest regions, and 2) expand the range of habitat types represented in our paired spectral-fungal dataset to remotely sensing mycorrhizal symbioses in all forest types.

SPUN has developed efficient data protocols and analysis pipelines for generating precise mycorrhizal fungal data in difficult-to-access regions of the world, including tropical forests in Colombia and Ghana. Our organization excels at community building, with a global network of 415+ Science Associates from more than 79 countries. Additionally, we have awarded a total of 92 Underground Explorer grants to an exceptional cohort of soil fungal researchers from 43 countries. Notably, 83% of these grants have been allocated to scientists based in the Global South. Our Underground Explorers are now conducting soil sampling across every continent, focusing on some of the world's most under-explored ecosystems. To maximize the impact of their research, we provide each Explorer with comprehensive technical and communications support. For specific locations in South America, Africa, Southeast Asia, SPUN can leverage our network of local researchers to engage and coordinate research activities with PANGEA to explore using satellite imagery to improve fungal biodiversity monitoring and belowground carbon accounting in tropical forest ecosystems.

We recognize the mutual benefits in sharing efforts, research methods (e.g., numerical models), datasets, resources, and experiences to advance understanding of terrestrial ecology and better leverage Earth observation to support our organization's goal. We hope that NASA's support of PANGEA will enable us to pursue this common research interest.

Dr. E. Toby Kiers
Professor, Faculty of Science, Ecology & Evolution, Vrije Universiteit Amsterdam
Executive Director & Chief Scientist, Society for the Protection of Underground Networks

Dr. Michael Van Nuland
Lead Data Scientist, Society for the Protection of Underground Networks

UK Centre for Ecology & Hydrology

UK Centre for Ecology & Hydrology
Maclean Building, Benson Lane
Crowmarsh Gifford, Wallingford
Oxfordshire
OX10 8BB
UK

T: +44 (0)1491 838800

Dr Elsa Ordway
Ecology & Evolutionary Biology
410K Botany Building
Los Angeles, CA
90095, USA

26 August 2024

Dear Dr Ordway

Re: Support for NASA Research Opportunities in Space and Earth Sciences (ROSES) programme PANGEA – PAN tropical investigation of bioGeochemistry and Ecological Adaptation

I am writing to offer the UK Centre for Ecology & Hydrology's (UKCEH) support for the proposed PANGEA project. We understand that PANGEA will link remote sensing data with on-the-ground measurements in tropical forests across the globe, to answer questions on tropical forest biodiversity, functioning, carbon stocks and sequestration, and how these will be affected by climate and land use change in the future. Answering these questions will lead to fundamental understanding that is crucial to mitigating climate change and enabling successful conservation and restoration of tropical forests.

UKCEH is an independent, not-for-profit research institute and the UK's leading institute for the terrestrial and freshwater sciences. We have a global impact, producing cutting edge scientific discoveries and contributing to understanding and monitoring the environment of our planet. We deliver these through valuable partnerships, using state of the art research facilities, managing interdisciplinary projects and comprehensive monitoring programs supported by 500 expert scientists.

Here at UKCEH we have a long history of collaborations in tropical forest ecology acorss Latin America, West and East Sub-Saharan Africa and Southeast Asia. My colleagues Dr Jill Thompson, Dr Lindsay Banin and others, are deeply embedded in long-term tropical research sites that could be focal landscapes for PANGEA, or provide complementary, contextual information. Our research questions in the tropics focus around climate change and greenhouse gases, forest functioning, plant community change, plant-animal interactions, land-use change and biogeochemical fluxes, social-ecological interactions, forest recovery and restoration. We also

UK Centre for Ecology & Hydrology

UK Centre for Ecology & Hydrology
Maclean Building, Benson Lane
Crowmarsh Gifford, Wallingford
Oxfordshire
OX10 8BB
UK

T: +44 (0)1491 838800

process remotely sensed data from a variety of sources and have foundational skills in data management, analysis and synthesis.

The PANGEA proposal could provide a unique opportunity to link remotely-sensed data at various scales with ground-based data that UKCEH could effectively contribute to. UKCEH could provide information and connections with international organizations to assist in site selection for PANGEA activities. We would be keen to seek independent and joint funding with PANGEA members to enable collaborative research between UKCEH and PANGEA to promote our scientific endeavours.

Yours sincerely

Prof Harry Dixon
Associate Director of International Research and Development
Email: harr@ceh.ac.uk

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095

Subject: Letter of Support for
PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

I am writing to express my strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical knowledge gaps on the impact of climate change on tropical forests such as the Congo Basin. PANGEA's work will make an important contribution to the activities led and carried out by the Science Panel for the Congo Basin, convened by the United Nations Sustainable Development Solutions Network.

The Science Panel for the Congo Basin (SPCB) was established in 2023 at COP28, in Dubai, as an independent platform for scientists from the region to synthesize the existing knowledge including Indigenous peoples and autochthonous knowledge on the functioning of, and threats to, the Congo Basin and its ecosystems. The Panel was inspired by the successful Science Panel for the Amazon (SPA). It collaborates with SPA along with the newly formed Science Panel for Borneo (SPB) to facilitate scientific communication across the three tropical forest ecosystems. SPCB is currently engaged in developing its first assessment report to present at COP30, in Belém.

We see several aligned efforts and general aims between the Science Panel for the Congo Basin and PANGEA, in assessing the impact of anthropogenic activities on tropical forest ecosystem health and resilience. We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

While our Panel excels at analyzing the current body of knowledge on the Congo Basin, we require a strong basis of existing information. PANGEA's efforts to expand knowledge on the impact of climate change in tropical forests will contribute to achieve our aim.

SUSTAINABLE DEVELOPMENT
SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

We believe that this is an important project with the potential for high impact. As Strategic Coordinator for the SPCB, I express my strong support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue the common goal to bring the status of the Congo Basin to the global forefront.

Emma Torres
Head of the New York Office and Vice President of the Americas
Strategic Coordinator of the Science Panel for the Congo Basin
United Nations Sustainable Development Solutions Network

UNIVERSIDAD NACIONAL DEL ALTIPLANO - PUNO
VICERRECTORADO INVESTIGACION
Ciudad Universitaria s/n Edificio Administrativo 2do Piso - Teléfono 51-365054

Dra. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Asunto: Carta de apoyo a la investigación PANtropical sobre biogeoquímica y adaptación ecológica (PANGEA)

Estimada Dra. Ordway,

Por intermedio de la Universidad de Oklahoma, agradezco por la invitación a colaborar en la investigación PANtropical de biogeoquímica y adaptación ecológica (PANGEA). La Oficina del Vicerrectorado de Investigación de la Universidad Nacional del Altiplano, Puno está encantada de apoyar el programa PANGEA cuando se confirme la financiación de la NASA.

La Universidad Nacional del Altiplano, Puno, una universidad pública fundada el 29 de Agosto de 1856 en la Ciudad de Puno, Perú con la misión de desarrollar y transmitir el conocimiento científico, tecnológico y humanístico, formando profesionales y posgraduados calificados y competitivos, impulsando el desarrollo de la investigación y la responsabilidad social, la práctica de valores y la identidad cultural, orientadas al estudiante y la sociedad, con miras a contribuir al desarrollo sostenible de la región y del país.

El objetivo de PANGEA es mejorar la comprensión de cómo el clima global y los cambios antropogénicos afectan la composición, la estructura y el ciclo biogeoquímico de los bosques en las regiones tropicales. Los nuevos hallazgos son necesarios para determinar la resiliencia y la vulnerabilidad de los ecosistemas forestales tropicales. Por lo tanto, la agenda de investigación de PANGEA está estrechamente alineada con nuestras prioridades de investigación. Esperamos apoyar los esfuerzos de PANGEA para aprovechar la observación de la Tierra y los datos y métodos multidisciplinarios para realizar investigaciones. Estamos particularmente entusiasmados con las perspectivas de interactuar con diversas comunidades en todo el trópico para avanzar en la comprensión científica, fortalecer la capacidad de investigación ecológica y apoyar la aplicación de los resultados científicos a la gobernanza y las prácticas de gestión sostenible de la tierra.

En caso de que se financie PANGEA, la UNAP proveerá espacios de colaboración para llevar a cabo estudios y experimentos especialmente en sus centros de investigación en la zona Amazónica y Andina así como la participación de profesores investigadores en el tema. La UNAP con su aliada estratégica la Universidad de Oklahoma (USA), buscarán desarrollar propuestas de investigación para buscar financiación para apoyar la participación en estudios relacionados con PANGEA.

UNIVERSIDAD NACIONAL DEL ALTIPLANO - PUNO
VICERRECTORADO INVESTIGACION
Ciudad Universitaria s/n Edificio Administrativo 2do Piso - Teléfono 51-365054

Llevamos adelante esta iniciativa con nuestros investigadores, las comunidades locales, especialmente en la zona Amazónica de Puno, Carabaya, San Gaban, Sandia que se alinean a los objetivos de PANGEA. LA UNAP en alianza con la Universidad de Oklahoma también facilitará alianzas con instituciones relevantes del gobierno para obtener datos históricos y apoyo para las investigaciones que PANGEA lleve a cabo.

La UNAP apoya esta iniciativa enfocada en el ecosistema Amazónico de la región Puno, donde los efectos del cambio climático afectan a la población y el medio ambiente. El ecosistema Andino-Amazónico en el suroeste del Amazonas es de importancia estratégica para PANGEA por ser la región que en la última década ha sufrido los mayores efectos de deforestación y contaminación ambiental del continente. La implementación de PANGEA nos ayudará a renovar y potenciar nuestras estaciones experimentales, su instrumentación y formar profesores expertos en la biogeoquímica y adaptación ecológica en Puno, Perú.

Si bien nuestra universidad se destaca en poseer participación comunitaria, recopilación y análisis de datos terrestres buscamos participar en PANGEA para desarrollar capacidad en investigación y educación para la siguiente generación de científicos formados en Puno. Igualmente nos ayudará a acceder a las tecnologías de NASA y aprovechar las imágenes satelitales por ejemplo para entender y mejorar el manejo del carbono.

Reconocemos los beneficios mutuos de compartir esfuerzos, métodos de investigación (por ejemplo, modelos numéricos), conjuntos de datos, recursos y experiencias para avanzar en la comprensión de la ecología terrestre y aprovechar mejor la observación de la Tierra para apoyar el objetivo de nuestra organización. Esperamos que el apoyo de la NASA a PANGEA nos permita perseguir este interés común de investigación.

Atentamente,

UNIVERSIDAD NACIONAL DEL ALTIPLANO
VICERRECTORADO DE INVESTIGACIÓN
PUNO PERÚ

Dr. Ariel Rogelio Velazco Cárdenas
VICERRECTOR DE INVESTIGACIÓN
UNA - PUNO

Universidad Nacional del Altiplano UNAP Letter of Support – English Translation

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

Through our partner the University of Oklahoma I thank you for the invitation to collaborate on the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA) Scoping Campaign. On behalf of the office of the Vice President for Research of the Universidad Nacional del Altiplano, Puno (UNAP) I am glad to support the PANGEA program once NASA funding is confirmed.

The UNAP It is a public university founded on August 29, 1856 in the city of Puno, Peru with the mission of developing and transmitting scientific, technological and humanistic knowledge, training qualified and competitive professionals and graduates, promoting the development of research and social responsibility, the practice of values and cultural identity, oriented to the student and society, with a view to contributing to the sustainable development of the region and the country.

PANGEA's aims to improve the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions. The new findings are necessary to determine the resilience and vulnerability of tropical forest ecosystems. Therefore, the PANGEA research agenda is closely aligned with our research priorities in the Amazon region of Peru. We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the Tropics to advance scientific understanding, strengthen capacity for ecological research, and support the application of scientific results to governance and sustainable land management practices.

Should PANGEA be funded, UNAP can provide the use of our university experimental stations and support for field work in the rainforest and Andean region. Similarly, we will involve our research faculty experts on the area. UNAP and its strategic partner the University of Oklahoma (USA), will work to develop research proposals seeking funding to support studies aligned with PANGEA

We pursue this initiative with local communities and institutions in the Amazonic and Andean regions that aligned with the objectives of PANGEA. UNAP and OU will also facilitate alliances with relevant government agencies to obtain historic and current data for the planed research.

UNAP supports this initiative focused on the Southern Amazon region of Peru where the effects of climate change effects severely the population and the environment. The Andean-Amazonian ecosystem in the southwest Amazon is of strategic importance for PANGEA because it is the region that in recent decades has suffered the most with massive deforestation, environmental pollution, and wildfires on the continent. The implementation of PANGEA will help us to renew and enhance our experimental stations, their instrumentation and train expert professors in biogeochemistry and ecological adaptation in Amazonas, Peru.

While our organization/institution excels in community engagement, local ground data collection, we seek to engage with PANGEA to help capacity building in research and education to train the next generation of scientists for the Amazon region in Puno. Similarly, we hope it will allow us access to new technology and information from NASA and benefit from the remote sensing information and maps to better understand for instance the carbon accounting in our region.

We recognize the mutual benefits in sharing efforts, research methods (e.g., numerical models), datasets, resources, and experiences to advance understanding of terrestrial ecology and better leverage Earth observation to support our organization's goal. We hope that NASA's support of PANGEA will enable us to pursue this common research interest.

Sincerely,

Dr. Ariel Velasco Cardenas
Vice Rector de Investigación
Universidad Nacional del Altiplano, Puno, Peru

Chachapoyas, 3 de octubre del 2024

CARTA N° 065-2024-UNTRM-R

Dra. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles

410K Botany Building
Los Angeles, CA, 90095

Asunto: Carta de apoyo a la investigación PANtropical sobre biogeoquímica y adaptación ecológica (PANGEA)

Estimada Dra. Ordway,

Por intermedio de la Universidad de Oklahoma, agradezco por la invitación a colaborar en la investigación PANtropical de Biogeoquímica y Adaptación Ecológica (PANGEA). En nombre de la Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas (UNTRM) deseo expresar nuestro apoyo al programa PANGEA, una vez se confirme el financiamiento de la NASA.

La UNTRM es una universidad pública creada el 18 de setiembre del 2000 en la Ciudad de Chachapoyas, Perú, con la visión ser líder y referente nacional e internacional en formación académica, investigación científica, tecnológica y humanista de calidad que contribuya al desarrollo de la sociedad.

El objetivo de PANGEA es mejorar la comprensión de cómo el clima global y los cambios antropogénicos afectan la composición, la estructura y el ciclo biogeoquímico de los bosques en las regiones tropicales. Los nuevos hallazgos son necesarios para determinar la resiliencia y la vulnerabilidad de los ecosistemas forestales tropicales. Por lo tanto, la agenda de investigación de PANGEA está estrechamente alineada con nuestras prioridades de investigación. Esperamos apoyar los esfuerzos de PANGEA para aprovechar la observación de la Tierra y los datos y métodos multidisciplinarios para realizar investigaciones. Estamos particularmente entusiasmados con las perspectivas de interactuar con diversas comunidades en todo el trópico para avanzar en la comprensión científica, fortalecer la capacidad de investigación ecológica y apoyar la aplicación de los resultados científicos a la gobernanza y las prácticas de gestión sostenible de la tierra.

En caso de que se financie PANGEA, la UNTRM proveerá espacios de colaboración para llevar a cabo estudios y experimentos, especialmente en sus centros de investigación en la zona Amazónica y Andina, así como la participación de profesores investigadores en el tema. La UNTRM con su aliada estratégica la Universidad de Oklahoma (USA), buscarán desarrollar propuestas de investigación para buscar financiamiento y apoyar la participación en estudios relacionados con PANGEA.

Llevamos adelante esta iniciativa con nuestros investigadores, las comunidades locales, especialmente en la zona Amazónica de la región Amazonas que se alinean a los objetivos de PANGEA, también, la UNTRM en alianza con la Universidad de Oklahoma promoverán la creación de alianzas con instituciones relevantes del gobierno para obtener datos históricos y apoyo para las investigaciones que PANGEA lleve a cabo.

La UNTRM apoya esta iniciativa enfocada en el ecosistema Amazónico de la región Amazonas, donde los efectos del cambio climático afectan severamente a la población y el medio ambiente. El ecosistema Andino-Amazónico en el oeste del Amazonas es de importancia estratégica para PANGEA por ser la región que en las últimas décadas ha sufrido los mayores efectos de deforestación y contaminación ambiental del continente. La implementación de PANGEA nos ayudará a renovar y potenciar nuestras estaciones experimentales, su instrumentación y formar profesores expertos en la biogeoquímica y adaptación ecológica en Amazonas, Perú.

Si bien nuestra universidad se destaca en poseer participación comunitaria, recopilación y análisis de datos terrestres buscamos participar en PANGEA para desarrollar capacidad en investigación y educación para formar la siguiente generación de científicos formados en la región Amazonas. Igualmente nos ayudará a acceder a las tecnologías e información de la NASA y aprovechar las imágenes satelitales, por ejemplo, para entender y mejorar el manejo del carbono.

Reconocemos los beneficios mutuos de compartir esfuerzos y métodos de investigación, tales como, modelos numéricos, conjuntos de datos, recursos y experiencias para avanzar en la comprensión de la ecología terrestre y aprovechar mejor la observación de la Tierra para apoyar el objetivo de nuestra universidad. Esperamos que el apoyo de la NASA a PANGEA nos permita perseguir este interés común de investigación.

Atentamente,

UNIVERSIDAD NACIONAL
TORIBIO RODRÍGUEZ DE MENDOZA DE AMAZONAS

Jorge Luis Maicelo Quintana Ph.D.
Rector

JLMQ/Rector
C.c. Archivo

Campus Universitario, Sede Administrativa, Calle Higos Urco N° 342-350-356
Teléfono 041-636400, Anexo N° 4002 Chachapoyas, Perú
Email: rectorado@untrm.edu.pe / www.untrm.edu.pe

Universidad Nacional Toribio Rodriguez de Mendoza (UNTRM) – English Translation

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

Through our partner the University of Oklahoma I thank you for the invitation to collaborate on the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA) Scoping Campaign. On behalf of the Universidad Nacional Toribio Rodriguez de Mendoza (UNTRM) I am glad to support the PANGEA program once NASA funding is confirmed.

The UNTRM It is a public university created on September 18, 2000 in the city of Chachapoyas, Peru with the vision of being a leader and national and international reference in academic training, scientific, technological and humanistic research of quality that contributes to the development of society.

PANGEA's aims to improve the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions. The new findings are necessary to determine the resilience and vulnerability of tropical forest ecosystems. Therefore, the PANGEA research agenda is closely aligned with our research priorities in the Amazon region of Peru. We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the Tropics to advance scientific understanding, strengthen capacity for ecological research, and support the application of scientific results to governance and sustainable land management practices.

Should PANGEA be funded, UNTRM can provide access to our university experimental stations and support for field work in the rainforest and surrounding Andean areas. Similarly we will involve our research faculty experts on the area. The UNTRM and its strategic partner the University of Oklahoma (USA), will work to develop research proposals seeking funding to support studies aligned with PANGEA

We pursue this initiative with local communities and institutions in the Amazonic and Andean regions that aligned with the objectives of PANGEA. The UNTRM and OU will also facilitate alliances with relevant government agencies to obtain historic and current data for the planed research.

UNTRM supports this initiative focused on the Northern Amazon region of Peru where the effects of climate change severely affect the population and the environment. The Andean-Amazonian ecosystem in the western Amazon is of strategic importance for PANGEA because it is the region that in recent decades has suffered the most the effects of deforestation, environmental pollution, and wildfires on the continent. The implementation of PANGEA will help us to renew and enhance our experimental stations, their instrumentation and train expert professors in biogeochemistry and ecological adaptation in Amazonas, Peru.

While our organization/institution excels in community engagement, local ground data collection, we seek to engage with PANGEA to help capacity building in research and education to train the next generation of scientists for the Amazon region. Similarly, we hope it will allow us access to new technology and information from NASA and benefit from the remote sensing information and maps to better understand for instance the carbon accounting in our region.

We recognize the mutual benefits in sharing efforts, research methods (e.g., numerical models), datasets, resources, and experiences to advance understanding of terrestrial ecology and better leverage Earth observation to support our organization's goal. We hope that NASA's support of PANGEA will enable us to pursue this common research interest.

Sincerely,

Dr. Jorge Luis Maicelo Quintana
President
Universidad Nacional Toribio Rodriguez de Mendoza,
Amazonas, Peru

UNIVERSIDAD NACIONAL DE PIURA
FACULTAD DE AGRONOMÍA
DECANATO

June 10, 2024

Elsa M. Ordway, Ph.D.
Department of Ecology and Evolutionary Biology Institute of the Environment and Sustainability
University of California, Los Angeles, USA

Dr. Ordway,

I am writing to express my sincerest gratitude for the invitation to participate in the PANGEA Workshop, held at the Pontifical Catholic University of Peru in Lima. It was an enriching and valuable experience, both professionally and personally. The opportunity to share knowledge and experiences with colleagues from various institutions and countries was invaluable.

Additionally, I would like to express the intention of the Faculty of Agronomy at the National University of Piura to collaborate with you. We are deeply interested in working together on the study, analysis, and development of alternatives to address the negative effects of climate change on agriculture and the forest environment of the Amazon. We believe that close collaboration between our institutions can generate innovative and effective solutions to mitigate the impact of climate change in these crucial areas, strengthening our academic development and professional exchange in various scientific specialties.

In the Piura Region, we currently have a diagnosis of the effects of climate change on agriculture. This study has allowed us to propose concrete recommendations to prevent the increased risk in food production and suggest alternatives for biodiversity conservation. We would like to share these findings with you and your team and explore possible areas of collaboration to strengthen our joint efforts.

We look forward to the possibility of working with you and the University of California, Los Angeles, on initiatives that promote the sustainability and resilience of our agricultural and forest systems in the face of climate change.

Once again, thank you for the invitation, and I hope to establish a fruitful collaboration.

Sincerely,

Ing. Jose Remigio
Dean of the Faculty of Agronomy, National University of Piura
51 990076076; jremigioa@unp.edu.pe, remigiopepe@gmail.com

UNIVERSIDAD NACIONAL DE PIURA
FACULTAD DE AGRONOMIA
ING JOSE REMIGIO ARGUELLO M.Sc
DECANO

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Louvain-la-Neuve, Belgium, July 25, 2024

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

Thank you for the invitation to collaborate on the PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA) Scoping Campaign. The Land Systems for Sustainability lab that I am leading at the Université catholique de Louvain (UCLouvain) in Belgium is happy to support the PANGEA program once NASA funding is confirmed.

Our lab is part of Earth and Life Institute (ELI). Established in 2009, ELI is UCLouvain's flagship research institute on sustainability and environmental sciences, with over 300 researchers and key research foci on land-use change, climate change, soil sciences, and biodiversity conservation. ELI has a longstanding research track record in Earth Observation, land-use and land-cover change (LULCC) and global change studies in tropical regions. Within ELI, the research in our lab focuses on how land use and more broadly land systems can contribute to sustainability.

PANGEA's aims—to improve the understanding of how global climate and anthropogenic changes impact forest composition, structure, and biogeochemical cycling across tropical regions—are clearly linked to our research agenda. We have been working on mapping and understanding tropical social-ecological systems, with a focus on the role of governance interventions (public, private and hybrid) and economic dynamics, in particular linked to international supply chains. We have been investigating various processes that are strongly linked to the PANGEA agenda, including tropical deforestation, reforestation, and agricultural expansion, intensification and extensification. Our team has strong expertise in understanding drivers of land use and land system changes, including governance and economic structures such as international supply chains. The work developed in PANGEA throughout its well-identified but strongly articulated Working Groups would be extremely useful for us for embedding our understanding of land system drivers into a broader understanding of their Earth System impacts, including biogeochemical cycles & carbon dynamics, ecosystem structure, function, biodiversity, and climate feedbacks and interactions. Further, we believe that we can develop valuable synergies with the social-ecological systems Working Group,

Croix du Sud, 2 bte L7.05.05, 1348 Louvain-la-Neuve, Belgique
Tél. +32 (0)10 47 23 74 – fax +32 (0)10 47 88 98 – president-eli@uclouvain.be – www.uclouvain.be/eli

which investigates questions that are very close to our research agenda, such as *how does governance structure, policy, and market dynamics interact with climate change, and land use and land cover change in tropical regions*, and *which interventions are most effective in restoring and adapting social and ecological processes to changes in tropical regions*.

We look forward to supporting PANGEA's efforts to leverage Earth Observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the Tropics to advance scientific understanding, strengthen capacity for ecological research, and support the application of scientific results to governance and sustainable land management practices. Although our team has been working in various contexts across the Tropics, we have developed a strong focus on the Miombo woodlands of Southern Africa, in particular Mozambique, where we collaborate with colleagues who have a very strong and long-standing expertise in ecosystem dynamics in these forests, in particular at Universidade Eduardo Mondlane (UEM). The Miombo woodlands are a highly understudied both in terms of social and ecological dynamics, and their interactions, and African research institutes are strongly under-represented in global change research. The teams led by our colleagues at UEM are pivotal in the research and the science-policy interface in Mozambique, being directly engaged with public authorities and administrations on policy-making and evaluation. I sincerely believe that engaging further in this region and with these partners would be highly beneficial for the research agenda and the positioning of PANGEA.

Should PANGEA be funded, we are willing to facilitate any engagement of PANGEA in that region, and to consider developing research proposals, including in other regions, to seek funding to support participation in PANGEA-related studies. We recognize the mutual benefits in sharing efforts, research methods (e.g., numerical models), datasets, resources, and experiences to advance understanding of terrestrial ecology and better leverage Earth observation to support our lab's goals. We hope that NASA's support of PANGEA will enable us to pursue this common research interest.

Yours sincerely,

Professor Dr. Patrick Meyfroidt

F.R.S. - FNRS &
Earth and Life Institute - UCLouvain
Place Louis Pasteur, 3
1348 Louvain-La-Neuve Belgium
Email : patrick.meyfroidt@uclouvain.be
Tel: +32 10 472 992 http://www.uclouvain.be/eli
http://landsystems-lab.earth/

UCLA Research & Creative Activities

Roger M. Wakimoto, Ph.D.
2248 Murphy Hall
Mail code 140501
Phone: (310) 825-7943
Email: rwakimoto@conet.ucla.edu

November 19, 2024

Elsa Ordway, Ph.D.
Assistant Professor, UCLA Department of Ecology and Evolutionary Biology
Co-Director, Congo Basin Institute, UCLA
Co-Director, UCLA Center for Tropical Research

RE: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Professor Ordway,

As the UCLA Vice Chancellor for Research & Creative Activities, I am writing to express my strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). This campaign, if selected, will fill critical data, methods, applications, and training gaps and needs related to the measurement, understanding, and scaling of remote sensing data in tropical forest regions.

If awarded, PANGEA will be able to draw upon the extensive research infrastructure at UCLA. As one of the country's largest and most productive research universities with over $1.5 billion in annual research funding, UCLA has experience managing large complex federal awards. UCLA's Office of Research Administration and other campus offices have the capacity, resources, and expertise needed to ensure appropriate award management.

In addition, UCLA has a history of nurturing international research programs, some of which will facilitate PANGEA's data collection and engagement. UCLA co-founded the Congo Basin Institute (CBI) in 2015 as a model for modern scholarship in Africa. Based in Cameroon and covering the Central African region, CBI has nearly a decade of operational experience, dozens of collaborations with local researchers, and relationships with numerous local communities. Another example, the Center for Tropical Research (CTR), has been housed at UCLA since 2001 and promotes pan-tropical research in the three major tropical basins.

PANGEA will also benefit from the enormous depth and breadth of scholarship at UCLA, which has over 140 departments and interdepartmental programs. Our highly engaged undergraduate and graduate student body will support PANGEA's capacity-building goals. Furthermore, UCLA's status as an emerging Hispanic-Serving Institution and our partnership with Morgan State University, a historically Black university, will facilitate engaging minority and first-generation students in PANGEA's research.

The PANGEA campaign has significant potential for high-impact research. UCLA is committed to supporting the project's success and helping it flourish as part of UCLA's expansive research enterprise.

Sincerely,

Roger M. Wakimoto

Roger M. Wakimoto, Ph.D.
Vice Chancellor for Research & Creative Activities

November 7, 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Dear Dr. Ordway,

LETTER OF SUPPORT FOR PAN TROPICAL INVESTIGATION OF BIOGEOCHEMISTRY AND ECOLOGICAL ADAPTATION (PANGEA)

I am writing to express my strong support for the proposed NASA Terrestrial Ecology Field Campaign: PAN tropical investigation of Ecological Adaptation (PANGEA). This campaign, if selected, will serve to fill critical training gaps and needs related to the measurement, understanding, and scaling of carbon, water, and energy fluxes in tropical forests and/or their interactions with biodiversity, climate change, human activities. PANGEA will also support and reinforce earth observation of forest through satellite imagery, forest biodiversity and conservation, landscape restoration, Non-Timber Forest Products (NTFP) conservation and utilization at the local level for food, energy and medicine, forest resources utilization for indigenous medicine, capacity building and research-related activities led and carried out by the University of Energy and Natural Resources.

The University of Energy and Natural Resources (UENR) is a public funded institution that was established in 2011 in Ghana. Our goal is to promote the development of human resources and skills required to solve the critical energy and natural resources challenges of society and undertake interdisciplinary academic research and outreach programmes in engineering, science, economics and environmental policy. To achieve our objectives, we currently do carbon flux tower monitoring project between atmosphere and tropical forest (https://eoric.uenr.edu.gh/?bunch_projects=carbon-flux-tower-project) in Bia-Tano Forest Reserve, Ghana, Non-Timber Forest Products cultivation and community development at Lake Bosomtwe, Ghana, Forest Phenology project (in selected forest reserves in Ghana) and Climate Forest Feedbacks Project, also at Bia-Tano Forest Reserve.

We see several aligned efforts and general aims between UENR and PANGEA, in earth observation research, climate change mitigation and adaptation, forest monitoring and conservation, carbon sequestration research, NTFP research and community development. We look forward to supporting PANGEA's efforts to leverage earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

We pursue forest monitoring and conservation, community capacity building for forest management initiatives with local communities, and national institutions and agencies such as Forestry Commission, Forestry Research Institute of Ghana (FoRIG), Environmental Protection Agency (EPA) and Local Government Authorities. These institutions have the legal, regulatory, scientific and technical mandate and capacity to support research, capacity building, data analysis and dissemination activities related to PANGEA. We conduct this initiative in Bia-Tano Forest Reserve, Tain II Forest Reserve, Tinte Bepo Forest Reserve, Bobri Forest Reserve within both moist and dry semi-deciduous forest ecosystems because it is special for habitation of indigenous forest species, biodiversity hotspot and buffers the forest zone from the harsh savannah ecosystems in Northern Ghana. This location may be of strategic importance to PANGEA because of their unique scientific and socioeconomic value. The UENR has been working in this location for twelve years and can facilitate PANGEA's implementation by helping with research, stakeholder engagement, capacity building and community development.

Should PANGEA be funded, UENR can provide in-kind support in the form of research support services, office space, IT services, financial management services and vehicles for travel and 20% of staff time (FTE) estimated at US $200,000.

While our institution excels at earth observation services (global navigation satellite systems, high performance computing, GIS and data analysis) multidisciplinary research, stakeholder engagement, collecting and analyzing ground-based data, strengthening capacity of local government authorities, we seek to engage in cutting-edge research, training and capacity building in emerging innovative methods and technologies within our area of expertise including leveraging satellite imagery to improve carbon accounting.

We believe that this is an important project with the potential for high impact across the globe and is mutually beneficial to all partners involved. As Director of Research, I express my utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue this common effort.

Name: Peter Sanful PhD
Title: Director of Research
Institution name: University of Energy and Natural Resources
Institution Address: P. O Box 214 Sunyani, Ghana

Signature: 

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This letter attests our support for the proposed NASA Terrestrial Ecology Field Campaign entitled PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA). If funded, PANGEA will advance data, methods, applications, training gaps/needs related to the measurement, understanding, and scaling of carbon, water, and energy fluxes in tropical forests and/or their interactions with biodiversity, climate change, human activities. The field campaign will contribute to understanding how tropical forests across the world are responding to changes in climate, land cover and land use. PANGEA's main goals are aligned with U.S. Forest Service International Programs work on sustainable forest management and biodiversity conservation internationally.

U.S. Forest Service International Programs has had long term technical cooperation in the Amazon and Central Africa that has been supported by USAID, Department of State and other donors. U.S. Forest Service International Programs activities include both specific cooperation with countries in the South America and Africa regions as well as pantropical programs such as SilvaCarbon to enhance capacity of tropical forested countries to monitor, measure, and report carbon in their landscapes.

PANGEA is an exciting mission and will advance our understanding of how forests are changing in response to shifts in climate and disturbance regimes. As the Director of International Programs, I confirm my support for the PANGEA Terrestrial Ecology Field Campaign.

Sincerely,

Valdis Mezainis Digitally signed by Valdis Mezainis Date: 2024.11.22 08:30:34 -05'00'

Val Mezainis, PhD

Forest Service
U.S. DEPARTMENT OF AGRICULTURE

INTERNATIONAL PROGRAMS | OFFICE OF THE CHIEF

Director
Forest Service
International Programs
Office of the Chief
201 14th Street SW, Stop 1127
Washington DC 20250-1127

01 BP 526, Cotonou, Bénin
Tel : + 229 21 36 11 19
www.uac.bj

Abomey-Calavi, 28 November 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles, USA

Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

This is to express my strong support for the proposed NASA PANGEA (**PANtropical Investigation of bioGeochemistry and Ecological Adaptation)** Terrestrial Ecology Field Campaign. The idea developed is relevant to advance our understanding of biogeochemical cycles in tropical forests, their dynamics and their feedbacks with climate, biodiversity, and human agricultural related activities. PANGEA will be also valuable in completing and reinforcing national and international collaborative research activities led currently by our research group. These are LMI REZOC a bilateral laboratory between INE (National Institute for Water) of University Abomey-Calavi (UAC) in Bénin and IGE (Institute of Geoscience and Environment, Grenoble, France); and AMMA-CATCH a regional hydro-meteorological observatory. This observatory has been monitoring since more than ten years water vapor, carbon dioxide fluxes as well weather data across ecosystems spanning from the South to the North of Bénin and Dr. Ossénatou Mamadou is the leader of the beninese flux sites.

Considering that Bénin has a large part of its territory covered by forest, culture and plantations, PANGEA will clearly help to elucidate how land use and land cover changes affect biogeochemical gas fluxes and forest dynamics using ground base data, drone, and remote sensing products in one of the most understudied regions of West Africa. Bénin is also at the frontier between two large tropical forested ecosystems (the Dahomey Gap), between Guinean and the Central African equatorial forests which offers an unique opportunity for developing a comprehensive understanding of beninese ecosystems.

Our research group has a keen interest and is enthusiastic about PANGEA's vision to combine observation data and multidisciplinary tools, approaches to co-produce and co-create knowledge by engaging local communities. This corroborates with our objectives to promoting scientific collaboration, building capacity for research and monitoring, nurturing the next generation of scientists, developing innovative results applicable to inform climate mitigation, adaptation, biodiversity conservation, ecosystem water-related services, and sustainable land-use practices.

We guarantee that if the PANGEA is funded, our research group, the LMI REZOC and AMMA-CATCH Benin team can offer logistical support across our three sites to validate and improve satellite-derived measurements. LMI REZOC will also directly support these activities through triggering funds and sharing of expertise with the AMMA-CATCH technical staff, permanent in Benin, to survey and collect data of the three sites. We will also provide our long term existing data to collaborate on PANGEA-related studies, which would benefit from dedicated research funding. Finally, we aim to expand opportunities for young beninese scientists by supporting their participation in Master's and Ph.D. programs that utilize flux towers data.

As a local principal investigator of beninese flux sites, I express my undeniable support for this campaign. Finally, we look forward to the possibility of contributing to PANGEA and are persuaded that this collaboration will generate impactful societal results for our country.

Ossénatou MAMADOU, PhD
Associate Professor, IMSP/UAC
Leader of the WAF-Net (West Africa Flux Network)

WCS

Global Conservation Program, 2300 Southern Boulevard, Bronx, NY 10460 USA tel: 718-220-5100

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing to express our strong support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will significantly contribute to the aims of the Wildlife Conservation Society's (WCS) Forests & Climate Change Program.

Established in 1895, WCS is a global 501 non-governmental organization committed to saving wildlife and wild places around the world. WCS leads active projects in more than 50 countries and more than 500 project locations around the world. WCS' Forests and Climate Change Program works to safeguard the long-term integrity of the tropical forest carbon sink, and leads the development of the HIFOR nature finance initiative to scale investments in these climate-critical ecosystems (www.hifor.org).

Several of PANGEA's goals align closely WCS' priorities, particularly in the development of a broader understanding of risks to the tropical land sink, how these risks vary over space and time, and the determinants of sink dynamics. PANGEA's planned activities will illuminate crucial relationships between tropical forest integrity, biodiversity, anthropogenic pressures, and resistance and resilience to climate variability that will inform WCS' efforts to implement effective, durable, and equitable forest conservation solutions. We are therefore eager to support PANGEA's use of Earth observation and multidisciplinary approaches to fill these knowledge gaps.

WCS currently collaborates with community, civil society, and government partners on the development, piloting, and scaling of HIFOR nature finance in more than 50 countries. Our partnerships and the unique qualities of these ecosystems may be of strategic importance to PANGEA's objectives, as our shared expertise and WCS's longstanding regional experience will provide strong local support for PANGEA's implementation.

If PANGEA is selected, WCS can provide in-kind support, including data -sharing and assistance with local logistics. Our team is also prepared to explore collaborative funding opportunities to participate in PANGEA-related research and applications activities.

We believe PANGEA represents a project with high potential impact. As the Executive Director of the Forests and Climate Change Program at WCS, I offer my full support for the PANGEA campaign and hope that NASA's endorsement of PANGEA will facilitate this valuable partnership and further our shared climate and biodiversity conservation goals.

Sincerely,

Signed by:

3407CE162A204FE...

Daniel J. Zarin, Ph.D.
Executive Director, Forests and Climate Change

Woodwell Climate Research Center

149 Woods Hole Road
Falmouth, MA 02540-1644

woodwellclimate.org
508 540 9900

info@woodwellclimate.org

November 29, 2024

Dr. Elsa Ordway
Assistant Professor, Ecology & Evolutionary Biology
University of California Los Angeles
410K Botany Building
Los Angeles, CA, 90095
USA

Subject: Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

I am writing to convey my strong support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will address essential gaps in data, methodology, and training, advancing our ability to measure, understand, and scale carbon cycle dynamics in tropical forests and their interactions with biogeochemical cycles, biodiversity, climate change, disturbance events, and human activities. PANGEA will also strengthen and enhance tropical forest conservation initiatives in the Democratic Republic of Congo and Brazil led by the Woodwell Climate Research Center (Woodwell Climate).

Woodwell Climate Research Center conducts science for solutions at the nexus of climate, people and nature. We partner with leaders and communities for just, meaningful impact to address the climate crisis. For nearly 40 years, we have combined hands-on experience and policy impact to identify and support societal-scale solutions that can be put into immediate action. Woodwell Climate was established in 1985 as the Woods hole Research Center. To achieve our objectives, Woodwell Climate conducts basic and applied research on the biophysical, economic, and social systems affecting tropical forest and land use dynamics in the Amazon (since 1985) and Congo (since 2008) Basins.

The Tropics team at Woodwell Climate see several aligned efforts and goals between Woodwell and PANGEA, in particular tropical forest and carbon cycle resilience and the role of biodiversity in maintaining healthy forests. We look forward to supporting PANGEA's efforts to leverage Earth observation and multidisciplinary data and methods to conduct research. We are particularly excited at the prospects of engaging with diverse communities throughout the tropics to advance scientific understanding, strengthen capacity for research and monitoring, and support the application of scientific results for climate mitigation, adaptation, biodiversity conservation, and sustainable land-use practices.

Woodwell Climate conducts its research with local partners/institutions such as the Amazon Environmental Research Institute in Brazil (IPAM), the Congo Regional Post-Graduate Training School on Integrated Management of Tropical Forests and Lands (ERAIFT), and Congo Basin Water Resources Research Center (CRREBaC). We carry out this work in mixed use landscapes consisting of native forest, large scale industrial agriculture, traditional uses, and cattle pasture. The remaining forests in these regions contain the bulk of the world's terrestrial biodiversity and play a crucial but still not well understood role in regulating our climate. These partnerships and locations may be of strategic

Woodwell Climate Research Center

149 Woods Hole Road
Falmouth, MA 02540-1644

woodwellclimate.org
508 540 9900

info@woodwellclimate.org

importance to PANGEA because of long term research programs and well-established connections to local research, community organisations, and policy management institutions. Woodwell Climate's deep experience in these landscapes and on these topics can facilitate PANGEA's implementation by supporting research, training, and capacity building.

If PANGEA is selected to move forward, Woodwell Climate can provide in-kind support in the form of internal grants and grants to our institution from private foundations and individuals to support participation in PANGEA-related research activities.

While Woodwell Climate excels at collecting and analyzing ground-based and satellite data, strengthening capacity of local students, researchers, and land managers, we seek to engage in leveraging satellite imagery to improve our understanding of the processes of forest degradation and the overall importance of forests for climate and agricultural productivity.

We believe that PANGEA is an important project with the potential for high impact. As Director of the Tropics Program, I express my utmost support for the PANGEA campaign and hope that NASA's support of PANGEA will enable us to pursue this common interest.

Michael T. Coe

Director of the Tropics Program
Woodwell Climate Research Center
149 Woods Hole Rd, Falmouth, MA, 02540

WORLD RESOURCES INSTITUTE

10 G Street, NE Suite 800 Washington, DC 20002 USA (PH) +1 (202) 729-7600 (FAX) +1 (202) 729-7610
Www.WRI.org

Subject:
Letter of Support for PAN tropical investigation of bioGeochemistry and Ecological Adaptation (PANGEA)

Dear Dr. Ordway,

We are writing to express our strong support for NASA's proposed Terrestrial Ecology Field Campaign, PAN Tropical Investigation of Ecological Adaptation (PANGEA). If selected, PANGEA will significantly benefit our Global Forest Watch and Land & Carbon Lab's initiatives, as led by the World Resources Institute (WRI).

WRI is a non-profit environmental think tank, incorporated under the laws of Delaware, USA, that goes beyond research to create practical ways to protect the earth and improve people's lives. WRI is committed to move human society to live in ways that protect Earth's environment and its capacity to provide for the needs and aspirations of current and future generations.

Our team pursues the development of high-quality information about land and its associated values (e.g. carbon, biodiversity) and make these universally accessible and useful for people worldwide, so as to empower them to manage landscapes sustainably and improve the livelihoods of local people through active projects in Food Land & Water Department especially Global Forest Watch and Land & Carbon Lab.

Several of PANGEA's goals align closely with ongoing efforts at WRI, particularly the Land & Carbon Lab and Global Forest Watch of improved land cover data, land cover changes and the impacts of these changes on biodiversity, carbon and people. We are eager to work with PANGEA to share our data, work in cooperation to develop new data, scale PANGEA data on our platforms, help get data used in our wide network and cooperate on advances in Earth observation capabilities and collaborative multidisciplinary approaches to understanding tropical forest, peatland, and wetland responses to global environmental change.

WRI currently collaborates on Global Forest Watch and the Land & Carbon Lab with many local and international partners as the University of Maryland, University of Minnesota, Purdue University, Cornell university, Wageningen University, German Research Centre for Geosciences, NASA, Google, Meta and international partners including ESA, IFPRI, World Bank and UN FAO. WRI's deep experience developing breakthroughs in geospatial mapping that power local-to-global solutions by making those capabilities accessible will provide critical support for PANGEA's translation of science to action.

If PANGEA is selected, WRI can provide in-kind support through expertise, data sharing, partnership engagement and user testing. Our team is also prepared to explore funding opportunities to participate in PANGEA-related research and applications activities.

We see an opportunity for PANGEA's focus on advancing carbon, biodiversity, and agricultural remote-sensing capabilities in the tropics to further our goals, such as enhance crop-type/yield mapping, biodiversity assessments, carbon flux mapping and supporting supply chain traceability.

We believe PANGEA represents a project with high potential impact. As Director of Partnership and Innovation for Land& Carbon Lab at WRI, we offer our full support for the PANGEA campaign and hope that NASA's endorsement of PANGEA will facilitate this valuable partnership and further our shared land, climate and biodiversity conservation goals.

Dr. Fred Stolle
Director Innovation & Partnership GFW/LCL
World Resources Institute
10 G street, NE, Suite 800, Washington DC, 20002,

B. PANGEA Partners and Engagement Activities

Table B-1. Overview of engagement strategies and example partners for each target group

Community	Description	Relevance to PANGEA	Engagement Strategy & Goals	Example Partners
NASA	NASA Research & Analysis and Earth Action Programs, NASA Capacity Building Program, and NASA initiatives	NASA is the driving force behind PANGEA	Advance scientific understanding, calibration, and validation, algorithm and product development, partnerships, and capacity building across the NASA enterprise through an integrative approach.	• Terrestrial Ecology, Biological Diversity & Ecological Conservation, NASA Land-Cover and Land-Use Change (LCLUC), Hydrology • Carbon Monitoring System, Climate & Resilience, Disasters, Wildland Fires, NASA Harvest, Water Resources • SERVIR, ARSET, DEVELOP, GLOBE, Indigenous Peoples Initiative
Other US Government Agencies	Non-NASA US federal research and development agencies	Many US government agencies support research and training efforts that directly align with PANGEA	Coordinate with program managers to identify opportunities for interagency solicitations where research and applications activities are mutually beneficial.	• DOE NGEE-Tropics* • NSF BIO, GEO, SBE, GOLD-EN, RISE • USAID CARPE, USAID-PEER** • USFS-International Program • USGS SilvaCarbon
International Space Agencies and Support Facilities	Non-NASA space agencies and federal institutes that support satellite monitoring and technical capacity.	These partners actively collaborate with NASA on many satellite missions and airborne campaigns. PANGEA is an opportunity to strengthen and expand these partnerships.	Support international collaboration on existing joint missions and airborne campaigns; build capacity to support greater engagement between NASA and space agencies in the tropics.	• Satellite Observatory of Central African Forests (OSFAC) • Gabonese Space Agency (AGEOS) • European Space Agency (ESA) • French National Space Agency (CNES) • The German Aerospace Center (DLR) • Indian Space Research Organisation (ISRO) • Brazil's National Institute for Space Research (INPE) • Japan Aerospace Exploration Agency (JAXA)

Community	Description	Relevance to PANGEA	Engagement Strategy & Goals	Example Partners
Foreign Government Agencies and National Research Institutes	National & local sectoral ministries; geospatial specialized institutions; govt.-led multistakeholder platforms	These partners take large-scale action (economic and environmental planning and modeling, law enforcement, investment in research, etc.), and support long-term data and analysis (e.g., weather).	Inform PANGEA science questions and activities via research institutions; set enabling conditions (institutional, financial, and programmatic) for the ownership of PANGEA's research outputs; capacity-building for staff at national and local levels.	• Brazil National Institute of Amazonian Research (INPA) • Cameroon National Observatory on Climate Change (ONACC) • Congo Basin Forest Partnership (CBFP) • Gabon National Center for Scientific and Technological Research (CENAREST) • Governors' Climate and Forests Task Force (GCF-TF) • Ministries of Environment, Forests, Fauna, Agriculture, and Scientific Research • Peruvian Mancomunidad Regional Amazónica • São Paulo Research Foundation (FAPESP)
Scientific Institutions	Universities and colleges; national labs; research institutes	These partners facilitate knowledge and tech transfer to generate capacity in the local and regional institutions to train the next generation of scientists	Co-develop research, analysis, and applications with these partners, and will strengthen local research capacity by supporting data management, infrastructure development, and early-career researcher training at local and regional institutions.	• Alexander von Humboldt Biological Resources Research Institute • Alliance Bioversity International & CIAT • Amazon Institute of Technology (AmIT) • Congo Basin Institute (CBI) • French National Research Institute for Agriculture, Food and Environment (INRAE) • International Institute for Tropical Agriculture (IITA) • K. Lisa Yang Center for Conservation Bioacoustics • LBA • Pontifical Catholic University of Peru (PUCP) • Woodwell Climate Research Center

Community	Description	Relevance to PANGEA	Engagement Strategy & Goals	Example Partners
Coordinated International Research Initiatives	Research consortiums; networks; networks of networks	These partners work at large scales that align with PANGEA's transdisciplinary and pantropical objectives.	Align efforts with these partners to ensure PANGEA activities strategically fill needed gaps rather than duplicate efforts.	• Alliance for Tropical Forest Science (ATFS) • AndesFlux • ASCEND • Congo Basin Science Initiative (CBSI) • CongoFlux • FLUXNET Regional Networks (e.g., AmeriFlux, ICOS, AsiaFlux) • GEO-TREES • Guyafor • Guyaflux • One Forest Vision initiative (OFVi) • West Africa Flux Network
Civil Society Organizations	National and international nongovernmental organizations (NGOs) and nongovernmental research initiatives with a presence in the target countries	These partners facilitate knowledge consolidation on carbon, biodiversity, and social-ecological systems; translate research outputs into ongoing CSO-led campaigns and actions	Co-produce applications that leverage PANGEA scientific and technical advancements.	• Conservation International • CTrees • World Resources Institute (including Global Forest Watch & Land and Carbon Lab) • MapBiomas • Small Mammal Conservation Organization
Indigenous Peoples and Local Community Alliances and Organizations	Indigenous people-, local community-, and women- led organizations and alliances active in the target countries	These partners are connected with relevant communities, leaders, and partners in targeted countries	Co-design science questions and applications that directly affect IPLCs, women, and other groups; co-design ground and airborne field campaign activities in territories and local communities; provide training to empower IPLCs in data collection, research, and communication	• Global Alliance of Territorial Communities • Rights and Resources Initiative • CBI School for Indigenous and Local Knowledge (SILK) • Dynamique des Groupes des Peuples Autochtones (DGPA-DRC)

Community	Description	Relevance to PANGEA	Engagement Strategy & Goals	Example Partners
Donor Community	Classic donors (bilaterals, family foundations, philanthropic organizations) Specialized (geospatial) agencies from donor countries	These partners raise complementary funding that offers targeted support to extend PANGEA beyond NASA funding support.	Target investment in PANGEA applications and product development, support for international collaborators, joint workshops, and the development of IPLC data collection and management tools	• Bezos Earth Fund • Ford Foundation • Individual donors • Mellon Foundation • Moore Foundation • Norwegian Agency for Development Cooperation (Norad) • Norway's International Climate and Forest Initiative (NICFI)
Private Sector	Agribusinesses, extractive industries, energy companies, big data firms, investment institutions, and ecotourism companies	These partners are important action-takers and decision-makers with far-reaching impact.	Work closely with NASA and applications partners to determine the most appropriate strategies for engaging with the private sector on various applications output.	• Roundtable on Sustainable Palm Oil, Cocoa, Soy, Biomaterials • Unilever • Olam • Green Resources • CNaught • Carbon Equity • Carbon Credit Capital
Inter-governmental Agencies	Organizations composed of multiple sovereign governments that collaborate to address common issues, develop policies, and coordinate actions on a regional or global scale	These partners provide authoritative, science-based assessments that inform global policy decisions and guide international efforts to combat climate change and promote sustainable development and a resilient planet.	Stay up to date on assessment reports and activities to ensure PANGEA science and applications outputs can be effectively utilized.	• Committee on Earth Observation Satellites (CEOS) • Group on Earth Observations (GEO) • Intergovernmental Panel on Climate Change (IPCC) • Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) • International Union for Conservation of Nature (IUCN) • United Nations Framework Convention on Climate Change (UNFCCC)

* DOE NGEE-Tropics is entering Phase 3 and will be sunsetting as PANGEA begins, enabling important continuity on constraining model uncertainty and data-model integration efforts.

** USAID PEER is going to be replaced by a new program called SPARK.

C. Engagement during the Scoping Study

The PANGEA Scoping Campaign was a collaborative effort that engaged over 800 individuals from 396 institutions spanning more than 60 countries across 5 continents (**Table C-1**) through (1) international working groups, (2) short information-sharing events, (3) multiday consultative workshops, and (4) bilateral meetings with potential partners. The PANGEA scoping effort began in November 2023, with a kick-off webinar. Activities that followed in 2024 are described below.

International Working Groups

Over 200 people participated in at least one of more than 60 PANGEA Working Group Meeting sessions virtually hosted by Working Group Co-Leads. At the start of the scoping campaign, 7 different working groups solicited input from the scientific and broader community:

- Climate Feedbacks and Interactions: 158 engagements
- Biogeochemical Cycles and Carbon Dynamics: 155 engagements
- Ecosystem Structure, Function, and Biodiversity: 101 engagements
- Social-Ecological Systems: 91 engagements
- Modeling and Data Synthesis: 141 engagements
- Community Engagement and Research Applications: 110 engagements
- Feasibility: 79 engagements

Engagements are defined to record the unique attendance of a participant to a unique Working Group meeting. For example, three unique participants in the same meeting or one unique participant at three consecutive meetings both weigh equally as 3 engagements. Therefore, this definition captures a wide range of interactions with working group participants that better represents the combination of online and offline contributions to the development of Working Group themes and objectives.

The Community Engagement and Research Applications (CERA) working group 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 by "word of mouth." Approximately 100 individuals signed up for 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 multiday workshops in Cameroon, US, Brazil and Peru.

Information-Sharing Events

The PANGEA Leadership Team engaged with hundreds of people through twelve information-sharing events conducted on five continents. These events included 1- to 2-hour presentation and discussion sessions at international academic conferences, webinars, regional events, and special meetings organized by the PANGEA community.

Engaging Indigenous communities in the scoping process to discuss co-produced science, data sovereignty, interests in training, and important aspects of the process was an important part of the PANGEA scoping process. Since specific countries that will be the focus of PANGEA will not be determined until the development of the Concise Experiment Plan, early involvement focused on boundary organizations, alliances, and community leaders. A major organization that was involved in the scoping of PANGEA was the Global Alliance of Territorial Communities. Regular meetings were held with GATC leadership, including leaders of the Women's and Youth movements within the GATC. These meetings were always held with interpretation and documents and emails were shared in English, French, Spanish, Portuguese, and Brazilian. An in-person meeting was held at COP16 with several GATC members do further discuss PANGEA and identify appropriate next steps if PANGEA is selected. A follow up meeting will be held in January to debrief the year of scoping with GATC leadership. Meetings were also held with the Rights and Resources Initiative (RRI) whose work focuses on empowering and engaging Indigenous Peoples, Afro-descendent peoples, local communities, and the women in these communities. In addition, PANGEA held a Workshop with Indigenous Communities in Panama, which convened 12 participants and representatives of the Embera, Wounaan, and Guna territories at the Smithsonian Tropical Research Institute on April 26, 2024. The hybrid in-person and online meeting was virtually co-hosted by the PANGEA Leadership Team and attended by 10 additional Zoom participants from 7 countries. If PANGEA is selected, there will undoubtedly be more communities to engage with in the PANGEA landscapes. However, this work lays the foundation from which those partnerships can flourish.

List of information-sharing events:

- **In-person town halls, presentations, and symposia at conferences:**
  - American Geophysical Union (AGU) 2023 & 2024 (forthcoming) – San Francisco, CA, and Washington DC
  - Association for Tropical Biology and Conservation (ATBC) – Kigali, Rwanda, July 2024
  - Congo Basin Forest Partnership (CBFP) 20th Meeting of the Parties presentation – Kinshasa, Democratic Republic of Congo (June 2024)
  - Ecological Society of America (ESA) – Long Beach, CA
  - European Geophysical Union (EGU) – Vienna, Austria (April 2024)
  - Global Land Programme (GLP) (forthcoming Nov 5, 2024) – Oaxaca, Mexico

- International Union of Forest Research Organizations (IUFRO) – Stockholm, Sweden
- NASA Biological Diversity and Ecological Conservation meeting in Maryland, May 2024
- Smithsonian Tropical Research Institute, Barro Colorado Island 100th Anniversary Symposium (BCI 100) – Gamboa, Panama (June 2024)

- **Virtual town halls:**
  - PANGEA – town halls open to all
  - PANGEA – working group specific town halls
  - ESA online town hall (March 2024)
- **Smaller workshops:**
  - Africa women's virtual session to spotlight research led by women in Central Africa (April 2024)
  - Meeting with Indigenous Communities in Panama (April 2024)
  - SBG Collab meeting with indigenous and community partners (June 2024)
  - Black Mammologists Week with Black scientists (September 2024)
  - Regular meetings with Global Alliance of Territorial Communities (GATC) leadership (July-November 2024)
- **NASA Science Team meetings:**
  - ECOSTRESS
  - EMIT
  - GEDI
  - OCO
  - SBG
  - SMAP

Multiday Consultative Workshops

The PANGEA Leadership Team organized four, multiday 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. The workshop activities were well attended by 263 in-person participants from 30 countries at the regional consultations hosted in Cameroon (90), Washington DC (103), Panama (10), and Lima (60). When the equipment and agenda permitted, these interactive events were extended to a broader virtual audience with engagement from 362 additional virtual participants from 33 countries at the regional consultations in Cameroon (54), Washington DC (298), and Panama (10). All events except the workshop in Manaus, Brazil had interpretation services to accommodate non-English speakers.

The Cameroon Workshop held on February 21-22, 2024, at Hotel Mont Fébé drew participation from 90 participants across 16 countries attending the event co-hosted with CIFOR, IITA, and the local University of Yaoundé. Hybrid sessions were joined by 54 additional Zoom participants. The DC Workshop held on April 9-11, 2024, at the AGU HQ was attended by 103 participants from 16 countries. The fully hybrid workshop included dialogue and participation from 297 Zoom participants throughout the 3-day event. The Lima Workshop held on June 3-4, 2024, at the PUCP Cultural Center was attended by 60 participants from 8 countries. The Lima workshop was held in partnership with the Governors' Climate and Forests Task Force (GCF-TF) and was an important opportunity to have roughly equal workshop attendance by scientists and policy makers. Governors from across Peru, Colombia, Bolivia, Brazil, and Ecuador were present in the meeting, which provided invaluable insights into the potential for Earth Science to Action outcomes from PANGEA in the Amazon.

List of PANGEA multiday consultative 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 through participation in 3-day SERVIR workshop, Bangkok, Thailand, July, 2024

Bilateral Meetings with Potential PANGEA Partners

The PANGEA Leadership Team and CERA working group members conducted bilateral meetings with hundreds of potential PANGEA partners, including U.S. federal agencies, the European Space Agency, SERVIR, private companies, U.S. and international research institutes, conservation organizations, government ministries, and more. Organizations and institutions are listed in **Table C-1**. Many partners (n=58) have shared letters of support to confirm their interest in collaborating on the PANGEA program (if funded).

Table C-1. All organizations and institutions engaged in the PANGEA scoping process.
CSO: Civil Society Organization

#	Organization/Institution	Type
1	Aarhus University (Denmark)	University
2	ACCA: Amazon Conservation (Peru)	CSO
3	ADC: Association Action for Community Development (Cameroon)	CSO

#	Organization/Institution	Type
4	ADPC: Asian Disaster Preparedness Center	CSO
5	African Environmental Network	CSO
6	AGEOS: Agency for Space Studies and Observations (Gabon)	Government
7	AGU: American Geophysical Union	Society
8	Akamai University	University
9	Akdeniz University (Turkey)	University
10	Alliance Biodiversity - CIAT: Alliance of Bioversity International and the International Center for Tropical Agriculture (Italy)	CSO
11	AmIT: Amazon Institute of Technology (Brazil)	CSO
12	Anawakalmekak	K–12 School
13	ANI: Africa Nature Investor Foundation (Nigeria)	Donor
14	Arbimon/Rainforest Connection	CSO
15	ARES: Airborne Research Facility for the Earth System	University
16	ASU: Arizona State University	University
17	ATBC: Association for Tropical Biology and Conservation	Society
18	BAERI: Bay Area Environmental Research Institute	CSO
19	Bezos Earth Fund	Donor
20	BHI: Biodiversity Hub International	CSO
21	Black Mammalogists	CSO
22	Boston University	University
23	Caltech: California Institute of Technology	University
24	Calvin University	University
25	Cameroon Ministry of Environment	Government
26	CAPC-AC: Central African Climate Application and Forecasting Centre (African Union)	Multilateral
27	Carboneers (Netherlands)	Research
28	Carnegie Institution for Science	CSO
29	Cary Institute of Ecosystem Studies	CSO
30	CBCS: Congo Basin Conservation Society (Dem. Rep. of Congo)	CSO
31	CBD: Convention on Biological Diversity	Multilateral
32	CBFP: Congo Basin Forest Partnership	Multilateral
33	CBI: Congo Basin Institute	Multilateral
34	CBSI: Congo Basin Science Initiative	Multilateral
35	CEAS: Center for Sustainable Amazonia Studies	CSO
36	CEEAC: Economic Community of Central African States (African Union)	Multilateral
37	CENAREST: National Center for Scientific Research and Technology (Gabon)	Government
38	CEW: Cameroon Environmental Watch (Cameroon)	CSO
39	CGIAR: Consultative Group for International Agricultural Research	CSO
40	Chapman University	University
41	CI: Conservation International	CSO
42	CICERO: Centre for International Climate and Environmental Research Oslo (Norway)	CSO
43	CIFOR-ICRAF: Center for International Forestry Research and World Agroforestry	CSO

#	ORGANIZATION/INSTITUTION	TYPE
44	CIRAD: Agricultural Research Centre for International Development (France)	CSO
45	CIRES: Cooperative Institute for Research in Environmental Sciences	CSO
46	CIRMF: Centre International de Recherches Médicales de Franceville	CSO
47	Climate Clock DRC (Dem. Rep. of Congo)	CSO
48	Climate Focus	Private Industry
49	CMEC: Coordinated Model Evaluation Capabilities	CSO
50	CNPq: National Council for Scientific and Technological Development (Brazil)	Government
51	CoEB: Center of Excellence in Biodiversity and Natural resource management (Rwanda)	CSO
52	College of William & Mary	University
53	Columbia University	University
54	COMIFAC: Central African Forest Commission	Multilateral
55	Congolese Action For Nature (Dem. Rep. of Congo)	CSO
56	Cordon Grande Forest Ejido (Mexico)	CSO
57	Cornell University	University
58	CRDPI: Research Center on Productivity and Sustainability of Industrial Plantations (Rep. of Congo)	CSO
59	CSU: Colorado State University	University
60	CTrees	CSO
61	CUNY: City University of New York	University
62	Denis Sassou Nguesso University (Rep. of Congo)	University
63	DOE: U.S. Department of Energy	Government
64	Duke University	University
65	East Carolina University	University
66	Eco-Consult	Private Industry
67	EcoAgriculture	CSO
68	Ecobed Biotech Brand	Private Industry
69	EDA: Enable the Disable Action	CSO
70	EEZA: Arid Zones Experimental Station (Spain)	CSO
71	EGU: European Geophysical Union	Society
72	Embrapa: Brazilian Agricultural Research Corporation (Brazil)	Government
73	Emory University	University
74	ENEF-Gabon: National School Water And Forests Of Gabon (Gabon)	Government
75	ERAIFT: Regional Post-Graduate Training School on Integrated Management of Tropical Forests and Lands (Dem. Rep. of Congo)	University
76	ESA: Ecological Society of America	Society
77	ESA: European Space Agency	Government
78	ESRI: Environmental Systems Research Institute, Inc.	Private Industry
79	ETH Zurich: Federal Institute of Technology Zurich (Switzerland)	University
80	FAP: Peruvian Air Force (Peru)	Government
81	FAPEAM: Amazonas Research Foundation (Brazil)	Government
82	FAPESP: São Paulo Research Foundation (Brazil)	Government

#	Organization/Institution	Type
83	FAPESPA: Pará Research Foundation (Brazil)	Government
84	First Technical University, Ibadan (Nigeria)	University
85	Florida Atlantic University	University
86	Florida State University	University
87	Fondation Eboko	CSO
88	ForestGEO	CSO
89	ForestPlots.net	CSO
90	FRMi: Forest Resources Management, Inc.	Private Industry
91	FSC: Forest Stewardship Council	CSO
92	FUPRO: National organization of cashew producers (Benin)	CSO
93	GADD: Support Group for Sustainable Development (Cameroon)	CSO
94	GATC: Global Alliance of Territorial Communities	Multilateral
95	GCF-TF: Governors' Climate and Forests Task Force	Multilateral
96	GEO-TREES	Multilateral
97	GEOGLAM: Group on Earth Observations Global Agricultural Monitoring Initiative	CSO
98	Geoindigena	CSO
99	George Mason University	University
100	Georgia Institute of Technology	University
101	GFZ-Potsdam: German Research Centre for Geosciences	University
102	Ghent University (Belgium)	University
103	GLP: Global Land Programme	Society
104	Google	Private Industry
105	Guna	CSO
106	Harvard University	University
107	HMEI: Princeton High Meadows Environmental Institute	University
108	Howard University	University
109	IBAY-SUP: Higher Institute of Environmental Sciences	University
110	ICOS: Integrated Carbon Observation System	Multilateral
111	IFA-Yangambi: L'Institut Facultaire des Sciences Agronomique de Yangambi	CSO
112	IIAP: Research Institute of the Peruvian Amazon (Peru)	CSO
113	IITA: International Institute for Tropical Agriculture	CSO
114	ILAMB: International Land Model Benchmarking	CSO
115	INDEFOR-AP: Instituto Nacional de Desarrollo Forestal y Manejo del Sistema de Áreas Protegidas, Guinea Equatorial	Government
116	India National Centre for Biological Sciences	Government
117	INPA: National Institute of Amazonian Research (Brazil)	Government
118	INPE: National Institute for Space Research (Brazil)	Government
119	INRAE: National Research Institute for Agriculture, Food and Environment (France)	Government
120	INRS: National Institute of Scientific Research (Canada)	University
121	Instituto Araguaia	CSO
122	Instituto Humboldt: Alexander von Humboldt Biological Resources Research Institute	CSO

#	Organization/Institution	Type
123	IPAM: Amazon Environmental Research Institute (Brazil)	CSO
124	IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services	Multilateral
125	IPCC: Intergovernmental Pannel of Climate Change	Multilateral
126	IRAD: Agricultural Research Institute for Development (Cameroon)	Government
127	IRCCB: International Reference Centre Chantal Biya (Cameroon)	CSO
128	IRD: Research Institute for Development (France)	Government
129	IRIC: Institut des Relations Internationales du Cameroon	CSO
130	ISDR: Higher Institute of Rural Development of M'Baïki (Central African Republic)	CSO
131	ISEA-Bengamisa: Higher Institute of Agronomic Studies of Bengamisa (Dem. Rep. of Congo)	CSO
132	ISP-Gemena: Gemena Higher Institute of Education (Dem. Rep. of Congo)	CSO
133	ISTA: Higher Institute of Applied Techniques (Dem. Rep. of Congo)	CSO
134	IUCN: International Union for the Conservation of Nature	Multilateral
135	James Cook University (Australia)	University
136	Karlsruhe Institute of Technology (Germany)	University
137	KU Leuven: Catholic University of Leuven (Belgium)	University
138	Kwara State University (Nigeria)	University
139	Labosystem s.r.l. (Italy)	Private Industry
140	LANL: Los Alamos National Laboratory	Government
141	LBNL: Lawrence Berkeley National Laboratory	Government
142	LCRP: Liberia Chimpanzee Rescue and Protection (Liberia)	CSO
143	Leiden University (Netherlands)	University
144	Leipzig University (Germany)	University
145	Lund University (Sweden)	University
146	Makererere University (Uganda)	University
147	Mancomunidata Regional Amazonica	government
148	MapBiomas (Brazil)	CSO
149	Marien Ngouabi University (Rep. of Congo)	University
150	Marymount University	University
151	Max Planck Institute (Germany)	CSO
152	McGill University (Canada)	University
153	Mendel University	University
154	Michigan State University	University
155	MINRESI: Cameroon Ministry of Scientific Research and Innovation	Government
156	MIT: Massachusetts Institute of Technology	University
157	Mora Institute (Mexico)	CSO
158	Morgan State University	University
159	MoveBank	Multilateral
160	Murray State University	University
161	Muteesa I Royal University (Uganda)	University
162	NASA Ames Research Center	Government

#	Organization/Institution	Type
163	NASA Earth Action	Government
164	NASA ECOSTRESS Science Team	Multilateral
165	NASA GISS: Goddard Institute for Space Studies	Government
166	NASA Global Ecosystem Dynamics Investigation (GEDI) Science Team	Multilateral
167	NASA GSFC: Goddard Space Flight Center	Government
168	NASA Harvest	Multilateral
169	NASA Indigenous Peoples Initiative	Government
170	NASA JPL: Jet Propulsion Laboratory, California Institute of Technology	University
171	NASA LRC: Langley Research Center	Government
172	NASA MSFC: Marshall Space Flight Center	Government
173	NASA Orbiting Carbon Observatory (OCO) Science Team	Multilateral
174	NASA Soil Moisture Active Passive (SMAP) Science Team	Multilateral
175	NASA Surface Biology-Geology (SBG) Science Team	Multilateral
176	National Agency for National Parks (Gabon)	Government
177	National Agrarian University (Peru)	University
178	National Foundation of Indigenous Peoples (FUNAI)	CSO
179	National Forestry School (Cameroon)	Government
180	National Geographic Society	CSO
181	National Taiwan University (Taiwan)	University
182	National University of Equatorial Guinea (Equatorial Guinea)	University
183	National University of Saint Anthony the Abbot in Cuzco (Peru)	University
184	National University of Singapore (Singapore)	University
185	National University of Ucayali (Peru)	University
186	Nature Tech Collective	CSO
187	NAU: Northern Arizona University	University
188	NCBS: National Centre for Biological Sciences (India)	Government
189	NCSU: North Carolina State University	University
190	NEON: U.S. National Ecological Observatory Network	Government
191	New Brunswick Museum (Canada)	Government
192	New York University	University
193	NICFI: Norway's International Climate and Forest Initiative	Government
194	NIOO-KNAW: Netherlands Institute of Ecology (Netherlands)	CSO
195	NOAA Global Monitoring Laboratory	Government
196	NSF: National Science Foundation	Government
197	OceanExpert	CSO
198	Official University of Bukavu (Rep. of Congo)	University
199	Ohio State University	University
200	Okapi Faunal Reserve (Dem. Rep. of Congo)	Government
201	Oklahoma State University	University
202	Omar Bongo University (Gabon)	University
203	ONACC: National Observatory on Climate Change (Cameroon)	Government

#	Organization/Institution	Type
204	Oregon State University	University
205	ORNL: Oak Ridge National Laboratory	Government
206	OSFAC: Satellite Observatory of Central African Forests	CSO
207	Pakwach District Local Government (Uganda)	Government
208	PAUWES: Pan African University Institute of Water and Energy Sciences	University
209	Penn State University	University
210	Piriati Emberá	CSO
211	Planet	Private Industry
212	Planet One–Mboa Hub	CSO
213	PNNL: Pacific Northwest National Laboratory	Government
214	Proforest (United Kingdom)	CSO
215	PUCP: Pontifical Catholic University of Peru (Peru)	University
216	Pueblo of Jemez	CSO
217	R2FAC: Réseau de Recherche sur les Forêts d'Afrique Centrale	Multilateral
218	Rainforest Connection	CSO
219	Rainbow Environment Consult (Cameroon)	Private Industry
220	Rainforest Foundation Norway	CSO
221	RAPEE: African Network for the Promotion of Environmental Education (Cameroon)	Government
222	Regional Government of Amazonas (Peru)	Government
223	Regional Government of Caqueta (Peru)	Government
224	Regional Government of Huanuco (Peru)	Government
225	Regional Government of Loreto (Peru)	Government
226	Regional Government of Madre de Dios (Peru)	Government
227	Regional Government of Piura (Peru)	Government
228	Regional Government of San Martin (Peru)	Government
229	Regional Government of Ucayali (Peru)	Government
230	REPALEAC: Network of Indigenous and Local Populations for the Sustainable Management of Forest Ecosystems in Central Africa	CSO
231	RIFFEAC: Réseau des Institutions de Formation Forestière et Environnementale de l'Afrique Centrale	Government
232	RIOFAC: Projet Renforcement et Institutionnalisation de l'OFAC	CSO
233	RRI: Rights and Resources Initiative	Multilateral
234	Rutgers University	University
235	San Diego State University	University
236	San Francisco State University	University
237	Satelligence	Private Industry
238	Schmidt Sciences	Donor
239	Science Systems and Applications Inc.	Private Industry
240	SERFOR: Organismo de Supervisión de los Recursos Forestales y de Fauna Silvestre, Peru	Government
241	SERNANP: Servicio Nacional de Áreas Naturales Protegidas por el Estado, Peru	Government
242	SERVIR	Multilateral

#	Organization/Institution	Type
243	SGN: Senckenberg – Leibniz Institution for Biodiversity and Earth System Research	CSO
244	SIG: Spatial Informatics Group	Private Industry
245	SMACON: Small Mammal Conservation Organization	CSO
246	Smithsonian Institution	Government
247	South Dakota State University	University
248	Southwest Research Institute	CSO
249	Spark Climate Solutions	Private Industry
250	SPCB: Science Panel for the Congo Basin	CSO
251	SPUN: Society for the Protection of Underground Networks	CSO
252	STA: Sustainable Tropical Actions	CSO
253	Stanford University	University
254	STRI: Smithsonian Tropical Research Institute	Government
255	Stroud Water Research Center	CSO
256	SURUDEV: United Nations Sustainable Run for Development	Multilateral
257	Swedish University of Agricultural Sciences, Uppsala	University
258	Sylvera	Private Industry
259	TERRA: Teaching and Research Centre (Belgium)	CSO
260	Texas A&M University	University
261	The David and Lucile Packard Foundation	Donor
262	The Gordon & Betty Moore Foundation	Donor
263	The National University of Colombia (Colombia)	University
264	TINTA: The INvisible ThreAd	CSO
265	TotalEnergies (Uganda)	Private Industry
266	Tulane University	University
267	UAB: Autonomous University of Barcelona (Spain)	University
268	UAC: University of Abomey-Calavi (Benin)	University
269	UB: University of Burundi (Burundi)	University
270	UCC: Catholic University of Congo	University
271	UCL: University College London	University
272	UCLouvain: Catholic University of Louvain (Belgium)	University
273	UEA: Amazonas State University (Brazil)	University
274	UFC: Federal University of Ceará (Brazil)	University
275	UFRJ: Federal university of Rio de Janeiro (Brazil)	University
276	UFSC: Federal University of Santa Catarina (Brazil)	University
277	UFSM: Federal University of Santa Maria (Brazil)	University
278	UFVJM: Federal University of Vales do Jequitinhonha e Mucuri (Brazil)	University
279	UK Center of Ecology & Hydrology (United Kingdom)	CSO
280	UK FCDO: Foreign, Commonwealth & Development Office	Government
281	UK NERC: Natural Environment Research Council	Government
282	UL: University of Lorraine (France)	University
283	ULB: Free University of Brussels (Belgium)	University

#	ORGANIZATION/INSTITUTION	TYPE
284	ULiège: University of Liège (Belgium)	University
285	UMR EcoFoG: Ecology of the Forests of French Guiana (France)	Multilateral
286	UN FAO: United Nations Food and Agriculture Organization	Multilateral
287	UN SDSN: United Nations Sustainable Development Solutions Network	Multilateral
288	UN-SDSN: United Nations Sustainable Development Solutions Network	Multilateral
289	UNA: National University of Agriculture (Benin)	University
290	UNAM: National Autonomous University of Mexico (Mexico)	University
291	UNAMAD: Amazon National University of Madre de Dios (Peru)	University
292	UNAP: National University of the Peruvian Amazonian (Peru)	University
293	UnB: University of Brasília (Brazil)	University
294	UNEP: United Nations Environment Programme	Multilateral
295	UNESCO: United Nations Educational, Scientific and Cultural Organization	Multilateral
296	UNGE: National University of Equatorial Guinea (Equatorial Guinea)	University
297	UNIKIN: University of Kinshasa (Democratic Rep. of Congo)	University
298	UNIKIS: University of Kisangani (Democratic Rep. of Congo)	University
299	Université de Versailles Saint-Quentin-en-Yvelines Laboratory for Climate and Environmental Sciences	University
300	University at Buffalo	University
301	University of Aberdeen (United Kingdom)	University
302	University of Alabama Huntsville	University
303	University of Alberta	University
304	University of Arizona	University
305	University of Arkansas	University
306	University of Bamenda, Cameroon	University
307	University of Bangui	University
308	University of Bern	University
309	University of Bordeaux	University
310	University of Buea, Cameroon	University
311	University of California, Berkeley	University
312	University of California, Davis	University
313	University of California, Irvine	University
314	University of California, Los Angeles	University
315	University of California, Merced	University
316	University of California, Santa Barbara	University
317	University of California, Santa Cruz	University
318	University of Campinas	University
319	University of Cape Town	University
320	University of Charleston	University
321	University of Colorado Boulder	University
322	University of Copenhagen	University
323	University of Delaware	University

#	Organization/Institution	Type
324	University of Delhi (India)	University
325	University of Douala (Cameroon)	University
326	University of Dschang (Cameroon)	University
327	University of Edinburgh (United Kingdom)	University
328	University of Energy and Natural Resources (Ghana)	University
329	University of Exeter (United Kingdom)	University
330	University of Florida	University
331	University of Georgia	University
332	University of Hong Kong (China)	University
333	University of Ibadan (Nigeria)	University
334	University of Idaho	University
335	University of Illinois Urbana-Champaign	University
336	University of Jambi (Indonesia)	University
337	University of Kindu (Rep. of Congo)	University
338	University of Leeds (United Kingdom)	University
339	University of Maroua (Cameroon)	University
340	University of Maryland	University
341	University of Miami	University
342	University of Michigan	University
343	University of Minnesota	University
344	University of Montana	University
345	University of New Hampshire	University
346	University of New Orleans	University
347	University of Ngaoundéré (Cameroon)	University
348	University of North Carolina at Chapel Hill	University
349	University of Notre Dame	University
350	University of Oklahoma	University
351	University of Oxford	University
352	University of Pretoria (South Africa)	University
353	University of Puerto Rico - Rio Piedras	University
354	University of Rwanda (Rwanda)	University
355	University of Science and Technology of Masuku (Gabon)	University
356	University of Southern California	University
357	University of the Rosary (Colombia)	University
358	University of Tokyo (Japan)	University
359	University of Tolima (Colombia)	University
360	University of Utah	University
361	University of Vermont	University
362	University of Victoria (Canada)	University
363	University of Virginia	University
364	University of Washington	University

#	Organization/Institution	Type
365	University of Wisconsin	University
366	University of Yaoundé I (Cameroon)	University
367	UNP: National University of Piura (Peru)	University
368	UNTRM: National University Toribio Rodríguez de Mendoza (Peru)	University
369	US Embassy Cameroon	Government
370	US Greenhouse Gas (GHG) Center	Government
371	US Naval Research Laboratory	Government
372	US State Department	Government
373	USAID: US Agency for International Development	Government
374	USDA: US Department of Agriculture	Government
375	USFS-IP: US Forest Service International Program	Government
376	USGS: US Geological Survey	Government
377	USP: University of São Paulo (Brazil)	University
378	USTM: Institut National Supérieur d'Agronomie et de Biotechnologie	CSO
379	UTEC: University of Engineering and Technology (Peru)	University
380	Utrecht University (Netherlands)	University
381	UTRGV: University of Texas Rio Grande Valley	University
382	UZH: University of Zurich (Switzerland)	University
383	Wageningen University (Netherlands)	University
384	Wake Forest University	University
385	Washington University	University
386	WCS: Wildlife Conservation Society	CSO
387	West Virginia University	University
388	Wilkes University	University
389	Wits: University of The Witwatersrand, Johannesburg (South Africa)	University
390	Woodwell Climate Research Center	CSO
391	World Bank	Multilateral
392	Wounaan	CSO
393	WRI: World Resources Institute	CSO
394	WWF: World Wild Fund for Nature	CSO
395	Wyss Academy for Nature	University
396	Yale University	University

D. Planned and Ongoing Research and Monitoring Activities

Table D-1. Planned and ongoing research and monitoring projects and programs in the tropics that could contribute to PANGEA.

NOTE: This is not a comprehensive list. A: Assessment project or program. E: Educational. L: Longer-term, continuing program or project likely to continue during PANGEA. M: Monitoring project or program. R: Research project or program. T: Tentative, not yet confirmed.

PROJECT/PROGRAM	PRIMARY SPONSOR(S)	COUNTRY/COUNTRIES/ REGION	GEOGRAPHIC SCOPE/CONTINENT	PROJECT/ PROGRAM TYPE	YEARS
1000 LANDSCAPES FOR 1 BILLION PEOPLE	Philanthropic	Colombia, Ecuador, Fiji, Guyana, Kenya, Indonesia, Mexico, Namibia, Nicaragua, Peru, South Africa	Global	L	2019–Ongoing
2NDFOR	Varied	25 countries	Pantropical	M,L	1990–Ongoing
AFR100: AFRICAN FOREST LANDSCAPE RESTORATION INITIATIVE	African Union Development Agency (AUDA)–NEPAD	Africa	Africa	L	2015-Ongoing
AFRISAR I	ESA, NASA	Gabon	Africa	R	2016
AFRISAR II	ESA, NASA	Gabon, Ghana, Cameroon, DRC, Rep. of Congo, Sao Tome and Principe	Africa	R	2023–2024
ALIVE (ADVANCED BASELINE IMAGER LIVE IMAGING OF VEGETATED ECOSYSTEMS)	NSF	Latin America	Americas	R	2024-Ongoing
AMAZON ESA-INPE CAMPAIGN	ESA, INPE	Brazil	Americas	R	2024–2026
AMAZON VS CONGO: UNDERSTANDING THE INTERCONTINENTAL DIFFERENCES OF TROPICAL RAINFOREST RESPONSES TO CLIMATE VARIABILITY	US Department of Energy (DOE)	Amazon, Congo	Africa, Americas	R	2024–2027
AMERIFLUX	US DOE	North and South America	Americas	M,L	1996–Ongoing
AMIT (AMAZON INSTITUTE OF TECHNOLOGY)	Moore Foundation, GCF, USAID	Amazon	Americas	L	2020–Ongoing

PROJECT/PROGRAM	PRIMARY SPONSOR(S)	COUNTRY/COUNTRIES/ REGION	GEOGRAPHIC SCOPE/CONTINENT	PROJECT/ PROGRAM TYPE	YEARS
AMMI (AFRICAN MASTERS OF MACHINE INTELLIGENCE)	Facebook, Google	Cameroon, Ghana Rwanda, Senegal, South Africa	Africa	L	2003–Ongoing
ANDESFLUX	National Oceanic and Atmospheric Administration (NOAA)	Amazon	Americas	L	2022–Ongoing
ANDEX	World Climate Research Program	Peru	Americas	R	2018–2025
ASCEND (ADVANCING SPECTRAL BIOLOGY IN CHANGING ENVIRONMENTS TO UNDERSTAND DIVERSITY)	NASA, NSF	Global	Global	R	2020–2025
ASIA-AQ (AIRBORNE AND SATELLITE INVESTIGATION OF ASIAN AIR QUALITY)	NASA	Philippines, South Korea, Taiwan, Thailand	Asia	R	2024
ASIAFLUX	Varied	Asia	Asia	L	1999–Ongoing
ATFS (ALLIANCE FOR TROPICAL FOREST SCIENCE)	NSF	Pantropical	Pantropical	R, L	2021–2025
ATTO (AMAZON TALL TOWER OBSERVATORY)	Max Planck, German Government, etc.	Amazon	Americas	L	2009–Ongoing
AVUELO (AIRBORNE VALIDATION UNIFIED EXPERIMENT—LAND TO OCEAN)	NASA	Panama	Americas	R	2025
BEYOND COUNTING TREES	WRI, Planet		Pantropical	R	2024–Ongoing
BIODIVERSITY—A NEW SPACE MISSION FOR MONITORING ECOSYSTEMS AT A FINE SCALE	ESA	Global	Global	T, L	TBD
BIOSCAPE (BIODIVERSITY SURVEY OF THE CAPE)	NASA, South African Government, UNESCO, etc.	South Africa	Africa	R	2023–Ongoing
CACAO DIVERSITY	Peru Ministerio de Agricultura y Riego, USDA, Cocao Seguro, USAID	Peru, Ecuador, Nicaragua, Honduras, El Salvador, Guatemala	Americas	L	2021–Ongoing

Project/Program	Primary Sponsor(s)	Country/Countries/ Region	Geographic Scope/Continent	Project/ Program Type	Years
CALeDNA: University of California Conservation Genomics Consortium Environmental DNA Program	UCSC Genomics Institute, UC Office of the President, HHMI, Global Genome Biodiversity Network	California	Americas	R	2017–Ongoing
Carbon-I	NASA	Global	Global	T	TBD
CARPE (Central African Regional Program for the Environment)	USAID		Africa	L	1995–Ongoing
Central African Plot Network	IRD	Cameroon, Gabon and DRC	Africa	R, L	2010–Ongoing
CliMA (Climate Modeling Alliance)	Schmidt Sciences	USA	Global	R	2018–Ongoing
CoForFunc (Congo basin forest functional composition)	BiodivERsA, the European Commission	Cameroon, Republic of Congo, Democratic Republic of Congo	Africa	R	2023–Ongoing
Colombia BON (Biodiversity Observation Network)	GIZ	Colombia	Americas	M,L	2015–Ongoing
Congo Basin Institute	NASA, NSF, Philanthropic	Cameroon, Democratic Republic of Congo, Gabon	Africa	R, L	2015–Ongoing
Congo Basin Institute for the New Climate Economy	USA, France, Germany, Bezos Earth Fund, etc.	Cameroon	Africa	L	2023–Ongoing
Congo Basin Science Initiative	Philanthropic	Democratic Republic of Congo, Gabon, Cameroon and Republic of the Congo	Africa	L	2024–Ongoing
CongoFlux	European Union	Democratic Republic of the Congo	Africa	L	2021–Ongoing
CongoPeat	UKRI NERC	Democratic Republic of Congo, Republic of the Congo	Africa	R	2018–Ongoing
DRC national lidar sampling	WWF	Democratic Republic of Congo, Gabon, Cameroon and Republic of the Congo	Africa	R	2012
Earth System Digital Twin for Central Africa Carbon and Biodiversity Corridors	NASA	Central Africa	Africa	R	2025–2027

Project/Program	Primary Sponsor(s)	Country/Countries/ Region	Geographic Scope/Continent	Project/ Program Type	Years
ED2: Ecosystem Demography Modeling Community	Varied	Global	Global	R	2001–Ongoing
EDGE	NASA	Global	Global	T	TBD
Elephant Listening Project	Cornell	Central and East Africa	Africa	L	1999–Ongoing
EU Horizon Funding (e.g. CONCERTO)	EU	Global	Global	R	2021–2027
FLUXNET	NASA, DOE, NSF	Global	Pantropical	R, L	1997–Ongoing
ForestGEO	Smithsonian, Varied	Global	Pantropical	R, L	1980–Ongoing
ForestPlots.net	ERC, NERC, Philanthropic	Pantropical	Pantropical	R, L	2009–Ongoing
GCF-TF (Governors' Climate & Forests Task Force)	Philanthropic	Bolivia, Brazil, Colombia, Cote d'Ivoire, Ecuador, Indonesia, Mexico, Nigeria, Peru, Spain, U.S.	Pantropical	L	2008–Ongoing
GATC: Global Alliance of Territorial Communities Women's Movement drone training & monitoring	Philanthropic	Pantropical	Pantropical	R, L	2014–Ongoing
GEDI airborne campaign–SE Asia	NASA	SE Asia	Asia	R	2025
GEM	OTB	Pantropical	Pantropical	R, L	2013–Ongoing
GEO-TREES	Philanthropic	Global	Pantropical	R, L	2024
GeoNEX	NASA, NOAA	Global	Global	M, R	2019–Ongoing
GFW: Global Forest Watch	World Resources Institute	Pantropical	Pantropical	L	2014–Ongoing
Gigante–pantropical large tree mortality study	NSF	Brazil, Cameroon, Malaysia, Panama	Pantropical	R	2023–Ongoing

Project/Program	Primary Sponsor(s)	Country/Countries/ Region	Geographic Scope/Continent	Project/ Program Type	Years
GLAD: Global Land Analysis and Discovery	NASA, Google, USDA, USGS	Global	Global	R, L	2013–Ongoing
Global Ecosystem Atlas	Group on Earth Observations (GEO)	Global	Global	L	2024–Ongoing
GLOBE: Global Learning and Observations to Benefit the Environment	NASA, NSF, NOAA, US Dept. of State	Global	Global	L	1994–Ongoing
GOFC-GOLD (Global Observations of Forest Cover and Land-use Dynamics)	NASA, ESA	Global	Global	L	1997–Ongoing
GRUAN	World Climate Research Program (RCRP), UNFCCC	Africa, Americas	Africa, Americas	L	2008–Ongoing
Guyaflux	INRAE	France (French Guiana)	Americas	L	2003–Ongoing
Guyafor	CIRAD, ONF, CNRS	France (French Guiana)	Americas	L	2000–Ongoing
KADI	European Union	Africa	Africa	R	2023–Ongoing
Land & Carbon Lab	World Resources Institute, Philanthropic	Pantropical	Pantropical	M	2021–Ongoing
Latin American Sustainability Initiative / PERU HUB	USAID	Peru	Americas	L	2019–Ongoing
LBA (Phases 1, 2, 3)	MCTI Brazil, NASA	Amazon	Americas	L	1998–Ongoing
MapBiomas	Philanthropic	Amazon, Indonesia	Americas, Asia, planned expansion to Africa	R, L	2017–Ongoing
NASA Harvest	NASA	Global	Global	L	2017–Ongoing
NGEE-Tropics	DOE	USA	Pantropical	R	2015–2028

Project/Program	Primary Sponsor(s)	Country/Countries/ Region	Geographic Scope/Continent	Project/ Program Type	Years
NICFI Planet Mosaics	NICFI	Pantropical	Pantropical	R	2020–2025
OFVi (One Forest Vision Initiative)	French Ministry of Higher Education and Research (MESR), French Ministry for Europe and Foreign Affairs (MEAE)	Democratic Republic of Congo, Gabon, Republic of Congo	Africa	R, L	2023–Ongoing
PEcAn	NSF, NASA, DOE	Global	Global	R, L	2011–Ongoing
Planet Tanager	Planet	Global	Global	R, L	2024–Ongoing
PPG-CLIAMB Program	UEA, INPA	Brazil	Americas	R, L	2009-Ongoing
Project Centinela	Planet	Bolivia, Brazil, Costa Rica, Democratic Republic of Congo, Indonesia	Pantropical	R	2024–Ongoing
R2FAC (Central African Forest Research Network)	Multi-Institutional	Cameroon, Central African Republic, Gabon, Republic of Congo, Democratic Republic of Congo, Belgium, France	Africa	L	2012–Ongoing
RECCAP2	European Space Agency, the International Carbon Coordination Project, EU-project	Global	Global	R, M	2017–2023
RESSAC	European Union	Angola, Burundi, Cameroon, Central African Republic, Chad, Equatorial Guinea, Democratic Republic of Congo, Gabon, Republic of Congo, Rwanda, Sao Tome & Principe	Africa	L	2024–Ongoing
RUBISCO Science Focus Area	DOE	Global	Pantropical	L	2011–Ongoing

Project/Program	Primary Sponsor(s)	Country/Countries/ Region	Geographic Scope/Continent	Project/ Program Type	Years
Rwanda Tree	Swedish Research Council	Rwanda	Africa	R, L	2021–Ongoing
SARI (South/Southeast Asia Research Initiative)	NASA LCLUC	South and Southeast Asia	Asia	R, L	2013–Ongoing
Science Panel for the Amazon	UN SDSN	Colombia, Bolivia, Ecuador, Peru, Suriname, Guyana, French Guiana, Brazil, and Venezuela	Americas	L	2020–Ongoing
Science Panel for the Congo	UN SDSN	Cameroon, Central African Republic, Gabon, Democratic Republic of the Congo, Republic of Congo, Equatorial Guinea	Africa	L	2023–Ongoing
Se.plan	FAO	Pantropical	Pantropical	M, L	2016-Ongoing
SELPER: Latin American Society for Remote Sensing and Space Information Systems	Varied	Latin America	Americas	L	1980-Ongoing
SERVIR Hub activities	NASA, USAID	Amazonia, Central America, Eastern and Southern Africa, Hindu Kush Himalaya, Southeast Asia, West Africa	Africa, Americas, Asia	L	2004–Ongoing
SILK (School for Indigenous and Local Knowledge)	Congo Basin Institute	Cameroon	Africa	R, L	2018–Ongoing
SilvaCarbon	USGS	Pantropical	Pantropical	L	2011–Ongoing
SMAP cal/val in Southeast Asia	NASA	Malaysia	Asia	R	2024–Ongoing
Sustainable Landscapes Brazil	USFS, USAID, DOS, Embrapa	Brazil, Peru	Americas	R	2008–2023
SWAMP (The Sustainable Wetlands Adaptation and Mitigation Program)	USAID, NICFI, Norad, IKI, Philanthropic	Asia-Pacific, Africa, Latin America and the Caribbean	Pantropical	R, L	2008–Ongoing

Project/Program	Primary Sponsor(s)	Country/Countries/ Region	Geographic Scope/Continent	Project/ Program Type	Years
Tallo (A global tree allometry and crown architecture database)	UKRI NERC	Global	Global	L	2022–Ongoing
TERN (Australia Terrestrial Ecosystem Research Network)	Australian Government	Australia	Australia	R, L	2009–Ongoing
TerraBio	USAID, Aliance of Biodiversity International/CIAT, private sector	Amazon	Americas	M	2023–2034
Terra-i	Aliance Biodiversity & CIAT, the Nature Conservancy	Latin America	Americas	M	2023–Ongoing
TmFO	Cirad, CGIAR, FTA, ESA, French Government	Pantropical	Pantropical	L	2017–Ongoing
Tropical Fluxnet-CH_4	Moore Foundation, NSF	Amazon, SE Asia, Botswana	Africa, Americas, Asia	R	2021–Ongoing
West Africa Flux Network	AMMA-CATCH Benin, FairCarboN	Benin	Africa	R, L	1997–Ongoing

E. Detailed PANGEA Measurements Table

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

Variable(s)	Science Questions	Ground Measurements	Observing Technologies	Earth Observation Assets	
				Satellite (Planned/Proposed)	Airborne (Drone/Aircraft)
GPP	Q1, Q2, Q4–Q8, Q10, Q11, Q13-Q15, Q17, Q18, Q20, Q22, Q26	Flux towers, leaf-level spectra	Infrared Spectroscopy	OCO-2/3, TROPOMI, GOES-R ABI, AHI, MTG-I, NASA GHG ESE*, Sentinel 5P/5*, FLEX*, CO2M*, GOSAT-2, GOSAT-GW*	NASA AVIRIS-NG/3 + HyTES, MASTER
ET	Q1, Q2, Q4–Q8, Q10, Q11, Q13-Q15, Q17, Q18, Q20, Q22, Q24-Q26	Flux towers	Thermal	Landsat, ECOSTRESS, SBG*, CHIME*, TRISHNA*, LSTM*, VIIRS, Sentinel-3, Commercial*, GEO weather satellites	NASA HyTES, MASTER
Ecosystem Respiration	Q1, Q2, Q4–Q8, Q10, Q13, Q15, Q17, Q18, Q20, Q22, Q26	Flux towers	Infrared Spectroscopy	GOES-R ABI, AHI, MTG-I	NASA AVIRIS-NG/3 + HyTES, MASTER
CO_2 & CH_4 Fluxes	Q1, Q2, Q4–Q8, Q10, Q11, Q13, Q14, Q18, Q20, Q22, Q26	Flux towers, chamber measurements	Hyperspectral	EMIT, MethaneSat, SBG*, Carbon-i*, CarbonMapper*	NASA AVIRIS-NG/3, UZH ARES, NEON AOP, GAO
			Airborne Eddy Covariance (AEC)		NASA CARAFE

Variable(s)	Science Questions	Ground Measurements	Observing Technologies	Earth Observation Assets: Satellite (Planned/Proposed)	Earth Observation Assets: Airborne (Drone/Aircraft)
Column $CO_2/CH_4/CO$	Q1, Q2, Q4–Q8, Q10, Q11, Q13, Q14, Q18, Q20, Q22, Q26	TCCON, COCCON, EM27/SUN Spectrometers	Infrared Spectroscopy	OCO-2/3, NASA GHG ESE*, Sentinel-5P/5*, FLEX*, CO2M*, GOSAT-2, GOSAT-GW*	NASA CFIS (SIF), DLR CoMet (CO_2/CH_4)
Aboveground Biomass	Q1, Q2, Q4–Q8, Q10, Q11, Q13, Q15, Q18, Q20, Q22	Forest inventory plot data, terrestrial laser scanning	Lidar	GEDI, ICESat-2, MOLI*, EDGE*	NASA LVIS, small-footprint lidar (drone and aircraft)
			Radar	Sentinel-1, NISAR*, BIOMASS*	NASA UAVSAR
Tree Mortality	Q9, Q11–Q13, Q15, Q17-Q22, Q25, Q27	Repeat census forest inventory plot data	Lidar, Radar, Multispectral	Landsat, Sentinel-1/2, Planet, GEDI, NISAR*, BIOMASS*, EDGE*	Repeat drone RGB or lidar
Canopy Height **Vertical Height Heterogeneity** **Canopy Gap Dynamics**	Q5-Q7, Q10–Q13, Q15, Q17-Q22, Q27	Terrestrial laser scanning	Lidar	GEDI, ICESat-2, MOLI*, EDGE*	NASA LVIS, small-footprint lidar (drone and aircraft)
			Radar	NISAR*, Sentinel-1, BIOMASS*	NASA UAVSAR
Spectral Diversity	Q5, Q10–Q12, Q15, Q18, Q21, Q27	Leaf-level spectra	Hyperspectral	EMIT, PACE, PRISMA, EnMAP, Planet's Tanager, SBG*, CHIME*, FLEX*	NASA AVIRIS-NG/3, UZH ARES, GAO
Functional Diversity	Q5-Q7, Q10–Q13, Q15, Q18, Q21, Q22, Q27	Plant taxonomic diversity; plant traits; IEK, TEK, LEK			
Canopy Foliar Traits: LMA, N, P, Ca, K, Pigments	Q5-Q7, Q10–Q13, Q15, Q18, Q21, Q22	Plant taxonomic diversity; plant functional traits			
Faunal Diversity: Presence/abs., abundance, movement, species interactions	Q5, Q10–Q12, Q18, Q27	Camera traps; bioacoustic sensors; animal movement tracking; eDNA; IEK, TEK, LEK; plant species inventories	Hyperspectral, Lidar, Radar	EMIT, PACE, PRISMA, EnMAP, Planet's Tanager, SBG*, CHIME*, NISAR*, BIOMASS*	NASA AVIRIS-NG/3, UZH ARES, GAO, NASA UAVSAR, NASA LVIS, small-footprint lidar

Variable(s)	Science Questions	Ground Measurements	Observing Technologies	Earth Observation Assets	
				Satellite (Planned/Proposed)	Airborne (Drone/Aircraft)
Phenology	Q2, Q4, Q11-Q15, Q18, Q22, Q27	Phenocams, Long-term ground-based phenological observations; IEK, TEK, LEK	Optical Radiometers (OR) and Hyperspectral	Landsat, Sentinel-2, Planet, OLCI, EMIT, PACE, PRISMA, EnMAP, SBG*, CHIME*, FLEX*	Repeat drone RGB
Water Stress: Soil moisture	Q1–Q4, Q6–Q9, Q13–Q19, Q22, Q24, Q25	Soil moisture probes	Microwave radar/radiometry	SMAP, SMOS, Sentinel-1, NISAR*, BIOMASS*, LSTM*,	NASA UAVSAR, AirMOSS
Water Stress: Leaf water content, leaf/plant hydraulic traits	Q2–Q4, Q6–Q9, Q12–Q19, Q22	Leaf water content, Leaf/stem water potentials & conductance, tower-based VOD (L-band GNSS)	GNSS-R/Signals of Opportunity, Imaging Spectroscopy	AMSR-E, EMIT, SBG VSWIR & TIR*, CHIME*, FLEX*, SNOOPI*, CYGNSS, Lemur-2	NASA AVIRIS-NG/3 + HyTES, MASTER
Thermal Stress: T50, land surface temperature, emissivity	Q2–Q4, Q6, Q7, Q9, Q12–Q15, Q19	FLIR cams	Thermal	Landsat, ECOSTRESS, SBG*, FLEX*, TRISHNA*, LSTM*, Commercial*	NASA HyTES, MASTER
Active Fire	Q3, Q4, Q6, Q7, Q9, Q12, Q13, Q19, Q20, Q23, Q27	Life fuel moisture, soil moisture, burn area, burn severity, IEK, TEK, LEK	Thermal	Landsat, VIIRS, Sentinel-3, SBG*, TRISHNA*, LSTM*, Commercial*	NASA HyTES, MASTER
Biomass Burning Aerosols	Q3, Q4, Q6, Q7, Q9, Q12, Q13, Q19, Q20, Q27	Fuel type, fuel density, aerosol measurements	UV/Infrared, Photometers, Lidar	OMPS, VIIRS, EMIT, PACE, OLCI, NISAR*, BIOMASS*, CALIPSO-CALIOP**, AOS*	
Land Use and Land Cover	Q1, Q3, Q4, Q6, Q7, Q9, Q12-Q14, Q16, Q19–Q20, Q25, Q27	Agricultural activity (crop type, yield, rotation), logging severity, fire practices, IEK, TEK, LEK, conservation management practices	Optical Radiometers (OR), Hyperspectral, Lidar, Radar	Landsat, Sentinel-2, Planet, VIIRS, OLCI, EMIT, PRISMA, EnMAP, SBG*, CHIME*, FLEX*, CarbonMapper*, PACE*	NASA AVIRIS-NG/3, UZH ARES, GAO, NASA UAVSAR, NASA LVIS, small-footprint lidar

Variable(s)	Science Questions	Ground Measurements	Observing Technologies	Earth Observation Assets	
				Satellite (Planned/Proposed)	Airborne (Drone/Aircraft)
Provisioning & Cultural Ecosystem Services: Food, fresh water, medicine, spiritual and ceremonial practices	Q27	Crop and NTFP harvest areas and yield, culturally and spiritually important forest type identification, water quantity and quality	Optical Radiometers (OR), Hyperspectral, Lidar, Radar	Landsat, Sentinel-1/2, Planet, VIIRS, OLCI, EMIT, PACE, PRISMA, EnMAP, SWOT, SMAP, SMOS, GRACE-FO, SBG*, CHIME*, FLEX*, CarbonMapper*	NASA AVIRIS-NG/3, UZH ARES, GAO, NASA UAVSAR, NASA LVIS, small-footprint lidar
Surface Water: Quantity, flows (discharge), inundation	Q1–Q4, Q6–Q9, Q14, Q16–Q19, Q24, Q25, Q27	Water-surface height, inundation extent, discharge characterization	Altimeter, Radar, Radiometer	SWOT, Sentinel-1, NISAR*, BIOMASS*	NASA UAVSAR
Groundwater & Terrestrial Water Storage	Q1–Q4, Q6–Q9, Q14, Q16–Q19, Q24, Q25, Q27	Well measurements	Gravimetric	GRACE-FO, MC*	
Atmospheric Moisture, VPD	Q1–Q4, Q6–Q9, Q14, Q17, Q19, Q22, Q24, Q25, Q27	Weather station	Microwave, infrared sounders, imagers	ATMS, GeoXO*, AOS*	
Wind	Q1–Q4, Q6, Q7, Q9, Q14, Q17, Q19, Q22, Q24, Q25	Weather station	Doppler wind lidar	Aeolus	Radiosonde measurements
Soil Nutrients and Texture	Q21, Q22, Q24, Q25, Q27	Soil samples	Hyperspectral	EMIT, PACE, SBG*, CHIME* Note: PANGEA will explore correlative relationships with remotely sensed variables, not direct measurements.	NASA AVIRIS-NG/3
Topography/ Geomorphology	Q1, Q8, Q19, Q21, Q22, Q24, Q25, Q27		Lidar, Radar	SRTM, Copernicus GLO-30	NASA UAVSAR, NASA LVIS, small-footprint lidar

F. Responses to Feedback

We are grateful for the feedback received in the NASA CCE survey responses. In particular, we would like to thank Alejandro Cueva (El Colegio de la Frontera Sur, Unidad Villahermosa), Bruno Ubiali (University of Georgia), Christiane Nimpa (University of Bamenda), Cristhian Saldarroaga Sanchez (Ing Forestal y del Medio Ambiente), Cyrille Bienvenu Bediang (Ministry of Secondary Education), Gerson Lopes (Instituto de Desenvolvimento Sustentável Mamirauá), David Carchipulla-Morales (Wake Forest University), Cristhian Saldarroaga Sanchez (Gobierno Regional Piura, Peru), Diana Rocio Carvajal-Contreras (Universidad Externado), Jeff Atkins (USDA Forest Service, Southern Research Station), Joe Berry (Carnegie Institution for Science), Joost van Haren (University of Arizona, Biosphere 2), Kyle Dexter (University of Turin), Lorena Santamaria Rojas (Stanford University), Louis Defo (University of Yaoundé I, Proforest), Luciana Pires (World Environmental Conservancy), Luiz A. T. Machado (IFUSP), Maricar M Aguilos (North Carolina State University), Ossenatou Mamadou (Universite d'Abomey-Calavi), Paul Stoy (University of Wisconsin), Peke Koukou Leon Cest la Vie (Groupement Agropastoral pour le Developpement de Yongoro), Wu Sun (Carnegie Institution for Science), and two anonymous respondents.

Process

Comments on the draft PANGEA White Paper were requested by the NASA Carbon Cycle and Ecosystems office through a 13-question web-based survey developed by the NASA Terrestrial Ecology Program. Comments were based on a draft White Paper released for public review in September 2024. Responses to the survey were delivered to PANGEA leadership regularly through November. The survey comments were used extensively to improve the final White Paper.

We respond to the comments first by summarizing key strengths and areas that require improvement highlighted by survey respondents, selected by the White Paper authors. We also provide a point-by-point response to the survey comments. We do not record comments where the response was simply "yes" or "no." In a limited number of cases, a survey respondent replicated the same answer to more than one question. We replied to identical comments only once.

Note on translation: A limited number of respondents to the survey used French and Spanish. We record their original comments and provide [in square brackets] our translation.

Key Strengths of PANGEA Highlighted by Survey Respondents

Direct quotes from survey respondents:

- "PANGEA captures a remarkably ambitious, yet achievable, research program that will address one of the greatest challenges facing us today -- understanding the patterns and processes and heterogeneity that govern tropical forests globally."

- "The scientific themes are comprehensive and touch the most important aspects of tropical ecosystem dynamics and their climate and social-ecological implications. Knowledge gaps and questions are clearly identified with community input."
- "The collaborative effort of PANGEA", which "is a prominent initiative that can support conservation strategies for the planet and will also integrate scientists from all over the world in a common effort to protect biodiversity."
- "The study is well-organized and multidisciplinary and captures the needed studies to fill the gaps in these most highly vulnerable ecosystems globally."
- "The structure and content of the PANGEA scoping study report is very clear. For example, we clearly understand that PANGEA will elucidate patterns of recent (5-30 years) and ongoing changes in tropical forests, landscapes, dynamics and feedbacks, as well as their geographical variations, with an environmental approach. Emphasis is placed on comparisons between the Americas and Africa."
- "This is really adapted to the field realities"
- **"**It is an integration of different areas; it is a multidisciplinary study."
- "This approach is what we need to better understand and forecast—simulate—how climate change and land use will impact climate and life."
- "This report is comprehensive and well organized. The introduction clearly laid out why this campaign is necessary and timely. Knowledge gaps and questions are well articulated and will serve as a roadmap for future research. The report also identifies satellite missions and data products that are essential to answering research questions of the PANGEA campaign."
- "I found the focus on African forests to be outstanding; PANGEA will address absolutely critical uncertainties of the role of the African continent in the Earth system while not excluding the central role that the Amazon rainforest plays."
- "The inclusion of a primary focus on tropical systems in Africa is a major strength"
- "The PANGEA process appears to have been very deliberate and intentional to include local communities, stakeholders and governments where needed. The inclusion of many communities from the target areas (South America and Central Africa) and the deliberate process of engagement show that. It is also clear that the PANGEA leadership will also engage other communities -not been identified yet- when their inclusion is suggested or required for success. "
- "The approach to diversity and inclusion is very strong."

The relevance of PANGEA was rated highly by most respondents, including with the use "excellent", "very good", and "very relevant".

Nearly all respondents found PANGEA to be feasible, with one response capturing the essence of these replies, "I find it to be fully feasible as it extends successful LBA research and decades of collaboration with tropical researchers and shifts focus to critical yet poorly understood African tropical forests with a comprehensive observational plan." In contrast, another respondent shared: "The implementation will require a lot of work, but without a more detailed plan of what sites to use and focus on it is hard to fully assess the feasibility."

We thoroughly appreciate and agree with comments that emphasized the important work ahead if PANGEA is selected. For example, "This is a huge scope of work that will count on the help and execution of several work groups as well as natives of the areas to be researched. After reading it carefully, the project seems well tied together. As research develops, specific improvements may be necessary, but overall the proposal is very well structured."

In addition to positive feedback, several weaknesses were shared, which the PANGEA White Paper authors worked to address in the final document. Our responses to survey responses requesting clarity and identifying areas for improvement are organized thematically below.

Areas of the PANGEA Study That Required Improvement

Excerpts from original comments are shown in plain type. PANGEA responses are in blue.

Biodiversity:

- "*Biodiversidad*" [Biodiversity]

  Section 2.2 in the substantially revised white paper pays close attention to the biodiversity themes relevant to PANGEA. Many specific science questions (e.g., Q5, Q6, and Q7) also focus specifically on biodiversity questions.

Short time window:

- "Although the effects of climate change and human action are considered, the project has a very short time window. You don't see the collaboration of other scientists like archaeologists. Limitations in not considering the temporal reference that the archaeology of Africa and Latin America can provide in relation to terrestrial ecosystems"
- "A long-term view is needed which is provided by paleoecological data and information from African and Latin American archaeology in relation to tropical forests."

  The time span of the project is the near past (the historical satellite era of about 50 years) to the end of the current Century. Archeological and paleontological studies undoubtedly would enhance our perspective, but resources are limited within the project and we had to make practical decisions to respond to the criteria of our NASA sponsors.

Collaboration process and exchange unclear:

- "It is shown as a collaborative project between scientists. It also includes local native and indigenous knowledge of ecosystems. I doubt whether the local populations are part of the collaborative team or mere recipients of the results."
- "Empowering local people to be more hands-on and involved rather than just helpers and hired laborers."
- "It is not clear to me the data collection process and the relationship between scientists in the United States and the communities in Latin America and Africa."

PANGEA has made strong efforts from the outset to involve local and Indigenous communities, scientists, government staff, and many other community members from the tropics. The process of co-production of knowledge began during the scoping of PANGEA and the writing of the White Paper, which has been carried out in collaboration with Indigenous leaders from the Global Alliance of Territorial Communities (GATC). If PANGEA is selected, co-production with Indigenous Peoples and Local Communities will begin immediately and will be sustained throughout. PANGEA's approach to equitable science, capacity building, and training will directly confront the issue of flyover campaigns and parachute science. Based on successes from LBA, we believe that PANGEA can publish 100 first-author papers from scientists in Africa, contributing to closing the Parachute Index gap in Central Africa (Culotta et al., 2024). These African scientists will continue the legacy of PANGEA, in collaboration with international peers across the tropics, well after the end of the project. *Section 8* in the White Paper explains our approach to community engagement. *Section 10.1.5* explains the composition of the science team. *Section 10.2* discusses opportunities for co-funding because NASA is limited to funding U.S. institutions. *Section 10.3* discussed the PANGEA approach to Open Science that will facilitate transparency and cooperation.

Most survey respondents reported enthusiastically that PANGEA will foster meaningful partnerships with stakeholders (e.g., local communities and governments). One respondent emphasized, "Yes it will, because PANGEA will offer information to local communities which help in decision taking [sic]."

Separation of terrestrial and aquatic ecosystems:

- "Seeing terrestrial ecosystems separated from aquatic ecosystems can give a biased view of phenomena such as climate change and the impact on humans on tropical forests due to their interconnectedness"

Terrestrial and aquatic systems are not separate in the conception of PANGEA. Perhaps the easiest way to show this is the lack of specific sections dedicated to terrestrial and aquatic science questions. These are woven together. PANGEA landscapes will contain both terrestrial and aquatic environments. Also, within our science questions 1 and 3 we implicitly link terrestrial and aquatic environments through lateral fluxes. In another example in question 21 we link forest disturbance and growth to freshwater resources.

Engagement of international scientists:

- "From my reading, it is clear and understandable. What is not clear to me is how we (non-Americans) can submit projects to NASA."

  NASA can only support research at U.S. institutions. However, as in LBA, we will seek to partner NASA studies with local partners who can access local funding. Moreover, we will actively seek co-funding from private organizations that are now very active in funding environmental research (*Section 10.2*).

Foreign government engagement:

- "The implementation of field research campaigns does not show any difficulties, except for the relationship between governments."

  This is a challenge for all international research. NASA has abundant experience through its many field and airborne science campaigns. Please see *Section 6.2.4* and *Box 2*.

Need for improved clarity on scientific elements:

- "Objective 1: Characterize and quantify heterogeneous tropical forest responses to anthropogenic changes. What about the response of tropical forests to natural and climate-driven disturbances (e.g., typhoons/hurricanes, droughts, flooding, landslides, etc.)?"

  Section 2.5 on disturbance dynamics has been substantially revised. We now treat not only anthropogenic disturbances but also natural disturbances through the mechanisms listed in the comment. Additionally, *Sections 2.3* and *3.3.2* address flooding.

- "PANGEA study need to improve the integration of Nature-Society interactions. Social and human sciences need to be more taken into consideration"

  The revised White Paper includes substantially revised sections describing the key questions for the study of Social-Ecological Systems (SES) (*Section 2.4*). This PANGEA science theme will investigate the interactions and feedbacks between social and ecological systems related to food production and food security, cultural practices, livelihoods, management strategies, and resilience of tropical systems.

- "We are in the century of artificial intelligence, which is having an impact on all areas of life and even on the way we approach current and future research questions. I think this aspect needs to be clearly defined in the report."

  In the revised White Paper *Section 6.3.1*, we confront this issue directly. For example, PANGEA will leverage artificial intelligence and machine learning (AI/ML) models for data synthesis because of their robustness in handling non-linearities and interactions among multifactorial processes and predictors. AI/ML can be further used to emulate process-based models and more efficiently explore models' parametric space or run short/long-term forecasting.

Lack of experimental elements in the PANGEA scope:

- "Section 3 does not have an inclusion of precipitation diversion, CO_2 fertilization or temperature experiments while Q8, Q9, Q19, and Q23 all depend on experimentation to address these questions."

  The PANGEA response to the NASA Terrestrial Ecology Program does not explicitly consider large ecosystem experiments. Those are valuable and may be co-funded by other agencies or private donors as was the case for the Seca-Floresta drought experiment conducted in the Tapajos National Forest, Brazil supported by NSF funds as part of LBA.

Exclusions from the PANGEA scope:

- "It seems to us that the tropical forests of Southeast Asia seem to be excluded from the PANGEA study, yet we are talking about tropical forest ecosystems and improving our understanding of how they function. Perhaps budgetary, strategic or geopolitical issues seem to come into play here, but we believe that taking into account all tropical forest regions would enable us to obtain more holistic results and to carry out modelling that affects all tropical forest ecosystems."
- "Dry tropics are left out, but they are as potentially important to the future of the terrestrial carbon cycle as the wet tropics, yet are less studied and less well understood."

  Resources limitations would not allow us to conduct field campaigns in all tropical regions. Please see *Section 1.4* on the PANGEA domain. We include an extended domain of pantropical moist forests, the broader area of scientific interest, where additional projects can take place through partnerships, and where satellite and modeling analyses will be conducted.

We do not claim that the dry tropics are unimportant, but we have made a case for the importance of moist forests in the global carbon and water cycles. It is unlikely that any other tropical biome can have as much importance for carbon as the moist forests. Moist forests have greater carbon storage and larger carbon fluxes than other tropical biomes.

In the following section we respond to all comments by survey respondents organized by the survey questions (Q1-Q13). Survey responses are shown in plain type. PANGEA responses are shown in blue. We did not reply to survey responses where the answer was a simple "yes" or "no". The responses are generally organized based on the order in which they were received. The order does not correspond to the order of respondents listed at the beginning of this document. In some cases, responses were re-ordered so we could provide a single reply to similar comments.

Q1. What are the key strengths of the PANGEA scoping study?

1. I believe that the collaborative effort of PANGEA is a prominent initiative that can support conservation strategies for the planet and will also integrate scientists from all over the world in a common effort to protect biodiversity.
2. *Ciclos biogeoquímicos, biodiversidad, interacciones y retroalimentaciones climáticas, sistemas socioecológicos y dinámica de las perturbaciones*. [Biogeochemical cycles, biodiversity, climate interactions and feedbacks, socio-ecological systems and disturbance dynamics.]
3. The study is well-organized and multidisciplinary and captures the needed studies to fill the gaps in these most highly vulnerable ecosystems globally.
4. PANGEA will used new tools to study tropical forest.
5. *C'est sur la collectes des données digitalisées* [It is about the collection of digitalized data.]
6. It is an integration of different areas; it is a multidisciplinary study.
7. The key strengths of PANGEA scoping study is the fact that the initiative is focusing in an area where there are a lot of gaps in knowledge and where African Government do not have financial and technical means to work.
8. I found the focus on African forests to be outstanding; PANGEA will address absolutely critical uncertainties of the role of the African continent in the Earth system while not excluding the central role that the Amazon rainforest plays.
9. One of the main strengths of the PANGEA scoping study lies in its thorough approach to addressing gaps in our understanding of tropical forests. The study highlights the issue of inadequate representation in field campaigns, which leads to the misrepresentation of physical properties in environmental dynamics. PANGEA aims to tackle this challenge by

implementing a multiscale campaign to describe biogeochemical processes in tropical forests, which is another significant strength. The authors have carefully considered existing data sources and devised a plan to prioritize and optimize data collection, making efficient use of time and resources. Additionally, PANGEA builds on the experience of NASA's previous Terrestrial Ecology campaign, the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), offering a chance to enhance NASA's global models by gathering more comprehensive spatiotemporal data on global dynamics.

10. The clarity of the research questions. The current state of knowledge on the topics to be explored. The partners involved in the various study regions. Training and educating perspectives of the next generation of scientists.

11. The scientific themes are comprehensive and touch the most important aspects of tropical ecosystem dynamics and their climate and social-ecological implications. Knowledge gaps and questions are clearly identified with community input.

12. PANGEA was perceptive in choosing to fill the gaps of previous campaigns and including addressing almost non-existent data for some tropical forests. The use of satellites is becoming essential for most environmental scientific studies and decision-making, and therefore, their accuracy in these research applications has become paramount. It is known that even the representation of models on forests, due to the difference in convective processes, presents great difficulty in parameterizations, generating responses with very large standard deviations. Sub optimally executed campaigns and lack of specific data complicate many of the existing studies even more. Analyzing and comparing forests which present different behaviors will be of great value to the scientific community in advancing studies on the future of our planet. The proposal seems to be successful in providing an opportunity for the new generation of scientists and to propose the creation of an open database. I was immensely happy to learn that this proposal potentially opens doors beyond academia and space institutions, to decision-makers, communities and anyone else interested in helping.

13. The scientific underpinning, the broad scope with clear focus areas, well developed plan of satellite use, well developed modeling plan, the inclusion of many local communities and well developed engagement plan, the implementation plan, and capacity building and education plan.

14. The focus on increasing the observation and understanding of some of the most unknown but vulnerable ecosystems. PANGEA tackles a well-known earth sciences research gap and challenge: lack of data and knowledge of the tropics.

15. The inclusion of a primary focus on tropical systems in Africa is a major strength. The diverse team associated with the project is impressive, especially the diverse and complementary skillsets of the team members. There is a strong understanding presented of the cross-scale advantages/disadvantages of various remote sensing approaches presented. Being familiar with the work of many of the team members, I am not surprised at all by this, but rather enthused at how well these issues are laid out and

addressed. Incorporating multiple remote sensing data sources can be complicated and this paper details how to approach this within the context of the science questions in a thorough and thoughtful way that shows great potential for the success of this project component. I really like the optimal, baseline, threshold framework that is used throughout. Tables one and four are of the most comprehensive tables of this sort (and easy to read) that I have ever seen. From what I can tell, this is solid consideration of working with local partners which is a must for this kind of science.

16. PANGEA captures a remarkably ambitious, yet achievable, research program that will address one of the greatest challenges facing us today -- understanding the patterns and processes and heterogeneity that govern tropical forests globally.
17. I could see the strengths of the study at two levels:
    a. The first is that of having succeeded in bringing together a vast scientific community from several horizons, not to say all the horizons of the earth. All the scientists from tropical countries and other regions of the world seem to be represented, which ensures that the majority of viewpoints are taken into account in order to address the major questions that pose challenges to a proper understanding of the functioning of tropical ecosystems.
    b. The second strong point of the study is that it takes into account the key issues facing humanity that are directly linked to the functioning of tropical forest ecosystems: this is a strong point of the PANGEA exploratory study. Indeed, climate change (which encompasses many other issues taken into account in the study, such as deforestation, land-use change, droughts, the carbon cycle, etc.) and biodiversity are among the major problems that pose major challenges to humanity and to life on planet earth.
18. PANGEA was perceptive in choosing to fill the gaps of previous campaigns and including addressing almost non-existent data for some tropical forests. The use of satellites is becoming essential for most environmental scientific studies and decision-making, and therefore, their accuracy in these research applications has become paramount. It is known that even the representation of models on forests, due to the difference in convective processes, presents great difficulty in parameterizations, generating responses with very large standard deviations. Sub optimally executed campaigns and lack of specific data complicate many of the existing studies even more. Analyzing and comparing forests which present different behaviors will be of great value to the scientific community in advancing studies on the future of our planet. The proposal seems to be successful in providing an opportunity for the new generation of scientists and to propose the creation of an open database. I was immensely happy to learn that this proposal potentially opens doors beyond academia and space institutions, to decision-makers, communities and anyone else interested in helping.
19. These are the concept developed around the optimal, baseline and threshold essential measurements needed to achieve the defined goals; the inclusivity approach and finally

the involvement of local scientists which will guarantee the sustainability of the study after such a campaign.

20. I believe the project has many strengths, among which I could cite well-developed objectives that seek to both advance knowledge and improve methods for understanding tropical forests, a large and competent team, and a range of partner organizations that will help to operationalize these ideas.
21. Community engagement, cross-continental perspective and emphasis on the role of divergent tree floras in driving intercontinental variability in ecosystem function
22. This is a huge scope of work that will count on the help and execution of several work groups as well as natives of the areas to be researched. After reading it carefully, the project seems well tied together. As a research develops, specific improvements may be necessary, but overall the proposal is very well structured.

We appreciate the comments above but otherwise have no direct response to them.

Q2. What areas of the PANGEA study need further improvement?

- It is shown as a collaborative project between scientists. It also includes local native and indigenous knowledge of ecosystems. I doubt whether the local populations are part of the collaborative team or mere recipients of the results.

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

- The implication of women in activities of carbon sequestration.

  PANGEA has made a strong effort to include women in all of the scoping activities. We do not specifically address the activities of women in carbon sequestration in our scoping report. That is one of many specific concerns that may emerge in the research projects. Our White Paper, while comprehensive, is still limited in space.

- *Sur le plan local national régional international et mondial* [On the local, national, regional, international and global plan]
- Be more coherent and specific concerning capacity building alignment with African government action plan, page 15 / 61.
- In the DR Congo for example

PANGEA engaged broadly in Africa, South America, and Asia, as detailed in *Appendix C* of the White Paper.

- How can we promote interdisciplinary integration, and how will local people be integrated into the project to actively participate? How is the idea of improving training, education, and science.

  The White Paper was formed by a highly diverse team as is detailed in *Appendix C*. In particular, we recognize the importance of the diverse team for improvement of training and education. PANGEA's approach to equitable science, capacity building, and training will directly confront the issue of flyover campaigns and parachute science. Based on successes from LBA, we believe that PANGEA can publish 100 first-author papers from scientists in Africa, contributing to closing the Parachute Index gap in Central Africa (Culotta et al., 2024). These African scientists will continue the legacy of PANGEA, in collaboration with international peers across the tropics, well after the end of the project.

- More interest on Nature-Societies interactions

  The revised White Paper includes substantially revised sections describing the key questions for study of Social-Ecological systems (SES) (*Section 2.4*). This PANGEA science theme will investigate the interactions and feedbacks between social and ecological systems related to food production and food security, cultural practices, livelihoods, management strategies, and resilience of tropical systems.

- Section 3.1.1 Carbon Stocks and Fluxes: I think this section fails to represent a serious limitation of current approaches for monitoring terrestrial ecosystems in the tropics. The carbon cycle in these ecosystems is approximately balanced, but given the large stocks and large fluxes (GPP, Respiration and biomass burning), slight changes in the balance of these process could have large consequences on the global carbon balance. Even perfect CO_2 measurements are unlikely to provide much useful information on carbon cycle processes, yet the predictive capacity of our Earth System models rests on their ability to model GPP, and respiration. These process models are poorly constrained (if at all) in the tropics by the current monitoring systems. Unlike temperate ecosystems that show large seasonal variations in net CO_2 exchange, tropical ecosystems show little seasonal variation because GPP and respiration tend to be nearly equal throughout the year. Therefore, atmospheric CO_2 is almost constant in the tropics - despite the presence of enormous gross fluxes. Furthermore, it is difficult to separate regional trends from carbon cycle "noise" due to day-to-day differences in cloudiness or the diurnal rectifier effect (Denning et al., 1995) on CO_2 concentration.

- There is a potential solution, carbonyl sulfide (OCS). This trace gas tracks GPP whereas CO_2 tracks NEE. This is because OCS is taken up by leaves but there is no (or very small) release of OCS from terrestrial ecosystems. Several years ago we proposed that

OCS could provide a new window into the carbon cycle - especially in the tropics (Berry et al., 2013). Satellite measurements by satellites, MIPAS (Stinecipher et al., 2022) and TES (Wang et al., 2023) showed significant depletion of OCS concentration in the upper troposphere. Over the past two years Luciana Gatti's group at INPE have conducted over 800 flask measurement of OCS (along with other GHG gases) from aircraft profiles conducted over the Amazon Basin. As expected these show much larger gradients (10-100 fold) in relative concentration of OCS than in CO_2. OCS is, therefore, provides a better basis for conducting atmospheric inversions, and it can provide direct information on GPP and respiration. Satellite measurements, aircraft profiles and possibly solar looking FT-IR spectrometry (Hannigan et al., 2021) are promising approaches for building an OCS-based carbon cycle monitoring program in the tropics.

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The comment raises a critical issue in the study of tropical forests that we have also confronted in our White Paper. To be more responsive to the specific question of using the variation of carbonyl sulfide (COS) atmospheric mixing ratios to constrain GPP, we have included the potential importance of that measurement in *Section 2.2*.

- One area that could be improved in the PANGEA study is the lack of a clear strategy for scaling up the results spatially. While this might be outside the current scope of the study or premature given that it's still a proposal, it is nonetheless important to consider how findings will be communicated to the general public. A key factor in the success of global projects like MODIS has been their ability to distill the world's complexity into a few primary drivers. For instance, the MODIS LAI product classifies canopies based on six biome types, offering a simplified yet effective global view for non-experts. However, such models often misclassify or misrepresent biomes due to insufficient data, which underscores the importance of PANGEA's results in filling those gaps.

The lessons of MODIS are highly relevant. PANGEA provides a framework for scaling and integrating airborne and satellite measurements with in situ field observations, eddy-covariance flux tower measurements, and models to advance scientific understanding and remote-sensing capabilities across thematic areas that directly address the goals of NASA's Carbon Cycle and Ecosystems Focus Area, in alignment with the Water and Energy Cycle and Climate Variability and Change Focus Areas. PANGEA will establish a network of coordinated field and airborne campaigns distributed across targeted tropical forest ecosystems to fill data gaps and enable scaling between field and remotely sensed datasets, as well as regional and pantropical scale modeling. As the comment notes, specific scaling approaches will be developed as part of the Concise Experiment Plan and through the proposals and activities of the Science Team.

- With respect to carbon dynamics, I see three key areas that need improvement:
    - Lack of airborne trace gas measurements to inform basin-scale carbon balance
    - Lack of a concrete plan to quantify basin-scale carbon flux components, namely, photosynthesis, respiration, and fire emissions
    - Lack of focus in the wet season
- These missing areas are critical to PANGEA's stated objective of "Constrain model uncertainty of future tropical carbon flux predictions" (line 312, page 10).
- The airborne science component of PANGEA currently focuses exclusively on airborne remote sensing observations (Section 6.2.3, page 64) with no mention of trace gas (e.g., CO_2, CO, and CH_4) observations to inform continental-scale carbon flux quantification. Without these measurements, it is unlikely that we will reduce the large uncertainty in basin-scale net carbon balance and carbon flux components or transform the understanding of continental-scale carbon dynamics over the tropics. It is worth noting that some global atmospheric inversions already assimilate satellite-observed column-average CO_2concentrations (e.g., OCO-2 MIP). These inversions have larger uncertainties in the tropics than in the midlatitude, due to frequent cloud cover in the wet season, the weaker seasonality and smaller signal of net carbon fluxes, and lack of in situ tower networks and airborne observations. If PANGEA resorts to using exclusively satellite-observed column-average CO_2 concentrations to

constrain the carbon budget of Amazon and tropical Africa, there is no advancement compared with the current state of the field, and this to me is a missed opportunity.

- I would also note that airborne trace gas measurements have played a key role in previous NASA field campaigns, such as the Manaus vertical profile measurements during LBA (https://doi.org/10.3334/ORNLDAAC/1175) and the CARVE and Arctic-CAP airborne trace gas measurements during ABoVE (Sweeney et al., 2022). These trace gas measurements help identify large methane emissions in the eastern Amazon (Miller et al., 2007) and boreal Alaska (Chang et al., 2014) and reveal biome-scale patterns of photosynthesis and respiration, which differ from terrestrial biosphere model simulations (Commane et al., 2017; Hu et al., 2021). The challenges with satellite-based greenhouse gas observations in the tropics (Frankenberg et al., 2024) should motivate more airborne trace gas observations to complement the view from satellites. Granted that PANGEA may not necessarily repeat what LBA and ABoVE have done, but given the dearth of in situ trace gas measurements coming from Amazon and tropical Africa, it would be remiss not to consider the unique values of airborne trace gas measurements for carbon cycle research.

- It may also help for PANGEA to identify local collaborating institutions in collecting airborne trace gas measurements. For example, much of the recent advance in understanding the Amazon carbon balance is based on airborne trace gas measurements collected by Luciana Gatti's group at Brazil's Instituto Nacional de Pesquisas Espaciais (Gatti et al., 2014, 2021, 2023). This means that PANGEA may not need to start from scratch for such measurements; there are already local partners to lean on. Leveraging local partnerships would seem critical to facilitating labor-intensive airborne trace gas measurements, which are key to the understanding of basin-scale carbon dynamics.

  One of the barriers to effective use of the current satellite total column abundance data for trace gases is the lack of effective calibration and validation data in the tropics (*Section 3.1.1*). The comment advocates for additional airborne measurements of trace gases that we recognize in *Section 3.1.1*.

- On a related note, there is also no indication how the planned airborne remote sensing campaigns and satellite observations will help solve the problem of partitioning photosynthesis and respiration from the net carbon balance. Separately quantifying photosynthesis and respiration are important because they respond differently to climate and this issue has been at the core of model uncertainty in future carbon cycle projections over the tropics. CO_2 concentration and flux measurements cannot uniquely constrain photosynthesis and respiration at the same time. Though the PANGEA white paper cites solar-induced chlorophyll fluorescence (SIF) as a proxy for photosynthesis, SIF cannot constrain the magnitude of photosynthetic carbon assimilation because current SIF-based models all rely on site-level statistical relationships between SIF and photosynthesis. Concurrent observations of a suite of carbon cycle trace gases, including carbon and oxygen isotopes (13C- CO_2 and 18O-CO_2), carbonyl sulfide, and carbon monoxide, are needed to fully constrain major carbon flux components and inform carbon cycle processes in models. There have been successful examples of using CARVE trace gas measurements to separately constrain photosynthesis and respiration over the ABoVE domain (Hu et al., 2021; Kuai et al., 2022), so this is not impossible.

As noted in response to (9) above we have considered carbonyl sulfide. In addition, we have listed CO, COS and isotopes among the potential measurements to resolve carbon partitioning questions.

- My last point for this question concerns the wet season. It baffles me that PANGEA would limit the measurements to "dry season onset" and "dry season end" without considering continuous measurements throughout the dry and wet seasons (line 477–484, page 15). First, we won't have an accurate knowledge of the carbon balance over a tropical region if we have measurement gaps half of the time. Second, the limited view on wet season carbon dynamics from greenhouse gas satellites (Frankenberg et al., 2024) should necessitate more not fewer measurements in the wet season. Third, wet-season disturbances such as windthrow of trees are major pathways of aboveground biomass loss. Granted that logistical challenges exist with the wet season, leaving this completely out of the picture is again a missed opportunity.

The terminology of "dry season onset" and "dry season end" was confusing and so we changed it. The point of campaign timing is to capture the forest when it is physiologically well watered (end of the wet season) and at the time when it is most water-stressed (end of the dry season). In order to balance the costs and benefits of airborne missions for surface remote sensing observations using optical sensors, we believe that avoiding the peak of the wet season is prudent. However, we have highlighted the importance of continuous measurements at field sites to cover the range of seasonal conditions. Moreover, we advocate for the potential of drone measurements to also provide seasonal coverage over limited areas.

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- It was unclear to me the extent that tropical forest to subtropical transition zones would be studied as surrogates for future conditions or the impacts of land surface changes on tropical forest function. The tropical forest delineation in Figure 6 is clear but if PANGEA means 'pan-tropical', and given the outsized role of tropical deforestation across all study systems, it was not clear to me how savanna/cerrado, deforested, agricultural, or grassland systems could be integrated to improve our understanding of the unique role of tropical forests themselves. Maritime Continent and southeast Asian forests provide critical context for other rainforest systems but also understand the need to keep the scope within reason, and these tropical systems will be integrated into the study.

  As the comment indicates, the potential range of PANGEA studies is vast. In the draft White Paper, we loosely used the term "tropics." However, our study proposal focuses on tropical moist forests. This is now clarified in *Section 1.4*.

- This is a huge scope of work that will count on the help and execution of several work groups as well as natives of the areas to be researched. After reading it carefully, the project seems well tied together. As a research develops, specific improvements may be necessary, but overall the proposal is very well structured.
- One thing that comes to mind is that the project is quite ambitious in terms of the breath of science questions it aims to address.

  We agree that the scope is large, which is why we have counted on partnership since the beginning of the scoping work. We are also actively exploring co-funding (*Section 10.2*).

- The involvement of local universities and research centers/national labs. From the study sites (equipped with eddy covariance) that are mentioned, looks like that those EC towers are the ones that the PIs are from the US, however, there might be others. Another point of interest that might be improved is considering Mexico. There are at least two EC sites in the area of interest of PANGEA:

- El Palmar in Yucatán (ref: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JG005629) La Orduña in Veracruz (ref: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018JG004911) Calakmul in Campeche (in construction, but should be in operation in 2025),
- Other study sites in operation in tropical dry forests in Sonora, the uppermost distribution limit includes: Alamos in Sonora (https://ameriflux.lbl.gov/sites/siteinfo/MX-Aog).
- That being said, I believe that involving local actors (i.e., MexFlux) in the white paper will be valuable, since they will be acknowledged, and could improve collaborations.

These are valuable comments that will be considered if we are selected to develop an operational plan especially with regard to the active researchers in MexFlux and the moist forest sites. We note that dry forests are outside of the scope of PANGEA.

- Weakness of open data near real-time approach: Open data sharing in the context of earth system science research is only useful if it means real-time free and unrestricted exchange of observational data. Any other type of data sharing that remains restricted to only PANGEA members or that requires a long time lag for data sharing won't be able to deliver the claimed benefits in this proposal. NASA is well aware of the benefits of global real-time open data sharing as thanks to that we have been able to revolutionize weather forecasting and fully leverage the power of remote sensing for weather prediction. The weather prediction breakthroughs could not have been achieved without a global commitment to real-time weather data sharing (see the World Meteorological Organization Unified Data Policy Resolution). The same principle applies to climate and carbon cycle actionable information in the tropics (timely, routinary). PANGEA must show a more explicit paradigm-shifting proposal on "real" data sharing and not fear this discussion. Without real-time free and unrestricted data sharing as a core PANAGEA principle, its potential for transforming research in the tropics through leveraging NASA's mission will remain illusory.

There are applications where data that need to be available in real-time or near-real-time such as weather forecasting. However, that is not true for all analyses. It is hard to make an argument for near-real-time data when the subject matter is interannual or interdecadal variability in ecosystem carbon flux. PANGEA is committed to the principles of NASA Open Science and will deliver data openly as quickly as practicable with reasonable cost constraints. The lags in data sharing will be minimized but enforcing a near-real-time or real-time criterion for all data is not practicable.

- "Naive" approach to the challenges of working in the tropics: The proposal touches upon the challenges of observing the tropics but reads weakly and naively about how PANGEA will address those challenges. There's a reason why terrestrial observation of the tropical forest has remained limited. PANGEA seems to understand these reasons but does not convey how those challenges will be overcome. Stating in Section 7.6 that PANGEA will use "MOUs" to overcome the difficulties of observing campaigns in the tropics seems like a naïve understanding of the size of the challenges there. The proposal needs a much more robust approach and definition of the critical measures that PANGEA will implement to overcome physical, operational, and socioeconomic disruptions, which are very likely in the places where PANGEA will operate. The involvement of actual governmental institutions (not only research institutions) from the core PANAGEA domains seems quite weak. Without clear commitments from countries and their governments, achieving functional and continuous observing networks in places like the Congo Basin or the Amazon seems like a high-risk program that NASA may not be willing to fund if proper assurances are not implemented early in the program conception.

  NASA has extensive experience with international scientific cooperation. NASA was a major participant in LBA which had enormous success in scientific discovery, in the strengthening of Brazilian science through development of human resources, and in building trust and long-term relationships among investigators that persist to this day. Focus on one sentence regarding MOUs (necessary for airborne campaigns) disregards both the history of NASA research in tropical forests and the process that PANGEA took to build an inclusive dialog (see *Section 8* on community engagement). Admittedly, operations in tropical countries with limited governance capacity and infrastructure are challenging. We do not deny those challenges, but the commenter may not be aware of the prior successes of NASA and their partners which makes the likelihood of success in PANGEA plausible.

- Path to action: It is clear that PANAGEA is a research proposal. However, the section on Earth Science to Action and the PANGEA pillar three on path to action seem weak and out of touch with the most relevant current multilateral processes for global action on climate change and earth observations. The description of relevant organizations in Sections 7 (Table 5) and 8 looks somewhat random. It does not seem to reflect the result of a systematic review exercise to understand the global landscape of organizations working on improving earth observations in the tropics. Key United Nations organizations like the World Meteorological Organization (currently leading the development of the Global Green House Gas Watch) and the Food and Agriculture Organization (key player for land management and land use investments in the tropics) are absent. The UNFCCC is barely mentioned (mentioned in sections of little relevance for what this organization does) despite being the most crucial organization needing the scientific outcomes of PANGEA to inform global commitments on climate mitigation and our carbon budget.

The commenter makes an excellent point. The draft section on Earth Science to Action was too general. This section (*Section 9*) has been substantially edited. It now discusses a more holistic strategy in greater detail.

- Upfront, there are no glaring issues here so consider these points minor. In the section outlining biogeochemical cycles, the only cycle really considered is carbon--just with a focus on CO_2 and CH_4 mainly. In the following section however, a mapped image from one of Dana Chadwick's papers is presented showing mapped concentrations of Ca etc. in the canopy (taken from hyperspectral imagery I think that has been correlated with leaf nutrient content). There is room here to possibly incorporate N and P cycling that may add to this project--particularly given the transfer that happens between atmospheric movement of P (dust from the Sahara I believe) that is blown over to the Americas. However, I am unaware of how much that impacts the Amazon directly as it is a greater consideration for the Yucatan region and the transfer from Africa comes far north of the forested regions in Africa. There is some way though to maybe consider additional biogeochemistry beyond C--fully acknowledging that would require far greater terrestrial sampling and that remote sensing approaches to scale those estimates are limited or prone to high error.

  This observation about the draft White Paper is correct. And we have taken action to include discussion of other biogeochemical cycles in the revised document with special attention to nitrogen and phosphorus.

- The disturbance section presents a dichotomy of natural vs. human induced disturbance. Consider the role that drought has in increasing the potential for human fire (e.g., drought dries the forest regions, creating a greater likelihood that people may then burn that area for clearing simply because their chances of success are higher). this has been observed in the Amazon, though an immediate ref escapes me. This section doesn't necessarily consider disturbance dynamics as fully. But maybe that is b/c those dynamics are less well understood in Africa, which would be a plus for this project as we may find out! - ICESat-2 data could be used to add additional structural data for forests in the region--I do see it in Table 2 though so I know it is on the "radar" (my on personal bump there!)

  Natural and direct human disturbances are separated for clarity of exposition. However, the interactions of climate and fire are well-recognized. For example, the interactions of high temperatures, drought and fire are a significant focus in the discussion of PANGEA science (e.g., Q26).

- This is beyond the scope of the PANGEA study given the scope of the NASA call, but getting at below ground processes -- nutrients, carbon dynamics, plant biomass and NPP allocation to roots, enzymes, exudates and symbionts -- is important for understanding processes regulating tropical forests. I mention this not as a criticism of PANGEA, but as a comment on the scope of the NASA call more broadly.

We appreciate that the commenter recognizes that NASA too has limitations.

- It seems to us that the tropical forests of Southeast Asia seem to be excluded from the PANGEA study, yet we are talking about tropical forest ecosystems and improving our understanding of how they function. Perhaps budgetary, strategic or geopolitical issues seem to come into play here, but we believe that taking into account all tropical forest regions would enable us to obtain more holistic results and to carry out modelling that affects all tropical forest ecosystems.
- Dry tropics are left out, but they are as potentially important to the future of the terrestrial carbon cycle as the wet tropics, yet are less studied and less well understood.

Limitations in resources would not allow us to conduct field campaigns in all tropical regions. Please see *Section 1.4* on the PANGEA domain. We include an extended domain of pantropical moist forests, the broader area of scientific interest, where additional projects can take place through partnerships, and where satellite and modeling analyses will be emphasized. We do not know for certain what areas the commenter includes in dry tropics but we have made a case for the importance of moist forests. It seems unlikely, for example, that any other tropical biomes can have as much importance for carbon as the moist forests.

- Please consider the identification of drivers to be completed to the major the gaps identified (see lines 426-427) page 55 / 61

Neither the page numbers nor the line numbers appear consistent with the text of the comment. We were unable to reply to this comment.

Q3. How clear and understandable was the overall structure and content of the PANGEA scoping study report? Please provide specific examples of sections/concepts that were unclear. Please cite page/line numbers where appropriate.

- It is not clear to me the data collection process and the relationship between scientists in the United States and the communities in Latin America and Africa
- From my reading, it is clear and understandable. What is not clear to me is how we (non-Americans) can submit projects to NASA.

PANGEA is a collaborative project where participants from the United States will work together with participants from tropical countries as equal partners. NASA can only support research at US institutions. However, as in LBA, we will seek to partner NASA studies with local partners who can get access to local funding. Moreover, we will actively seek co-funding from private organizations that are now very active in funding environmental research (*Section 10.2*).

- Objective 1: Characterize and quantify heterogeneous tropical forest responses to anthropogenic changes. What about the response of tropical forests to natural and climate-driven disturbances (e.g., typhoons/hurricanes, droughts, flooding, landslides, etc.)?

  Section 2.5 on disturbance dynamics has been substantially revised. We now treat not only anthropogenic disturbances but also natural disturbances through the mechanisms listed.

- The structure and content of the PANGEA scoping study report is very clear. For example in Page 96, line 1954-1956, we clearly understand that PANGEA will Elucidate patterns of recent (5–30 years) and ongoing changes in tropical forests, landscapes, dynamics and feedbacks, as well as their geographical variations, with an environmental approach. Emphasis is placed on comparisons between the Americas and Africa.
- *C'est la prise en compte de la dynamique social des communautés local a la base.* [It is taking into account the social dynamics of local communities at the base.]

  No reply to these comments.

- One aspect of the report that appears unclear is the expected outcome regarding "Mapping and quantifying methane flux predictions" from the study on Carbon Sequestration Stability and Methane Fluxes (page 108). While the rest of the project seems to focus on present-time analyses, the inclusion of a forecasting analysis appears out of scope. Given that PANGEA will collect data until the end of the campaign, the time available for conducting such a forecasting analysis seems limited.

  The White Paper has been substantially revised and future projections are not out of scope (*Section 3.3*). For example, the issue of carbon sequestration stability is central to one of our projection science questions (e.g., Q25. In a changing climate which functionally distinct forest types are most vulnerable to becoming net sources of carbon to the atmosphere in a changing climate, which forest types are resistant, and why?).

- In my opinion, there is no particular misunderstanding of the overall structure and content. I follow many communications on this PANGEA scoping study report.
- This report is comprehensive and well organized. The introduction clearly laid out why this campaign is necessary and timely. Knowledge gaps and questions are well articulated and will serve as a roadmap for future research. The report also identifies

satellite missions and data products that are essential to answering research questions of the PANGEA campaign.

- The timetables to me were clear and political instability (2425) was well addressed, and Box 1 laid out a well-reasoned advanced plan to get PANGEA started with international partners. I am a bit less familiar with scoping studies that are not meant to describe specific site-level details and feel that the plan as written is well reasoned and flexible for all of the different opportunities that a funded project will present.

  No reply to these comments.

- The project generally is presented quite clearly, but the definitions of some acronyms should be checked according to their first appearance in the text. (e.g., the definition of gross primary productivity GPP appears in Figure 3, but this acronym is previously used in Figure 1). My suggestion is that the definitions of all acronyms, even those that are simple for people in the field, should be inserted into the text where first used on each page they are mentioned to make easier reading by people from other fields.

  All acronyms are now defined when they are first mentioned, and we have included an acronym definition list (*Section 14*).

- The overall structure was very well worked out and the content was overall clear. A couple issues that I noticed reading through the document were: 1) the methane flux observations and rationale appears to be a last hour addition. It is an important addition, but not including Pangala et al. 2017 in line 119, the section on methane fluxes in 1321-1335 should be included in Section 2.1.

  The commenter is correct and the section has since been rewritten and more thoroughly integrated (*Sections 2.1*. and *3.1.1*).

- Section 2.4 socio-ecological systems section reads very different than all other 2.x sections. It has more statements on what PANGEA will do (1061-1069; 1090-1093 1161-1163), this section also would benefit from the Levis et al. 2017 (Science 355, 925-931) study on PreColumbian peoples influence on tree abundance and distributions. Later on the concept of 'cultural forests' is brought up, which Levis et al. would be very appropriate for. In 2.4 the paragraph 1095-1115 has large blocks of references, that would be better separated by the different forces or impacts they refer to.

  Section 2.4 has been thoroughly revised to be consistent with the other 2.x sections. The perspective of Levis and colleagues is very important and we cite their recent (2024) review that summarizes much of their earlier work including the studies of pre-Columbian influences on tree abundance and distributions.

- In the discussion of large mammal impact on nutrient distributions (940) include Doughty et al. 2016 PNAS in the refs.

  The importance of megafauna is discussed in *Sections 2.2* and *3.2.1*. We cite the earlier paper on megafaunal impact by Doughty et al. (2013).

- in Disturbance dynamics, line 1198 the deeper understanding of the drivers is to my knowledge not in Section 2.4. Line 1229 not sure where the statement in brackets comes from. Line 1261 tropical cyclones have the most effect in ocean/marine exposed forest systems. I would suggest merging that paragraph with the paragraph starting at line 1227.

  Disturbance is now discussed in *Section 2.5*, and the section has been significantly revised. The understanding of disturbance depends, in part, upon social-ecological systems discussed in *Section 2.4*.

- In line 1315 include Saleska et al. 2003, Science as a reference for carbon sink strength change. Line 1402 talking about eddy covariance, it would be good to have a map of EC locations and GeoTree locations. Section 3 does not have an inclusion of precipitation diversion, CO_2 fertilization or temperature experiments while Q8, Q9, Q19, and !23 all depend on experimentation to address these questions. One site in Peru where the forest borders a hot spring are potentially interesting sites (Kullberg et al. 2023, New Phytologist) to focus on to determine the impact of increased temperature on tree species and their thermal resilience.

  Potential sites and locations are listed as part of PANGEA landscapes that include eddy covariance and forest inventory studies as shown in the table in *Section 6.2.2*.

  The PANGEA response to the NASA Terrestrial Ecology Program does not explicitly consider large ecosystem experiments. Those are valuable and may be co-funded by other agencies or private donors as was the case for the Seca-Floresta drought experiment conducted in the Tapajos National Forest, Brazil supported by NSF funds as part of LBA.

- Please, line 1168-1169 in the sentence 'PANGEA activities... need to govern... effectively'; would you mean 'manage' instead of 'govern'?

  We use the word "govern" to distinguish the activities of decision makers.

- The project is very well written and structured.
- My first, general suggestion is to highlight that the project is building on existing knowledge in order to advance it. Thus, rather than aiming to fill knowledge gaps, I would use something like "advance knowledge (or scientific understandings)".

The existence of some knowledge on tropical forest does not exclude the existence of gaps in that knowledge. We will retain the current language.

- The first two questions seem descriptive. I suggest finding a relational factor (e.g., analyze the relationship between X and Y), as is done in question 3.

  The questions were developed through an exhaustive process involving large working groups. While the comment is valid, we do not want to make changes to the questions unless they are unclear or would lead to ineffective studies. We do not think it is necessary to change Q1 or Q2.

- The word "Anthropocene" appears for the first time in question 2. If you consider relevant keeping it, I suggest introducing and explaining the concept earlier (noting that there is quite a heated debate on what it really means).

  The scientific debate related to the Anthropocene is a matter mainly restricted to stratigraphers. We initially used the word in its colloquial context as the time when the Earth system is dominated by humans. There is little debate about this human domination. However, we no longer use the term "Anthropocene" in the white paper.

- Objectives 1–3 do not seem to directly align with questions 1–3.

  There are now 5 objectives, 3 transdiscplinary questions that parse out the overarching question and many thematically specific subquestions. We do not expect them to directly align as some of the objectives are science oriented and others are related to applications and training.

- Q1) Would it be helpful to specify the social-ecological interactions? Also, the question seems a bit broad as it tackles many different variables.

  Please see *Section 2.4* for discussion of social-ecological interactions.

- Q3) It is not clear to me whether we are talking about variations among different forests or variations in time in the same forest. Maybe it's both, but I would suggest making that clear.

  The question has been modified for clarity.

- Q6) I suggest splitting that question in two – although it makes perfect sense, it seems a bit long and hard to follow.

  We have many questions. Because this question "makes perfect sense," we preferred not to split it.

- Q9) I suggest i) specifying the tropical continents you are talking about; ii) splitting the question into two different but interrelated ones.

As noted above we have many questions and we prefer not to split them further. We see no advantage to specifying continents in this question.

- Q17) The question seems descriptive. I would suggest something like "To what extent and how do different human activities and management practices support the resilience of the tropical carbon sink?"

  We see the suggested rewording for this question as largely equivalent to the question developed through our working group process. We retain the original wording.

Q4. How well does the PANGEA scoping study address the key scientific questions or objectives?

- *Se evidencia un buen planteamiento de preguntas y objetivos a alcanzar*. [A good formulation of questions and objectives to be achieved is evident.]
- *C'est sur la collecte le traitement et l'analyse des données*. *C'est sur la collecte le traitement et l'analyse des données*. [It is about the collection, processing and analysis of data.
- The PANGEA scoping study did a great job of addressing the key scientific questions. The scientific questions were present whenever thinking of ecological and geophysical variables relevant to the campaign (pgs. 60 to 62), method suggestions to answer research questions (pgs. 76 to 77), and research applications (pgs. 107 to 115).
- Up to date and for the next generations of scientists and nonscientists.
- The vision to address the scientific questions is impressive.
- From my perspective (physics of the Climate), PANGEA covers most of the main topics. One topic that I would suggest addressing is the long-range transport of important nutrients to the forest and how it will change with climate change. Another important topic is bioaerosol; it is important in cloud (ice) formation, biodiversity, vertical transport, and long-range transport.

  The long-range transport of nutrients is mainly important for the very long term. Bioaerosols are fascinating and important for cloud formation. Both of these topics fall into categories of research related to PANGEA but not part of our core studies. We will seek to collaborate with groups who have strengths in these areas such as the INPA- Max Planck ATTO consortium.

- Overall the scoping study addresses the key questions and objectives well, though the scoping study would benefit from the inclusion of experimental sites across the tropics to link them into the satellite observations.

The PANGEA response to the NASA Terrestrial Ecology Program does not explicitly consider large ecosystem experiments. Those are valuable and may be co-funded by other agencies or private donors as was the case for the Seca-Floresta drought experiment conducted in the Tapajos National Forest, Brazil supported by NSF funds as part of LBA.

- The general aim of the PANGEA exploratory study is to improve our understanding of how tropical forest ecosystems function, by building on current studies and experiments to fill the data gaps, particularly in tropical regions of Africa. To achieve this, PANGEA plans to collect field measurements, particularly at candidate sites in Africa, to fund doctoral and Masters studies on issues related to the functioning of tropical ecosystems in order to confirm hypotheses that have been put forward, to create significant partnerships with the governments of tropical countries and local communities, and to benefit from financial and logistical support from the prestigious NASA, all of which we believe are factors that will help the PANGEA project to achieve its objective. Nevertheless, the exclusion of the tropical regions of South-East Asia is a problem that will make it impossible to make global projections for all tropical forest regions. This is an obstacle to the PANGEA project.

  Limitations in resources would not allow us to conduct field campaigns in all tropical regions. Please see *Section 1.4* on the PANGEA domain. We include an extended domain of pantropical moist forests, the broader area of scientific interest, where additional projects can take place through partnerships, and where satellite and modeling analyses will be conducted.

Q5. Were the proposed methodologies and tools (e.g., remote sensing, data analysis) appropriate for addressing the PANGEA study's goals?

- *Si, muy adecuadas para el estudio PANGEA*. [Yes, very adequate for the PANGEA study.]
- Local airplane routine data collection, and the integration with global networking such as ACTRIS, promote ARM-DOE proposals to help solve specific PANGEA topics...

  These are welcome suggestions that seem appropriate for investigator proposals. ACTRIS is active in Europe and may not be active in the PANGEA domain. Use of the DOE ARM facilities may be appropriate for some investigations. Separate proposals to DOE would be needed.

- There is a thorough review of methodologies (Tables 1 and 4) that the authors used to showcase the amount of resources we have nowadays and that have not been applied in tropical forests. PANGEA makes a good case when pointing out that these methodologies are not absolute and researchers should push the limits of their understanding of science.

No reply to this comment.

- The observational plan was comprehensive but there are a couple of distinctions about geostationary satellites that need a bit more description. I like the inclusion of geostationary satellite observations, which are well-posed to observe tropical ecosystems as they are positioned above the equator in geostationary orbit and make sub-daily observations on time scales of minutes to tens of minutes, that help inform us about sub-daily processes while frequent measurements make it more possible to find cloud-free periods. The ABI on the GOES-R series, especially GOES-16 and GOES-19, sit above South America with great views of the Amazon, but the Advanced Himawari Imager (AHI) is on the Himawari 8/9 series above the Maritime Continent with views primarily of Eastern Asia, Australasia, and surrounds. Imagers on the Fengyun-4 series and GEO-KOMPSAT-2 series also observe Eastern Asia. There's a bit of a gap in geostationary coverage over far Eastern Africa, and MTG-I1 hasn't been commissioned yet to METEOSAT-12 even though it's been flying for almost two years now and will be absolutely critical for observing Africa. As written, the AHI was noted as observing the Amazon (this needs to be corrected). The GeoNEX initiative of NASA has been critical for synthesizing terrestrial observations from geostationary satellites, and it was not clear if their expertise would be integrated (which I would strongly recommend; I also don't know if NASA teams can be explicitly included in NASA scoping projects). It's also important to note that GOES-R can be used to infer GPP and ecosystem respiration through models as with other satellite-based carbon flux estimates. Further emphasizing their ability to infer sub-daily downwelling shortwave radiation and land surface temperature might really help explain how they create a unique real-time observational platform for critical earth system processes.

  We appreciate the detailed commentary on geostationary observations but given the large array of satellite platforms and sensors that we deal with in the White Paper, we cannot take advantage of all this information in the document. We appreciate the identification of the error regarding AHI and this is now corrected.

- Yes, overall the methodologies appear to be appropriate, though I do think that the PANGEA study leaves out the experimental sites to further investigate the impacts of climate change drivers such as drought and carbon dioxide enrichment and land use change sites such and the TMFO sites (see the stakeholder/communities response section). The scientific scoping talks about climate change impacts and I wonder whether those can be fully addressed with just observational studies.

  The PANGEA response to the NASA Terrestrial Ecology Program does not explicitly consider large ecosystem experiments. Those are valuable and may be co-funded by other agencies or private donors as was the case for the Seca-Floresta drought experiment conducted in the Tapajos National Forest, Brazil supported by NSF funds as part of LBA.

- The scoping study seems comprehensive enough. However, the methods and measurements/variables observations seem to fall short in some areas related to increasing the understanding of natural sources and sinks in the tropics. For example, the use of isotope fractioning as a constraint for tow-down and bottom-up modeling is absent in the proposed observing needs and methods (only slightly mentioned in Table 4). There is strong evidence that the systematic collection of isotopic data is a powerful approach for partitioning emissions sources. That is why stable isotope measurements in the northern hemisphere has become a key component of observing networks. Given the constraints and costs of collecting and analyzing these data in the tropics, the proposal should explicitly mention it as one of the areas of observation that PANGEA will seek to strengthen.

  We agree that isotopic methods can provide strong constraints for partitioning ecosystem processes. These are listed among the methods for integrative analyses in *Section 6.3*.

- I would like to suggest you to consider some specific periods of the year (transition period, from dry to wet and vice versa) for activities described in line 2112-2113. Because of their peculiar atmospheric characteristics they have. These periods in West Africa, especially in the northern Benin are those with a lot of mis-understanding

  The White Paper targets intensive campaign periods at the start and end of the dry seasons which can include transitions. This will vary by region and thereby affect campaign timing.

Q6. Did the PANGEA study successfully identify key challenges or uncertainties in the proposed field campaign?

- *Muy de acuerdo ya que las propuestas se han recogido de manera participativa en muchas reuniones* [I totally agree, as the proposals have been collected in a participatory manner in many meetings.]
- Yes, I guess so, but multi-countries, each country with specific administrative procedures as licenses for measurements, airplanes, etc could be a challenge.
- Yes, the study effectively identified key challenges and uncertainties, particularly in Section 7, which discusses Technical and Logistical Feasibility. The authors addressed several potential issues, such as the complexity of managing a large team, and presented solutions to avoid communication bottlenecks by streamlining the campaign's organizational structure. Other challenges, such as potential community disengagement or international funding issues, were also acknowledged, with

strategies like engagement plans and leveraging networks for alternative funding suggested as solutions.

- As noted elsewhere I found the notes regarding political instability to be well-reasoned.
- The proposed field campaign fully addresses the issues of climate change and biodiversity, both of which include deforestation, land-use change, fires, droughts and so on. Climate change, the repercussions of which lead to numerous losses of human life and infrastructure, is linked to the flow of carbon contained in CO_2 and CH_4, among other things.
- The main challenge identified by PANGEA is linked to the uncertainty of the quality of the response of tropical forest regions to climate change, which is itself largely linked to carbon flows in the atmosphere. The certainty is that the diversity of tropical forest landscapes and the anthropogenic threats they face inevitably lead to heterogeneity in the response and vulnerability of these landscapes to anthropogenic threats. Thus, understanding atmospheric carbon flux and its current and future trends will be important for a better understanding of the problem of climate change, which is the greatest challenge facing mankind today. The PANGEA campaign is therefore helping to identify the greatest contemporary challenge facing humanity.

Through our extensive consultations, we gained a great deal of wisdom and perspective regarding challenges and uncertainties.

Q7. How would you rate the relevance of the proposed study design for advancing our understanding of terrestrial ecosystems?

- *El diseño aborda puntos específicos para comprender el funcionamiento y dinámica de los ecosistemas.* [The design addresses specific points to understand the functioning and dynamics of ecosystems.]
- PANGEA is necessary because field campaigns in tropical forests would allow scientists to study the natural state of the tropical biomes and how human activities impact it:
  - Understanding the natural state such as how aerosol particles form, grow, and travel within the tropics, e.g., dust from Africa to South America;
  - Measuring human impact such as pollution and deforestation moved through the atmosphere from temperate latitudes to tropics;
  - Identifying critical zones that are considered tipping points for terrestrial emissions; and

- Measuring and validating land variables such as the leaf area index (LAI) and the fraction of absorbed photosynthetically active radiation (FAPAR), which are essential forcing variables for different models.

- The team did an outstanding job emphasizing the outsized role of tropical ecosystems in the earth system with extensive focus on coupled biogeochemical/hydrological cycles, state-of-the-art sensing systems, and critical questions that extend beyond disciplinary and geographical boundaries.
- I would consider the relevance of this proposal high based on the approaches used and the importance of tropical regions to the global c cycle (and of course how these areas are threatened by climate change).

  No reply to these comments.

- The relevance of the study design is very important for our understanding of terrestrial ecosystems. However, I do think that the study scope is too observational and could benefit from experimental sites or identify sites that have very specific conditions, like the hot spring 'natural warming' experiment.

  We have previously replied to similar comments regarding experiments whether artificial or "natural."

- PANGEA's objective, which is to gain a better understanding of how terrestrial ecosystems function, is a good and laudable one; achieving this objective will probably make it possible to develop appropriate policies to deal with problems such as climate change and the loss of biodiversity. PANGEA is strategically designed on the basis of a set of hypotheses linked in particular to the heterogeneity of the response and vulnerability of tropical regions to anthropogenic threats. PANGEA provides for these hypotheses to be verified by coordinating field, airborne and satellite data. We believe that this is relevant to achieving PANGEA's objectives. What is most interesting about PANGEA is that it focused particular attention on African tropical forests, giving priority to terrestrial and aerial measurements because of the major gaps in data and knowledge in this tropical region. Although this is a good orientation for the PANGEA project, it remains partial because of the exclusion of the tropical forests of South-East Asia, whose inclusion in the study would have made it possible to obtain global data and to make more global projections for all tropical forest regions. How feasible do you find the proposed technical and logistical implementation of the field campaign? The technical and logistical implementation of the proposed field campaign seems feasible for two reasons:
  - The first is that scientists from the various human and social sciences from all walks of life, and particularly from tropical forest landscapes, are involved in the study. Scientists from tropical regions have the advantage of mastering the reality of what is happening in terms of climatic disturbances or the consequences of these

disturbances and threats to biogeochemical balances and local biodiversity. This is an advantage in terms of addressing the right scientific questions and obtaining the right information from data or measurements collected on the ground.

- Secondly, NASA's potential sponsorship is a major asset, both financially and above all logistically, as PANGEA will have no difficulty in obtaining reliable data from NASA's airborne and satellite observations. This data could also potentially come from other organisations with the capacity to obtain this type of information. In addition, PANGEA has an empirical study area represented by tropical forest areas, which are of paramount importance in the fight against climate change and the protection of diversity. In empirical terms, the choice of this study area is an important factor in the relevance of the PANGEA project.

We have commented previously about the inclusion of Asia. Asia is not excluded: It is part of the extended domain. PANGEA is not seeking resources for campaigns in Asia. Partnership with other sponsors could extend PANGEA work to Asia following similar scientific themes and approaches.

- Missing the dry tropics!

Please see the response to this topic above.

Q8. How feasible do you find the proposed technical and logistical implementation of the field campaign?

- *La implementacion permitirá validar información local con las metodologías apropiadas a cada región*. [The implementation will allow local information to be validated with the methodologies appropriate to each region.]
- Considering the number of people involved in this campaign makes the implementation feasible. As with any other project, this field campaign might not be exempt from stumps on the development, but it would just mean that extra studies in the proposal might not be prioritized if they do not answer a research question directly. For example, as mentioned before, the forecasting analysis of gas fluxes might become secondary as authors might prioritize finishing any data collection project by the end of the campaign.
- There is an inherent level of elevated complexity with conducting fieldwork in remote areas and (as outlined in the proposal) even greater concerns in parts of Africa given the political and social instability of the region. Acknowledging this however, I do think that given the partners listed, the expertise of the team involved… that with sufficient resources it would be very feasible. It will be logistically challenging, though I think the folks involved and partnerships outlined indicate great potential of success.

- I am an expert in on the ground field ecology, so I cannot comment on the remote sensing aspects, but it all appears feasible.
- The project is quite ambitious, both in terms of its scope and geographical extent – it covers many forest areas in different countries in Brazil and South America. However, the technical and logistical approaches are well grounded and have a great potential for succeeding in their implementation on the ground.

  No reply to these comments except to appreciate the votes of confidence.

- As someone from the tropics in the Philippines who has worked in the Amazonian forest, I would say the project team should consider the safety aspect of the infrastructure/equipment deployment. Extreme events, terrain, and manpower support must also be considered. An eddy covariance flux tower I worked with, the Amazon, always faces instrument failure due to wildlife interference/intrusion. Power supply (mainly solar panels) due to cloudy days is a significant problem. The safety of personnel and equipment is vital.

  All of these are important concerns that are not the main subject of our conceptual document but will be strong considerations if we are selected to develop an operational experiment plan. We note that the NASA project office has extensive tropical forest experience and has dealt with problems similar to those raised above.

- I consider the proposal still quite open to discussion of implementation, but this first step of the test bed is very important to give a momentum. I hope the proposal will be open to non-Americans, too.

  NASA has done more than a "testbed" in tropical forests through its experience as part of the Brazilian led LBA. Non-Americans are welcome to participate although NASA has limitations in funding institutions outside of the U.S. We are actively seeking co-funding, as noted in *Section 10.2*.

Q9. Are there any potential barriers or challenges that the PANGEA scoping study did not adequately address?

- *Si hay barreras, son las culturales y de idioma, ya que en el ámbito de intervención de Pangea existe una gran diversidad cultural y de idiomas que debe abordarse con mucha importancia* [If there are barriers, they are cultural and language barriers, since in the area of Pangea there is a great cultural and language diversity that must be addressed with great importance.]

  During the scoping process PANGEA worked to break barriers. For example, we held regional meetings with simultaneous translation. We made the draft White Paper available in several languages including Spanish. We have responded to comments on the document that were provided in Spanish and French. Our White Paper document (including these replies) will be translated into Spanish, French, Portuguese, and Bahasa Indonesia. Our intention is to continue these practices in order to minimize barriers.

- The issue of the security of some study field.

  Safety of project participants is a top priority. Evaluation of field site safety will be the responsibility of the Project Office. Sites that are at high risk may need to be avoided. See *Section 10.5* for a discussion of risks and risk mitigation.

- One potential challenge that PANGEA may not have fully addressed is the underrepresentation of Asia in the scoping groups, despite the study's focus on tropical regions. While this omission may not hinder the achievement of individual project goals, it could become a barrier when attempting to present the campaign's findings on a global scale.

  Because of the limitations in resources, we devoted more attention to Africa and the Americas than to Asia. However, we did outreach in Asia and if funded we will continue to reach out to avoid the potential barrier raised in this well-placed comment.

- A key knowledge gap not addressed in the scoping study is how tropical deep convection impacts our view of the carbon cycle. Current global atmospheric transport models vary in convective parameterization, and we lack a clear grasp of the carbon flux misattributions caused by inadequately resolved vertical transport in the tropics (Stephens et al., 2007). Recent advances in cloud resolving models show promise in accurately representing tropical convection and its impact on the distribution of carbon cycle tracers. This may help improve top-down carbon flux estimates in the tropics. A modeling/data assimilation system that incorporates the latest advances in atmospheric transport representation should help us more accurately interpret trace gas observations across scales for an improved understanding of tropical carbon dynamics.

- The report identifies that "fluxes from respiration, methane emissions, and lateral flows of carbon, have been shown to be substantial in tropical forests" (line 1319–1321, page 36), but does not provide any concrete plan to measure lateral carbon transport in the field. Instead, it is stated that "inundation from NISAR and BIOMASS will support tropical forest wetland mapping and will be integrated with measures of surface water flows from SWOT, enabling direct measurements of lateral carbon fluxes from tropical systems" (line 1374–1376, page 38). I am perplexed how this is achievable given that none of the aforementioned satellites track dissolved inorganic carbon or dissolved/particulate organic carbon. Perhaps PACE would be helpful? But field measurements would still be needed to track lateral carbon transport and validate satellite data products and models.

Reference

Stephens, B. B., Gurney, K. R., Tans, P. P., Sweeney, C., Peters, W., Bruhwiler, L., Ciais, P., Ramonet, M., Bousquet, P., Nakazawa, T., Aoki, S., Machida, T., Inoue, G., Vinnichenko, N., Lloyd, J., Jordan, A., Heimann, M., Shibistova, O., Langenfelds, R. L., … Denning, A. S. (2007). Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO_2. Science, 316(5832), 1732–1735. https://doi.org/10.1126/science.1137004

Improvements in understanding of atmospheric transport is outside of the scope of PANGEA. Proposed research using model inversions will be subject to peer review that should identify problems with the transport models used.

Quantifying lateral fluxes is a research problem that we have identified but we have not identified the solution.

- There are likely granular issues that could always be considered in greater detail, but I think the scoping document sufficiently addresses concerns at this stage.

  No reply to this comment.

- Need to keep up engagement with partners in Africa and South America, doing this well is a challenge

  We absolutely agree. In *Section 10,* where we discuss the project organization, we mention a number of mechanisms for facilitating ongoing interactions. We have learned from previous projects that we need to build strong interpersonal relations based on work together as equals. This is always a challenge for everyone involved but as we learned during LBA, it is not a barrier.

Q10. Do you think the PANGEA study will foster meaningful partnerships with stakeholders (e.g., local communities, governments)?

- This isn't easy but could be improved over the years if there is an understanding of the stakeholders and local communities...Christmas parties, etc, will not make local people integrated

  We are certain that the commenter is being ironic. We made no mention of activities like Christmas parties. The White Paper contains a full section (*Section 8*) on community engagement and we do recognize the challenge and present strategies to confront the challenge. We also point to another comment quoted here regarding the confidence gained from our draft White Paper, "The plan to engage local communities and governments early on in the plan is critical and I feel that the plan is very cognizant of all of the dynamics that can emerge once the project is funded; there are many more entities at stake than for ABoVE. "

- Yes, PANGEA can foster meaningful partnerships with stakeholders. But as I have already said, it will be important to secure government's commitment and involvement very early. The same with private sector working in the forestry sector for example

  We agree with the comment. We provide evidence that we have initiated the process of engagement in our appendices, including letters of support (*Appendix A*) and *Appendices B* and *C*, which detail the outreach that we did with governments and other institutions.

- As it is an international campaign, PANGEA will enforce relationships with local governments and NGOs based on topics.
- Yes. Work much more with communities than the state authorities.
- I believe so, yes. The tropical regions need as much support we can lend, given that the support would be lasting and not lip service. This scoping document I feel addresses this sufficiently. I encourage the team to keep avoiding "helicopter science" at the forefront of their work though (as they have done herein).
- PANGEA is impressive in how it will form effective partnerships with stakeholders.
- Yes, I believe the project has already managed to gather a very committed group of entities. I also believe that, as the project progresses, many more people will become interested. This problem of forest conservation is becoming a universal concern and the tendency is that partnerships will only increase.
- Yes because PANGEA if funded will bring solutions for some challenges stakeholders and governments are facing. For example here in Benin, in Lama Forest Reserve (South Benin), a Mosaic of Natural, Degraded and Teck Plantation Forest managed both by the national agency of wood and forest are searching how to combat efficiently the bushfires in the dry season. These consume a lot of tree populations and probably affects the productivity of their plantation thus their economies. So the PANGEA scope study will undoubtedly foster meaningful partnership with stakeholders.

  We appreciate these comments and have no direct response.

- Ideally, but as it is now, the proposal is very vague in demonstrating how sustainable, long-term partnerships for the operation and maintenance of the observing networks will work. Guaranteeing continuous network operation with real-time data sharing is a massive endeavor in the tropics that requires support and commitments from all national governance levels, not only research communities. Deployment of experts, communications, and technology in the PANGEA domains requires coordination across several actors in the field, but the proposal seems to focus intensely on research institutions, which have a limited scope of action to address legal, political, and socioeconomic challenges that the field campaigns will face.

The White Paper presents a conceptual plan as opposed to an operational plan. Many of the issues raised here are operational. This may account for the characterization of the plan as "vague." Through its long history of campaigns including LBA and ABoVE the NASA project office has demonstrated success in field deployments, data collection and data sharing.

- Everything depends on what PANGEA does to achieve this objective. A number of prerequisites need to be met before these partnerships can be put in place, and in my opinion they are essential if the PANGEA project is to achieve its objectives. Indeed, without the support of the local communities living in the candidate sites identified and chosen by the PANGEA project, and whose community areas are included in the study for experimental purposes, PANGEA runs the risk of being rejected by these populations. It is therefore necessary and essential for the PANGEA project to carry out actions targeted at these populations in order to guarantee their support and acceptance of the PANGEA project. Similarly, without the support of the governments of tropical countries, particularly those in the Congo Basin, PANGEA will not be able to achieve its objectives. For this reason, the formal and legal nature of compliance with legislation on access to candidate territories or landscapes will not be enough. It will be necessary to integrate additional motivations and incentives addressed directly to these local communities and to members of the government in order to encourage the establishment of meaningful partnerships with these two entities. This will ensure their full cooperation and support for the PANGEA project's objectives.

  Building relationships with governmental and local community partners is always important. This is a valuable comment.

Q11. Are there additional stakeholders or communities that should have been involved in the PANGEA study?

- *Las comunidades campesinas y nativas o cualquier otra que este posesionada en el territorio donde se desarrollara el proyecto, ya ellos cuentan con saberes ancestrales*. [The peasant and native communities or any other that is located in the territory where the project will be developed, already have ancestral knowledge.]

  PANGEA expresses interest in integration of Indigenous, local, and traditional knowledge with remote sensing. See, for example, *Section 9.1* of the White Paper.

- The project has covered almost all stakeholders needed for the project.

- Sure, but it will only be possible to clearly identify on the field. So, the project should be open to broadening the scope.
- Private sector, especially those working in the field of forestry, agriculture and mining should be strongly involved.
- It will be nice to involve local communities directly (their representative), without going through the authorities. To avoid fraud.
- It might also be a good idea to include the network of African parliamentarians, who are often involved in the conservation and sustainable management of forest ecosystems in Central Africa.

  We have no specific replies to these comments.

- I'm not sure if it's an option to include NASA initiatives in the scope itself, but the NASA-sponsored GeoNEX team (https://www.nasa.gov/nasa-earth-exchange-nex/earth-observations-geonex/data-products/) has been instrumental in creating and disseminating geostationary data products across multiple satellites.

  We recognized the importance of Geostationary observations (e.g., *Section 3.1*), but we did not specifically call out GeoNEX. We are aware of those activities and they have much to contribute to PANGEA.

- Any study this size has to keep an open mind to including other stakeholders that might present, though on the science side I think the experimental science community appears to be left out. I understand that NASA is all about observations (especially from satellites), but leaving out the AMAZON FACE CO_2 enrichment, EsecaFlor drought experiment, TmFO (Tropical managed Forest Observatory) for forest disturbance, and Luquillo experimental forest appears to be out of place. The focused satellite observations at these sites can help inform the science questions the program is trying to address.

  We have responded previously to the question of ecosystem experiments (see above.)

- I think it would be possible to enumerate university partners in the regions.

  Appendices B, *C*, and *D* list many of these partners.

- The World Environmental Conservancy (WEC), a private American nonprofit foundation, would be happy to be involved in this project. WEC has many Brazilians involved in its projects who are part of Brazilian universities, institutes and entities who likely would be happy to provide the necessary support on site.

  This is excellent news. PANGEA will be in touch.

- I suggest including the conserved upland (terra firme) forests alongside the PA-370 (km 107) (2°53'7.95"S; 53°57'37.79"W). They occur on clay soils and have a high diversity of large trees such as Brazil nuts (Bertholletia excelsa). This area constitutes a new regional agricultural frontier. This is an understudied landscape that is part of my dissertation research. The larger Curuá-Una region in Santarém has characteristics of both old and new frontiers, namely decades-long monocultural fields (old frontier) and ongoing deforestation for mono-crop expansion (new frontier) (Coelho et al., 2021; Schielein & Börner, 2018). The region is in the Santarém Plateau, an extensive upland area adjacent to the confluence of the Tapajós and Amazon Rivers (Barros et al., 2020). Travelling from Santarém towards Uruará on the PA-370 highway, one sees stark differences in land use and forest conservation between the areas before and after the Curuá-Una hydroelectric dam. Before the dam, there is an area of long occupation for agricultural purposes (starting in the 1960s), with current predominance of large-scale monocultural fields (soybeans/corn). After the dam, the occupation is much more recent (starting in the 2010s) and forest cover is much higher. The presence of areas with different occupancy times allows for temporal land-use analysis, which could be a useful lens to understand heterogeneity in forest dynamics. I believe including this landscape would provide i) compelling data to compare with the well-studied Tapajós National Forest (km 67 of the BR-163), and ii) useful insights to understand tropical forest landscapes. I have partnerships with local communities in this region (Aprocad Farmers' Association), a smallholder farmer cooperative (COOPBOA – Cooperative of Family Farmers of the Boa Esperança Community), and local scholars at the Federal University of Pará (UFOPA), in Santarém—Dr. Tiago Vieira, Dr. Helionora Alves, Dr. Diego Amoedo—and Federal University of Western Pará (UFPA), in Belém—Dr. Valério Gomes, Dr. Raquel Santos, and Dr. Katiane Silva.

  This is an excellent suggestion for the extension of the potential landscape near Santarem. It provides a rich area for comparison to the BR-163.

- In Colombia, I suggest including the El Caraño community (01°44′47.1" N, 075°41′35.9″ W), located on the eastern slopes of the East Andes ridge, between the Andes and Amazonian ecosystems in Florencia, Caquetá. The tropical Andes are among the most biologically diverse areas of the world in terms of species richness and endemism. The high biodiversity rates are frequently attributed to characteristics of and changes in landscape through time (Moritz et al. 2000; Trénel et al. 2008; Sarkinen et al. 2012). The Andean Tropical Montane Cloud Forest (TMCF) is a tropical Andean ecosystem that plays an essential role in the local and regional water cycles (Aldrich et al. 1997; Fahey et al. 2016). However, expansion of agriculture and urbanisation are causing much deforestation in TMCF areas (Etter & Wyngaarden 2000; Armenteras et al. 2003). Consequently, this ecosystem has been highly fragmented (Aldrich et al. 1997; Brummitt & Lughadha 2003; Gotsch et al. 2015). The cloud forests characteristic of the region are remarkable for their high occurrence of the family Arecaceae, with 24 genera and 109 species of palms (Borchsenius & Moraes 2006). I also have partners in Colombia who could greatly contribute to this project: Dr. Oscar Perdomo (Full Professor at University of Boyacá) and Edwin Trujillo (Professor at University of the Amazon).

Montane environments are undoubtedly important but we have decided to exclude them from PANGEA because they cover very small areas compared to the lowlands and require specific and detailed sampling to account for heterogeneity in topographic and edaphic characteristics, which because resources are finite would limit sampling in other large-scale gradients.

Q12. Are there areas where the approach to diversity and inclusion could be improved?

- *Si, en comunidades establecidas en el ámbito del bosque, ya que ellos son lo que hacen uso directo del bosque o ecosistema*. [Yes, in communities established in the forest area, since they are the ones who make direct use of the forest or ecosystem.]
- *Approche basée sur le dynamique social, la prise en compte du gémi local des communautés local a la base, l'implication des communautés local dans les prise des décision , la prise en compte des aspect de la protection transversale , l'inclusion social , lutte contre la violence basée sur le Genre,l'implication des ONG national dans la mise en œuvre des activités , le renforcement des capacités des communautés local a la base , la formation professionnelle et techniques , l'appui pour la résilience des communautés local a la base , appui pour le développement économique social et durable , la mobilisation communautaire*. [Approach based on social dynamics, taking into account the local grievances of local communities at the grassroots, the involvement of local communities in decision-making, taking into account aspects of cross-cutting protection, social inclusion, the fight against gender-based violence, the involvement of national NGOs in the implementation of activities, capacity building of local communities at the grassroots, vocational and technical training, support for the resilience of local communities at the grassroots, support for social and sustainable economic development, community mobilization.]

  Working with local communities will require strong local partnerships. See *Section 8* of the White Paper for our strategy, which has been substantially revised from the first draft.

- The project articulated nicely connections with Indigenous and local communities, and I know that this is not necessarily within the scope of NASA, but connecting findings to underserved US-based communities can further improve outcomes, help train the next generation of US scientists, and improve the future of international collaboration.

One of the areas where PANGEA can connect to underserved US communities is through workforce development. This may be possible through participation in NSF Research, Innovation, Synergies, and Education (RISE) and Geoscience Opportunities for Leadership in Diversity (GOLD-EN) programs (*Section 7.1*).

- Not to my knowledge. The team has done a remarkable job and is using strong tested methodologies to be inclusive.

No reply to this comment except that we like it a lot.

Q13. Do you have any additional suggestions or feedback for the proposed PANGEA field campaign?

- *Es una brillante oportunidad para conservar y manejar sosteniblemente los ecosistemas tropicales*. [It is a brilliant opportunity to conserve and sustainably manage tropical ecosystems.]
- *Nous souhaitons signer une convention cadre de partenariat avec votre institution , travailler avec vous en partenariat consortium, bénéficier de l'assistance techniques , avoirs soutient financier, logistique équipement pour la mise en œuvre du projet*. [We wish to sign a framework partnership agreement with your institution, work with you in a consortium partnership, benefit from technical assistance, financial support, logistics equipment for the implementation of the project.]
- Better communication around the campaign.
- Providing much time and resources for fieldwork, in my opinion; it will be the more challenging, particularly in Africa.

No reply to these comments.

- If funded, create space for outside collaborations/collaborators to help augment and extend the work. Develop lasting infrastructure in the study regions. And also know that you put together a great scoping document/proposal here. A joy to read!

Outside collaborations will be an important part of PANGEA's success (see *Sections 8* and *10.2*). History suggests that while development of infrastructure is important, it is far more important to develop human resources. We will do what we can to promote both as described in the White Paper but people will be our priority.

- I would love if you can consider two tropical forest landscapes located in Benin as candidate for this scoping study. Both are suitable and fulfill all details provided in the white paper (accessibility, at least 100km2; availability of flux tower; etc.).
  - The first one - Bellefoungou (9.79115 N ; 1.718 E) is established above a clear forest with an eddy covariance of energy, water vapor and carbon dioxide fluxes, ground

and weather measurements, geophysical survey. Bellefoungou is running since 06/2008 until today thus a long term flux data are available.

- The second one - Lama Forest Reserve (6.57360N; 2.10480E). The eddy covariance site will be installed in 2025 above a Mosaic of Natural, Degraded and Plantation Forests (Tectona grandis and Senna siamea). The Lama Forest reserve is known worldwide, studied since a while. Its total area estimated at 16.250 ha and easy to access. The anthropogenic disturbances combined with climate change influence the growing conditions at this landscape and modify the demographic parameters such as germination, seedling and sapling growth and mortality rates.

These Benin sites are included among the candidate study locations in 6.2.2.

G. Topics beyond the Scope of PANGEA

While PANGEA is ambitious and integrative, there were several topics that were determined to be beyond scope by PANGEA Working Groups and leadership. Those items are listed in Table G-1.

Table G-1. Items, topics, and questions that were determined to be beyond the scope of PANGEA

ITEM/TOPIC/QUESTION EXCLUDED	WHY
HOW ARE SOIL CARBON STOCKS CHANGING?	There is no direct remote sensing link, and mineralogy matters more than productivity for controlling carbon stocks. Eddy covariance flux towers cannot separate autotrophic respiration from heterotrophic respiration, and there is too much heterogeneity to scale between soil chambers and towers
NITROUS OXIDE (N_2O)	Tropical forests are an important global source of N_2O. However, because of the extremely long tropospheric lifetime of N_2O, it is difficult to quantify regional and local sources and sinks using techniques that depend upon atmospheric sampling such as flux inversion and eddy covariance. The lack of these top-down techniques results in limited constraints on regional and local sources and sinks of N_2O. N_2O ecosystem measurements are mainly limited to chamber techniques. Because N_2O fluxes are highly episodic and spatially variable, the sampling effort required to adequately quantify N_2O sources is very large. Despite the importance of N_2O, the costs of adequately quantifying N_2O are very high compared to other studies that can be done as part of PANGEA.
MANGROVES AND MONTANE FORESTS	Tropical mangrove and montane forests both constitute relatively small domain areas within the broader tropics, although both are highly relevant due to the unique adaptation of organisms to micro-environments and important contributors to carbon cycling. Montane and coastal environments require specific and detailed sampling to account for heterogeneity in topographic and edaphic characteristics, which would limit sampling in other large-scale gradients. Coastal environments pose additional challenges with the timing of sampling (especially for lidar). There are, however, opportunities for PANGEA to align efforts with other tropical mangrove and montane forest research.
HOW CAN WEATHER FORECAST DURATION AND RELIABILITY BE IMPROVED IN THE TROPICS? **HOW CAN PREDICTIONS OF CLIMATE VARIABILITY AND CHANGE BE IMPROVED IN THE TROPICS?**	These are important scientific questions but were considered outside the scope of a terrestrial ecology field campaign. However, the outcomes of PANGEA on improved understanding of the biosphere controls on energy, water, and carbon cycles will contribute indirectly to improving weather forecasts and predictions of climate variability.
ROOT FUNCTIONING AND SOIL FAUNA/MICROORGANISM INTERACTIONS WITH ECOSYSTEM FUNCTIONING	These topics were not included in the main scope of PANGEA due to the present-day challenges of scaling below-ground processes using remote sensing. Elements of this research area may be included through synergistic projects with current and forthcoming activities.

Table G-1. Items, topics, and questions that were determined to be beyond the scope of PANGEA	
ITEM/TOPIC/QUESTION EXCLUDED	WHY
HOW ARE NUTRIENTS DISTRIBUTED VERTICALLY IN A FOREST CANOPY (E.G., CONCENTRATION, SEASONALITY, VARIATION WITH RESOURCES, AND GEOGRAPHY)?	Retrieving vertical heterogeneity of leaf traits would require far more intensive field sampling, which would severely limit the ability to capture variation across gradients in top-of-canopy dynamics. However, this is an important question and may be investigated at small scales through synergistic projects.
WHAT SURFACE PROCESSES DRIVE CONVECTIVE DEVELOPMENT, PRECIPITATION, AND EXTREME EVENTS IN TROPICAL FORESTS, AND HOW ARE THEY INFLUENCED BY CLIMATE CHANGE?	This research topic is partially addressed in Q20, but the intended measurements during PANGEA will not be sufficient to address this question as a stand-alone project. Elements of this question may be addressed through broader collaborative projects.
HOW DO CHANGING CLIMATE AND EXTREMES IMPACT CLOUD-AEROSOL INTERACTIONS, ATMOSPHERIC CHEMISTRY, AND ASSOCIATED TROPICAL FORESTS LAND-ATMOSPHERE FEEDBACKS?	The intended measurements during PANGEA will not be sufficient to address this question as a stand-alone project. Elements of this question may be addressed through broader collaborative projects.
HOW DO SOCIO-ECONOMIC FACTORS, SUCH AS LAND TENURE, ACCESSIBILITY, AND POLICY, INTERACT WITH BIOPHYSICAL AND CLIMATIC FACTORS TO INFLUENCE FOREST REGENERATION AND ECOSYSTEM SERVICE PROVISION?	This question provides an important foundation for understanding why land-use and land cover are changing. However, this question relies more on social, policy, and economic data and there is no clear link between this question and remote sensing. Some PANGEA-funded projects may opt to tackle this question using innovative methods. There are also opportunities to align PANGEA activities with related efforts to address this question.
WHAT ARE THE CONNECTIONS BETWEEN SOCIAL TIPPING POINTS AND ECOLOGICAL TIPPING POINTS IN THE TROPICS, AND HOW DO THEY VARY ACROSS DIFFERENT TROPICAL GEOGRAPHIES?	While understanding the relationship between how social and ecological feedbacks influence the potential of tropical forests to reach critical transitions is needed, there is no direct link between this question and remote sensing. Some PANGEA-funded projects may opt to tackle this question using innovative methods. There are also opportunities to align PANGEA activities with related efforts to address this question.
RELEVANT QUESTIONS WITHIN THE SCOPE OF PANGEA BUT NOT DIRECTLY DEFINED IN THE WHITE PAPER	
HOW SENSITIVE ARE LAND MODEL PROJECTIONS TO DIFFERENT PARAMETERIZATIONS OF PLANT FUNCTIONAL DIVERSITY (E.G., PANTROPICAL VS. CONTINENT-SPECIFIC DIVERSITY PARAMETERIZATIONS; DIVERSITY WITHIN SIMULATED COMMUNITIES/GRID CELL)? WHAT FUNCTIONAL TRAITS ARE MISSING FROM PARAMETERIZATIONS?	These two questions are not included in the science questions in PANGEA because they are not directly related to remote sensing measurements. However, quantifying and constraining parameter uncertainty of models will be a major mechanism by which models will be integrated with observations, and the lack of functional traits that can be measured by PANGEA will be assessed in consultation with modelers during the elaboration of the Concise Experimental Plan.
WHAT ARE THE IMPACTS OF EDGE EFFECTS ON FOREST RESILIENCE AND STRUCTURAL COMPLEXITY?	This question is not directly listed as a key PANGEA scientific question, but this will be part of a broader investigation of the impacts of multiple questions (e.g., Q15, Q16, Q20).

Table G-1. Items, topics, and questions that were determined to be beyond the scope of PANGEA	
ITEM/TOPIC/QUESTION EXCLUDED	**WHY**
HOW DO DIFFERENCES IN THE LEGACY OF DEFORESTATION AND DEGRADATION ACROSS CONTINENTS AFFECT THE FOREST RECOVERY AND THE RESTORATION OF KEY ECOSYSTEM SERVICES?	This question relies mostly on historical data, which may be outside the scope of PANGEA. However, this line of research will be fundamental for contextualizing observations in PANGEA and will be addressed through partnerships (e.g., MapBiomas).