SCIENCE PLAN

Next-Generation Ecosystem Experiments (NGEE)-Tropics

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DEPARTMENT OF ENERGY
Office of Biological and Environmental Research (BER)

Next Generation Ecosystem Experiments (NGEE)-Tropics

Phase 2 Proposal

Submitted to the Climate and Environmental Sciences Division,
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Use of Human Subjects: No
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ACRONYM LIST

AMSR-E—Advanced Microwave Scanning Radiometer - Earth Observing System (NASA's Aqua satellite)
ARM—Atmospheric Radiation Measurement, DOE user facility for atmospheric observations
ATS—Advanced Terrestrial Simulator
BCI—Barro Colorado Island in Panama (research site)
BER—DOE Office of Biological and Environmental Research
BNL—Brookhaven National Laboratory
CERFACS—Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (France)
CESD—DOE's Climate and Environmental Sciences Division
CFFDRS—Canadian Forest Fire Danger Rating System
CLM—Community Land Model
CLM-PAWS—CLM Process-based Adaptive Watershed Simulator
CMIP5—Coupled Model Intercomparison Project Phase 5
CMIP6—Coupled Model Intercomparison Project Phase 6
COSMOS–Cosmic-ray Soil Moisture Observing System
CZO—Critical Zone Observatory
DHSVM—Distributed Hydrology Soil Vegetation Model
DOC—Dissolved organic carbon
DOE–Department of Energy
DRO—Daintree Rainforest Observatory in Australia (research site)
E3SM—DOE Energy Exascale Earth System Model
EC—Executive Committee (cf. Management Plan)
ECMWF–European Centre for Medium-Range Weather Forecasts
ED–Ecosystem Demography
ED2—Ecosystem Demography model version 2
EH&S—Environmental Health and Safety
ELM—E3SM Land Model
EMSL—Environmental Molecular Sciences Laboratory (DOE user facility at PNL)
ENSO—El Niño Southern Oscillation
ESM—Earth System Model
ESS-DIVE—Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (DOE sponsored)
ET—Evapotranspiration
FATES—Functionally Assembled Terrestrial Ecosystem Simulator
FATES-Hydro–FATES' plant hydrodynamic module
FFDI—McArthur Forest Fire Danger Index
FIA—USFS Forest Inventory and Analysis database
FLUXNET–Flux Network
ForestGEO—Forest Global Earth Observatory, a global network of forest research sites and scientists focused on forest function and diversity
FRAMES–NGEE-Tropics metadata reporting framework
GEDI—Global Ecosystem Dynamics Investigation
GEM—Global Ecosystem Monitoring, a global network of forest research sites and scientists focused on forest carbon budgets and function
GLDAS—Global Land Data Assimilation System
GLiHT—Goddard's Lidar, Hyperspectral & Thermal Imager: a portable, airborne imaging system that simultaneously maps composition, structure, and function of terrestrial ecosystems
GPP—Gross primary productivity
GRACE—Satellite data offering Level-3 data grids of monthly surface mass changes
GSWP3—Global Soil Wetness Project Phase 3
GWT—Groundwater table
H3D—Hybrid-3D hillslope hydrological model
HPC—High performance computing
Hs—Hypotheses
ICESat/GLAS—Ice, Cloud, and land Elevation Satellite/Geoscience Laser Altimeter System
ILAMB—International Land Model Benchmarking, a model-data intercomparison and integration project
INPA—National Institute of Amazonian Research
IRGA—Infrared gas analyzer
ISS—International Space Station
J_{max}–Maximum electron transport rate
JGI—Joint Genome Institute, DOE user facility at LBNL
K34—Tower at Manaus research site
LAI—Leaf area index
LANL–Los Alamos National Laboratory
LBA—Large-Scale Biosphere-Atmosphere Experiment in Amazonia
LBNL–Lawrence Berkeley National Laboratory
LH—Lambir Hills in Malaysia (research site)
LH–Latent heat flux
LMA—Leaf mass area
LTER—Long-term Ecological Research
LUH2—Land-Use Harmonization
LUMIP–Land-Use Model Intercomparison Project
LUNA—Leaf utilization of nitrogen for assimilation (mechanistic model)
MAAT—Multi-assumption architectural testbed
MFV—Macropore flow velocity
ModEx—Model and experimental integration
MODIS—Moderate Resolution Imaging Spectroradiometer
N_a–Area-based leaf nitrogen
NASA–National Aeronautics and Space Administration
NCAR—National Center for Atmospheric Research
NCEP–National Centers for Environmental Prediction
NDVI—Normalized difference vegetation index
NEE–Net Ecosystem Exchange flux
NFDRS—US National Fire Danger Rating System
NGD—Next Generation Development
NGEE–Next Generation Ecosystem Experiments
NPP—Net primary productivity
NSC—Non-structural carbohydrates
OCO-2–Orbiting Carbon Observatory-2
ORNL–Oak Ridge National Laboratory
P-cycle—Phosphorus cycle
ParFlow—Parallel hydrological flow model that simulates the hydrologic cycle from bedrock to top of the plant canopy
PARTEH—Plant Allocation and Reactive Transport Extensible Hypothesis
PAW—Plant available water
PDF—Probability distribution functions
PEcAn—Predictive Ecosystem Analyzer, a suite of ecosystem modeling tools
PFT—Plant functional type
PHS—Plant hydraulics scheme
PNM—Parque Natural Metropolitano (Panama research site)
PNNL—Pacific Northwest National Laboratory
Qs—Science Questions (associated with RFAs)
QA/QC—Quality Assurance and Quality Control

Rainfor-GEM—Amazon Forest Inventory Network-Global Ecosystem Monitoring
RFAs—Research Focus Areas
ROs—Research objectives
SAB—Scientific Advisory Board
SIF—Solar-Induced chlorophyll Fluorescence
SLZ—San Lorenzo (Panama research site)
SPITFIRE—SPread and InTensity of FIRE (mechanistic global fire regime model)
STRI—Smithsonian Tropical Research Institute
TBM—Terrestrial biosphere model
TDR–Time domain reflectometry
TPU—Triose phosphate use
TRACE—Tropical Responses to Altered Climate Experiment project
tRIBS—TIN(triangulated irregular network)-based Real-time Integrated Basin Simulator
USFS—U.S. Forest Service
USO—Unified stomatal optimization
$V_{c,max}$—Maximum carboxylation capacity
VDM—Vegetation demographic model
VPD—Vapor pressure deficit
WPs—Work Packages
ZF2—Zona Franca 2 in Manaus, Brazil (research site)

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A. EXECUTIVE SUMMARY

Next Generation Ecosystem Experiments (NGEE)—Tropics Phase 2 (FY2020–2023)—Advancing Predictive Understanding of Tropical Forest Responses to Global Changes Across Scales

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Tropical forests cover less than 7% of the Earth's surface but cycle more carbon, water, and energy than any other biome. These forest-atmosphere exchanges play a major role in regulating Earth's climate. However, tropical forests are currently experiencing rapid changes with increasing temperature, intensifying drought, rising atmospheric CO_2 concentration, and anthropogenic land-use. Tropical forests are responding to these changes, and feedbacks from these responses impact carbon, energy and water cycling both regionally and globally. To understand these responses and feedbacks, and to project the major role that these forests will have on future Earth system dynamics, requires comprehensive and accurate representation of tropical forests in Earth system models (ESMs).

Currently the structure and function of tropical forests are poorly represented by ESMs, so how tropical forests will impact global processes is highly uncertain. ESMs are missing key biogeochemical and ecological dynamics, they include parameterized process representations that are poorly validated by observations, and key forest structural properties are not accurately represented. Substantial improvements in model structure, parameterization, and evaluation, using experiments and observations, are thus required to capture the important roles tropical forests play in our Earth system.

In support of DOE BER's mission to advance a predictive understanding of complex biological, Earth, and environmental systems, the overarching goal of NGEE-Tropics is to develop a greatly improved predictive understanding of tropical forests and Earth system feedbacks to changing environmental drivers. To attain this goal, NGEE-Tropics will deliver a state-of-the-art process-rich tropical forest ecosystem model that accurately represents forest structure and function, and provides robust projections of tropical forest responses to global change. The first version of this model—the Functionally Assembled Terrestrial Ecosystem Simulator (FATES)—was developed and coupled to DOE's Energy Exascale Earth System Model (E3SM) in Phase 1 of NGEE-Tropics. Our proposed work in Phase 2 will continue to develop and evaluate FATES, a next-generation dynamic global vegetation model that represents forest demography and ecophysiology, and that explicitly simulates competition among trees of different sizes and functional types.

Our fundamental approach to advancing understanding and model representation of tropical forests in FATES is a strong coupling of model development and evaluation with experiments and observations. This deliberate and focused integration of models and experiments (termed ModEx) ensures that model development is informed by the latest empirical knowledge, and that field measurements are explicitly designed to target gaps in process understanding or parameterization, thereby addressing substantial uncertainty in E3SM-FATES. This approach requires that we develop model testbeds—which bring site-specific meteorological and plant trait data to drive the model together with other observations to test the model—to evaluate model performance at individual, community and regional scales.

Our work in Phase 1 revealed several high-priority areas for model development, evaluation, and parametrization, leading to the identification of three **Research Focus Areas (RFAs)** for Phase 2 that will advance understanding and model representation of processes at the individual (RFA1), community to regional (RFA2), and regional and global (RFA3) scales in E3SM-FATES. The science within these RFAs is organized into ModEx **Work Packages (WP)**. Each WP is tightly coupled to existing model code within E3SM-FATES, or focused on developing new process representation in the model. The WPs within each RFA are coordinated to enable the delivery of RFA-level goals for FATES development and evaluation. E3SM-FATES is the unifying platform at the center of this organizational structure, providing integration of scientific advances across all three RFAs, and ultimately enabling the NGEE-Tropics team to address our key science questions. This RFA and WP structure along with our comprehensive ModEx approach

also allows testing of scientific hypotheses and reduction of uncertainty in emergent model outcomes for our **RFA Science Questions (Qs)**. The three RFAs and associated Qs are briefly described below.

- **RFA1: Climate change effects on tree function, stress response, and mortality.** Phase 2 research will focus on advancing water sourcing, hydrodynamics, leaf and canopy exchange of CO_2 and water, storage of carbon, plant respiration, defense, and damage associated with elevated mortality risks that occur at the individual (cohort) level. RFA1 will provide new understanding and model representation that will enable FATES to more accurately predict functional responses, stress, and mortality of trees under drought and elevated temperature. One overarching Science Question motivates all research within RFA1—***(Q1): How do drought and elevated temperature impact tree physiology and mortality?***
- **RFA2: Forest structure and functional composition along environmental gradients**. Representation of tropical forest community structure and functional composition, and how they mediate Earth system scale responses to climate forcing and disturbance, are key innovations that FATES provides to E3SM. In Phase 2 we will focus on developing accurate representation of forest structure and functional diversity along water-availability, nutrient-availability, and disturbance gradients to enable reliable projections of forest-climate system interactions under global change scenarios. RFA2 will also develop a new nutrient-enabled version of FATES, allowing forest functional assembly to vary with competitive interactions for limiting nutrients. The overarching Science Question for RFA2 is— ***(Q2): How do forest structure and functional composition vary in response to plant available water, soil fertility, and disturbance regimes?***
- **RFA3: Tropical forests and coupled Earth system processes**. Precipitation recycling and seasonal timing of precipitation are tightly coupled to changes in climate and forest structure, and play out across spatial scales from hillslopes to continents, and along regional environmental gradients that include both natural and anthropogenic disturbance. Work in RFA3 requires an informed coupling of FATES with E3SM soil hydrology, development of new data products to serve as model benchmarks, and fully coupled E3SM-FATES interactions at regional and global scales. The overarching Science Question for RFA3 is—***(Q3): How do precipitation recycling and the seasonal timing of precipitation respond to changes in climate and forest structure?***

Work in each RFA builds mechanistic foundational understanding that becomes incorporated in process representation at progressively larger scales up to a next-generation ESM grid cell. Process advances in RFA1 enable functional assembly in RFA2 to emerge mechanistically, providing more accurate projections of how vegetation structure and function responds to a changing climate. RFA1 processes and RFA2 functional assembly will then integrate with regional soil hydrology (RFA3) and enable fully coupled evaluations of E3SM-FATES in RFA3.

NGEE-Tropics takes a pantropical perspective using new research and data from across the globe. We will conduct intensive research activities for Phase 2 at three primary locations: Puerto Rico, Panama, and the Amazon Basin. These will be supplemented with several additional pantropical sites with essential data, including globally-distributed forest dynamics plots. Site selection balances scientific needs with logistical and infrastructural requirements. To maximize the impact of our research, NGEE-Tropics will continue to publicly share our model code and data following our data and software policy. Phase 2 advances in FATES and ModEx will provide greatly improved projections of vegetation dynamics in the next generation of E3SM.

B. NARRATIVE

1 ABSTRACT

Tropical forests play important roles in regulating Earth's climate by cycling vast amounts of carbon, water and energy. Stronger droughts and storms, higher temperatures, rising atmospheric CO_2 and degradation from logging and fire are creating unprecedented change for these forests. As tropical forests become more susceptible to these stressors, slower growth, higher tree mortality, and changes in functional diversity will alter forest carbon balance, increase atmospheric CO_2, and change global precipitation patterns. This makes the development of robust predictions of tropical forest responses a challenge of global importance. The complexity of tropical forests is currently poorly represented in large-scale models, which results in large uncertainty in Earth system change projections. NGEE-Tropics takes a novel approach to solving this problem by combining new data on the structure and function of tropical forests with a model that explicitly represents forest diversity and function across gradients in soils, hydrology, and disturbances including drought, fire and storms. In Phase 1, we developed and publicly released the model FATES (Functionally Assembled Terrestrial Ecosystem Simulator). Through continuous iterations between FATES and data, we identified critical model components requiring further development and data collection. In Phase 2, new and existing data will be comprehensively employed to further develop and test FATES, which will yield a greatly improved representation of tropical forest responses to drought, elevated temperature, and disturbance at the individual, community and landscape scales. FATES within DOE's Earth system model E3SM will then enable dramatically improved projections of future Earth system dynamics.

2 BACKGROUND AND JUSTIFICATION

Tropical forests[1] play essential roles in Earth system function as they exert strong controls over the large-scale coupled biogeochemical cycling of carbon, nutrients and water. Tropical forest fluxes include 34% of total terrestrial gross primary productivity (GPP; Beer et al. 2010), 33% of the land-atmosphere water exchange through evapotranspiration (ET; Schlesinger and Jasechko 2014), and 50% of the global intact forest carbon sink (Pan et al. 2011). However changes to tropical forests are affecting these dynamics, including a reduction in the forest carbon sink (Brienen et al. 2015; Liu et al. 2017), and impacts to water cycling and energy balance, driven both by a warming of the climate system, and anthropogenic land-use activities (Khanna et al. 2017; Spracklen et al. 2012; Swann et al. 2015). Most current Earth system models (ESMs) treat tropical forests simply as layers of big leaves without resolving the size structure, functional diversity, and competitive dynamics that exert large effects on ecosystem process responses to environmental change (U.S. DOE 2012; Powell et al. 2013; Negrón-Juárez et al. 2015; Fisher et al. 2018). Thus accurate projections of future Earth system dynamics and climate conditions require a greatly improved representation of tropical forests in ESMs.

Under the current rate of climate warming, tropical forests will experience temperature extremes beyond those experienced by these forests for thousands, if not millions, of years (Lüthi et al. 2008; Pearson and Palmer 2000; Williams et al. 2007). These unprecedented warmer temperatures also drive up the vapor pressure deficit (VPD), resulting in additional plant moisture stress even under the same precipitation regime (McDowell and Allen 2015; Williams et al. 2012). In contrast to increasing temperature, changes in precipitation regimes will vary spatially, with both increases and decreases in precipitation depending on region and season, along with more extreme storm intensity and annual variability (Malhi and Wright 2004; Berg et al. 2013; Coumou and Rahmstorf 2012). Overall, climate system warming will push tropical forests to states not experienced in recent evolutionary history. At the same time ongoing land-use and land-cover changes will compound the impacts of these novel climate conditions on tropical forests (Ciais et al. 2013).

As tropical forest regions continue to warm over the next century, and VPD effects heighten the ecological impact of drought, tropical trees must acclimate or face elevated risk of mortality (Aleixo et al. 2019). At the scale of individual trees, responses to temperature and drought will vary with traits that confer resistance to the damaging effects of elevated temperatures and moisture stress (McDowell et al. 2018). For example, as demonstrated in our NGEE-Tropics Phase 1 work, daily temperature extremes

[1] Tropical forests, as defined for NGEE-Tropics, include closed-canopy high-biomass forests, while also addressing transitions of these forests to other states under fire disturbance and global changes.

experienced by upper-canopy leaves in forests near Manaus, Brazil, frequently exceeded 40°C, and then further increased (>45°C) under moisture stress, resulting in negative effects on leaf physiology and biochemistry (Fontes et al. 2018; Jardine et al. 2017). At the ecosystem scale, tree responses to temperature and drought will depend on evolved resistances and competitive outcomes among different functional strategies under 21st century climate.

Tropical forests harbor the planet's greatest tree species diversity as well as an associated diversity of functional strategies. Capturing the essential traits that govern emergent forest responses to environmental variation at Earth system scales represents an enormous challenge for terrestrial biosphere models (TBMs). Trait filtering and functional assembly occur through recruitment processes and competitive dynamics that follow a mortality event. A changing environment mediates shifts in tropical tree communities by altering the balance of competitive outcomes among functional strategies, while also providing opportunities for recruitment of new strategies more suited to novel environments. The functional assembly that follows disturbance is also affected by soil nutrient status, with higher fertility sites expected to select for species with faster life history strategies (McDowell et al. 2018; Quesada et al. 2012). Higher temperature, more intense drought, and rising concentration of atmospheric CO_2 will also influence these functional assembly processes (Anderson-Teixeira et al. 2013). Other disturbance agents such as increasingly intense storms under a warmer climate, and fire that also influences forest-savanna biome boundary transitions, will further influence regeneration dynamics and functional composition following disturbance (Negrón-Juárez et al. 2018; Hoffmann et al. 2012). Compound these effects with prevalent land-use such as logging and deforestation, and these disturbance-recovery processes and altered ecosystem states can have important effects on land-atmosphere interactions and Earth system dynamics (Khanna et al. 2017; Swann et al. 2015).

Coupled ESM experiments have long demonstrated that ET in the Amazon basin is essential for precipitation recycling, with deforestation resulting in downwind reductions in precipitation that impact forest regeneration (Shukla et al. 1990; Spracklen et al. 2015). Other studies have demonstrated that the loss of tropical forest can affect global climate states, with a number of projected teleconnections to extra-tropical biomes (Avissar and Werth 2005; Medvigy et al. 2013). Additional work explored the potential for widespread tree mortality across the Amazon basin under a warmer climate, with this "die-back" hypothesis identified as one of the possible tipping-points in Earth system dynamics (Nepstad et al. 2008; Silvério et al. 2013; Cowling et al. 2004). Recently, carbon cycle changes associated with temperature and moisture anomalies were captured by the Orbiting Carbon Observatory-2 (OCO-2) during the 2015–2016 El Niño Southern Oscillation (ENSO) event, demonstrating varied responses of tropical forests. Liu et al. 2017, for example, found large gross primary production (GPP) reductions in tropical South America, increased fire carbon release in tropical Asia, and increased respiration carbon release in Africa under elevated temperature, but without declines in precipitation.

Processes impacting individual trees under climate stress, the functional assembly and coexistence of multiple strategies within a forest ecosystem following disturbance, and related impacts to regional-scale fluxes of carbon, water and energy have large potential effects on Earth system dynamics. Poor model representation of these forest-atmosphere interactions is one of the most substantial sources of terrestrial uncertainty in projections of Earth's future climate (Friedlingstein et al. 2014; Friedlingstein et al. 2006; U.S. DOE 2012). Thus, in light of the importance of tropical forests in Earth system processes, and in support of BER's mission to advance a predictive understanding of complex biological, Earth, and environmental systems, NGEE-Tropics' overarching goal is to develop a greatly improved predictive understanding of tropical forests and Earth system feedbacks to changing environmental drivers over the 21st Century. A strong synthetic coupling of modeling and experiment-observational methods (ModEx) is our fundamental approach toward attaining this goal. **Our grand deliverable, and central integrating framework for all of our research, is a representative, process-rich tropical forest ecosystem model—the Functionally Assembled Terrestrial Ecosystem Simulator (FATES)—which extends from the bedrock to the top of the vegetative canopy-atmosphere interface, and in which the evolution and feedbacks of tropical ecosystems in a changing Earth system can be modeled at the scale and resolution of a next generation ESM grid cell.**

2.1 NGEE-TROPICS MODELING AND INTEGRATION FRAMEWORK

For Phase 1 of NGEE-Tropics, we developed FATES as a vegetation module within DOE's Energy Exascale Earth System Model (E3SM). FATES is a size-structured vegetation model that represents the dynamics of cohorts of trees grouped by plant functional type (PFT), size, and successional age, and resolves disturbance processes that are vital for the maintenance of functional diversity and forest structure. At the level of cohorts, FATES resolves key physiological processes of photosynthesis, respiration, phenology, carbon allocation, root water uptake, water transport through the plant, and transpiration. At the community level, the model simulates light and water competition among cohorts of different tree sizes and PFTs, with forest composition and function as emergent properties. At the regional scale, coupled E3SM-FATES enables us to explore climate feedbacks from forest structure and functional changes. Using this size-structured representation of forest demography, FATES can be used to explore ecological dynamics at scales up to that of the planet, but informed by data at the scale of individual trees (e.g., forest census data and ecophysiological measurements) and the ecosystem (e.g., eddy covariance and streamflow). Phase 1 key goals included building and testing the basic framework of FATES, and developing a plant hydrodynamic module (FATES-Hydro, now integrated into FATES) for testing process representation directly against measurements made during our field campaigns. For Phase 2, we will continue testing FATES against observations, improve process fidelity, further explore and test FATES ecological dynamics, build new process representation with a particular focus on vegetation nutrient cycling, and explore the use of E3SM-FATES to address science questions of the coupled vegetation-atmosphere system across multiple scales.

2.2 NGEE-TROPICS ALIGNMENT WITH DOE-BER STRATEGIC PRIORITIES AND GRAND CHALLENGES

DOE-BER's Climate and Environmental Sciences Division (CESD) recently released its five-year strategic plan for 2018 to 2023 (U.S. DOE 2018), which identified five key Scientific Grand Challenges. NGEE-Tropics Phase 2 is poised to deliver on four of these Grand Challenges. The first is the Integrated Water Cycle Scientific Grand Challenge, in which we will address the role of variability and heterogeneity in ecosystem hydrologic function and how it contributes to variability and change in the Earth system. Work packages in the project will focus on the specific traits that lead to variation in hydraulic function, identify critical thresholds that lead to changes in ecosystem hydrologic function, explore gradients within watersheds that determine the relative contributions of unsaturated-zone soil water and saturated-zone groundwater in plant water uptake, and explore the role of plant hydraulic traits in governing climate as represented in coupled land-atmosphere model simulations.

The second grand challenge is the Biogeochemistry Scientific Grand Challenge. We will examine both carbon and nutrient cycling in tropical forests to understand how individual scale processes, such as growth and mortality, govern ecosystem-scale carbon turnover time, using the novel structured ecosystem model (FATES) within the E3SM Land Model (ELM). By identifying thresholds that lead to tree mortality and community restructuring, the role of perturbations and climate extremes in governing the long-term behavior of biogeochemical cycles will be investigated. We will also develop representation of nitrogen and phosphorus cycling into ELM-FATES to address how biogeochemical cycles mediate plant competition, growth, and turnover. Both anthropogenic and natural disturbance and subsequent recovery will be explored across the island of Puerto Rico.

The third Grand Challenge we address is the Drivers and Responses in the Earth System Scientific Grand Challenge by developing a proven capability to represent critical ecosystem processes within E3SM. This will enable us to ask questions about how climate variability and change will both affect and be affected by tropical forests. This work will identify thresholds where natural hydroclimate variability may give way to abrupt ecosystem change in tropical forests. We will develop key benchmarking datasets on the role of land use in governing forest size distributions, and recovery from prior land use in Puerto Rico. Coupled-model simulations will be conducted to identify the role of ecosystem processes in governing a potential Earth system tipping point—the length of the dry season across the Amazon basin—to ask how hydraulic trait variation may act to stabilize or destabilize this important Earth system dynamic.

Lastly, we address the Data-Model Integration Scientific Grand Challenge. With our strong NGEE-Tropics ModEx approach, and integration within and among our RFAs and WPs, we are supporting the integration and management of models, experiments, and observations across a hierarchy of scales and complexity to address major challenges at the intersection of tropical forest dynamics and important Earth system processes.

2.3 PHASE 2 EXPERIMENTAL APPROACH

Our work in Phase 1 revealed several high-priority areas for model development, evaluation and parametrization. This work has led to three **Research Focus Areas (RFAs)** for Phase 2 to advance understanding and E3SM-FATES representation of processes at the individual (**RFA1**), community to regional (**RFA2**), and regional and global (**RFA3**) scales. The science within these RFAs is organized into 12 ModEx **Work Packages (WP)** (**Figure 1)**. Each WP is tightly coupled to existing model code within E3SM-FATES, or is focused on new process representation, enabling coordinated model development and evaluation. E3SM-FATES resides at the center of this organizational structure and serves as the unifying platform for the project, enabling integration of scientific advances across the three RFAs toward addressing our key science questions and hypotheses. The scope of each RFA is outlined below:

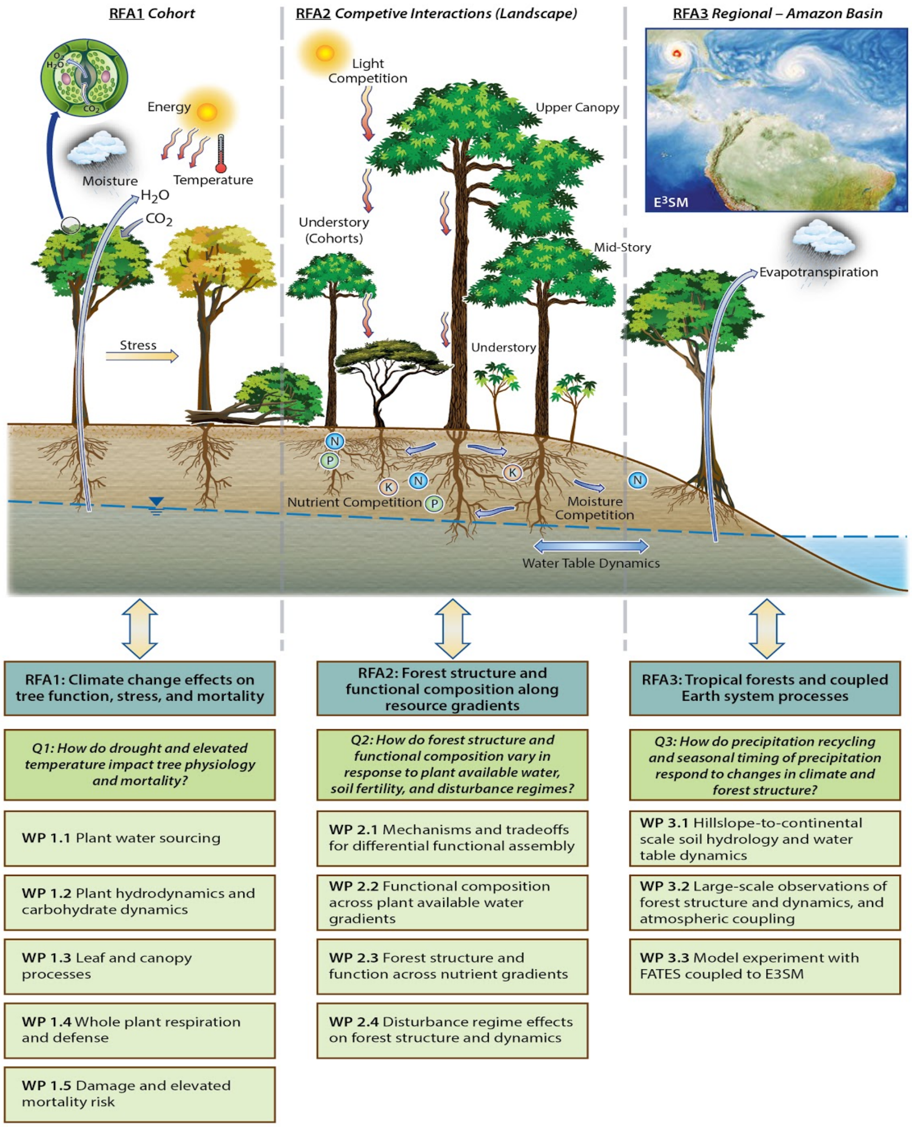

Figure 1. (Top) Process representation and scaling approach in FATES (from cohort, to landscape, to regional scales). (Bottom) Phase 2 NGEE-Tropics science organization aligns with process structure in FATES represented with three Research Focus Areas (RFAs), associated Science Questions (Qs) and Work Packages (WPs).

- **RFA1: Climate change effects on tree function, stress response, and mortality**. Phase 2 research will focus on advancing water sourcing, hydrodynamics, canopy exchange of CO_2 and water, storage of carbon, plant respiration, defense strategies, and damage associated with elevated mortality risks. RFA1 will provide new understanding and model representation of specific physiological processes that will enable FATES to more accurately predict functional responses, damage, and mortality to trees experiencing drought and elevated temperature. One overarching Science Question motivates all research within RFA1—***(Q1): How do drought and elevated temperature impact tree physiology and mortality?***

- **RFA2: Forest structure and functional composition along environmental gradients.** Representation of tropical forest community structure and functional composition, and how they mediate Earth system scale responses to climate forcing and disturbance, are key innovations that FATES provides to E3SM. In Phase 2 we will focus on understanding the mechanisms leading to stable functional coexistence in FATES, and developing accurate representations of forest composition and functional diversity along water availability, nutrient availability, and disturbance gradients to enable reliable projections of forest-climate system interactions under global change scenarios. RFA2 will also develop a new nutrient-enabled version of FATES, allowing forest functional assembly to vary with competitive interactions for limiting nutrients. The overarching Science Question for RFA2 is—***(Q2): How do forest structure and functional composition vary in response to plant available water, soil fertility, and disturbance regimes?***
- **RFA3: Tropical forests and coupled Earth system processes.** Precipitation recycling and seasonal timing are tightly coupled to changes in climate and forest structure and play out across spatial scales from hillslopes to continents, and along regional environmental gradients that include both natural and anthropogenic disturbance. Work in RFA3 includes an informed coupling of FATES with E3SM soil hydrology, development of new data products to serve as model benchmarks, and fully coupled E3SM-FATES interactions at regional and global scales. The overarching Science Question for RFA3 is—***(Q3): How do precipitation recycling and the seasonal timing of precipitation respond to changes in climate and forest structure?***

Work Packages (WPs) within these RFAs constitute sets of tasks with clearly identified milestones and deliverables (see Appendix F), and associated science advances. Each WP is linked to specific FATES or E3SM code to be developed or tested, along with clearly delineated data requirements to inform model benchmarking and parameterization. As appropriate, activities within WPs will apply emerging E3SM-FATES capabilities to high-priority science questions, model evaluation at site to regional scales, and new model developments that are required to enable future science advances. WPs also include data processing and synthesis tasks, and field and laboratory activities to generate essential new data. This WP structure is designed so that integration within and among RFAs will result in a number of high-impact outcomes. Team interactions within and across RFAs and WPs will also enhance integration, and leverage the use of project infrastructure and logistics among our team and collaborators. Building on significant Phase 1 science advances, research within the three RFAs and associated WPs will position our team to address challenging questions on processes that control forest ecosystem responses to environmental variation, and how those processes interact with important Earth system dynamics.

NGEE-Tropics has a pantropical scope, engaging in research and data collection across the globe. We will conduct specific research activities for Phase 2 at three primary locations: Puerto Rico, Panama, and the Amazon Basin. Additional pantropical sites, including a network of forest dynamics plots, will supplement these sites with essential datasets. Site selection balances scientific needs with logistical and infrastructural requirements including canopy access and ongoing ecosystem-scale manipulations. To maximize the impact of our research, NGEE-Tropics is committed to publicly sharing our data and model code following our data and software policy.

3 VISION

The NGEE-Tropics vision is a greatly improved predictive capacity for tropical forest responses and feedbacks to global change. This capacity requires the development and testing of model structures that reflect tree functional diversity, heterogeneity in plant resource availability and use, and an ability to carry out fully coupled simulations in E3SM. Model representation requires deep understanding of linked processes occurring at scales of individual trees, within dynamic forest functional communities, and across landscapes and regions subject to diverse disturbance regimes and environmental change. Our NGEE-Tropics team, along with national and international partners, is well positioned to deliver on this vision for a strong predictive capacity of tropical forest change and Earth system dynamics.

Because FATES serves as a unifying platform across all of our research activities, Phase 2 outcomes will be inherently integrative, enabling a number of emergent high level outcomes that align with our vision. For example, drought and elevated temperature research within RFA1 focuses on providing ecophysiological insights into processes occurring within individual trees. Next, process advances in RFA1 enable functional assembly across moisture and disturbance gradients in the RFA2 domain to emerge mechanistically, providing more accurate projections on vegetation structural and functional responses to climate change. Finally, RFA1 processes and RFA2 functional assembly play out in RFA3 across hillslopes to regions as influenced by soil properties and hydrology, and interactions with fire.

The research we propose in Puerto Rico represents another example of how our integrated vision will deliver. Phase 2 work includes the development of island-wide FATES simulations of forest regrowth in Puerto Rico (1951–2016), focused on long-term forest development following land abandonment and afforestation in the 1950s when the island had near-minimum forest cover. These FATES simulations will examine how climate, soil properties, and prior land use influenced multidecadal biomass recovery. Our Phase 2 work will benefit from the NASA GLiHT flights that we funded in Phase 1, providing extensive forest biomass benchmarks from GLiHT lidar data extending across all forest types on the island. FATES simulations will then explore the complex interactions of carbon and water cycle dynamics. Site-level testbeds on contrasting soil types to investigate plant-soil ecosystem processes will also enable development and testing of nutrient-enabled FATES. This regional capacity for Puerto Rico will then prepare NGEE-Tropics for pantropical simulations across complex anthropogenic landscapes in Phase 3.

Initial experiments using FATES fully coupled with E3SM represent another major advance proposed for Phase 2. Due to its vast size and huge influence on Earth system dynamics, we selected the Amazon Basin for initial continental scale E3SM experiments. The Amazon has the additional benefit of historical continental-scale research, and extensive datasets including those that we are processing and further developing with our institutional partners in Brazil and Peru. In Phase 2 we will initiate large-scale regional simulations to better understand how the spatial heterogeneity in plant-available water and tree physiological responses affect forest-atmosphere coupling and feedbacks to climate, with a focus on water recycling across the basin. Integrative outcomes for our Amazon work will be enabled by process advances at the scale of individual trees in RFA1, work on functional assembly across moisture gradients in RFA2, and regional hydrology and continental-scale data analysis and benchmark development in RFA3. Our Phase 2 work will also set the stage for exploring global-scale questions in Phase 3. These advances are also highly relevant for general vegetation dynamics representation in E3SM, including for temperate and high-latitude ecosystems.

3.1 OUR DECADAL VISION

NGEE-Tropics was designed to be conducted over 10 years, divided into three phases:

The primary goal of **Phase 1 (2015–2019)** was to determine the greatest uncertainties in ESM treatment of tropical forests with respect to key Earth system processes, and to develop a comprehensive research plan and model framework to rigorously address those uncertainties. To attain that goal, our mandate was necessarily broad, with Phase 1 research carried out under six Research Objectives (ROs), along with modeling, data and field objectives. Phase 1 progress is detailed below in Section 4.

Phase 2 (2020–2023) will further develop and strengthen our use of FATES within E3SM as the central modeling framework that integrates our research. Continued FATES development and testing will be motivated by several high-priority model uncertainties that we identified in Phase 1, along with the activities and data required to address those uncertainties. Specifically, we will focus on improving and evaluating model representation of key mechanisms to predict responses of tropical forests to drought, warming and disturbance. In view of the importance of nutrient limitation for tropical forest dynamics, a new modeling capability for nutrient dynamics will be added to FATES. Model development, testing, and application will take place at sites in Puerto Rico, Panama, and the Amazon Basin. Additional pantropical sites will be utilized to take advantage of logistical infrastructure including canopy access (Lambir Hills and Daintree), an ongoing ecosystem-scale drought experiment (Daintree), and pantropically distributed forest dynamics plots across the tropics (with our ForestGEO partners).

Phase 3 (2024–2026): By the end of Phase 3, FATES will include a well-tested mechanistic representation of cohort-scale response to tree stress and mortality under drought and higher temperatures, varied functional assembly of forested ecosystems under altered environmental conditions and disturbance regimes, and community-scale effects on fully coupled Earth system dynamics and forest-atmosphere interactions. We aim to deliver a comprehensive and validated modeling platform, E3SM-FATES, that will provide informative projections for the future of tropical forests under a number of global change scenarios projected for the 21st Century. These advances will also set the stage for greatly improved representation of vegetation dynamics at the global scale.

4 PHASE 1 PROGRESS (2015–2019)

The primary objective of Phase 1 was to determine the greatest uncertainties in ESM treatment of tropical forests, and to develop a comprehensive research plan and model-data integration framework to address those uncertainties. Toward this objective, Phase 1 research improved understanding and model representation of: (1) responses to changing temperature, precipitation, and atmospheric CO_2; (2) disturbance and land-use change impacts on carbon, water and energy fluxes; and (3) how these responses vary with spatial and temporal heterogeneity in a number of belowground processes. We conducted initial measurements for our ModEx approach at pilot field sites in Puerto Rico, Panama and Manaus (Brazil). To provide data products via a community portal, we developed a data synthesis and management framework. Phase 1 accomplishments are highlighted below; details are in 4.1–4.5:

- Our NGEE-Tropics model FATES (Functionally Assembled Terrestrial Ecosystem Simulator)—now an optional configuration within DOE's E3SM—delivers on our Phase 1 model objectives: process insights associated with plant hydrodynamics, drought-induced mortality, dynamic carbon allocation, fire impacts on carbon cycling, initial phosphorus and nitrogen cycle model functionality (integrated with ELM), and fine-scale lateral and vertical soil hydrology.
- Rigorous analyses of parametric and structural model uncertainty inform a more focused ModEx approach for Phase 2.
- Comprehensive benchmarks for soil hydrology and plant physiology in response to the 2015–2016 ENSO event that caused widespread drought in tropical forests.
- ModEx pilot sites established in Puerto Rico, Panama, and Manaus (Brazil), and pantropically with ForestGEO, which enabled our team to determine priority ModEx activities for Phase 2.
- Team members have published a total of **87** data packages (many containing multiple datasets) to our NGEE-Tropics data archive with **69** shared with our NGEE-Tropics team, **28** shared publicly, **36** data DOIs, and **1085** data downloads, representing an enduring legacy of NGEE-Tropics.
- **115** papers (**102** peer-reviewed) published with NGEE-Tropics support, including papers in *Science*, *Nature Ecology and Evolution*, and organization of, and contributions to, a Special Issue published in *New Phytologist* on drought impacts to tropical forests. Fisher et al. (2018) is currently the most cited article in *Global Change Biology* published in 2018. Rogers et al. (2017) is currently the second highest cited article in the *New Phytologist* published in 2017.
- NGEE-Tropics has benefited from, and contributed to, many national and international partnerships and collaborations, greatly leveraging our ability to carry out world-class science.

4.1 PHASE 1 PROGRESS IN ADVANCING NGEE-TROPICS' MODELING AND INTEGRATION FRAMEWORK

The grand deliverable for NGEE-Tropics, specified in our guidance, is a "representative process-rich tropical forest ecosystem model." In Phase 1 we met a major milestones for this deliverable with the release of FATES. We accomplished this with a multi-disciplinary team effort and by building on the Ecosystem Demography (ED) concept (Moorcroft et al. 2001) implemented as a land surface scheme (Fisher et al. 2010; Fisher et al. 2015). FATES represents the dynamics of cohorts of trees at the scale of an ESM. These dynamics are essential for the emergent behavior of carbon and hydrological feedbacks in the climate system. Moreover, a size-structured array of model cohorts can be tested against observations available from forest inventories, thereby further enabling the ModEx approach. The E3SM codebase now includes a stable, tested and flexible version of FATES.

Additional science goals that we achieved in Phase 1 are: (1) developing the FATES-Hydro plant hydrodynamics module; (2) extensive sensitivity testing and uncertainty quantification; (3) introducing flexibility in parameterization schemes for allocation, allometry and physiology; (4) developing model testbed sites with appropriate boundary conditions and validation data; (5) developing a tool to probe structural uncertainty of processes in ESMs; (6) initial assessment of ecological dynamics and plant hydraulics. Key Accomplishments for NGEE-Tropics' Modeling and Integration Framework in Phase 1 are:

FATES-E3SM integration, public release, tutorials, community-building: In summer 2017, we successfully reached a major milestone—the integration of FATES with E3SM (**Figure 2**), and the public release of FATES on GitHub. To build the FATES community, we hold annual public FATES tutorials for interested community members and we have migrated model development to our public GitHub code repository. FATES has been gaining wide community support. A recent paper that synthesized the results of a 2016 workshop, organized to assess and review the state-of-the-art in demographic ESMs and inform future FATES work (Fisher et al. 2018), is currently the most cited paper in *Global Change Biology* published in 2018. We established a FATES development Google group and well-attended (10–30 participants) bi-weekly model development calls, as well as an ELM-NGEE focus group to plan developments around land-use.

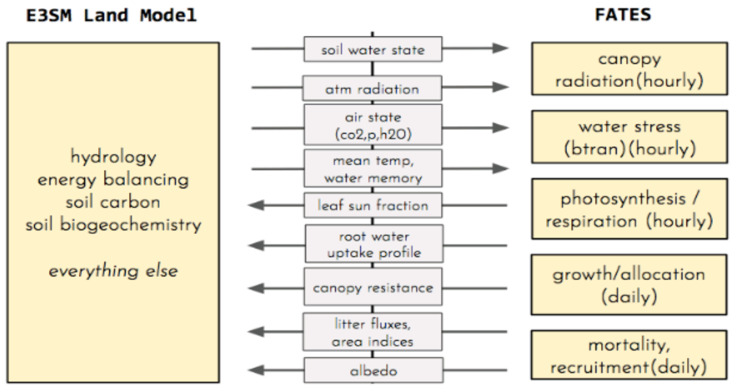

Figure 2. Interface of FATES and E3SM Land Model (ELM). FATES exchanges information with ELM on half-hourly and daily timesteps to compute carbon, water and energy exchange with the atmosphere.

Integration of plant hydraulics into FATES: A core science focus in Phase 1 of NGEE-Tropics was the representation of water flow through the soil-plant-atmosphere system mediated by plant traits and driven by climate. We built a detailed plant hydraulics model (FATES-Hydro) based on Sperry et al. 1998 and Christoffersen et al. 2016. We parameterized and tested the model with key observations of plant hydraulic function, including sapflow and tissue water potentials. While FATES-Hydro was under development, we used the related model ED2-Hydro to explore how plant hydraulic trait diversity affects ecosystem structure and function in response to drought (Powell et al. 2018).

Model explorations with FATES: A critical feature of Phase 1 was exploration of model uncertainty. We conducted a parameter sensitivity study (Massoud et al. 2019) and developed an emulator of FATES for efficient parameter estimation (Massoud 2019). We also developed reduced-complexity modes for running FATES to remove feedbacks and isolate specific dynamics. Our team implemented a logging module that represents land use and anthropogenic disturbance (Huang et al. 2019). We identified regimes of PFT coexistence in FATES, created a software foundation to explore nutrient dynamics, and made many other process improvements as detailed in subsequent sections.

In software testbeds, we can bring together data to drive FATES, such as plant trait distributions and covariances, meteorological data, and site conditions, with benchmarking data such as ecosystem fluxes and forest census data. Barro Colorado Island (BCI), Panama, served as a key testbed bringing together a broad range of datasets, which allowed us to assess parameter sensitivity and model fidelity against observations (**Figure 3**). We will develop testbeds for other sites in Phase 2.

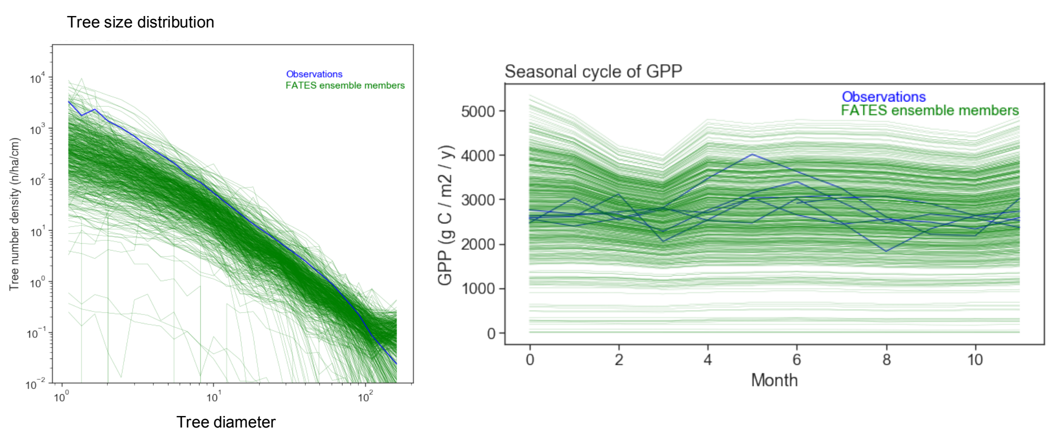

Figure 3. Ensemble of FATES simulations at BCI testbed site, with ensemble members each consisting of a single PFT as randomly sampled from observation-derived plant trait data across Panama. From Koven et al. In Prep.

Structural uncertainty testing using the MAAT framework: A key question in complex, comprehensive ecosystem models such as FATES-E3SM is how structural uncertainty in representing an individual process contributes to the uncertainty in emergent outcomes. Because FATES and related models are based strongly on carbon, water and energy exchanges that occur at leaf surfaces, the representation of photosynthesis is a particularly powerful lever for controlling model behavior, and one in which ESM structural diversity may be most easily explored. We built a photosynthesis model within the Multi-Assumption Architecture and Testbed, MAAT (Walker et al. 2018b), to explore this structural uncertainty and to serve as a prototyping platform for updating the representation of photosynthetic processes in FATES. This led us to change the FATES photosynthesis scheme. MAAT identified a high degree of uncertainty in representing co-limitation of photosynthetic capacity ($V_{c,max}$) and maximum electron transport rate (J_{max}), which was mitigated by reducing the degree of smoothing between the two limitation regimes in FATES.

4.2 PHASE 1 PROGRESS IN NGEE-TROPICS' DATA SYNTHESIS AND MANAGEMENT FRAMEWORK

The NGEE-Tropics project generates and uses ecological, hydrological, and meteorological datasets from tropical forests. These data are central to modeling efforts, but need to be quality checked, processed and synthesized. Our challenges are to employ quality control methods (e.g., outlier identification, gap-filling), and to harmonize data across different data formats, collection methods, and versions in a consistent manner across field sites.

In Phase 1, primary objectives for Data Synthesis and Management were (1) to provide infrastructure and services to support the project, and (2) to create data products as drivers and benchmarks for the scientific and modeling studies. The first goal facilitated project-wide data curation by building common data management infrastructure, working with the science teams to archive and share data within the team, and publicly releasing data with standardized metadata. The second goal focused on the development of the datasets themselves through collecting project and external datasets, performing Quality Assurance and Quality Control (QA/QC) of data, and creating data processing pipelines to generate consistent synthesis products that include model drivers and benchmarks. Phase 1 Key Accomplishments for NGEE-Tropics' Data Synthesis and Management Framework include:

Data archiving and public release: We developed the NGEE-Tropics Archive to internally curate and publicly release project datasets with data DOIs. The archive serves as the primary repository for archiving and sharing data within the project, and for releasing data publicly. The team has archived several datasets (**Table 1**), many of which were standardized using the FRAMES metadata templates. NGEE-Tropics public data are available at (http://ngt--data.lbl.gov/dois) with project-specific DOIs (in the format http://dx.doi.org/10.15486/ngt/).

Table 1—NGEE-Tropics Data Metrics (as of May 2019)

# Archived Datasets	# Team Datasets	# Public Datasets	# Data Downloads	# Unique Users
87	69	28	1085	142

Release of metadata standards for sensor observations: With data provider and modeler input, we developed a metadata framework, FRAMES, as a set of excel-based templates to standardize reporting of sensor data and metadata for ecohydrological measurements (Christianson et al. 2017). FRAMES was developed for our 2015–16 ENSO field campaign, in which data providers for six core NGEE-Tropics field sites in Brazil, Panama, and Puerto Rico, as well as collaborators, used the templates to submit data packages to the NGEE-Tropics Archive. The standardization enabled the hydraulic modeling team to extract and assemble sap flux time series for analysis of drought impacts during the ENSO event. The FRAMES templates have been applied to subsequent datasets. We have created additional parsers for reading the templates to further the use of associated data.

Development of site-specific driving data for NGEE-Tropics modeling efforts: We have developed site-specific meteorological drivers for ecohydrological modeling at three sites in Panama—the San Lorenzo Protected Area (SLZ), Barro Colorado Island (BCI), and Parque Natural Metropolitano (PNM) (Faybishenko et al. 2018; 2019a,b)—using public data obtained from the Smithsonian Tropical Research Institute (STRI) meteorological stations. The products were created using a flexible, multi-stage approach involving semi-automated QA/QC (e.g., consistency checks, time-shifts, detection and removal of outliers) and gap-filling. The products are periodically revised as new data become available. For example, three revisions of driving data for BCI were created, with each version extending the length of the datasets, requiring additional QA/QC. The driving datasets have been used extensively as inputs for the Ecosystem Demography model (ED2-Hydro) and FATES simulations (Powell et al. 2018; Knox et al. In Prep; Koven et al. In Prep; Fisher et al. In Prep; Xu et al. In Prep; Serbin et al. In Prep).

Acquisition and processing of Amazonian Micrometeorological and Hydrological Datasets: We have partnered with Brazil's Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) program to obtain and process high-value hydrological and micrometeorological datasets from the Amazon spanning decades and multiple eddy flux towers for use in NGEE-Tropics modeling efforts. A particular focus for Phase 1 has been on micrometeorological and soil moisture data collected at the K34 tower. We have conducted QA/QC and processing of numerous datasets (available from 1999 onwards), and used the data from 2012–2017 to create model drivers. Hydrological and micrometeorological datasets are currently being processes for the same time period that includes the 2015-16 ENSO event. A number of publications are in development based on this partnership (e.g., Ferreira et al. In Prep).

Sapflow Synthesis Framework: The standardized FRAMES templates have been used to synthesize the sap flux measurements collected across nine field sites during the 2015–2016 ENSO event. The synthesized dataset includes data collected from independent field efforts and incorporated community input from over 20 researchers. A tool created for the ENSO campaign tool has been tested for the Manaus site, and will be implemented for other NGEE-Tropics sapflow measurements in Phase 2 (Varadharajan et al. In Prep).

4.3 PHASE 1 PROGRESS IN ADVANCING UNDERSTANDING OF CARBON-HYDROLOGY-TEMPERATURE INTERACTIONS IN TROPICAL FORESTS

Predictive understanding of hydraulic and carbohydrate response to water stress: We focused on quantifying mechanisms by which plants regulate carbon and water balance in relation to drying and warming using both empirical measurements and modeling with FATES. For the empirical side, a network of measurements was established for sapflow, leaf water potential, hydraulic traits, and non-structural carbohydrate sampling in Manaus, Puerto Rico, Australia, and Panama in response to the 2015–2016 ENSO event. Non-structural carbon response to drought stress showed that plants maintain a relatively high level of storage with the progress of droughts (Dickman et al. 2019) and similarly high stomatal conductance (Wu et al. In Review a). Using the sapflow data, we explored the sensitivity of sapflow to vapor pressure deficit (VPD), and found that the sensitivity increases with higher precipitation (Grossiord et al. In Revision). These datasets and others in preparation all provide trait-relationships critical for parameterization and evaluation of FATES, and inform our approach to data synthesis and management (Christianson et al. 2017).

We conducted a first model sensitivity analysis of FATES that showed the importance of photosynthetic capacity, carbon storage and allometry on vegetation dynamics (Massoud et al. 2019). We developed and integrated the hydraulic code (FATES-Hydro) into FATES (**Figure 4a**; Christoffersen et al. 2016), which provides a foundation to better predict tropical vegetation response to droughts. We used a clustering approach on traits and environmental conditions to identify PFTs related to strategies for growth and survival under drought (Wei et al. 2019). This will provide a framework to better parameterize hydraulic-related functional types in FATES.

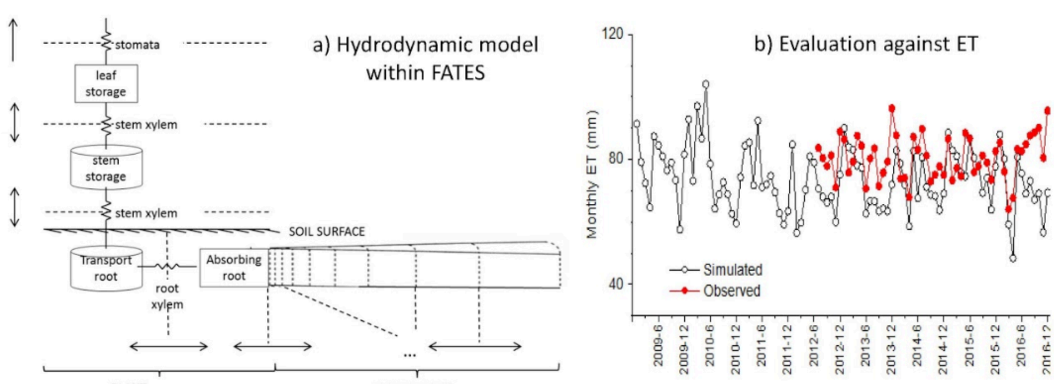

Figure 4: (a) Representation of hydrodynamic model (Christoffersen et al. 2016) within FATES and (b) its evaluation against evapotranspiration (ET) at Barro Colorado Island, Panama.

Model simulation at BCI demonstrated that aboveground biomass is sustained under lower rainfall via shifts in the functional composition of the forest (Powell et al. 2018). Finally, a sensitivity analysis was conducted based on hydraulic traits that showed the importance of belowground hydraulic control to vegetation dynamics (Xu et al. In Prep). For model-data integration, we analyzed tree mortality from the ForestGEO network compared to FATES mortality simulations. This showed that FATES underestimated mortality for large trees (Johnson et al. 2018). FATES-Hydro was set up for the BCI site and evaluated against observations of ET, GPP, sapflow, and leaf water potentials to assess the risks of hydraulic failure (**Figure 4b**; Wei et al. In Prep). We captured ET and GPP by adding a simple scheme of leaf age.

We made significant progress in synthesizing the existing models and data to understand the vegetation response to drought. A workshop was organized in 2015 to review the state of knowledge of tropical forest mortality and to focus areas for future research (McDowell et al. 2018). We conducted a synthetic analysis of 13 CMIP5 Earth system models to understand the impact of drought on plant production (Xu et al. In Revision). Our analysis highlighted the impact of extreme drought on GPP in the tropical regions. Finally, our synthesis of wood decomposition after mortality in relationship to climate versus wood traits showed that wood traits, including wood volume and nitrogen content, could contribute more than climate to the prediction of wood decomposition (Hu et al. 2018).

Model representation of leaf and canopy processes: Although Terrestrial Biosphere Models (TBMs) use variations of the same foundational model (Farquhar et al. 1980), both parametric (Bonan et al. 2011; Rogers 2014) and structural uncertainty controls the response of those TBMs to key environmental drivers (Rogers et al. 2017). In Phase 1 we published a roadmap that identified the variation in leaf and canopy level processes among TBMs, and the effect of this variation on the modeled response of photosynthesis to environment, including, temperature, VPD, and soil moisture content, providing a foundation for the physiological considerations that will underpin representation of photosynthesis in FATES (Rogers et al. 2017). Development of photosynthesis models within the Multi-Assumption Architecture and Testbed (MAAT) tool (Walker et al. 2018b), in which alternative model structures are treated as testable hypotheses, has begun to identify surprising sensitivities of photosynthesis, e.g., empirical smoothing introduced a hidden limitation on photosynthesis (Walker et al. In Prep). Removing this numerical (but not biological) limitation led to a modification of FATES that resulted in a 20% increase in modeled GPP.

Our data has expanded coverage of important leaf traits that drive the response of tropical forests to environmental change, and helped inform process representation within FATES. For example, we identified that the unified stomatal optimization (USO) model formation for representing stomatal conductance (Medlyn et al. 2011) was superior to alternative formulations when evaluated with data from tropical forest sites, and showed that the stomatal slope parameter was more dependent on biotic factors than abiotic factors (Wu et al. In Review a). Furthermore, this work demonstrated that including leaf water potential as an additional variable did not improve model representation of stomatal conductance, highlighting the need for rigorous evaluation of FATES-Hydro in Phase 2.

Understanding the vast spatial and temporal variation in leaf traits that occurs across tropical forest biomes is a daunting but critical task (Schimel et al. 2015). Spectroscopy can enable us to rapidly accelerate the collection of leaf traits (Serbin et al. 2012, 2016), and build a foundation for the use of remote sensing to collect canopy level traits for model parameterization and evaluation (Stavros et al. 2017). A key step is the development of spectra-trait models that enables us to estimate leaf traits rapidly and non-destructively from leaf spectra. In Phase 1, we developed and tested spectra-trait models that are capable of predicting leaf mass area (LMA) and maximum carboxylation capacity ($V_{c,max}$) in tropical forests (Serbin et al. In Review; Wu et al. In Review b).

Leaf phenology plays a critical role in determining photosynthetic seasonality (Wu et al. 2016). To represent this phenomenon in FATES, we formulated a model compatible with the Wu et al. 2016 seasonal controls and the Farquhar et al. 1980 model of photosynthesis as implemented in a multi-layer canopy (Wu et al. 2017). We deployed a network of field cameras to capture leaf phenology. We evaluated model performance for our test sites using prescribed phenology from this network and theoretical foundation for model representation of photosynthetic seasonality in FATES (Wu et al. 2017).

Understanding and modeling of water available to plants:

Improper parameterizations of soil moisture and groundwater table (GWT) dynamics may lead to large uncertainties in modeling drought response, as GWT influences belowground moisture available to plants. Phase 1 activities in soil hydrology have focused on understanding uncertainties in modeling these processes and making hydrologic measurements to inform modeling. A community workshop was organized to solicit input on a model intercomparison to understand model uncertainties. Workshop participants led and contributed to a review article on improving representation of hydrologic processes in earth system models (Clark et al. 2015). Six models—the one-dimensional E3SM Land Model (ELM), three distributed hydrology models (DHSVM, CLM-PAWS, and tRIBS), and two three-dimensional models (ParFlow, ATS)—participated in the model comparison. Fang et al. (2017) compared the 1D ELM and 3D ParFlow models over the Asu catchment near Manaus. The significant differences in soil moisture and GWT depth simulated by the models were attributed to subsurface lateral flow that produces distinct signatures of GWT response to precipitation in the plateau vs. the valley (**Figure 5**), but the process is ignored in 1D models. We further identified the importance in modeling coupled plant hydraulics-soil hydrology processes that determine the ET changes during drought. Motivated by this study, a subgrid parameterization of subsurface lateral flow (Maquin et al. 2017) has been implemented in ELM. On coupled plant hydraulics-soil hydrology processes, the simple plant hydraulics scheme (PHS) of Kennedy et al. (2018) has been implemented in ELM and evaluated using measurements from BCI and Manaus (Fang et al. In Prep). The PHS and subsurface flow parameterization have been included in the roadmap of E3SM and lay the foundation for further development in Phase 2.

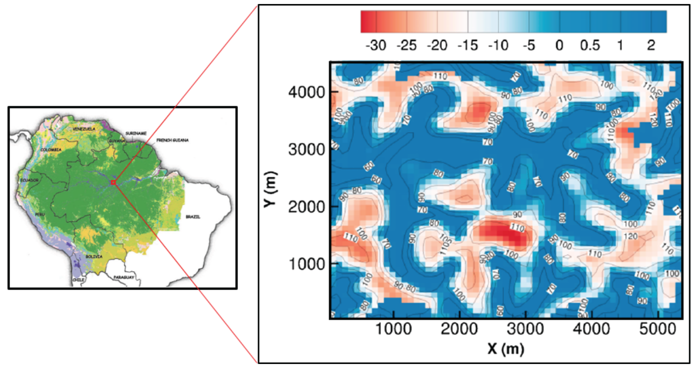

Figure 5. Difference in groundwater table depth (m) comparison 1D and 3D hydrologic simulations in Manaus, showing the impacts of subsurface lateral flow.

We analyzed and collected data to complement modeling. A meta-analysis using macropore flow velocity (MFV) measurements across the globe identified the dominant controls on MFV (Gao et al. 2018) to inform parameterization development in Phase 2. Solander et al. (In Prep) studied the pantropical response of soil moisture during three super ENSO events using data and found an amplified soil moisture response relative to the precipitation response in the Amazon and Sahel/East Africa. We used novel measurement technologies to make hydrologic measurements in the Asu catchment at the Manaus site. These include measurements of moisture content and soil matric potentials at individual core tree scales and multiple depths within the root zone and within the 30m-deep K34 pit. Along plateau, slope and valley topographic gradients, real-time percolation rates are directly monitored. At intermediate scale, soil moisture content is being measured using the COSMOS probe. Data collected in 2017–18 combined with new measurements will be used in model evaluation and analysis in Phase 2.

4.4 PHASE 1 PROGRESS IN ADVANCING UNDERSTANDING OF DISTURBANCE-RECOVERY DYNAMICS IN TROPICAL FORESTS

Modeling advances: Fire determines vegetation size structure, biomass accumulation, and the balance between trees and grasses in the tropics (Bond et al. 2005; Hoffmann et al. 2012; Staver et al. 2011). To capture fire behavior and effects, we implemented the SPITFIRE module within FATES. FATES-SPITFIRE simulates differential fire mortality based on tree size and fire resistance traits, altering forest structure and response to future fire. Following comprehensive code review, we updated and tested parameters for coarse woody debris, fuel combustion and drying, as well as growth allometry for tropical trees and grasses, with sensitivity testing across South America for fire rate of spread and burned area (**Figure 6**; Shuman et al. In Prep).

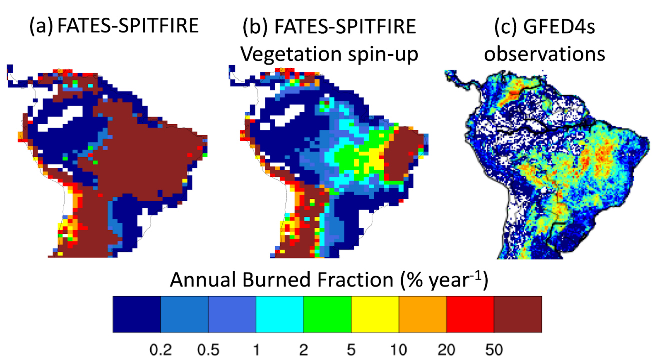

Figure 6. Average annual burned fraction (% per year). FATES-SPITFIRE results for 20-year average with tree-grass competition after 50 years of active fire for (a) simulation with live grass fuel moisture varied by climate and a reduced influence of wind, and (b) simulation with the updates from (a) and 10 years of vegetation initialization prior to fire disturbance, and (c) for satellite product GFED4s averaged across years 1997 to 2014 as reported by Van der Werf et al. 2017.

Selective logging is a dominant mode of disturbance for moist and wet tropical forests. We modeled on-site and exported carbon pools within FATES. Test simulations were developed for a logging experiment in the Tapajós National Forest, Brazil, with results compared to paired logged vs. intact eddy covariance tower data (Miller et al. 2011). While simulations captured seasonal dynamics (**Figure 7**; Huang et al. 2019) and the rates of recovery of carbon and water fluxes, biases in gross fluxes must be addressed.

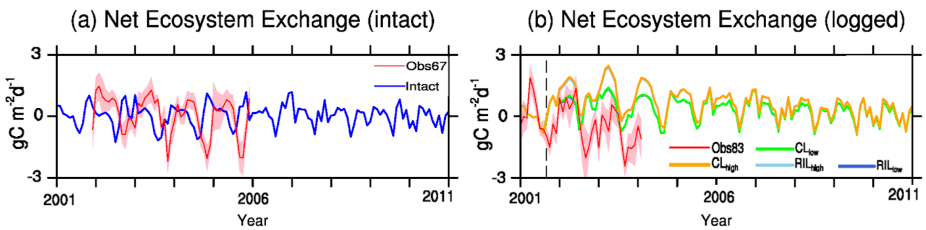

Figure 7. FATES simulations of intact (left) and logged (right) net ecosystem exchange, as compared to observations (red traces) at the Tapajós National Forest, Brazil (Huang et al. 2019).

Forest functional composition is determined, in part, by selective recruitment of seedlings and saplings (Engelbrecht et al. 2007). We reviewed vegetation demographic model (VDM), gap model, and forest landscape model representations of regeneration processes (Hanbury-Brown and Kueppers In Prep), and developed an improved FATES simulation approach and tested it at BCI (Panama). Functional assembly during recruitment was represented with tree size-dependent allocation to reproduction; light- and moisture-sensitive tree emergence, survival and recruitment; and PFT differences in environmental sensitivities (Hanbury-Brown et al. In Prep).

Empirical analysis and model benchmark development: Tree mortality in FATES is partially determined by a background mortality term. We aim to explicitly resolve key mortality processes, so we analyzed existing datasets, and collected new ones to inform new algorithms. Our analysis of tree survival across the ForestGEO network revealed four demographic modes into which tree mortality can be grouped (Johnson et al. 2018). We assessed tree mortality causes within a 50ha plot in Lambir Hills, Malaysia, finding that crown damage was the strongest predictor of mortality (Arellano et al. 2019). To expand the data available for developing and testing mechanistic models of mortality, we designed and initiated annual mortality surveys across multiple tropical forest plots (McMahon et al. 2019). To lay the foundation for explicit simulation of wind-driven mortality, we used satellite observations to quantify variation in the frequency and seasonality of blow-down events across the Amazon Basin. Simulation of increased disturbance rates with an individual-based model led to a shift toward early successional species (Negrón-Juárez et al. 2018; Negrón-Juárez et al. 2017). FATES reproduced the observed patterns of forest disturbance and trajectories of forest recovery from windthrows and clearcuts (Negrón-Juárez et al. 2019 In Review).

Direct human disturbance of tropical landscapes has resulted in extensive degraded and secondary tropical forests (Pan et al. 2011). Spaceborne lidar data offer an approach to developing globally consistent datasets, therefore we explored the use of satellite IceSat/GLAS data and developed new approaches to classifying forest degradation based on airborne lidar data (Rangel Pinagé et al. 2019). Airborne lidar in intact and disturbed Central Amazon forests showed that branch fall is important to the carbon cycle (Leitold et al. 2018) in intact and degraded forests and across climates, with an average background disturbance rate of 1.79% y^{-1} in intact and 1.98% y^{-1} in fragmented forests. Drought associated with El Niño led to a 62% increase in annualized

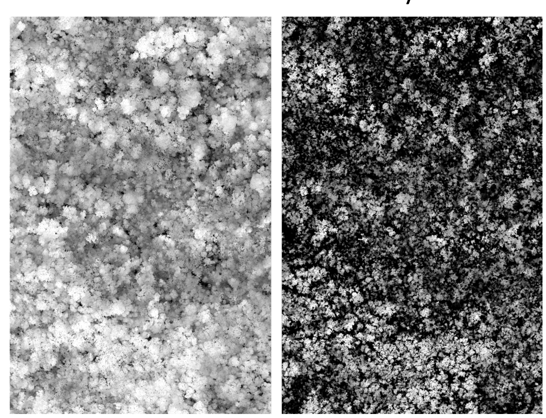

Figure 8. Pre- (left) and post-hurricane (right) GLiHT lidar canopy height models (25cm resolution) for the Luquillo Forest Dynamics Plot (LFDP, 16ha). Light shades are high; dark shades are low. Mean canopy height in the region surrounding the plots declined from 20.3m in 2017, six months prior to Hurricane María, to 13.3m in 2018, 8 months following the storm (unpublished result D. Morton).

canopy turnover rates. (Leitold et al. 2018). Repeated airborne lidar measurements in Puerto Rico between 2016 and 2017 showed a similar background canopy disturbance rate of 1.7% y^{-1}. Hurricane Maria in 2017 caused extraordinary canopy damage (Feng et al. 2018). In the El Verde area of Puerto Rico, 59% of the canopy area lost more than 3m height and overall canopy mean height decreased 7m (**Figure 8**).

4.5 PHASE 1 PROGRESS IN ADVANCING UNDERSTANDING OF SOIL PROPERTIES AND COUPLED BIOGEOCHEMICAL CYCLES IN TROPICAL FORESTS

Field investigations of soil P dynamics and root-soil interactions: Analysis of sources of uncertainty in the P model of ELM identified two functions needing improved data input to better constrain the model: (1) biochemical mineralization of organic P to plant-available P; and (2) P sorption dynamics and its controls on soil P availability. We documented root phosphatase activity in different tree species in sites in Puerto Rico differing in P availability and reported a negative relationship between site-average phosphatase and P availability and related phosphatase activity to root traits (Cabugao et al. 2017). The phosphatase data have provided a benchmark for the ELM P model, which was parameterized for three research sites in Puerto Rico. We measured P and dissolved organic carbon (DOC) sorption isotherms on 23 soils from tropical Oxisols, Ultisols, Inceptisols, Andisols, and Aridisols from around the globe and determined statistically significant correlations among Langmuir P and DOC sorption parameters and soil characteristics, including particle size, pH, and aluminum (Al) and iron (Fe) oxides (Brenner et al. 2018). However, the dataset is admittedly small. A comparable study involved over 200 soils (Mayes et al. 2012), which allows greater confidence in global-scale application.

Continuing work on this task has included sampling secondary forest sites in Puerto Rico before and after Hurricane Maria and a model-guided campaign to analyze root function and soil properties in relation to soil depth. Next steps involve expanding the database and increasing the inference space for both the phosphatase activity and sorption extents across multiple soil types and land uses and in contrasting tropical biomes. Model sensitivity analysis will determine the influence of these new sorption parameters in ELM in Phase 2. Ongoing analysis of root and soil traits as a function of depth will interface with existing model structure of root distribution and provide function to that distribution.

Physiological response to variation in foliar nutrients: Another area of uncertainty in model representation of tree response to P nutrition is the physiological mechanisms whereby P supply influences plant performance. We analyzed photosynthetic parameters, foliar nitrogen and phosphorus contents of a diverse population of tree species at two sites in Panama with contrasting soil fertility (Norby et al. 2017). The relationships between photosynthetic parameters and nutrients were of similar strength for nitrogen and phosphorus and robust across diverse species and site conditions. The strongest relationship expressed maximum electron transport rate (J_{max}) as a multivariate function of both nitrogen and phosphorus. This relationship was improved with the inclusion of independent data on wood density. The relationships established in Panama between photosynthetic parameters and foliar N and P may increase the capability of models to predict future conditions in P-limited tropical forests, especially when combined with data on edaphic conditions and other environmental drivers. This dataset is contributing to the development of leaf processes and trait representations in FATES.

Model development: Implementation of P cycle and P limitation in the E3SM land model (ELM v1) was shown to improve simulated spatial pattern of net primary productivity (NPP; Yang et al. In Revision). The P-enabled ELM v1 captures the declining west-to-east gradient of productivity, consistent with field observations. These model simulations show that the consideration of P availability lead to a smaller carbon sink associated with CO_2 fertilization effects and suggest P limitation would significantly reduce the carbon sink associated with CO_2 fertilization effects through the 21st century. We conclude that P cycle dynamics affect both sources and sinks of carbon in the Amazon region, and the effects of P limitation will become increasingly important as CO_2 increases. We contributed model results to a model intercomparison project of CO_2 responses at the Manaus Amazon forest plots and the role of P cycle processes (Fleischer et al. In Press).

Root traits and productivity: Development of a nutrient-enabled FATES model will require better data on tropical root traits and root production. As described above, root trait analysis was part of investigations of root phosphatase activity in Puerto Rico (**Figure 9**). A synthesis and analysis of root research in Puerto Rico over the past 50 years was prepared from published and unpublished data (Yaffar In Review). We also supported measurements of root production by collaborators in Puerto Rico, where the response to experimental warming and Hurricane Maria are documented (Yaffar et al. In Prep), and in Brazil, where the importance of deep fine roots is emphasized (Cordeiro et al. In Review).

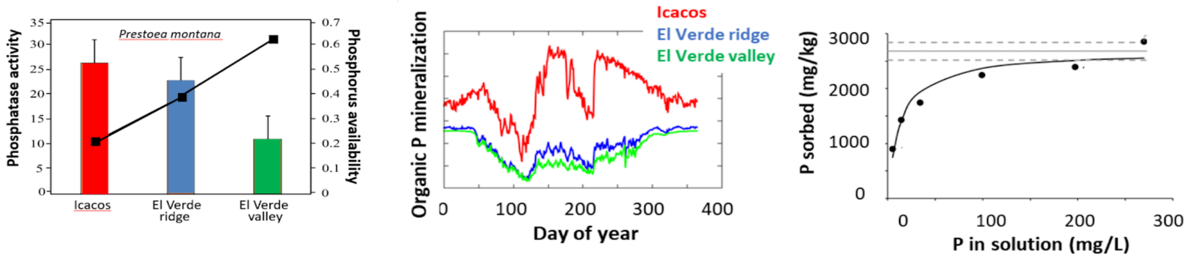

Figure 9. Root phosphatase activity observed for *Prestoea montana* (colored bars, left panel; modified from Cabugao et al. 2017 and modeled with ELM (middle panel) at different sites in Puerto Rico: Icacos (red), a ridge at El Verde (blue), and a valley at El Verde (green). These three sites are increasing order of available phosphorus (black line, left panel). Also shown is a characteristic P sorption isotherm for the Oxisol in the valley at El Verde (right panel; Brenner et al. 2019).

4.6 IMPACT AND RELEVANCE OF PHASE 1 RESEARCH ADVANCES

As outlined above, Phase 1 has established a strong foundation for development of Phase 2 science. Phase 1 work has focused the project around three RFAs and associated WPs for development in Phase 2, and the use of E3SM-FATES as our central modeling and ModEx platform. Phase 1 will continue until the end of September 2019. Several ongoing activities are fully funded with Phase 1 resources, including: (1) purchase and deployment costs for comparable instrumentation for all RFA1 sites, and some associated science FTE; (2) development of a canopy access system for Manaus with our INPA partners using an articulated boom lift capable of accessing the upper canopy (~30m height); (3) additional FTE for software engineering support to assist with FATES development; and (4) data team support for large complex datasets. Overall, foundational Phase 1 work has positioned our NGEE-Tropics team for the delivery of quality high-impact science in Phase 2, as detailed below in our Research Plan.

5 PHASE 2 RESEARCH PLAN

Phase 2 research is structured into a set of three **Research Focus Areas (RFAs)** and associated **ModEx Work Packages (WPs)**. Process organization within RFA1 lies at the scale of individual plants (cohorts in FATES), including varying responses to stressors, with focus on drought and elevated temperature, as determined by differences in plant functional traits and life history strategies. RFA2 level organization represents competitive dynamics among cohorts for limiting resources at the site scale, enabling simulation of emergent forest communities, with functional assembly that varies with changing environmental conditions. The RFA3 level comprises fully coupled processes in E3SM, including linkages among vegetation, soil hydrology and water table dynamics; the large-scale forest-atmosphere coupling of water, carbon and energy; and the potential for biome-boundary transitions (e.g., forest-savanna).

This RFA and WP structure, along with our comprehensive ModEx approach, enables the testing of scientific hypotheses and the reduction of uncertainty in emergent model outcomes for our **RFA Science Questions (Qs)**. Computational models such as FATES represent a number of hypotheses as sets of equations defining process understanding for key ecosystem properties. While some of these processes can be represented with a high degree of certainty, others are necessarily represented at a level of aggregation that leaves significant remaining uncertainty, both in the algorithms defining how a process is represented, and in the parameters that govern process representation. We are constructing FATES to allow numerous unconstrained processes to be specified via alternative structures. In particular, the processes that govern the allocation of carbon and nutrients in plant tissues show enormous structural uncertainty. Therefore, we have developed the Plant Allocation and Reactive Transport Extensible Hypotheses (PARTEH) approach in FATES to compare these structures as alternate hypotheses. A given set of model structures also leads to emergent outcomes, which enables testing of larger-scale dynamics against observational benchmarks. Identifying and developing key process-level benchmarks and sensitivity analyses that differentiate and test these hypotheses at the appropriate scale then provide greater reliability in emergent model outcomes.

With FATES and ModEx guiding our approach, we have identified six high-level **Hypotheses (H)** to guide research in Phase 2. Tests for each hypothesis require input from multiple WPs, and will enable the delivery of highly integrative outcomes. Comprehensive testing for many of these hypotheses will also continue in Phase 3 toward achieving our larger NGEE-Tropics goals and vision. While some hypotheses can be tested explicitly with experiments and observations, other hypotheses can only be explored in the model. From an epistemological perspective, one may argue that we cannot formally test hypotheses in the model. However, we can explore model outcomes and ask what assumptions of the model lead to the rejection of a given hypothesis. This model exploration provides insights both into model behavior and future ecosystem responses.

- **H1**: The sensitivity of trees to drought-induced stress and mortality varies with plant water sourcing (e.g., water table versus vadose zone) and the dynamics of water availability, which are dependent on climate, topography, and soil properties.
- **H2**: Traits that limit tree exposure to drought, such as drought deciduousness and deep roots, or that limit the effects of drought and elevated temperatures on tree growth and metabolism, such as carbohydrate storage and temperature acclimation, will become more prevalent under future warmer climates.
- **H3**: Reduced carbon assimilation and increased respiration during intensified droughts and elevated temperatures from a warming climate will result in a shift in tropical forests from a net sink to a net source of carbon with a determinable stress threshold.
- **H4**: Greater nutrient availability increases productivity and accelerates biomass recovery following disturbance, while also increasing mortality rates through size-dependent mortality and dominance by resource-acquisitive species with low defense investment, such that forest biomass is highest at intermediate nutrient availabilities.
- **H5**: Climate variation and disturbances from land use, windstorms, and fire are the primary drivers of tropical forest functional trait composition, structure, and dynamics, causing important differences that underpin forest-atmosphere exchange across the landscape.
- **H6**: Variation in plant photosynthetic and hydraulic traits, both in space across environmental gradients, and in time from phenological and longer-term vegetation responses to global change, modify diurnal and seasonal cycles of ET, which in turn affect atmospheric convection and the dry-to-wet-season transition in the Amazon.

Table 2. Integrative relationships among RFAs, WPs and Hypotheses

		HYPOTHESES					
Research Focus Area	Work Package	H1	H2	H3	H4	H5	H6
RFA 1	WP1.1	●	●				●
	WP1.2	●	●				●
	WP1.3		●	●	●		●
	WP1.4			●	●		
	WP1.5	●		●			
RFA 2	WP2.1					●	
	WP2.2		●	●		●	●
	WP2.3				●	●	
	WP2.4				●	●	
RFA 3	WP3.1	●					
	WP3.2						●
	WP3.3						●

5.1 RESEARCH FOCUS AREA 1: CLIMATE CHANGE EFFECTS ON TREE FUNCTION, STRESS AND MORTALITY

Science Question (Q1): How do drought and elevated temperature impact tree physiology and mortality?

As the Earth's climate continues to change, tropical forests are projected to experience two major environmental challenges: unprecedented warming, and increasing intensity and frequency of drought (Boisier et al. 2015). Many studies have been conducted to better understand forest response to these changes (Bretfeld et al. 2018; Engelbrecht et al. 2007; Zuleta et al. 2017; Doughty et al. 2015; Phillips et al. 2009). However, due to ecosystem complexity resulting from high species diversity and nonlinear interactions of multiple processes (e.g., deep rooting and water table dynamics), our knowledge of the key processes responsible for tropical forest response remains limited. The majority of current studies focus on the observed response of tropical forests to either drought or elevated temperature, with few studies focused on a predictive understanding of the cascade of physiological and ecological processes that comprise forest responses to change.

In Phase 1, we developed a demographic plant hydrodynamic module for FATES (FATES-Hydro) that is the first of its kind in an ESM context, and that enables NGEE-Tropics to address a set of unique questions (Christoffersen et al. 2016). For example, the model simulates different diurnal and seasonal cycles of photosynthetic response to water stress depending on strategies related to diverse hydraulic traits (e.g., the hydraulic safety margin defined as the difference in minimum leaf water potential and stem water potential that leads to 50% loss of conductivity) (Anderegg et al. 2018; Matheny et al. 2017). These strategies are difficult for traditional ESMs to capture, as they can only relate stomatal conductance to soil moisture with no consideration of the stem water storage (Matheny et al. 2014). Our uncertainty analysis of hydraulic traits showed that belowground hydraulic properties (e.g., rooting depth and root diameters) are critical for the prediction of forest carbon and water fluxes, yet we have limited measurements of plant water sourcing, which we aim to improve in Phase 2. Furthermore, while we have the key representation of hydraulic traits and hydrodynamics within FATES, the model has only been evaluated at the BCI site in Panama. Extensive evaluation of the model across different plant functional strategies and sites is needed for a credible pantropical application of the model for predicting diverse and complex vegetation responses at the cohort level. Finally, while we have focused on the model evaluation at the level of individual system components (e.g., leaf water potential), we have not yet fully assessed integrated system responses to drought and temperature.

Another important factor to consider for RFA1 is that controlling drought conditions is challenging in the field. We will employ three approaches to address this limitation. First, model development and benchmarking will focus on regional variation in precipitation seasonality, and strong diurnal changes in plant moisture status and leaf temperature. Second, we will test the model against an ongoing drought experiment at the Daintree Rainforest Observatory (DRO) in Australia, to directly test drought-impacts hypotheses both empirically and with the model. If FATES is able to capture seasonal and diurnal moisture and temperature stress benchmarks, experimental results, and available drought response data, including sapflow and water potential response to the 2015–2016 ENSO event measured during Phase 1, we will have more confidence that the modeled drought response is accurate. Third, at Lambir Hills, Malaysia, and Barro Colorado Island, Panama, mortality is strongly predicted by empirical models (e.g., including growth rate and canopy position) based on multiple decades of forest plot data observations including during drought-mortality events (Condit et al. 1995; Itoh et al. 2012). We will sample and model vulnerable and resistant trees allowing informed tests on the likelihood of drought responses. If FATES is able to match our comprehensive stress benchmarks, that will increase confidence in FATES projection of emergent outcomes under future warmer and more variable tropical climates.

To better predict vegetation response to drought and warming at the cohort level (i.e., a group of trees of similar size and functional traits), we will conduct a set of integrated measurements in key process areas (**Figure 10**) including: rooting depth and water uptake **(WP1.1)**; plant water storage, hydraulic function, and carbohydrate status **(WP1.2)**; leaf and canopy processes **(WP1.3)**; plant respiration and defense **(WP1.4)**; and damage and mortality **(WP1.5)**. This coordinated approach will include the development of integrated leaf, canopy, stem, root and soil water measurements that together allow us to build physiological model testbeds for evaluating process representation within FATES, and enable us to refine model process representation and predictive understanding that integrates rooting dynamics up to canopy level fluxes, and emergent impacts on tree growth and mortality patterns. We will also identify a key set of plant traits and the corresponding processes that dominate tropical forest ecophysiological responses to water and temperature stress. Overall, research carried out in RFA1 will build a firm foundation for functional assembly processes in RFA2, and large scale simulations in RFA3.

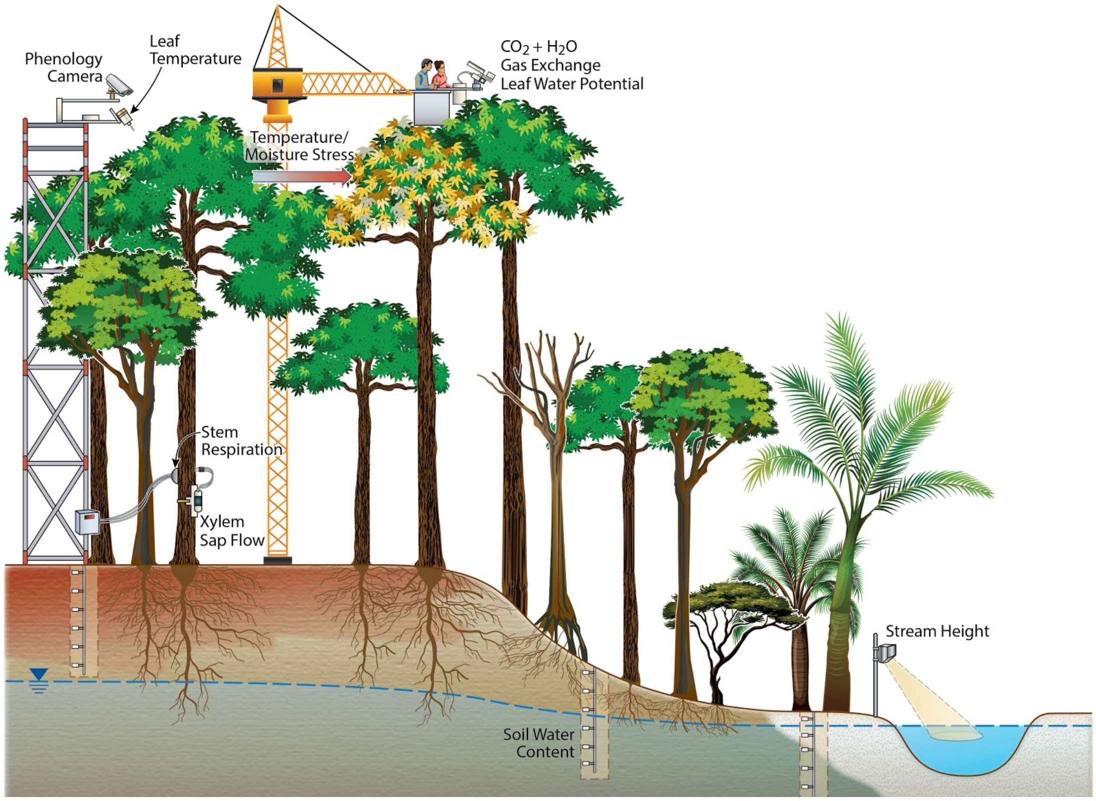

Figure 10. A set of integrated measurements and monitoring systems are being further developed for all RFA1 field sites (Manaus, Panama, Lambir Hills, Daintree), as illustrated here for the Manaus "hillslope site", to ensure comprehensive comparative studies of temperature and moisture stress effects on tree ecophysiology across sites.

WP1.1 Plant water sourcing

WP1.1a. Objective: Using existing and new data collected pantropically, we will improve mechanistic representation of water extraction patterns and their direct linkages to tree root distribution, soil-plant hydraulic traits, and hydraulic stress in FATES.

WP1.1b. Rationale: A fundamental challenge to the prediction of plant responses to drought is understanding the depth at which plants acquire water, how water sourcing changes during drought, and how to represent those dynamics in models. Deep roots are known to help reduce acute water stress during drought and thus maintain carbon uptake in the tropics (Nepstad et al. 1994; Markewitz et al. 2010). Root presence or function in deep soils can be dynamically upregulated through new growth or changes in permeability (e.g., Johnson et al. 2014). While most TBMs have limited root functional representation (Warren et al. 2015), new modeling efforts are mimicking root dynamics via optimality principles (Schymanski et al. 2008; Drewniak 2019) or directly modeling dynamic root water uptake based on drought-dependent plant and soil hydraulics (Fisher et al. 2007; Christoffersen et al. 2016; Mencuccini et al. 2019). Our Phase 1 uncertainty analysis using the FATES soil-plant hydraulics model found that belowground plant hydraulic traits, carbon allocation to roots, rooting depth, and depth of water extraction during drought are all significant sources of uncertainty for simulated carbon fluxes anstocks (Xu et al. In Prep). As such, WP1.1 is focused on direct quantification of root distribution within the soil profile, soil water extraction dynamics, and average depth of water uptake during drought, and then application of those data for further development and validation of FATES.

Species-specific tree water uptake profiles during moisture deficits are linked to plant hydraulic strategies along the isohydric continuum that are reflected in tree growth, branch dieback, and mortality. As drought-dependent mortality rates increase in the tropics (McDowell et al. 2018), there is a pressing need to characterize the hydraulic trait-dependent mechanisms that underlie hydraulic failure and ultimately forest demographic changes across the landscape. Prior hydrological modeling work indicated that deep-rooted species can be more vulnerable to prolonged drought than shallow-rooted species, largely due to persistent depletion and delayed recharge of deep soil water (Ivanov et al. 2012;

Chitra-Tarak et al. 2018). Even so, many of the larger trees at the Amazonian Tapajós research site were able to access deep water and maintain high rates of transpiration during the 2015–2016 ENSO drought (Brum et al. 2018). In addition, some small trees could also source deep water (Brum et al. 2019) illustrating some size-independence of this hydraulic trait. Phase 1 efforts at Brazil's National Institute for Amazon Research (INPA) research site ZF2, near Manaus, also revealed species-specific shifts in water uptake during drought as site-level water sourcing moved to progressively deeper layers (Gimenez et al. In Revision; Ferreira et al. In Prep; Spanner et al. In Prep). Data from a 14m-deep pit in the clayey uplands also indicated live roots up to 10m depth. In contrast, species in the sandy floodplain with a high water table largely maintain roots only in the shallow oxic layer, potentially exposing them to higher risk during extreme drought with a dropping of the water table. Spatial patterns of soil water availability are also dependent on subsurface groundwater flow (e.g., from uplands to valleys), that act as groundwater discharge points. Because of the tight coupling between plant water availability and hydrology, WP1.1 activities will be integrated with hydrology observations and modeling activities in RFA3, and in collaboration with hydrology scientists and students with Brazil's Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), also located at INPA in Manaus.

WP1.1c. Phase 2 Approach and Methods

Field measurements and data analysis: WP1.1's overall field scope is to quantify the vertical profile of soil water availability, root distribution within that profile, where roots are actually taking up water, and how root water uptake varies with plant hydraulic traits, tree size and landscape position. Some sites have a distinct topographic gradient that provides an opportunity to assess soil water availability and hydraulic survival strategies across diverse floristic compositions and soil conditions. A set of automated sensors and field measurements are required to address WP1.1's research scope including automated soil moisture and water potential sensors (1–2m depth) to assess water availability and extraction patterns, characterization of upper fine root distribution profiles and their morphological traits to assess root-specific uptake patterns, and seasonal patterns of stable water isotopes (^{18}O and ^{2}H) in tree xylem, soils, and groundwater to assess average species-specific water extraction depths. For very wet conditions, natural abundance isotopes may be difficult to link to plant water sourcing. In that case, we may amplify the signal using dual pulse labeling with ^{18}O and ^{2}H into the soil at different depths. We will also assess nutrient status with depth (in concert with RFA2) to provide an integrated linkage between seasonal patterns of water and nutrient availability. Along with paired measurements from WP1.2 (sapflow, leaf water potential, diameter growth), stand characterization, and meteorological driving data, these water-uptake depths and rooting strategies will be evaluated against extensive existing or newly measured data on aboveground hydraulic traits to better represent whole-plant drought strategies in FATES, and improved simulations of tropical forest response to water stress.

Model development and evaluation: To represent water sourcing difference among species in FATES, we will group species into PFTs (e.g., shallow- vs. deep-rooted) based on rooting depth. To address the sensitivity of trees to drought-induced stress and mortality, we will first inverse-estimate the rooting profiles by fitting ELM-FATES observed soil moisture, sapflow and leaf water potentials prescribed with observed stand structure and parameterized with observed hydraulic traits. The estimated rooting profile will then be validated using measurement of stable water isotopes. To understand the water sourcing for a large number of species and different tree sizes, we will also inverse estimate the rooting profile by fitting the modeled diameter growth based on long-term inventory (Chitra-Tarak et al. 2018), which will be evaluated against the estimated rooting profile for a small number of species with intense measurements.

The PFT-specific rooting profile will allow us to capture the first order difference in water sourcing strategies. However, since functional rooting depth is not static (i.e., upper root embolism, new root growth, increased soil to root water potential gradients, root upregulation of radial conductivity), we will develop dynamic active rooting depth in FATES to better capture seasonal water uptake dynamics. We will adapt the rooting profile to water availability in the soil based on existing work in ELM (Drewniak 2019). The parameters of dynamic rooting will be fitted to seasonal observations of sapflow and leaf water potential from con-specific trees at different landscape locations. After improved representation of PFT-specific rooting profiles and dynamic rooting depth, FATES will be used to test the role of soil water uptake patterns in the context of ecosystem resistance and resilience to historical and future droughts.

WP1.1d. Research Locations: Water extraction patterns and root trait distribution are complementary to other WPs within RFA1, such that most field data will be collected at the same core sites. The successful Phase 1 focus that linked seasonal patterns of sapflow with vertical patterns of soil water extraction at ZF2 Manaus, Brazil, will be emulated in Phase 2 at Barro Colorado Island (BCI), Panama, Lambir Hills (LH), Malaysia, and Daintree Rainforest Observatory (DRO), Australia. Xylem water isotopes require iterative sampling of branch tissue, or more invasive stem cores, and thus sites with favorable canopy access (e.g., canopy crane) are ideal, including LH, DRO and Manaus (pending acquisition of an articulated boom lift). In concert with other WPs, core research will be focused on intensive plots (e.g., underneath the cranes). At ZF2 Manaus we will also leverage a long-term LBA catchment hydrology study that encompasses plateau, slope and valley (the Manaus "hillslope site"; **Figure 10**), where WP 1.1 measurements will be linked with sapflow (WP1.2) and stem respiration (WP1.4). With our Manaus INPA/LBA collaborators we will extend soil moisture and sapflow (WP1.2) measurements to all three topographic positions, increasing trait diversity, and providing synergistic data for scaling hillslope soil hydrology into models via RFA3 WP3.1. At some sites, we will also leverage our measurements of soil water isotopes and water sourcing to simultaneously collect available soil nutrients in support of RFA2.

WP1.1e. Deliverables

- Pantropical quantification of root distribution and morphological traits
- Seasonal patterns of soil water extraction dynamics at multiple sites that vary in tree hydraulic traits and drought severity
- Vertical depth dynamics of plant water sourcing and nutrient availability during drought
- Improved belowground representation in FATES-Hydro, including dynamic vertical root allocation
- Site-specific and pantropical public datasets and manuscripts characterizing and modeling plant water sourcing under dynamic environmental conditions

WP1.2 Plant hydraulics and carbohydrate dynamics

WP1.2a. Objective: We will advance process understanding and model accuracy regarding the responses of plant hydraulics, gas exchange, and carbon metabolism to drought and elevated temperatures.

WP1.2b. Rationale: The hydraulic component of FATES in Phase 1 (Christoffersen et al. 2016) represents an important development for E3SM that uniquely enables a more mechanistic representation of plant water use under a range of environmental conditions within a demographic framework (e.g., compared to those approaches reviewed in Powell et al. 2013). This mechanistic representation of hydraulics allows testing of hydraulic failure as a mechanism of death, which is paired in this WP with carbon starvation as another major driver of mortality under drought. In addition to allowing testing of hydraulic failure vs. carbon starvation, FATES-Hydro includes major advances for simulating transpiration and downstream processes such as GPP, NPP, and survival in E3SM (Xu et al. In Prep).

Our uncertainty analysis of the hydraulic traits demonstrated critical influences of the new hydraulic code (e.g., traits such as P50 or turgor loss) on plant carbohydrate balance, growth, and transpiration and hydraulic failure (Xu et al. In Prep). In Phase 1, FATES-Hydro has only been evaluated (partially) for the BCI (Panama) site, so there is a critical need for extensive evaluation across multiple sites to ensure the model credibility at large scales. The scope of WP1.2 is to apply and evaluate FATES-Hydro across multiple NGEE-Tropics testbed sites, and to test competing physiological hypotheses against existing and new targeted datasets. Corresponding measurements of hydraulics, carbon and water fluxes, and growth and mortality rates will be carried out across a broad range of sites, enabling model performance evaluation of sapflow, plant water potential, GPP, growth, and survival in response to water stress. Essential model improvements (e.g., xylem refilling following embolism and representation of irreversible hydraulic dysfunction) will be carried out as determined with our ModEx approach including data-informed (e.g., Dickman et al. 2019; Pivovaroff et al. In Prep A, In Prep B) uncertainty and sensitivity analyses (e.g., Xu et al. In Prep).

WP1.2c. Phase 2 Approach and Methods: To ensure FATES accuracy and that our hypothesis tests have pantropical relevance, we are using sites in Manaus, Panama, Australia, and Malaysia. At all four core locations we will have continuous measurements of soil moisture and sapflow and dendrometer-based growth on nine overstory (canopy dominant) trees and five understory trees. An additional hillslope site at Manaus will have soil moisture, sapflow, and stem respiration in a set of canopy trees (**Figure 10**). Trees at each site have previously been, and will continue to be, distributed across the widest range of wood density possible. The use of canopy dominants minimizes the confounding influences of size and light, while the understory tree measurements allow us to better capture the potential importance of hydraulic control on the outcomes of competition. These trees will also have continuous measurements of leaf phenology (see WP1.3) and campaign-based measurements during the dry and wet seasons of leaf-level gas exchange, water potential, carbohydrate content, and embolism presence (using both whole-plant sapflow-derived and stem and twig-level staining indices), all in relation to static traits (e.g., leaf and wood traits like specific leaf area and wood density).

The measurements collected either continuously (e.g., sapflow) or periodically (e.g., water potentials), and on seasonal campaigns (e.g., gas exchange, embolism and carbohydrates) will enable us to address how temperature and drought impact the physiology and survival of tropical trees. Each measurement (described above) will be used as an evaluation metric to benchmark FATES simulations. FATES simulations at each site will be driven by available meteorological data, initialized with existing forest inventories, and parameterized with measured hydraulic traits. We will assess the model development needs based on comparison observations and leverage other WPs (e.g., dynamic rooting depth from WP1.1 and canopy damage from WP1.5). Currently, FATES does not have representation of embolism refilling and impact of water stress on carbon storage and new tissue growth. Based on our existing simulations at BCI (Panama), we anticipate improving representations of embolism and carbohydrate storage (Wei et al. In Prep) using empirical measurements at each site. Once model developments are identified, they will be employed to allow better model fitting to the observations.

WP1.2d. Research Locations: We are making core measurements (described above) at four sites, located in BCI (Panama), Manaus (Brazil), LH (Malaysia), and DRO (Australia). A key value to using BCI and LH is that we have empirical models that predict tree mortality at both sites (Camac et al. 2017; Arellano et al. 2019). While all four sites will each have nine target trees, at these two sites we will capitalize on the species drought-vulnerability knowledge for BCI and LH (Condit et al. 1995; Itoh et al. 2012) by additionally sampling at least five individuals of each group (vulnerable vs. resistant to drought-induced mortality), allowing a rigorous hypothesis test of the traits that underlie drought vulnerability. Some of the data collection overlaps with WP1.5 due to the shared experimental design, enabling large cost savings in time and material. We have already begun measurements (Pivovaroff et al. In Prep A) at the active drought experiment at DRO. In Manaus (Fontes et al. 2018) and Panama (Pivovaroff et al. In Prep A) we are building off existing and continuous data streams regarding plant water relations, sapflow, carbohydrates, growth and soil moisture. We will install new or maintain existing continuous sapflow measurements, and commit to maintenance and seasonal campaigns at all four sites.

WP1.2e. Deliverables

- State-of-the-art representation of plant hydraulics including the occurrence of embolism and its impact in FATES
- Pantropical evaluation of FATES for carbohydrate and embolism risk under variable climates and in relation to static traits
- Identification of underlying mechanisms regarding the role of plant hydraulics and carbohydrate dynamics in plant responses to drought and temperature changes in tropical forests

WP1.3 Leaf and canopy processes

WP1.3a. Objective: Through model development and measurement we will advance the representation of physiological processes at the leaf and canopy scales including associated processes, such as light capture, in FATES to improve projections tropical forest responses to rising temperatures and drought.

WP1.3b. Rationale: WP1.3 is focused on the leaf level physiology that underlies the response of photosynthesis, respiration, and transpiration to warming and drought. These are gateway processes that determine the potential for growth, carbon storage and survival of tropical forests, and play a major role in the land surface energy balance and water cycling. Therefore accurate model representation of these processes and their response to rising temperature and drought is critical to the success of FATES. Furthermore, accurate representation of leaf physiology is essential to capture the response of tropical forests to rising CO_2 because the direct and initial effect of elevated CO_2 on plants is enhanced carboxylation and reduced stomatal conductance, and all other responses are downstream of these two primary leaf-level responses (Ainsworth and Rogers 2007). Accurate handling of these downstream responses to CO_2, which include nutrient and water interactions, will be enabled by the developments in WP1.1, 1.2, 1.4, and 2.3. Model development work and measurements in this WP are focused on addressing key uncertainties in FATES. Specifically, how spatial, temporal and vertical variation in physiological processes and parameters affects the ability of FATES to capture the response of tropical forests to warming and drought. Measurements will include sampling of early and late successional species in NGEE-Tropics pantropical locations (Panama, Brazil, Malaysia, and Australia) to efficiently cover as much of the potential trait space as possible, and enabling the parameterization of new PFTs or strategies to represent variation in traits within FATES including investigating the need for PFT specific relationships to describe trait-trait covariance, e.g., the leaf N-respiration relationship may differ between early and late successional species or across environmental gradients.

Phase 1 work identified huge variation in current ESMs for photosynthesis and stomatal conductance and their response to temperature and soil moisture. Newly developed modeling tools enabled the dissection of leaf-level models, and demonstrated that uncertainties are attributable to both parametric and structural variation among ESMs, which is further amplified by spatial, temporal and vertical scaling. Phase 1 synthesis and modeling work (Rogers et al. 2017; Wu et al. 2017; Walker et al. In Prep; Serbin et al. In Prep; Rogers et al. In Prep a) enabled us to focus Phase 2 measurements on critical parameters that underlie model uncertainty, which will inform Phase 2 model development. In Phase 1 we began development of an approach to predict key physiological traits from leaf level spectroscopy (Serbin et al. 2019; Wu et al. 2019). This work is key to enabling the rapid collection of leaf traits planned in Phase 2, and also lays the foundation for the retrieval of leaf traits from remotely sensed data (e.g., GLiHT).

WP1.3c. Phase 2 Approach and Methods

Model development: We have several initial targets for model development in FATES based on our Phase 1 research. This work includes: removal of triose phosphate use (TPU) limitation (Kumarathunge et al. In Revision; Rogers et al. In Prep b; Walker et al. In Prep); replacement of the Ball-Berry stomatal model (Ball et al. 1987) with the unified stomatal optimization (USO) model (Medlyn et al. 2011; Rogers et al. 2017; Franks et al. 2018, Wu et al. In Revision a); implementation of photosynthetic seasonality (Wu et al. 2017, 2016); implementation of thermal acclimation (Kattge and Knorr 2007; Lombardozzi et al. 2015) with updated algorithms covering a wider (>35°C) temperature range (Kumarathunge et al. 2019); and updating the functional relationship of dark respiration with carboxylation capacity and leaf N content (Atkin et al. 2015). We will also evaluate the ability of FATES to represent the vertical scaling and canopy heterogeneity of key physiological traits and emergent canopy fluxes with our planned measurements. We will continue evaluation of leaf level model uncertainty and sensitivity associated with photosynthesis and transpiration using the Multi-Assumption Architecture & Testbed (MAAT) and Predictive Ecosystem Analyzer (PecAn) uncertainty and variance decomposition tools in combination with data from our field sites (Dietze et al. 2014; Walker et al. 2018a).

Field measurements: Photosynthetic capacity ($V_{c,max}$) and the stomatal slope parameter (g_1 in the USO model) are key drivers of model uncertainty for CO_2 assimilation and transpiration (Rogers et al. 2017; Wu et al. 2017; Wu et al. In Review a; Serbin et al. In Prep). Variation in $V_{c,max}$ with leaf age has been shown to drive photosynthetic seasonality in the tropics and accounts for a 4 Pg fluctuation of seasonal GPP in the Amazon Basin (Wu et al. 2016). Capturing leaf phenology and canopy temperature with a network of cameras and infrared radiometers, and determining $V_{c,max}$, respiration and g_1 across leaf cohorts (young, mature and old) at our 3-4 field sites are therefore critical measurements for model input and evaluation. In addition, we plan to investigate potential leaf age dependent variation in realized quantum yield resulting from photodamage or photoprotection at high temperature. Measurements of diurnal gas exchange and fluorescence (periodic measurements of *in situ* gas exchange throughout the photoperiod) are a critical leaf level benchmark for evaluating FATES, and are central to RFA1, where, in combination with measurements of leaf water potential, they provide important input for RFA1 WPs. Diurnal measurements provide assessments of leaf level parameterization in FATES, and the ability of current model structure and parameterization to capture the responses of photosynthesis, respiration, and stomatal conductance to variations in temperature and soil moisture content. Another important canopy scale benchmark is GPP derived from solar induced fluorescence (SIF; Gu et al. 2019b), and we have purchased a recently developed SIF instrument (Gu et al. 2019a). In Phase 2 we will deploy this SIF system in Manaus at the ZF2 site to provide a critical new benchmark and enable further evaluation of the system. Depending on success in Manaus, we may also move the system to collect canopy level GPP at other core sites.

FATES currently represents vertical scaling of *LMA*, N_a, and $V_{c,max}$ following Lloyd et al. (2010). Collectively these traits are used to determine vertical gradients in carbon acquisition and respiration that ultimately affect the viability of understory cohorts. In Phase 2 we will use a combination of spectroscopy (see below) and traditional methods (destructive sampling and gas exchange) to measure leaf optical properties, physiological traits, leaf area index and light transmission at different heights (representing different canopy layers). This will provide a critical benchmark for FATES evaluation.

Capturing biotic, temporal and vertical variation in key traits such as *LMA*, N_a and $V_{c,max}$ is extremely labor intensive: traditional gas exchange methods take about one hour for a single measurement of $V_{c,max}$. In Phase 1 we developed an approach that uses spectroscopy to predict the leaf traits *LMA* and $V_{c,max}$, with high accuracy and low error across a large proportion of trait space (Serbin et al. 2012; Serbin et al. In Review; Wu et al. In Review b). The spectral models we developed in Phase 1 will enable us to explore these axes of variation by enabling rapid measurement of leaf traits using spectroscopy that will be validated with a lower density of concomitant traditional measurements. Previous work has also demonstrated that this powerful technique can be used to derive many other key traits for FATES parameterization and evaluation such as total non-structural carbohydrates (Serbin et al. 2016; Singh et al. 2015; Ely et al. 2019; Asner and Martin 2015), enabling WP1.3 to provide key input for WP1.2 and 1.5. We will continue to evaluate and develop spectra-trait models for key parameters of interest. This work will provide large datasets and improve understanding of variance, and covariance, of key traits through space and time and environmental gradients. Furthermore, the development of leaf level spectra-trait relationships is a first step towards enabling the retrieval of canopy level traits using remote sensing.

WP1.3d. Research Locations: Canopy access is key to advancing the science associated with WP1.3. Our initial work will continue our Phase 1 focus on the STRI canopy crane sites located at a seasonally dry forest in the Parque Natural Metropolitano (PNM) near Panama City and a wet evergreen forest in the San Lorenzo (SLZ) Protected Area, Colon Province. As Phase 2 continues, we will expand to other sites with high quality canopy access, i.e., LH (Malaysia), Manaus (Brazil), and return to the DRO (Australia), for the drought experiment on a time schedule that depends on tree stress status. Continued development of spectra-trait models in combination with shotgun sampling will also enable us to sample upper canopy foliage in key NGEE-Tropics sites that lack good canopy access, e.g., BCI.

WP1.3e. Deliverables

- State-of-the-art and tropics-specific representation of leaf physiological processes in FATES
- Pantropical parameterization of these underlying physiological processes with key traits
- Spectra-trait models for key plant traits to enable rapid trait collection and to build a foundation for trait collection using remote sensing
- Collection of leaf and canopy level benchmark datasets for FATES testbeds
- A series of FATES simulations at site and regional scales to evaluate the impact of new model development and parameterization on leaf-level physiology and emergent canopy fluxes

WP1.4 Whole plant respiration and defense

WP1.4a. Objective: We will advance process understanding and model representation of whole plant respiratory response to elevated temperature and drought, understory respiration and carbon balance, and costs associated with functional defenses against the negative effects of environmental stressors.

WP1.4b. Rationale: The representation of plant respiration and carbon allocation due to defense in tropical forests is less well developed in FATES than the processes described in WPs 1–3, but are required to accurately determine stress responses and ecosystem carbon balance. Uncertainty analyses using an early version of FATES showed that carbon allocation to storage and respiration costs are important to accurately determine vegetation demography and carbon stocks through their impacts on survival and growth strategies (Massoud et al. 2019). Studies from temperate forests show that hydraulic control of respiration is a key component for prolonged survival in a drought experiment (Sevanto et al. 2014). In subsequent FATES developments, we found that (1) sapwood respiration exerts an important control on plant carbon balance, particularly in large trees, and thus its magnitude needs to be understood in the context of leaf and wood economic spectra; and (2) we needed to include a capacity for trees to reduce maintenance respiration when their storage pools became depleted, at the cost of elevated mortality rate from carbon starvation, to represent trees in the understory that bide their time but do not grow for extended periods. The latter conclusion is based on Sevanto et al. 2014's limited observations from temperate forests. While this logic allows us to capture observed rates of understory mortality, its mechanistic basis, associated parameters, and relationship to tree respiratory responses to other types of stresses all need to be tested in the field. Thus, it is critical to understand how plant carbon allocation, especially respiration, responds to stressful environments in the tropics, given its large impacts on growth and survival through impact on plant functions and defense.

Results from field studies and modeling experiments suggest a wide range of respiratory responses as a function of moisture and temperature stress (Meir et al. 2008; Doughty et al. 2015). Given that even the sign (i.e., positive or negative) of these responses is uncertain, investigations are required to better understand underlying processes and how they respond to stressful conditions. The framework for understanding tree respiratory responses to drought proposed by McDowell et al. (2008) suggests that both hydraulic failure and carbon starvation arise from how the plant's xylem responds to dry soil conditions. Isohydric plants are more able to conserve water during high temperatures and droughts and therefore may be more likely to experience carbon starvation and downregulate respiration as a consequence of depleted non-structural carbohydrate (NSC) pools. In contrast, anisohydric plants, which are less conservative with water, would be more likely to experience strong reductions in stem water potential, hydraulic failure, and desiccation, potentially showing enhanced NSC pools and respiratory fluxes (McDowell et al. 2008). Thus, simultaneous observations of stem temperature, CO_2 efflux, NSCs, and water potential across plant functional types during the wet and dry seasons can be directly compared with FATES model simulations, which treats stem respiration as a function of stem NSCs, nitrogen content, and sapwood allometry with a Q10-based temperature dependence.

Recent evidence suggests that leaf and stem respiration responses to drought and high temperature are tightly coupled to growth responses (Ryan 2011). These findings predict that during drought and heat anomalies, respiration upregulates in trees that accelerate growth, and downregulates in trees that decelerate growth, with response a direct function of substrate NSC availability. Although non-biological reductions in stem efflux have been attributed to xylem transport of CO_2, woody tissue respiration may also be reduced under low stem water potential (Salomón et al. 2018). Numerous studies have demonstrated that xylem transport of respired CO_2 away from the source of production in live woody tissues can result in errors in respiratory flux measurements (Angert et al. 2012; Trumbore et al. 2013). We will deploy an automated stem respiration system that will reduce these xylem transport related errors. With this approach, we will quantify wood tissue respiration as a function of stem temperature and height together with key biological processes including growth rate, sapwood volume, wood tissue nitrogen concentration NSCs, and stem water potential.

Tree taxa that are well defended against the negative effects of drought and elevated temperature display an array of defense traits including high wood density, lignification, latex, terpenoid resins (Chave et al. 2006; Walter 1992; Piva et al. 2019), and other diverse secondary metabolites including phenolics, flavonoids, and alkaloids to minimize herbivory and pathogen attack. When plants become drought stressed, they become more vulnerable to attack (Anderegg et al. 2015). Secondary metabolite accumulation is strongly dependent on a variety of environmental factors such as light, temperature, soil water, and nutrient availability (Yang et al. 2018). In addition to defending against herbivores and pathogens through physical and chemical mechanisms, secondary metabolites can also play dual roles by participating in the plant antioxidant defenses, immunity, and signaling system that protect tissues under stress (Marden et al. 2017). There are respiratory and carbon costs associated with the biosynthesis of both constitutive and inducible defenses, but the fraction of respiration and total carbon allocated to these defenses has not been well quantified in the tropics. A few studies have attempted to quantify the raw materials costs for the production of plant secondary defense compounds using methods developed for calculating growth yield and efficiency in microbes (Gershenzon 2017). These costs can be represented in FATES as a growth-defense tradeoff and further explored in field investigations (Fine et al. 2006; Bazzaz et al. 1987).

WP1.4c. Phase 2 Approach and Methods: WP1.4 will focus on stem CO_2 efflux work at the ZF2 Manaus sites to further quantify how woody tissue respiration varies with tissue functional traits, growth rate, and temperature and moisture stress, toward improving process representation in FATES. Additional field studies will focus on respiration in understory trees, and associated links to carbon balance and understory mortality. We will also explore the representation of a growth-defense tradeoff in FATES with data from existing studies, including those carried out in Phase 1, and additional work in Phase 2 on vulnerability to drought and plant functional traits from studies at the ForestGEO sites (WP1.5), to evaluate and modify the relevant processes in FATES. FATES development for respiration and defense will also benefit from integration with data from WP1.2 (plant hydraulics) and 1.5 (carbohydrates) and WP1.3 (leaf respiration).

Continuous stem respiration: In coordination with WP1.1 (water sourcing) and WP1.2 (plant hydraulics), a measurement system will be developed and installed on nine sapflow trees at the Manaus hillslope site to assess diurnal patterns of stem respiration and its linkage to tree growth, functional traits, soil water availability and topographic position. A simple system will be employed based on a stem enclosure using miniature CO_2 infrared gas analyzer (IRGA) sensors integrated into an automated stem respiration chamber and sealed to the stem (Hilman and Angert 2018). This system is based on development of a real-time flow through system using a Li7000 system with the two IRGAs run in differential mode to give a time resolution of 5min (Cobello et al. 2019). These initial observations revealed highly dynamic stem CO_2 efflux suppression during daytime hours linked to transpiration and stomatal conductance, but equilibrating to stable measurements of stem respiration during nighttime hours. Sapwood area will be determined using established relationships between sapwood area and diameter, verified by taking stem cores, and analyzed for sapwood depth, nitrogen content, and NSCs. To evaluate potential hydraulic controls over stem respiratory fluxes, a miniature stem water potential sensor collecting real-time data will be installed at breast height. Stem flux will be collected in both the wet season and dry season. These automated stem respiration chambers and water potential sensors will be installed on the same experimental sapflow trees described in WPs 1.1 and 1.2 at the Manaus hillslope site with line power (**Figure 10**).

Understory plant respiration and carbon balance: For understory responses of respiration to light limitation, we will conduct a pilot experiment in Manaus. We will identify a small number of open gaps containing young trees, and will place shade cloth to block light from reaching half of a set of selected saplings that vary in species-specific shade tolerance as assessed from census data. Leaf respiration rates will then be measured over time (months to years) on these light-stressed saplings to assess whether respiration rates drop in tandem with leaf carbohydrate levels, assessing the realism of the process of respiratory throttling currently modeled in FATES. Together, these canopy and understory respiration measurements will allow us to better understand how respiration responds to light availability in the understory, and improve the representation of associated mechanisms in FATES. Currently FATES downregulates maintenance respiration when plants are under long-term negative carbon balance, such as in the understory, at the cost of higher mortality for these individuals. This experiment will be used to assess the realism of this representation, and identify the physiological traits and their values that mechanistically define shade tolerance.

Plant defense/growth tradeoff: Construction and maintenance costs for resistant plant structures and biochemical defenses ultimately reduce resources available for plant growth and reproduction, while conferring resistance against agents of mortality. Currently in FATES, higher wood density results in less volume growth per unit carbon allocation for that cohort. An appropriate benefit for this cost would be lower mortality rates, although that relationship is not currently represented in FATES. Hydraulic traits do relate directly to drought mortality in FATES through higher mortality with decreasing fractional xylem conductance, and therefore linked to xylem P50. There are suites of additional defense traits that incur a cost, and we understand that fractions of total site-scale mortality should be modeled as a function of multiple traits. Traits shown to be associated with a growth-defense trade-off include tissue chemistry and toughness to reduce herbivory (Fine et al. 2006; Carmona et al. 2011; Endara and Coley 2011), and biochemical and physiological defenses against elevated temperature and oxidative stress (Bussotti 2008; Vickers et al. 2009). However the total energetic cost associated with suites of defenses is poorly quantified, making the representation of a growth-defense tradeoff in FATES challenging. We will approach this challenge in two ways. First, we will carry out a meta-analysis of existing research, including work during NGEE-Tropics Phase 1, to develop a better understanding of the carbon and nutrient costs associated with different suites of defenses. This cost of defense analysis will be linked to work carried out in WP1.5 from the forest dynamics plot networks to better understand what species with which traits are more resistant to drought induced mortality following extreme droughts; for example, the 2015-2016 ENSO event.

FATES development and benchmarking: We will use the stem respiration measurements to test the representation of sapwood respiration in FATES which is currently a simple linear function of total stem nitrogen content. In particular, we will seek to empirically relate stem respiration to leaf and wood traits such as wood nutrient concentrations, wood density, sapwood area, and stem size. In FATES, sapwood confers an advantage to plants because increased sapwood cross-section increases the hydraulic conductance of the plant while increasing respiratory demand. Both the costs and benefits of sapwood are amplified for larger trees, since they scale relative to leaf processes with the height of the plant. Drought has been shown to both increase (Costa et al. 2014) and decrease (Doughty et al. 2015) stem respiration, potentially determined by drought duration and severity and its impacts on plant hydraulics. However, FATES currently has no relationship between stem water potential and respiration. Thus, we will use the high frequency stem respiration measurements and stem water potential to assess whether including a direct link between stem tissue water status and respiration better fits observations. We will test whether these general relationships are correct in the model, and seek to better parameterize the specifics of the relationships. We will also compare respiration in FATES to the shading manipulation experiment by tracking respiration in cohorts as they are demoted from the canopy layer to the understory and thus transition to a light-limited environment. For all of these model-data comparisons, we will conduct multiple parameter sensitivity experiments to assess parametric control on responses. These detailed model developments and evaluation of respiration and defense costs will support the development of whole-tree resource acquisition and allocation schemes in WP2.3. Finally the growth-defense work will enable us to develop improved mechanistic representations of mortality in FATES with appropriate costs and benefits.

WP1.4d. Research Locations: Wet and dry season observations of stem CO_2 efflux and associated measurements of stem water potential, sapwood volume, growth rate, other species characteristics will be measured in Manaus at the hillslope site. Depending on the degree of moisture stress at the Daintree drought experiment site in Australia, we may deploy stem respiration measurements there later in Phase 2. The understory respiration response to shading experiment will be developed in Manaus. Defense-growth tradeoff work will use existing data and ForesGEO plot-level Phase 2 results.

WP1.4e. Deliverables

- Improved understanding of controls on stem respiration for the Manaus hillslope trees, including and how rates vary with wood traits, stem temperature and water potential, and other factors including nitrogen and NSCs.
- Understory leaf respiration and response to sun→shade transition in Manaus
- Improvements to the growth-defense tradeoff in FATES

WP1.5 Damage and elevated mortality risk

WP1.5a. Objective: WP1.5 aims to determine the mechanistic links between embolism, carbon storage, crown damage and subsequent mortality, and improve relevant processes in FATES.

WP1.5b. Rationale: Tropical forest biomass carbon stocks have extensive spatial variation at local, regional, and global scales. This variation is explained in large part by variation in woody residence times—i.e., by tree mortality rates—rather than by variation in woody productivity (Johnson et al. 2016). Uncertainty in biomass residence time dominates uncertainty in terrestrial responses to future global change (Friend et al. 2014). Yet we still have a limited understanding of what mechanisms drive tree mortality in tropical forests, and models lack realistic, mechanistic representations of many types of mortality (McDowell et al. 2018). To enable accurate prediction of woody residence time, and thus future tropical forest carbon pools, requires improved understanding of processes driving tree mortality rates, and improved representation of these processes in ESMs.

In Phase 1, we showed that post-drought mortality was greater for trees in valley positions at a Colombian Amazon site (Zuleta et al. 2017), and that the likelihood of mortality at Lambir Hills (LH), Malaysia, was strongly linked to tree damage (Arellano et al. 2019). Drought and other stressors (e.g., high temperature) result in tree damage, loss of leaf area, and physiological function, ultimately resulting in higher mortality rates. However, our predictive capacity of relationships among stress, damage and mortality is extremely weak. Resolving these relationships is critical because stress-related damage reduces canopy photosynthetic rates and transpiration fluxes, with impacts on storage reserves and autotrophic respiration, and consequently forest-atmosphere exchange of CO_2, H_2O and energy.

To achieve this goal, WP1.5 will employ a hierarchical set of field measurements from individual sites with high frequency measurements to multiple distributed sites with annual measurements to test potential mechanisms of tree mortality within FATES (including carbon starvation, hydraulic failure, fire vulnerability, and canopy structural damage). FATES-Hydro will be evaluated for these processes at two core sites, and then more broadly using a pantropical suite of ForestGEO sites. Model development includes incorporating the capacity for FATES to simulate partial crown damage, a new hydraulic embolism threshold that results in partial crown loss (i.e., dieback), and allowing the impacts of crown loss and irreversible leaf damage from stress to affect physiological processes (e.g., reduction in carbon assimilation) over multi-year periods.

WP1.5c. Phase 2 Approach and Methods

Field work: In Phase 1, we developed a detailed tree mortality protocol for assessing tree status and vulnerability in tropical forests (Arellano and Davies In Prep). This protocol provided visual assessments of canopy and trunk conditions, crown damage, and light environment and related environmental conditions for 6,000–10,000 trees per site. Using this protocol, seven ForestGEO plots were surveyed annually in Phase 1, and surveys will continue throughout Phase 2 for these sites and for three additional sites. These 10 sites span broad gradients in rainfall, and in edaphic and natural disturbance conditions. Data analyses will continue to explore pantropical patterns of tree mortality in relation to a range of individual and environmental conditions, with a focus on how responses to stress (e.g., increased drought and elevated temperature) result in tree damage and consequently elevated mortality risk (e.g., Arellano et al. 2018). A broad goal of these pantropical mortality surveys is to provide greatly increased resolution on what kills tropical trees, and, consequently, how the "background" mortality rate present in FATES (i.e., mortality that is not associated with carbon starvation, hydraulic failure, and fire) is related to other common processes such as windthrow, lightning, and disease (McDowell et al. 2018).

For a subset of these 10 sites, frequent intensive surveys will be conducted where crown damage and mortality are related to indices of carbon starvation and hydraulic failure. Individual trees across a spectrum of damage levels, as observed from prior surveys, will be selected for monthly assessment of survival, leaf and stem carbohydrate concentrations, carbon isotope discrimination, and embolism that determines the loss of conductivity. This hierarchical set of field measurements (including Phase 1 sites with experimental droughts, sites with intensive ENSO sampling, and ForestGEO sites with annual mortality surveys) will be used to test existing and potential new mechanisms of mortality within FATES, including carbon starvation, hydraulic failure, and canopy dieback following stress.

Modeling development and evaluations: We will develop a crown damage algorithm that can lead to reduced carbohydrate concentrations and increased embolism risk and subsequent mortality. The crown damage could be caused by partial hydraulic failure and windthrow, and linked to different functional traits (WP2.4). We will build a statistical model to link levels of embolism and canopy damage for different species. The crown damage will be represented by altered allometry within FATES, which will influence downstream growth, carbon storage and water uptake. After model development, we will run the model at the corresponding sites to test if the model is able to capture key metrics of GPP, carbon storage, water potential, and sapflow related to different levels of crown damage. Finally, we will evaluate simulated mortality from carbon starvation and hydraulic failure related to different levels of crown damage. The crown damage representation in FATES is synergistic with work in WP2.4.

WP1.5d. Research Locations: Annual mortality surveys will be conducted at 10 ForestGEO sites spanning a range of forest types in Latin America and Southeast Asia. For high frequency intensive sampling of indices of hydraulic failure, carbon starvation and defense allocation, we will capitalize on two of the best monitored ForestGEO plots for WP1.5: BCI (Panama) and LH (Malaysia). These sites are unique in that empirical models based on crown structure and tree growth provide excellent predictions of tree mortality (Camac et al. 2017 and Arellano et al. 2018, respectively). We do not have this information at other sites. However, with knowledge from these empirical models, we are able to conduct informed sampling at other ForestGEO sites. Through collaborators, both sites have boundary and initialization conditions for modeling (eddy covariance data is available at Lambir; cf. Tomo Kumagai, personal communication). One site will be used for model calibration purposes, and the other for model validation. Sampling will occur on trees expected to die (based on the empirical models) and those expected to survive to allow contrasting tests.

WP1.5e. Deliverables

- Incorporation of new stress-related damage thresholds associated with crown loss into FATES, to capture reversible/irreversible effects of stressors on forest mortality and physiological function

- Improved model representation of how mortality processes affect forest-atmosphere coupling
- Pantropical benchmarks for how carbon residence times vary in relation to site conditions (soils, climate) and PFT composition

5.2 RESEARCH FOCUS AREA 2: FOREST STRUCTURE AND FUNCTIONAL COMPOSITION ALONG RESOURCE GRADIENTS

Science Question (Q2): How do forest structure and functional composition vary in response to plant available water, soil fertility, and disturbance regimes?

ESMs are challenged to predict future tropical forest carbon stocks and turnover times, ET rates, and resilience in response to hotter droughts, altered fire regimes, stronger wind storms, and human land use. Traditional "big-leaf" dynamic vegetation models do not capture the critical dynamics that give rise to forest structure and composition. Therefore, in Phase 1, NGEE-Tropics developed representations of dynamic tree competition for light and water to predict tropical forest structure and functional composition in FATES, and provided this capability to E3SM. The trait-filtering approach embodied within FATES, wherein physiological, demographic, and ecological processes select those traits best adapted to the environmental and ecosystem context, is a cutting-edge capacity for global land surface modeling. There is significant scope for high impact science in this area, particularly coupled with high quality model testbed development. The Phase 2 goal for RFA2 is accurate representation of priority processes, including nutrient acquisition and allocation, that give rise to forest structure and functional diversity along important environmental gradients to enable reliable projections of forest-climate system interactions under global change and disturbance scenarios.

Numerous mechanisms in FATES impact its capacity to represent the high functional diversity of tropical forests. We will systematically probe the mechanisms in FATES which modulate functional coexistence, and assess the impact on forest functionality and future transient scenarios. Further, we will focus on three primary drivers of tropical forest composition and associated function: water, nutrients and disturbance. Cohorts of plants in FATES currently compete for light and water. We will build on this capacity, including our implementation of the FATES hydrodynamic scheme in Phase 1 (Christoffersen et al. 2016), to test FATES predictions under varied hydrological and disturbance regimes. Given the observed importance of nutrient availability to tropical forest productivity and functional composition (e.g., Quesada et al. 2012; Turner et al. 2018), RFA2 will also develop a nutrient (N and P) enabled version of FATES, allowing forest development and cohort competition to be sensitive to these primary limiting nutrients. We will also enhance fire-induced mortality and regeneration processes that are sensitive to environmental conditions, as well as introduce a mechanistic representation of wind disturbance in FATES. Finally, island-wide airborne campaigns that characterized forest structure across Puerto Rico in Phase 1 offer an unprecedented opportunity to evaluate FATES simulations across sharp environmental gradients in forests with heterogeneous land-use and disturbance histories. WPs for RFA2 leverage diverse collaborations for data synthesis and use in model development and evaluation, with targeted observational efforts.

WP2.1 Mechanisms and tradeoffs for differential functional assembly

WP2.1a. Objective: WP2.1 will investigate how trait selection, model abstraction assumptions, demographic process representation, and temporal variation within FATES impact the capacity of the model to simulate functionally diverse ecosystems.

WP2.1b. Rationale: Representation of a range of functional types is increasingly recognized as an important feature of model predictions for tropical forest responses to change (Sakschewski et al. 2015; Longo et al. 2018; Powell et al. 2018). An emerging literature, focused on sampling plant functional traits in tropical forests, further illustrates that real tropical forest ecosystems typically comprise plants with markedly contrasting strategies in their use and acquisition of water (Maréchaux et al. 2015; Bartlett et al. 2016; McFadden et al. 2019), nutrients (Norby et al. 2017) and carbon (Poorter 2009), as well as survival from fire (Brando et al. 2012), wind disturbance (Curran et al. 2008) and extreme climate events (Rowland et al. 2015; Anderegg et al. 2016). Whether and how we can capture this functional diversity, and how variation in model representation of diversity might impact emergent forest structure and responses to environmental change, is the focus of RFA2 and WP2.1.

The capacity to maintain functional diversity in FATES depends to some extent on our ability to represent individual physiological processes and the plant traits that control them (or to simulate a variety of functional 'niches'). Models like FATES, which represent detailed plant physiology as well as the community assembly processes that modulate functional diversity, are a relatively recent innovation (Fisher et al. 2018). Thus little is known about how the models' assumptions concerning recruitment, resource competition, mortality and spatial aggregation feed forward into community composition (including the coexistence or extinction of available PFTs), or how differences in community organization impact responses to environmental forcing in an ESM context.

During Phase 1, at the BCI (Panama) testbed site (Koven et al. In Prep; Powell et al. In Prep), ZF2 Manaus testbed site (Holm et al. In Review) and pantropically (Fisher et al. In Prep; Shuman et al. In Prep), we investigated the capacity of FATES, and the similar ED2 model, to represent coexistence of multiple physiologically distinct PFTs, drawn from observed trait distributions. These activities illustrated that maintenance of functional diversity is complex, and FATES and allied models currently display a tendency towards monodominant or low diversity systems (Fisher et al. 2010; Fisher et al. 2015; Powell et al. 2018). Coexistence is likely more difficult to simulate within spatially and biologically averaged cohort models (designed for efficient ESM simulations), given the absence of fine-scale environmental niches (Chesson 2000), stochastic processes (Chesson 2000; Chesson and Warner 1981), and spatial dynamics (Fisher 1937; Freckleton and Watkinson 2002) that are considered important for maintenance of biodiversity.

We already understand that modification of the strength of resource acquisition and reproductive feedbacks can alter the degree to which coexistence is stable (Fisher et al. 2010; Bohn et al. 2011), that inclusion of negative demographic feedback is a widespread feature of theoretical ecosystem models (Chesson 2000), that temporal climate variation facilitates coexistence (Powell et al. 2018; Powell et al. In Prep), that coexistence within tropical forests can be simulated by stochastic, individual-based schemes (Maréchaux and Chave 2017), and that coexistence in these schemes is not necessarily dependent on their stochastic nature. We will systematically modify these processes within FATES to ascertain their impacts on the maintenance of realistic functional diversity for ESM-scale questions.

WP2.1c. Phase 2 Approach and Methods: We will undertake systematic hypothesis testing and sensitivity analyses within FATES across a suite of processes that are known to impact the maintenance of functional diversity. These include modifications to (1) recruitment and seed rain parameterizations (constrained by advances in WP2.4), (2) light competition (size vs. resource acquisition assumptions, in connection with WPs 1.3, 1.4, and 2.3), (3) PFT-specific density dependent survival rates, and (4) parameterization of the severity and impacts of disturbance events, informed by developments in WP1.5 and 2.4. We will also investigate the capacity of interannual variability in plant water availability to maintain diversity (WP2.2). We will ultimately generate parametric 'response surfaces' of how FATES predictions of functional diversity are modified by these features, to inform functional assembly strategies across all RFA2 activities.

We expect that the capacity of FATES to maintain functional diversity will depend on the degree to which the sampled diversity aligns with the environmental heterogeneity that is represented within FATES. Further, whether changes in functional diversity influence ecosystem responses to climate forcing will depend upon plant physiological sensitivity to selected traits. Therefore, we will conduct our sensitivity analysis across a range of alternative trait spaces that represent the state-of-the-art understanding of how plant traits covary through tropical forest systems. We will investigate axes of trait coordination along which coexistence can be simulated based on these trait databases: (1) the carbon and allometric trait space used by Marechaux and Chave (2017) for the French Guiana site, for which they were able to simulate stable and realistic coexistence profiles; (2) carbon and allometric trait space developed by Koven et al. (In Prep) at our Panama (BCI) testbed site; and (3) tropical carbon, allometric, and plant hydraulics trait database developed within WP2.2. We will investigate strategies for high and low diversity sampling of trait space, in coordination with an external project (PI Jeremy Lichstein, U. Florida) that focuses on this question for a suite of vegetation demographics models.

We will develop functional composition testbeds for our two target sites, BCI in Panama and Paracou in French Guiana, by building a trait × species × site database for core and secondary traits. The primary target output for FATES tests will be forest inventory data (species × abundance, size, recruitment, growth, mortality). Auxiliary benchmarks will include leaf area index (LAI), NPP components, soil moisture, sapflow, building on Phase 1 data team efforts in Panama and a wealth of previous studies in Paracou.

WP2.1d. Research Locations: Site-specific sensitivity analyses will focus on our core site at (BCI) Panama, with well-developed datasets from Phase 1, and Paracou (French Guiana), where there are substantial 'classic' and hydraulic trait databases (e.g., Baraloto et al. 2010; Maréchaux and Chave 2017) and pre-existing work on maintenance of diversity within an individual-based model (Maréchaux and Chave 2017).

WP2.1e. Deliverables

- Functional composition testbeds for BCI (Panama) and Paracou (French Guiana)
- FATES sensitivity analyses to trait definitions, parameterization of recruitment, resource acquisition feedbacks, and PFT-specific density-dependant survival in French Guiana and Panama
- Contribution to demography model intercomparison project (comparison of FATES, aDGVM, LPJ-GUESS, LPJ-mlFIT, FORMIND, LM3-PPA and TROLL) sited at Paracou

WP2.2 Functional composition across plant-available water gradients

WP2.2a. Objective: WP2.2 will explore how diversity in tree hydraulic strategies governs forest responses to local and regional plant available water (PAW) gradients and determines forest structure and functional composition.

WP2.2b. Rationale: The uneven spatial and temporal distribution of predicted precipitation change across the tropics over the coming century (IPCC 2014; Padrón et al. 2019; Pendergrass and Knutti 2018), coupled with wide topographic and edaphic variation, is likely to cause large and diverse impacts on PAW. How functionally diverse tropical forests will respond to such changes in PAW is highly uncertain (Aleixo et al. 2019). Therefore, a range of hydraulically different PFTs will be constructed within FATES by drawing various hydraulic trait combinations (Kraft et al. 2015) from observed distributions to predict how changes in tropical forest PAW impact forest-atmosphere interactions and C-stocks.

Our Phase 1 work used the ED2 model (similar to FATES) to demonstrate that temporal variability in PAW helps to maintain functional diversity in moist tropical forests, but chronic decreases in PAW shift composition towards drought-tolerant species (Powell et al. 2018). These simulations also predict that the outcome of competition for PAW depends on the relative differences in hydraulic trait combinations of neighboring trees, suggesting that cohort-scale interactions will govern emergent landscape-scale responses to changes in hydroclimate (Powell et al. In Prep). So far this work has been limited to temporal changes in PAW at a single site (BCI) and only includes variation in drought tolerance as a PFT strategy. While drought avoidance algorithms have been developed (e.g., Dahlin et al. 2015; Xu et al. 2016), the interaction between drought tolerance and drought avoidance (e.g., rooting depth and deciduousness) has not been rigorously evaluated in model simulations incorporating PAW gradients determined by precipitation, topography, and soil properties. Measurements of key hydraulic traits in Phase 1 and synthesized by others (e.g., Bartlett et al. 2016; Christoffersen et al. 2016; Martin-StPaul et al. 2017) now position us to better explore how hydraulic diversity controls FATES predictions.

WP2.2c. Phase 2 Approach and Methods: We will design three test cases to evaluate FATES's ability to capture vegetation responses to PAW resulting from different drivers:

- Test Case 1 (precipitation gradient): Evaluate FATES's ability to capture the transition in vegetation type and ecosystem function across the precipitation gradient in Panama using San Lorenzo (SLZ), Barro Colorado Island (BCI), Parque Natural Metropolitano (PNM) as wet, intermediate and dry sites, respectively.
- Test Case 2 (water table gradient): Evaluate FATES's ability to capture the transition in vegetation type and ecosystem function in topographically variable landscapes using the hillslope gradients in Amazon forest near Manaus and on BCI.
- Test Case 3 (soil texture gradient): Evaluate FATES's ability to capture the transition in vegetation type and ecosystem function from white sand to clay gradient in the terra firme Amazon near Manaus, across sites with common meteorology.

To understand the importance of interactions between neighboring cohorts with distinct hydraulic strategies, two parameterizations of FATES will be evaluated for each of the test cases. The first parameterization will be considered the baseline or null hypothesis and use the existing default drought-deciduous and evergreen tropical PFT with mean hydraulic traits that vary by their observed biogeographic distributions, thereby reducing competition to a process that is mediated only by size-structure and not by hydraulic functional diversity. Relationships between mean hydraulic traits and environment will be estimated from the literature (e.g., Condit et al. 2000; Baltzer et al. 2008; Maréchaux et al. 2015; Bartlett et al. 2016) and developed from global hydraulic trait datasets that were archived during Phase 1 of the project (Christoffersen et al. 2016; Christoffersen 2019a; Christoffersen 2019b). In contrast, the second parameterization will be comprised of multiple PFTs based on a combination of early/late successional strategies as determined by growth rate and background mortality rate, and drought-tolerance and -avoidance strategies as determined by hydraulic traits, leaf phenology, and rooting depth. In this parameterization, direct interactions between cohorts with different hydraulic strategies are explicitly represented, thereby allowing forest composition to emerge through competition mediated by both size and hydraulic strategies for each of the PAW gradients. Model predictions will be benchmarked against the observed biogeographic trait distributions that are used for the above single-PFT parameterization. This second parameterization will also enable us to explore if functional diversity in topographically or edaphically complex terrain buffers landscape scale vegetation responses to drought in a similar way that it buffers forests when PAW is temporally variable, and where more drought tolerant trees compensate for the loss of function by the more vulnerable trees during droughts and wet periods (Powell et al. 2018). Outcomes from WP2.1 will inform the model specifications to enable stable coexistence of realistic ranges of hydraulic functional diversity.

For Test Case 1, the model will be set up for SLZ, BCI and PNM with precipitation ranging from 1850mm/yr to 3500mm/yr. Model predictions will be benchmarked against measurements of leaf water potential, sapflow, leaf temperature (Wolfe et al. 2019a,b,c,d) and diurnal leaf gas exchange (Rogers et al. 2019; Serbin et al. 2019) made during Phase 1 of the project at the individual tree level leveraging on the proposed work on WP1.1, WP1.2 and WP1.3, and against long-term inventory plot measurements of stand structure, composition and demographic rates (Condit et al. 2012). PAW will be validated against water content measurements made at each site during Phase 1 and prior campaigns. FATES will be forced with locally measured meteorological data from SLZ (Faybishenko et al. 2019a), BCI (Faybishenko et al. 2018) and PNM (Faybishenko et al. 2019b), which were QA/QC'd and gap-filled during Phase 1.

Test Case 2 will simulate the upper and lower portions of the hillslopes at BCI and Manaus. The defining feature of this test is to vary access to the water table with the same meteorological forcing (Holm et al. in Review; Faybishenko et al. 2018) between the two simulated forests. We will run the model with same soil texture or observed soil texture to assess the relative importance of soil texture and water table depth. Model predictions will be benchmarked against the same BCI dataset as in Test 1, and a comparable set for Manaus including sapflow and hydraulic traits (Jardine et al. 2019), forest inventory data (Holm et al. In Review) and soil water content measurements across the hillslope (using existing soil moisture at plateau from Phase 1 and new measurement from the valley in WP1.1 in Phase 2).

Test Case 3 will simulate the upland white sand forest north of Manaus. The defining feature of this test is to vary soil texture while keeping meteorological forcing the same. We will initially compile vegetation, trait and soil data gleaned from the literature (e.g. Fine et al. 2006; Baraloto et al. 2011; Demarchi et al. 2018) for this area and then make comparisons to model simulations across edaphically controlled PAW gradients.

To understand how present-day forests occuring along PAW gradients respond to future changes in hydroclimate, we will add climate extreme and warming trends from CMIP6 projections to observed climate drivers and run FATES for Test Cases 1–3 to evaluate forest vulnerability to future climate conditions, using single- or multi-PFT parameterization according to results of the prior work.

WP2.2d. Research Locations: Primary research locations will be SLZ, BCI, and PNM in Panama with precipitation and hillslope gradients for Test Cases 1 and 2, and Manaus, Brazil, with hillslope and soil texture gradients for Test Cases 2 and 3.

WP2.2e. Deliverables

- An improved ELM-FATES that is able to capture vegetation response across diverse PAW gradients
- Tropical PFT parameterizations based on hydraulic traits
- An improved understanding of potential compensatory effects arising from PFT interactions on water and carbon cycles under current and future hydroclimate conditions

WP2.3 Forest structure and function across nutrient gradients

WP2.3a. Objective: WP2.3 will develop the empirical basis and ELM-FATES algorithms to represent nutrient acquisition, allocation, and demand in tropical trees to enable ELM-FATES to simulate key features of tropical forest structure and function across nutrient gradients.

WP2.3b. Rationale: The availability of primary soil nutrients varies over several orders of magnitude among tropical forests (Quesada et al. 2011). Even within forests there is substantial spatial and temporal variability in soil nutrient availability driven by lithology, species feedbacks, and disturbance history (Zemunik, Davies, and Turner 2018). Soil nutrient availability interacts with vegetation dynamics to affect tropical forest structure via production and function (Quesada et al. 2012; Zemunik et al. 2018), and functional composition (Batterman et al. 2013; Condit et al. 2013). Increased production is common in response to greater nutrient availability, and is likely to accelerate forest recovery following disturbance. Increased production could also increase mortality rates by shortening the time taken for individuals to reach a size where size-dependent mortality becomes prevalent (Bennett et al. 2015; Büntgen et al. 2019). On top of these effects, variability in functional composition across nutrient gradients can either amplify or dampen the influence of nutrient availability on forest production and function (Russo et al. 2007; Turner, Brenes-Arguedas, and Condit 2018). Therefore, accurate ESM predictions of tropical forest structure and responses to changing climate, rising CO_2, and disturbance requires a much deeper understanding of the interplay between soil nutrient availability and forest production, function, and functional composition.

The inclusion of nutrient cycling is a high priority for ELM-FATES development in Phase 2. How plant nutrient availability regulates carbon allocation is a key source of uncertainty in model predictions of tropical forest responses to environmental change, as demonstrated in Phase 1 (e.g., Fleischer et al. In Press; Yang et al. 2016; Holm et al. In Review; see also Zaehle et al. 2014). This uncertainty is manifest in the diverse ways in which processes related to nutrient acquisition, allocation, and function have been conceptualised and represented within ecosystem models. Embracing this diversity along with in-depth model evaluation will enable the development of a robust, well understood nutrient-enabled version of ELM-FATES. Such a model will allow the investigation of the trade-offs among the effects of nutrients on production, recovery from disturbance, larger-sized individuals, and functional composition that together determine tropical forest biomass across nutrient gradients.

WP2.3c. Phase 2 Approach and Methods: Our approach to the development of a nutrient-enabled version of ELM-FATES explicitly recognizes that plant nutrient cycling involves a complex suite of processes that also interact with carbon acquisition and allocation, and water acquisition and use, in an economic tradeoff among resources required by a plant (Bloom et al. 1985). This means that allocation to roots, for example, must result in both costs (of resources allocated) and benefits (of resources acquired). In a size-structured model, organ sizes of the cohort average individual are determined by allometry and these allometries currently guide carbon allocation in FATES. Thus allometry must also be integrated as part of a complete resource acquisition and allocation scheme. This complexity results in many possible ways to model nutrient cycling, leading to diverse model structures and ultimately large uncertainty in model carbon-cycle projections (Koven et al. 2015; Friend et al. 2014; Walker et al. 2015). Due to the many possible ways to represent nutrient cycling processes and the tradeoff between tractability and realism, we will represent a given process multiple ways and evaluate and compare model dynamics at our testbed sites to select the most appropriate representations.

Plant nutrient cycling developments in FATES will focus on these three key areas: (1) acquisition, root uptake of nutrients; (2) function, nutrient effects on photosynthesis; and (3) allocation, nutrient and carbon allocation to growth and resource acquisition. For acquisition we will start with relative-demand and root-trait representations that currently exist in ELM (Thornton et al. 2007; Zhu et al. 2017; Yang et al. 2016). We will also expand the root-trait representation of acquisition to include the supply and demand approach of McMurtrie and Näsholm 2018. For function, we will start with empirical relationships of photosynthetic parameters to nutrient content (Walker et al. 2014; Norby et al. 2017) and explore optimization approaches such as least-cost (Wang et al. 2017) and the LUNA models (Ali et al. 2016) in conjunction with WP1.3. For allocation, the FATES PARTEH module allows us to specify alternative allocation schemes with flexible coupling among carbon and nutrients. We will represent both fixed and flexible C:N:P stoichiometry (e.g., Ghimire et al. 2016), and start with carbon allocation based on PFT-specific fixed allometries. We will also consider newer source-sink allocation theory (Thum et al. 2019). Further, a new synthesis and analysis of pantropical allocation, allometry, and nutrient data from the Global Ecosystem Monitoring (GEM) network (Malhi et al. 2004) will support the development of a flexible allocation scheme that is integrated with a dynamic representation of allometry.

More model development in Phase 2 involves a key control on plant nutrient availability—soil mineral sorption, which effectively removes P from solution and can inhibit plant uptake. Using literature synthesis and Phase 1 data from global tropical soils, Brenner et al. (2019) identified that the Langmuir equation was inappropriate for modeling P sorption in tropical soils. We will address this issue by developing a simpler sorption model, parameterised with empirical relationships (Brenner et al. 2019) of sorption parameters with more easily measured soil characteristics (pedotransfer functions), such as texture, bulk density, and Al and Fe contents built from soil samples across 14 ForestGEO plots. Many samples will be required to develop rigorous statistical correlations; Mayes et al. 2012 used about 200 soils, while our early work on P sorption (Brenner et al. 2019) used only 20 soils. The empirical soil P sorption parameters and their relationships to soil properties will be coded into ELM (which handles soil biogeochemistry) to improve the simulation of soil P association and its influence on plant P availability.

To evaluate nutrient model developments, we will develop a pantropical analysis of nutrient controls on tropical forest structure and functional composition. The analyses, and existing data from the literature and from collaborators, will be synthesized into a suite of model testbed sites used to evaluate and benchmark ELM-FATES nutrient cycle representations. Pantropical analysis of nutrient controls on tropical forest dynamics, structure, and functional composition will be based primarily on data from 14 ForestGEO sites, which have detailed, spatially explicit, nutrient-availability maps (John et al. 2007) and data on forest structure and dynamics. Using these data, we will test the general observation that forest productivity is greater on high nutrient soils (Malhi et al. 2004). We will expand on recent analyses from the ForestGEO plot in BCI (Panama) that showed strong, but differential, P control of tree growth rates (Zemunik, Davies, and Turner 2018), supporting the widely held view that P is the primary limiting nutrient in tropical forests (Vitousek 1984; Quesada et al. 2012). Similar analyses exploring forest structure, including stem size distributions, PFT composition, biomass growth, regeneration dynamics, and mortality patterns across fertility gradients, will be done for the 14 nutrient-mapped ForestGEO plots.

In coordination with WP2.4, we will synthesize site-scale data from manipulative experiments (canopy trimming, nutrient enrichment; Zimmerman et al. 2014; Cusack et al. 2011) and observations in and around the Luquillo Experimental Forest in Puerto Rico to evaluate how FATES represents forest regeneration rates following disturbance among sites with varying nutrient availability. These evaluations will inform developments in WP2.4 of FATES regeneration processes (allocation to reproduction, dispersal, seed and seedling survival, recruitment) in the context of nutrient availability.

Early in Phase 2, the Luquillo (Puerto Rico) and LH (Malaysia) ForestGEO sites have been selected for intensive nutrient model evaluation. In addition to being well characterized, with rich research history and extensive available data on forest nutrient cycling, Luquillo and LH provide a valuable contrast for nutrient model evaluation. They differ in nutrient availability and, importantly, have substantial within-site variability in nutrient availability (Tan et al. 2009; Cabugao et al. 2017), allowing development of two testbed forests for each site that have contrasting nutrient availability but very similar climate and weather. Existing data for Luquillo and LH include soil physical and chemical properties, nutrient forms and availability, vegetation stoichiometry, production, and root traits (Tan et al. 2009; Brokaw et al. 2012). Development of these sites as model testbeds will benefit from the considerable plot-based measurements that already exist in Luquillo and LH through collaborations with Long-Term Ecological Research (LTER), ForestGEO, the Tropical Responses to Altered Climate Experiment (TRACE), and GEM. These data include: long-term censuses of stem growth, canopy height, tree community composition, aboveground biomass of many species, species-specific leaf and litter nutrient content, and litterfall. Phase 1 measurements at several sites in Luquillo, seasonal variation in soil-solution nutrient concentrations (Newman et al. In Prep), P sorption (Brenner et al. 2019), and phosphatase activity (Cabugao et al. 2017) will provide data to evaluate biological, geochemical, and enzymatic linkages in the nutrient-enabled ELM-FATES. In Phase 2, soil-solution measurements at Luquillo will continue and at LH we will initiate measurements of soil-solution nutrient content (additional measurements are described below). The synthetic analyses of the Luquillo and LH ForestGEO plots and the disturbance studies in and around the Luquillo Experimental Forest in Puerto Rico will provide valuable additional benchmarks to evaluate nutrient-cycling developments in ELM-FATES at these intensive testbed sites. We envision the development of the other 12 nutrient-mapped

ForestGEO plots for testbed sites later in Phase 2 and Phase 3 for an extensive evaluation of the nutrient model.

To supplement the synthesized datasets of the nutrient model testbed, we will implement a sampling campaign targeting influential plant traits. Phase 1 measurements in Luquillo identified considerable variability in root phosphatase activity across nutrient gradients (Cabugao et al. 2017) and with soil depth. Knowing that root phosphatase activity is a driver of substantial variability in modeled carbon dynamics (Yang et al. In Revision; Fleischer et al. In Press), in Phase 2 we will sample a subset of the 14 ForestGEO plots for root phosphatase, size, and depth-distribution. Additional trait measurements are likely to include leaf, wood, and root stoichiometry to evaluate their covariance to characterize multivariate trait space in support of the development of PFTs in FATES. These measurements will be guided by sensitivity analysis and the coexistence simulations early in Phase 2.

Facilitating the trait-filtering approach in ELM-FATES, we will design nutrient acquisition and allocation modules so that PFT-specific trait values will confer alternative nutrient acquisition and allocation strategies. In support of and informed by WP2.1, we will use the nutrient model testbed sites to test alternative strategies (PFTs with differing trait combinations) against each other at these sites with varying nutrient availability. Trait-filtering, coexistence simulations will be performed initially using simple nutrient acquisition and allocation hypotheses, and later will involve more complex hypotheses. Along with sensitivity analysis to identify influential parameters, the competitive dynamics that emerge from these simulations will provide information on the tradeoffs and outcomes for coexistence across nutrient gradients within FATES.

WP2.3d. Research Locations: Primary research locations will be the ForestGEO network and GEM network with emphasis on the Luquillo Experimental Forest in Puerto Rico and Lambir Hills in Malaysia to leverage Phase 1 and planned Phase 2 investments, as well as Mayes' Early Career Award (see letter of collaboration). Fourteen ForestGEO plots (16–52ha, including Luquillo and Lambir Hills) have detailed characterization of available nutrients (e.g., 12.5 soil samples per ha on 50ha plot at BCI; Zemunik et al. 2018) providing nutrient maps against which forest structure, demographics, and functional composition can be assessed. Soil sorption will be measured using ~100 archived soil samples across these 14 sites. The sites will be the focus of plant trait sampling campaigns. We identified GEM plots (1ha) with measurements of NPP and its components, as well as nutrient stoichiometries and allometry which can be analyzed to help develop the model allocation and nutrient acquisition scheme. At Lambir Hills, the ForestGEO network and the GEM network intersect, with two GEM plots within the ForestGEO plot. The model evaluation testbed will initially be developed at Luquillo and Lambir Hills, each of which have subsites with contrasting nutrient availabilities. At Luquillo, El Verde and Icacos have Oxisol and Inceptisol soils, respectively. At Lambir Hills, two sites within the ForestGEO plot are on sandstone-derived loam and shale-derived clay.

WP2.3e. Deliverables

- A robust, nutrient-enabled ELM-FATES
- Synthesis and evaluation of theory on resource acquisition and allocation in tropical forests suitable for a demographic model like FATES
- Pantropical development of P sorption functions and parameterizations
- Analysis of tropical forest structure and functional composition across nutrient gradients, both within sites (multi-patch scale) and across sites
- Analysis of the effects of nutrient availability on functional assembly of tropical forest early in secondary succession
- Nutrient gradient testbeds to evaluate ELM-FATES at El Yunque (Luquillo and Icacos) and Lambir Hills (two sites on contrasting soil types)
- Improved above- and belowground trait parameterization for nutrient enabled ELM-FATES

WP2.4 Disturbance Regime Effects on Forest Structure and Dynamics

WP2.4a. Objective: WP2.4 will develop and test the ability of ELM-FATES to predict forest structure and composition in response to landscape-scale disturbances and variation in disturbance regimes, including fire, wind and agricultural land use.

WP2.4b. Rationale: Individual disturbance events—from fire, wind and land use—can dramatically alter the height, stem density and biomass of a forest, with differential effects on tree sizes and functional composition. Differences in disturbance regimes (frequency and intensity of repeating events) change regional forest structural features, as well as traits defining resistance and resilience to disturbance (e.g., Magnabosco Marra et al. 2018; Negrón-Juárez et al. 2019 In Review). In the tropics, fire influences overall vegetation size structure, biomass, composition and coexistence of trees and grasses (Hoffmann et al. 2012; Staver et al. 2011; Balch et al. 2015; Shuman et al. In Prep). The interaction of a warming climate with more frequent, and potentially more severe, fires could cause a shift in fire regime, which has the potential to change forest structure and shift biome boundaries by favoring fire-adapted tree species or conversion to grasslands (Pellegrini et al. 2017; Silvério et al. 2013; Balch et al. 2008). A key question for WP2.4 is: What are the consequences of a shift in climate and forest fire regime for tropical forest structure and composition? We will build on our development and testing of the SPITFIRE module within FATES in Phase 1, evaluating predictions of fire behavior and effects on forests in Phase 2.

Wind is an important driver of tropical tree mortality that determines the spatiotemporal variability of forest structure (Negrón-Juárez et al. 2010; Chambers et al. 2013). Warmer and wetter conditions are expected to increase large-scale wind disturbance events (Seidl et al. 2017), which cause differential mortality and damage (Marra et al. 2014; Rifai et al. 2016; Negrón-Juárez et al. 2018). Susceptibility of forests to wind is determined by tree, stand and site characteristics (Silvério et al. 2019; Peterson et al. 2019). Wind disturbance represents a large model uncertainty that is not currently represented in FATES. Therefore, we will develop and evaluate a mechanistic wind mortality algorithm for FATES, including functional traits associated with wind damage and resistance.

Regeneration processes, including tree reproductive output, dispersal, germination, seedling establishment, and sapling growth and survival, are known to be sensitive to variation in light, water, temperature, and soil nutrients and set the stage for the future of forests in an era of global change (Engelbrecht et al. 2007; Rüger et al. 2009; Wright and Calderon 2005). Following landscape-scale disturbances, the rate of forest recovery or transition to an alternate state is dictated by regeneration processes (Comita et al. 2009; Norden et al. 2009). Post-disturbance seedling dynamics are crucial to predicting forest resilience to changing fire regimes or when hurricanes alter understory conditions that enable differential seedling success (Comita et al. 2009). Regenerative sprouting is also a key process promoting forest recovery (Uriarte et al. 2012; Vesk and Westoby 2004; Van Bloem et al. 2007). Land clearing and land use that exhausts the seed bank or eliminates seed dispersal by animals over large distances can dramatically slow secondary forest development due to dispersal limitation. Despite the central importance of regeneration processes to forest structure and the pace of post-disturbance regeneration, the algorithms for these processes are simplified and largely neglected within vegetation demographic models, introducing biases and uncertainties in the model dynamics (Fisher et al. 2010; Powell et al. 2018). To evaluate our hypothesis that the rate of post-disturbance structural recovery and functional composition of tropical forests are strongly influenced by tree regeneration strategies and interactions with light, water and nutrient availability, we will build on Phase 1 efforts to improve regeneration algorithms within FATES, testing them across RFA2 testbed sites.

Finally, tropical forest structure and functional composition across the island of Puerto Rico have been shaped by sharp gradients in precipitation, temperature, light availability, soil substrates, and exposure to wind disturbance. In addition, Puerto Rico's complex land use histories and species invasions have yielded diverse and novel forests (Lugo 2013). Puerto Rico's land use history includes an intensive agricultural period with sugarcane, coffee and other commodity crops, along with subsistence agriculture and pasture. Beginning in the mid 20th century, when deforestation accelerated in much of the global tropics, farmland abandonment and active afforestation in Puerto RIco resulted in extensive secondary forest across climate zones and soil types (Kennaway and Helmer 2007). Episodic hurricanes overlay a natural disturbance regime on this anthropogenic landscape. A rich history of research on landscape changes over the last 70 years, our Phase 1 airborne surveys, and satellite-based remote-sensing analyses of forest structure across large portions of the island present a unique opportunity for evaluating FATES' ability to capture the island's key gradients. In Phase 2, we propose to use FATES to simulate secondary forest development following agricultural abandonment in Puerto Rico considering climate and wind disturbances. We will examine the consequences of varied regeneration trajectories for hydrologic and carbon cycles.

WP2.4c. Phase 2 Approach and Methods:

Approach for fire: In Phase 2, we will further develop the FATES-SPITFIRE module to improve prediction of fire occurrence, include live fuel moisture impacts on combustion, and update parameterization of fire traits across tropical PFTs. Currently, SPITFIRE uses the Nesterov fire weather index—a function of daily meteorological conditions—to determine fire ignition and behavior. We will expand SPITFIRE to use additional indices that determine fire risk by including fuel characteristics: (1) CFFDRS (Wotton 2019; Wang et al. 2017); (2) NFDRS (Jolly 2019; Jolly and Freeborn 2017); and (3) FFDI (McArthur 1967). This allows for a more detailed evaluation of the relationship between climate, vegetation and fire behavior, such as duration and area burned. Results will be evaluated pantropically against existing data products for the current period (1979–2015) provided by collaborator Jolly (Jolly et al. 2015; van der Werf et al. 2017). We will incorporate FATES predictions of live fuel (living tree) moisture into calculations of flammability and combustion. Live fuel moisture content shifts daily (Woodruff et al. 2015), seasonally (Jolly et al. 2014; Jolly et al. 2016), and inter-annually (Wever et al. 2002) due to growth and water uptake that alters ignitability (Jolly et al. 2016; Jolly and Johnson 2018). FATES-SPITFIRE simulations will be evaluated at Tanguro, Brazil (Balch et al. 2015; Brando et al. 2016), for years with and without drought conditions to assess temporal changes in live and dead fuel state and fire behavior. Finally, we will develop and evaluate parameterizations of tropical PFTs reflecting varied fire-related traits and ecological strategies (e.g., bark thickness, resprouting; Hoffmann et al. 2012) to better capture biome ecotones, forest structure and composition (Hoffmann et al. 2012; Dantas et al. 2013; Balch et al. 2015). Implementation of a resprouting routine is a planned regeneration process update in FATES (see below). We will use data compilations across the tropics from collaborators Pellegrini and Hoffmann for bark thickness and species distribution (Pellegrini et al. 2016, 2017; Hoffmann et al. 2009, 2012a, 2012b) together with data for Tanguro, Brazil, provided by collaborators Balch and Brando (biomass and mortality, LAI, fuel moisture, load and combustion, rate of fire spread, flame height, burn pattern) (Balch et al. 2008, 2011, 2013, 2015; Brando et al. 2012, 2014, 2016) to test predictions of fire effects on vegetation under experimental conditions.

Approach for wind: In Phase 2, we will quantify wind disturbance pantropically, assess E3SM's capability to reproduce extreme winds and characteristics of these winds, and produce a module within FATES to capture wind damage and tree mortality. Pantropical assessment of wind disturbance will based on remote sensing data, from which we will also obtain the return frequency (Negrón-Juárez et al. 2018). E3SM is capable of reproducing extreme rainfall events (**Figure 11**) associated with strong winds at the surface in the Amazon. E3SM's atmospheric model retains probability distribution functions (PDFs) describing turbulent transport as vector quantities that can be used to derive wind speed and direction (vertical and horizontal). We will analyze the lowest atmospheric layer wind speed PDFs from E3SM and other atmospheric models to quantify spatial and temporal patterns across the Amazon basin, and during modeled hurricanes at low latitudes, assessing whether the PDFs overlap with observations of wind and canopy damage thresholds (Negrón-Juárez et al. 2018; Peterson 2019). We will use these PDFs to calculate daily wind-loading statistical values for the maximum wind speed and the proportion of the grid cell impacted, adjusting for biases in the atmospheric model. Wind interacts with vegetation factors (tree size, crown characteristics, and wood density) and site characteristics (stand density and topography), which influence the potential for damage and mortality (Larjavaara and Muller-Landau 2010; Fournier et al. 2013; Gardiner et al. 2016; Rifai et al. 2016; Magnabosco Marra et al. 2018; MacFarlane and Kane 2017; Seidl et al. 2017; Negrón-Juárez et al. 2014; Feng et al. In Prep). These factors are key to effective modeling of the impacts of wind on vegetation (Gardiner et al. 2008; Seidl et al. 2011). We will develop functional relationships using vegetation factors, site characteristics, and wind loading values to predict likelihood of stem breakage, guided by recent observational studies (Negrón-Juárez et al. 2018). A portion of wind-induced mortality is often delayed (Walker 1991; Uriarte et al. 2019; Magnabosco Marra et al. 2018), so we will develop an algorithm relating canopy damage to subsequent mortality rates, building on analyses by collaborator Uriarte in Puerto Rico and our data in the Central and Western Amazon (Chambers et al. 2013; Rifai et al. 2016; Magnabosco Marra et al. 2018). PFT-specific resprouting may occur after damage, with regrowth handled by a new scheme (see below). We will compare variation in wind mortality and

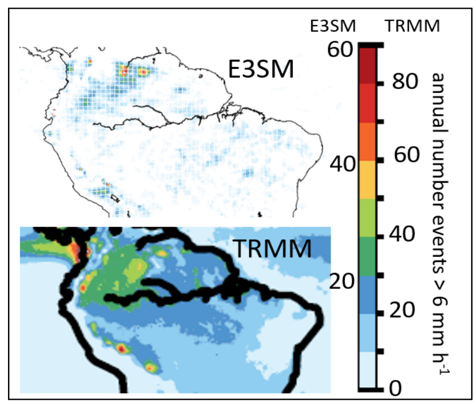

Figure 11. Comparison of Amazon extreme rainfall events (> 6mm/h) using E3SM (3h, 0.25°, 1 year) and TRMM (3h, 0.25°, period 1998-2018). Extreme rainfall events produce strong downbursts resulting in windthrows (uprooted and broken trees). Negron-Juarez et al. In Prep.

damage predictions to spatial patterns across the Amazon basin (Negrón-Juárez et al. 2017) and in Puerto Rico (Uriarte et al. 2005; 2019; Feng et al. 2018, In Prep) quantified in Phase 1 .

Approach for regeneration: FATES currently has an invariant allocation to reproduction, a seed pool, no sensitivity of recruitment to environmental factors, and no dispersal limitation. While this approach may be adequate for mature, steady state forests, we expect it to falter in capturing post-disturbance regeneration. In Phase 1, we reviewed VDM, gap and landscape model approaches to simulating regeneration processes and developed a conceptual approach for FATES that introduces size- and PFT-dependent reproductive allocation, prognostic seed and seedling pools, and light- and moisture-sensitive emergence, seedling mortality and recruitment (Hanbury-Brown and Kueppers In Prep; Hanbury-Brown et al. In Prep). In Phase 2, we will implement and test this scheme within FATES across the Panama PAW gradient discussed in WP2.2. Our expectation is that environmental filtering of PFTs will shift from a mature tree process to one influenced by seedling and sapling phases (e.g., Feeley et al. 2011). We will use observations of regeneration processes following hurricanes and land use change in Puerto Rico and the Amazon (Comita et al. 2009; Uriarte et al. 2005; Shiels et al. 2010; Negrón-Juárez et al. In Review), and fire in Tanguru (Balch et al. 2013) to further test the regeneration scheme. Resprouting is a key ecological strategy to accelerate regeneration following wind and fire disturbance (Balch et al. 2013; Bellingham and Sparrow 2000). Within FATES, trees that lose a fraction of their canopy can regrow, but there is no scheme allowing sprouting from surviving root systems. We will implement a resprouting scheme and test whether it improves regeneration after fires and hurricanes in collaboration with Hoffman and Uriarte (see letters of collaboration). With WP2.3, we will also consider nutrient constraints on reproductive allocation, seedling survival, and recruitment, synthesizing data from experiments and observations in Puerto Rico, Panama and ForestGEO sites to determine whether tradeoffs (e.g., between growth and survival) that occur across nutrient gradients (Russo et al. 2007) emerge strongly early in life history, and require further modifications to the recruitment scheme. Finally, because dispersal strategy can be an important determinant of secondary forest community assembly that interacts with nutrient and other resource availability (van Breugel et al. 2019), we will implement and test a dispersal scheme in FATES, beginning with explicit inter-patch dispersal. we will closely coordinate these activities with investigations of recruitment impacts on community composition in WP2.1.

Approach for land use simulations in Puerto Rico: In Phase 1, we developed a logging module to represent the ecological, biophysical, and biogeochemical processes following a logging event (Huang et al. 2019). The module tracks land clearing and changes in canopy structure and forest composition following disturbance, enabling FATES to track compound disturbance regimes. In Phase 2, we will establish a landscape- to regional-scale testbed for model-data integration from 1950 to present for Puerto Rico, refine FATES capability to simulate land use transitions, and evaluate compound effects of forest clearing, disturbance, and regeneration in coordination with wind and regeneration tasks. (1) We will assemble climate forcing, land cover, topography, soil, and hydrogeology datasets over the island as inputs at ~1km resolution. We will develop a set of climate drivers that extend back to 1950 at 1km x 1km using the Daymet algorithm (Thornton et al. 2017), station observations in Puerto Rico, and/or a synthesis of recent year data that reflect the historical climate state (as in Powell et al. 2018), which will be interpolated to hourly values. Historical and recent land cover maps (Brockman 1952; Kennaway and Helmer, 2007; Hansen et al. 2013) will be combined into a multidecadal time series formatted according to the land use model intercomparison (LUMIP) standard (Lawrence et al. 2016) in ELM-FATES format. (2) We will synthesize in-situ and remotely sensed products, such as streamflow records (Beck et al. 2013; McDowell et al. 2013), forest size and composition inventories, and litter/wood debris measurements at long-term research sites (e.g., LTER, CZO) for model validation. Airborne lidar from the Phase 1 NASA GLiHT flights combined with USFS FIA forest inventory and information on climate, soils, and time since agricultural abandonment will be used to develop a benchmark map of forest biomass in Puerto Rico in 2016. (3) We will perform a suite of transient ELM-FATES simulations at 1km resolution to quantify rates of forest regeneration and recovery. These simulations will follow the protocol defined in the Trendy/Global Carbon Project (Sitch et al. 2015; Le Quéré et al. 2018) as a framework to partition surface fluxes (e.g., NEE, LH), biomass, necromass, and forest structure/composition among drivers such as climate variability, CO_2 fertilization, and land use legacy by sequentially adding these factors. Analyses will quantify dominant factors modulating ecosystem demography, carbon and water dynamics in different phases of forest development benchmarked against observations.

***WP2.4d. Research Locations*:** WP2.4 will generate and use testbeds across multiple sites to evaluate: fire processes at Tanguro, Brazil, and pantropically; wind damage and mortality across the Amazon basin and Puerto Rico; regeneration processes across the Panama precipitation gradient, Tanguro (Brazil), Puerto Rico, and across ForestGEO sites; and the ELM-FATES simulations for moist and wet forests in Puerto Rico, island wide.

WP2.4e. Deliverables

- A refined fire module in FATES that has been evaluated for tropical forest responses, including differential resistance and regeneration according to functional traits
- A new wind mortality and damage module in FATES tested at the regional scale
- A more sophisticated regeneration scheme in FATES that better captures variability in recruitment and regeneration following disturbance and environmental change
- An island-wide Puerto Rico testbed and ELM-FATES simulations of the effects of compound disturbances and recovery in a changing environment

5.3 RESEARCH FOCUS AREA 3: TROPICAL FORESTS AND COUPLED EARTH SYSTEM PROCESSES

Science Question (Q3): How do precipitation recycling and the seasonal timing of precipitation respond to changes in climate and forest structure?

Tropical forests play a crucial role in the physical climate system by providing a large fraction of the water that is available for precipitation, which in turn governs the recycling of water in the coupled forest-atmosphere system. This is particularly true over the Amazon, where the ET contribution to precipitation is extremely high (Salati et al. 1979; Gat and Matsui 1991; Costa and Foley 1999; Negron-Juárez et al. 2007), and where anthropogenic impacts are starting to show. Observations suggest that, over recent decades, the transitions from dry to wet season in large parts of the forest have become delayed (Butt et al. 2011; Sena et al. 2018), and that precipitation rates and basin-wide ET rates have decreased (Li et al. 2008; Swann and Koven 2017). Empirical evidence and model predictions demonstrate that these coupled land-atmosphere hydrologic fluxes will change substantially in the future as a result of further warming, land use, changing vegetation distributions, CO_2 fertilization, aerosols, and other factors (Spracklen et al. 2012; Khanna et al. 2017; Kooperman et al. 2018). At the same time, the models used to make these projections have weak representation of many critical processes, in particular the physiological and ecological controls on ET fluxes. ESMs typically lack representation of vegetation canopy structure, detailed treatment of disturbance, mechanistic plant hydraulics, variation in hydrodynamic function across contrasting ecological niches, and realistic representation of soil hydrology and groundwater dynamics that control water available to plants.

Because NGEE-Tropics grand deliverable at the end of Phase 3 is a next-generation, process-rich tropical forest ecosystem model for use within E3SM, we must begin exploring the dynamics of coupled E3SM-FATES in Phase 2 of the project. Doing this requires focusing on dynamics relevant at the larger scale. One key question is how hydrological variation leads to different sources of water across hillslope gradients, so that we can represent this heterogeneity within future versions of E3SM. A second question is how to best leverage new remote sensing capabilities to benchmark and initialize complex structures in a model like FATES. Critically, we need to begin working with FATES in a coupled land-atmosphere configuration so we can better understand how feedbacks between ecological and climatic gradients interact within the E3SM model.

FATES representation within E3SM is ideally suited to address questions about the role of the forest in the coupled land-atmosphere system. We will explore FATES dynamics at scales of continental to pantropical regions in the three work packages within this RFA: (1) **WP3.1** will explore basin-wide hydrological simulations to better assess the role of landscape heterogeneity in governing ET, with a crucial focus on understanding how much of the Amazon ET is sourced from the vadose zone versus from groundwater; (2) **WP3.2** will build large-scale datasets needed to test and initialize FATES simulations, particularly using the Global Ecosystem Dynamics Investigation (GEDI) lidar instrument aboard the International Space Station (ISS) to observe the structure of the vegetation canopy at a level that will allow testing of the heterogeneous representation within FATES; and (3) **WP3.3** will conduct coupled land-atmosphere experiments using FATES within E3SM to explore the role of plant hydraulic diversity and water available to plants in governing diurnal, seasonal, and interannual patterns in forest ET, and how variation in these patterns affect precipitation across the Amazon.

WP3.1 Hillslope-to-continental scale soil hydrology and water table dynamics

WP3.1a. Objective: WP3.1 will explore basin-wide hydrological simulations to better assess the role of landscape heterogeneity in governing ET, with a crucial focus on understanding how much of the Amazon ET is sourced from the vadose zone versus from groundwater. We will improve modeling of soil moisture and groundwater, and extensive field datasets for model development and benchmarking.

WP3.1b. Rationale: Tropical forest access to water in the vadose zone and groundwater is an important constraint on ET, with global implications for precipitation recycling (Miguez-Macho and Fan 2012). Understanding and modeling the spatial variability in the partitioning of water between the vadose zone—the unsaturated soil layers—and groundwater in relation to the root profile is therefore important for modeling water cycle and tropical forest response to changes in greenhouse gases and land use. The vertical distribution of water in the vadose zone and groundwater is influenced by both vertical and horizontal hydrologic processes, most of which occur at hillslope scales that are too fine to be resolved by land surface models used in ESMs (Clark et al. 2015; Fan et al. 2019). Most importantly, such models ignore subsurface lateral flows that play a critical role in distributing water between plateaus and valleys and controlling groundwater table depth. This deficiency was identified in our Phase 1 research as a key uncertainty in modeling groundwater dynamics in ELM (Fang et al. 2017). Furthermore, macropore flows play a significant role in governing hydrological processes including infiltration, soil moisture distribution, and groundwater table dynamics in tropical forests (e.g., Jones 2010; Cheng et al. 2017). Building on our Phase 1 research in characterizing uncertainty in hydrologic modeling through comparison of one-dimensional and three-dimensional hydrology models, this work package will evaluate subgrid approaches to model subsurface lateral flows and macropore flows currently being implemented in ELM by our project team. Our goal is to use hillslope-to-basin scale hydrological simulations to better assess the role of landscape heterogeneity in governing tropical forest ET to improve understanding of the water sourcing from the vadose zone versus from groundwater. Such understanding is important as variations (e.g., during ENSO) and long-term changes (e.g., due to warming or land use change) in the partitioning of water between the vadose zone and groundwater have important implications for forest dynamics and mortality.

Tropical forest trees that obtain significant PAW from the water table may be particularly vulnerable to a dropping of the water table under extreme drought (e.g. Zuleta et al. 2017). The amount of water available for plants is influenced by the seasonal precipitation as well as the hydrologic mechanisms that buffer the seasonal deficit. For example, horizontal redistribution of water by subsurface lateral flows may buffer trees in the valley against shortage of precipitation but, at the same time, increase the vulnerability of trees in plateau and slope positions to precipitation deficit. Increased infiltration by macropore flows may increase groundwater storage and also buffer the seasonal precipitation deficit (Cheng et al. 2017). The ultimate influence of drought on water available to plants may depend on the time scale and magnitude of the precipitation deficit and those of the horizontal and vertical redistribution of water by subsurface lateral flow and preferential macropore flow that buffer drought. More specifically, a flash drought such as a single season drought related to ENSO may have little influence on water available to plants if the time scale of the buffering effects is longer than a season. By corollary, a chronic drought even of smaller magnitude may have larger influence because the cumulative precipitation deficit dominates over the buffering effects. To understand the influence of drought on water available to plants, we will investigate the relative impacts of subsurface lateral flow and vertical macropore flows on water available in the vadose zone and groundwater in plateaus vs. valleys. We will also determine which processes (e.g., rain intensity and duration, lateral flow, vertical macropore flow) have more dominant influence on the time scales of hydrologic buffering of drought.

WP3.1c.Phase 2 Approach and Methods: To address our questions on water sourcing of Amazon ET, we will make use of 1D ELM and 3D ParFlow models and measurements. Through Phase 1, we have been implementing a subsurface lateral flow parameterization based on the Maquin et al. (2017) method, and a simple macropore flow parameterization to ELM. In addition, a simple plant hydraulics scheme based on Kennedy et al. (2019) and a more sophisticated plant hydraulics scheme based on Christoffersen et al. (2017) have been implemented in ELM. In Phase 2, these parameterizations will be tested within FATES in combination at Manaus and BCI in Panama, and analysis will be performed to characterize the sensitivity of model simulations to parametric uncertainty. In parallel, we will couple ELM-FATES with ParFlow. The coupled ELM-FATES-ParFlow applied at hillslope scale (e.g., ~90m) together with hydrologic measurements at Manaus and BCI will serve as benchmarks for ELM-FATES simulations.

A stable water isotope model will be implemented in ELM-FATES and ELM-FATES-ParFlow to facilitate comparison with isotopic measurements. We will collaborate with the WP1.1 team on depth dependent soil water isotope transport modeling and measurements to identify the depth at which water is drawn by the plant roots for ET. Numerical experiments will be designed to compare ELM-FATES and ELM-FATES-ParFlow with parameterized and resolved subsurface lateral flow and macropore flow, respectively. Simulations will be compared against measurements such as soil moisture, soil matric potential, leaf water potential, sapflow, ET, streamflow, soil water isotopic ratio, and soil hydraulic parameters at Manaus, BCI, and Agua Salud. Agua Salud contains chronosequences of secondary forests recovering after pasture abandonment (Cheng et al. 2017; Cheng et al. 2018).

We anticipate the need to improve parameterizations of subsurface lateral flow and macropore flow, as informed by the comparison of ELM-FATES with ELM-FATES-ParFlow and measurements. In consultation with the E3SM Next Generation Development (NGD) land project, we may explore other approaches such as the H3D model (Hazenberg et al. 2015) that will be implemented by the NGD project in ELM to more explicitly represent subsurface lateral flow. This will be followed by more numerical experiments and sensitivity analysis to benchmark the updated ELM-FATES with ELM-FATES-ParFlow and measurements.

Lastly, multidecadal simulations will be performed using ELM-FATES and ELM-FATES-ParFlow over the Amazon basin to assess the vadose zone moisture and groundwater table depth and how they are modulated by surface heterogeneity in the basin. Comparison of ELM-FATES and ELM-FATES-ParFlow simulations with satellite data (e.g., GRACE, AMSR-E, MODIS) and Global Land Data Assimilation System (GLDAS) data will quantify biases and uncertainties in estimating water sourcing using ELM. To understand the relative impacts of subsurface lateral flow and macropore flow on the water sourcing and processes that influence the time scale of hydrologic buffering of drought, we will perform numerical experiments by disabling processes one at a time in ELM-FATES and ELM-FATES-ParFlow and varying soil properties and rain intensity for comparison and analysis.

WP3.1d. Research Locations: As discussed above, Manaus and Panama (BCI and Agua Salud) will be two primary locations used for testing and evaluating models. These locations feature contrasting landscape, climate, soil, and plant response to droughts. For example, the Asu catchment near Manaus has smaller topographic variations and ET is less water limited compared to BCI and Agua Salud in Panama. For large basin-scale analysis and modeling, we will focus on the Amazon basin where numerical experiments will be used to address our science questions and link to WP3.3.

WP3.1e. Deliverables

- Well-tested and constrained parameterizations of subsurface lateral flow and macropore flow in ELM-FATES for modeling drought response of tropical forest
- Assessed spatial distribution of vadose zone moisture and groundwater table depth across the Amazon with uncertainty bounds
- Hydrologic measurements to support WP3.1 and RFA1

This WP has a strong connection with RFA1, including coordinated field measurements and analysis of plant hydraulics and water available to plants.

WP3.2 Large-scale observations of forest structure and dynamics, and atmospheric coupling

WP3.2a. Objective: WP3.2 will build new detailed data products to test and initialize FATES simulations including pantropical representation of heterogeneous forest structure and regionally variable phenology and local quantification of water and energy fluxes and hillslope hydrology.

WP3.2b. Rationale: ESMs require data for boundary conditions and as benchmarks for testing model performance. In WP3.2 we will leverage new remote sensing capabilities and mine older datasets on tropical forest function. Specifically, we will develop new data products that (1) map the pantropical variations of forest structure, (2) quantify the seasonal variation of canopy phenology at selected pantropical sites, and (3) comprehensively process and analyze eddy covariance fluxes and hydrological datasets from long-term research sites across the Amazon.

Earth System models require simplified representations of ecosystem structure that can be applied globally and that smoothly connect historical land use data with predicted future patterns of land use. The current standard representation LUH2 (http://luh.umd.edu/index.shtml) used for CMIP6 (Lawrence et al. 2016) has a long and successful heritage (Hurtt et al. 2006; Hurtt et al. 2011). To represent forest lands globally, this model divides forested land into primary and secondary categories.

Primary forests are modeled as potential vegetation while secondary forests develop following complete clearing. This parsimonious approach has been expanded based on global data for forest harvest. In tropical forests, activities that modify forest structure without removing forest cover such as selective logging (Asner et al. 2005) and understory fire (Morton et al. 2013) have now affected a majority of forest areas, and it has been estimated that less than 25% of extant tropical forests can be considered "intact" (Lewis et al. 2015). Quantifying the structure of tropical forests using consistent global datasets has been extremely difficult owing to the lack of high-quality systematic forest inventories in most tropical countries. However, the combination of targeted forest inventories with new extensive airborne lidar acquisitions and the recently launched GEDI lidar orbiting on the ISS provide a new opportunity to quantify forest structure and dynamics across the tropics.

Compared to other ecosystems, moist and wet tropical forests are relatively aseasonal. Nonetheless, tropical forests have evolved seasonal phenology that result in seasonal variations in LAI (Negrón Juárez et al. 2009). For example, many tree species shed old leaves and flush new leaves in the dry season to avoid herbivory by insects that are highly sensitive to desiccation (Coley and Barone 1996). Recently, Wu et al. (2016) demonstrated that seasonal phenology not only changed LAI but also controlled the annual pattern of GPP in two Amazon forests because of the differences in photosynthetic capacities among immature, new, and old leaves. Even before this demonstration of phenological control on GPP, an apparent green-up was identified from moderate scale optical remote sensing (Huete et al. 2006; Saleska et al. 2007), although much of this apparent signal can be attributed to artifacts from sun-sensor geometry (Morton et al. 2014). The degree to which moderate resolution satellites can accurately identify subtle phenological changes is still a matter for debate (Saleska et al. 2016) but it is clear that new tools should be brought to bear on this question because of the importance of phenological controls on productivity. The recently launched Vegetation and Environment monitoring on a New Micro-Satellite (VENμS) platform, a near polar sun-synchronous orbit micro-satellite launched in 2017 with a 2-day revisit orbit, provides valuable data to address this problem. At a resolution of 5m, data from the 123 sites (at 27km × 27km) globally that are being imaged will provide sufficiently high spectral and spatial resolution to resolve the detection of tropical forest leaf phenology at a landscape scale (Ferrier et al. 2010). VENμS data in synthesis with field, drone, Landsat and MODIS data will enable novel approaches to exploring large-scale phenology dynamics.

WP3.2c. Phase 2 Approach and Methods: New regional data products are required to initialize, parameterize and benchmark FATES and E3SM for fully coupled Amazon basin experiments in WP3.3. We require initial conditions for forest structure both to conduct experiments during the development of prognostic land use in FATES, and afterwards due to the incomplete representation of global land use datasets. First, we will explore using existing datasets (Hurtt et al. 2011 and LUH2) and compare these products to new products developed with remote sensing of forest structure. Airborne lidar data from across the Amazon region demonstrate strong variations of forest structure from edaphic and climatic influences and from the stronger human influences through logging and fire (Longo et al. 2016). While biomass estimation and mapping is the most common application of lidar in tropical forests (e.g., Asner et al. 2013), lidar point clouds have been used for years to estimate wood volume, basal area, stem density and other structural variables in temperate and boreal forests (Lefsky et al. 2002; Lim et al. 2016). Structural datasets from lidar may also serve as model benchmarks for processes such as biomass recovery in secondary forests (Helmer et al. 2009).

We will use common area-based statistical methods for prediction of stem diameter distribution, basal area, and biomass (White et al. 2013). We will start with airborne lidar data co-located with over 800 plots from the Amazon region of Brazil and French Guiana (a superset of data from Longo et al. 2016) to develop calibrations. Based on multiple regression models from lidar metrics, preliminary estimates of stem density performed relatively well (R2 = 0.65). We will explore machine learning approaches (random forests, generalized boosted models, neural networks) as alternatives to regressions, although early tests show no improvement in performance. After the Amazon, we will develop calibrations for airborne lidar for the Congo and Kalimantan areas where we have similarly extensive calibration data. We will develop fully pantropical products using GEDI data by transferring the calibrations from aggregated airborne lidar data (synthetic waveforms) to GEDI waveforms.

Vegetation phenology is an integrated and sensitive indicator of ecosystem function that responds to disturbance, seasonality, major climate modes (e.g., ENSO), and climate change (Hoffman et al. 2010; White et al. 2005). Phenology modifies the surface energy balance and hydrology. Drawing upon recent advances in remote sensing (Shiklomanov et al. 2019) for the detection of spatiotemporal variations in vegetation phenology from phenocams (RFA1), drones (RFA2), and satellite platforms (RFA3), we will combine multi-sensor, multi-spectral radiative measurements across scales, from in situ to orbital, with structural data from lidar (GEDI) to attribute phenological variations to underlying mechanistic processes. High resolution, high repeat frequency observations will provide novel information about modes of phenological variation in tropical vegetation across scales. Phenological variations have been difficult to observe at moderate resolution (e.g. MODIS) in dense tropical forests, so we will combine observations of differing spatial and temporal resolutions to extract a stronger signal. A consortium of researchers, led by Forrest Hoffman, developed a proposal prior to the VENµS satellite launch, for selection of 13 tropical forest sites overlapping with NGEE-Tropics study areas; 11 were selected. Using VENµS, we will develop a set of seasonal and interannual phenometrics from observations using change point detection and machine learning to incorporate into model performance metrics, and integrate these with other remote sensing phenology data sources. We will then further develop pantropical phenoregions using a data mining method (Hoffman et al. 2013) to understand the context of site measurements and to provide a basis for extrapolation point measurements.

We partnered with INPA/LBA in Brazil in Phase 1 to identify benchmarks for ET, net carbon flux, and energy balance, drawing from data collected from eddy covariance towers located at multiple Amazon forest sites. Data for five tower sites were shared, including almost 20 years of records (the longest in a tropical forest) for K34 near Manaus. Data for two sites in the Eastern Amazon are already available via the AmeriFlux network. Three Peruvian Amazon sites are also developing, and we are actively processing these data with our Peruvian collaborators. From these 10 Amazon sites, we will compile the most comprehensive harmonized eddy covariance dataset in existence for the Amazon. The meteorological data (rainfall, temperature, relative humidity, net radiation, etc.) are undergoing harmonization and quality control and will also be used for the initialization tests for FATES runs at the Manaus site. We will process eddy covariance measurements (fluxes of carbon, water and energy) using the ONEFlux code pipeline (https://github.com/AmeriFlux/ONEFlux) of the AmeriFlux and FLUXNET networks to generate gap-filled and partitioned fluxes, with accompanying uncertainty estimates. These products will represent forest response to weather and disturbance events and evaluate the vegetation-atmosphere coupling in FATES. We will also explore other sources of ET estimates (da Motta Paca et al. 2019; Negron-Juárez et al. 2007) and use GRACE data with a water balance approach (Swann and Koven 2017; Maeda et al. 2017). We will employ planned ILAMB global gridded GPP products based on solar induced fluorescence (SIF) retrievals from satellites (Yu et al. 2019; Li and Xiao 2019) and atmospheric carbonyl sulfide (Campbell et al. 2017) as carbon flux benchmarks. Finally, a comprehensive set of completed ILAMB (Collier et al. 2018) benchmarks will also be used to evaluate model performance.

WP3.2d. Research Locations: Three tropical regions are sufficiently large to influence Earth system-scale dynamics for a test of our coupled model: Southeast Asia, the Congo Basin, and the Amazon Basin. Considering our extensive Phase 1 work in the Amazon, our strong collaboration with research groups throughout the region, along with decades of data at all the relevant scales, research under this WP will focus on the Amazon Basin toward fully-coupled global runs of E3SM-FATES in Phase 3. Dataset development for forest structure and phenology will explore the pantropics in preparation for Phase 3.

WP3.2e. Deliverables

- Amazon Basin, Congo Basin, and Borneo airborne lidar-based stand structure
- Amazon Basin and Pantropical GEDI-based stand structure
- Tower-level ecosystem fluxes (carbon, water and energy) at multiple Amazon sites
- VENµS-based NDVI and NDVI variability and phenological persistence maps for 11 sites
- Pantropical phenoregion, eco-phenoregion and phenology representativeness maps

WP3.3 Model experiment with FATES coupled to E3SM

WP3.3a. Objective: WP3.3 will explore the role of plant hydraulic diversity and water availability to plants in governing diurnal, seasonal, and interannual patterns in forest evapotranspiration, and how variation in these patterns affect precipitation across the Amazon.

WP3.3b. Rationale: Continental tropical forests play a crucial role in the circulation and hydrologic cycle that supports them, by transpiring large quantities of water into the atmospheric boundary layer that then is recycled into the forest as precipitation. This is particularly true in the Amazon basin, where recycling is high and models predict that the forest is acutely vulnerable to changes in land use, CO_2 fertilization, and climate change (Zemp et al. 2017; Costa et al. 2007; Staal et al. 2018; Boers et al. 2017).

While we have begun developing FATES in a purely offline manner, as driven by meteorology at the scale of individual sites and as compared to observations at the scale of site-level testbeds, we also need to understand how the model dynamics will scale up to the continental or larger domain, and feed back with atmospheric dynamics to modulate the coupled land-atmosphere system. We will begin to explore these dynamics using E3SM-FATES to understand the role of differing plant hydraulic processes in governing ET dynamics in space and time, and how these feed back to govern the climate in the region.

By representing plant hydraulics and leaf age phenology within a model that resolves ecosystem heterogeneity, we expect that this heterogeneity will substantially change the dynamics of ET, both in time at the scale of diurnal and seasonal cycles, and in space across ecotones of hydrodynamic function. Moreover, we expect that this variation in ET will feed back via atmospheric circulation on the function of the ecosystem at the scale of an entire basin such as the Amazon.

For Phase 1, our key goal was to build an initial version of FATES as coupled within the E3SM land model, including both a representation of plant demography and a representation of plant hydraulic dynamics. Having completed that, we have begun to explore the parametric and boundary condition uncertainty of the model at the scale of individual forest sites. While we are beginning to understand these parametric and climatic controls on forest function, we must also be aware that these interactions work in both ways: just as climate affects physiological and ecological function, the differing physiological dynamics also feed back to affect climate. Meanwhile, all of this coupling takes place in a context in which anthropogenic disturbance and climate change is shifting these dynamics. These are key uncertainties that we must begin to explore in Phase 2 of NGEE-Tropics.

WP3.3c. Phase 2 Approach and Methods: We will explore these interactions using FATES coupled within E3SM. Because the fully-coupled E3SM-FATES is highly complex, we will progress from relatively simple site-level experiments that are the bases of other WPs, towards a fully coupled configuration in increments. The first step will be to look at regional simulations driven by offline meteorological reanalysis data (GSWP3; Van den Hurk et al. 2016), which we will benchmark against multiple datasets. These will include the broad set of benchmarks that are captured by ILAMB (Collier et al. 2018); specific analyses of variation across the Amazon in biomass and size structure, as derived from WP3.2; key hydraulic traits; diurnal and seasonal cycles of ET as compared to eddy covariance sites across the Amazon; and large-scale water-budget derived ET seasonality (Swann and Koven 2017), as applied to sub-basins within the Amazon. The second step will be to take offline meteorological drivers from a prior fully-coupled E3SM simulation conducted without FATES, and use these to drive FATES offline. Again, we will assess simulation against multiple observational constraints, with the goal of assessing the sensitivity of ecosystem predictions to the likely climate biases present in the coupled configuration. Lastly, we will conduct coupled simulations, again in the context of multiple observational benchmarks.

Our proposed experimental protocol will investigate the impact of representing a set of ecosystem properties on the coupled simulation of climate in E3SM. As our control, we will use FATES without plant hydraulics or dynamic leaf age phenology. We will then conduct a second experiment with plant hydraulic processes and associated hydraulic traits, and then a third with dynamic leaf age phenology. We will compare these to the control to ask how representing these processes affects the coupled model climate. We will also coordinate offline components of these experiments with the INLAND modeling group at INPE, who have focused on offline specification of trait variation across the Amazon (Castanho et al. 2013; Anderson de Castro et al. 2018), by sharing model forcing and parameter data, to compare approaches to representing regional variation in trait distributions across the Amazon basin.

For the coupled experiments, because we are interested in the effect of forest processes on the feedbacks between land and atmosphere, we will also assess metrics of atmospheric model fidelity and land-atmosphere coupling strength. Currently ILAMB includes benchmarks on atmospheric variables such as precipitation, so we will be able to leverage these capabilities in this experimental framework. We will also investigate the contribution of ET to the atmospheric moisture budget, to infer whether the changes to FATES allow a better representation of the role that the forest plays in moistening the atmosphere above it during the transition between dry and wet seasons.

We expect that these simulations will require additional regional-specific datasets to be successfully conducted. Across the Amazon, key gradients in soil hydrologic properties (Marthews et al. 2013) are not well represented in global datasets. We will need to include these in simulations. Because the Marthews et al. 2013 dataset is derived for a van Genuchten model rather than the Clapp-Hornberger represented in ELM, we may need to add a van Genuchten parameterization into ELM to accomplish this. We will also drive the model using global land use datasets (Lawrence et al. 2016) and assess the model prediction of biomass as mediated by anthropogenic impacts against observations from GEDI as derived from WP3.2. As an alternative approach we will initialize the model forest structure using the GEDI data instead of benchmarking the model predictions against the GEDI data, as a way of separating parametric and initial condition uncertainty on model predictions of interest. Changing any aspect of the model process representation or parameters will lead to changes in the FATES predictions of ecosystem structure. In turn, structure indirectly affects model-predicted rates such as ET. We may wish to isolate the direct from indirect effects by initializing the forest structure at the scale of the Amazon, just as we can currently do at the site level using census data.

WP3.3d. Research Locations: These numerical experiments will necessarily be done at large scales. For offline simulations, we will focus on the Amazon as a whole, as that basin in its entirety acts in a coordinated way at the scale of the Earth System. For coupled simulations, we will necessarily require global-scale simulations. We will aim to isolate the behavior of the Amazon as much as possible, which may require adding a capability to invoke plant hydraulics only for a specific region of interest so as to hold constant the behavior outside the Amazon as we progressively add physiological dynamics to the FATES-E3SM system. We will use fixed sea surface temperatures for all coupled experiments so as to reduce the role of ocean variability and increase the signal-to-noise of the terrestrial changes.

WP3.3e. Deliverables

- Pantropical offline experiments using ELM-FATES with varying plant hydraulic traits across key climate gradients arising from trait filtering
- Global scale simulations using E3SM-FATES with and without plant hydraulic processes and dynamic leaf age phenology to assess the role of ecosystem processes on land-atmosphere exchange of water
- Large-scale benchmarks of ecosystem structure, ecosystem function, and coupled land-atmosphere dynamics based on offline and coupled simulations as compared to multiple datasets

5.4 SITE SELECTION AND DESCRIPTIONS

Site selection for NGEE-Tropics Phase 2 was determined by factors that are essential to attaining our goals and deliverables. First, developing FATES and ModEx from regional to continental perspectives requires gradients in key model drivers and boundary conditions to evaluate the model's ability to accurately simulate key emergent benchmarks. Puerto Rico provides an excellent regional testbed for exploring how anthropogenic and natural disturbance processes impact forest structure and function across gradients in precipitation, soil fertility, and variation in time since disturbance (**Figure 12**). Puerto Rico, with its many rich datasets, provides a number of tests of FATES at a regional scale, and will help enable the team address anthropogenic disturbance at larger scales in Phase 3. At the continental scale, due to its vast size, the Amazon basin exerts a number of strong effects on Earth system dynamics. Phase 2 research in the Amazon will benefit from decades of previous research including in Phase 1, and will include new activities conducted at individual (RFA1), hillslope (RFA2) and basin-wide (RFA3) scales. This contintal-scale work will represent the first fully-coupled E3SM-FATES simulations, and will establish a strong foundation for global-scale research in Phase 3. Another challenge for our Phase 2 experimental approach is canopy access to enable the measurement of key process from the deep soil to the canopy-atmosphere interface. Canopy access sites include two Panama locations (Parque Metropolitano and Parque Nacional San Lorenzo), Lambir Hills on the island of Borneo (Sarawak, East Malaysia), the Daintree Research Observatory in northeast Australia, and at INPA's Experimental Station for Tropical Silviculture north of Manaus in Brazil. These canopy access sites will be instrumented and studied using comparable methods and instrumentation for RFA1 research activities. Phase 2 research will also continue to benefit from a strong partnership with ForestGEO, including mortality surveys for WP1.5 that include 10 ForestGEO sites spanning a range of forest types in Latin America and Southeast Asia. Additional sites include Paracou, French Guiana, for tree functional composition data (WP2.1), and the Agua Salud project in Panama for additional hillslope hydrology activities (WP3.1). Overall our Phase 2 work will build upon infrastructure developed at our our pilot sites in Phase 1, while also leveraging extensive infrastructure and logistical support for additional Phase 2 sites with our international partners and collaborators.

PUERTO RICO

Puerto Rico, an island in the Greater Antilles with an area of about 9000km^2, has a long history of tropical forest research by the USFS, the University of Puerto Rico, individual PIs from many institutions, and NSF-funded research networks (LTER, CZO, and NEON). NGEE-Tropics has benefitted from archived data and collaborations with these institutions and individuals. Puerto Rico includes six Holdridge life zones, and rainfall ranges from 700 to over 5,000mm y^{-1}. Puerto Rico has diverse geological formations including karst, volcanic, ultramafic, granitic, sandy, and alluvial that form substrates for a wide variety of soils. The vegetation of Puerto Rico includes hundreds of native and naturalized species.

After World War II Puerto Rico experienced among the highest rates of agricultural abandonment and spontaneous and assisted reforestation of any region on Earth. This massive forest regeneration covers all parts of the island (**Figure 12**) and is well documented thanks to historical aerial photography. Abundant information on climate, soils, forests, and land use history make Puerto Rico one of the best known tropical regions. USFS and other scientists have developed island-wide data products on past land use, forest age, soils and bedrock, as well as downscaled meteorology, that are available to NGEE-Tropics researchers (see letters of collaboration). Major hurricanes impacted El Yunque National Forest and the rest of the island in 1928 and 1932, and more recently in 1989 (Hugo), in 1998 (Georges) and in 2018 (Irma and Maria), with major impacts on vegetation, land use, and recently human population decline (E. Meléndez and J. Hinojosa (2017), Research Brief Centro RB2017-01).

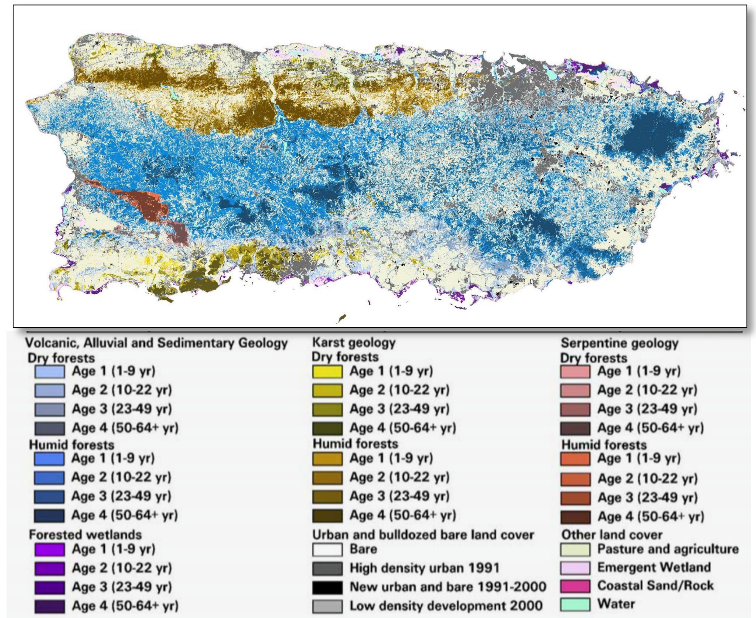

Figure 12. A map of forest age(circa 2000) in Puerto Rico shown by geological substrate.

All upland forests of Puerto Rico will be a focus of model studies of forest regeneration. NGEE-Tropics will continue field work at Sabana, El Verde, and Icacos sites, all part of the Luquillo Experimental Forest (LEF) sited within the El Yunque National Forest.

Sabana Site—The Sabana Field Research Station is in the Rio Sabana watershed, contains a monitoring station on the Rio Sabana, and is a short drive from the Bisley Long-term Ecological Research watersheds. (CZO website). The TRACE experiment (http://forestwarming.org) is located at Sabana.

El Verde Site—The El Verde research site is located within El Yunque National Forest in Puerto Rico, surrounded by tropical rainforests representative of many Caribbean island ecosystems. Research at El Verde focuses on forest dynamics, stream ecology and hydrology, and ecosystem processes. Most research is conducted by the Luquillo Long-Term Ecological Research (LTER) program and by scientists from the University of Puerto Rico and universities in mainland US. Located at El Verde, the Luquillo Forest Dynamics Plot is a 16ha, long-term observational site for forest dynamics that is part of the Luquillo LTER and ForestGEO network. Topography at El Verde is characterized by ridges and valleys which sit on a volcaniclastic parent material.

Icacos Site—The Icacos site is located alongside Road 191 toward an instrumented river on the south side of the Luquillo Mountains. Rio Icacos is one of the study areas in the Long Term Ecological Research Program in the Luquillo Experimental Forest (LTER). The Rio Icacos watershed area is 326ha with an elevation range of 600–800m. The watershed is almost entirely covered by mature montane wet evergreen forest. Rio Icacos includes about 85% palo colorado forest, 13% sierra palm forest, and 2% other montane wet forest.

PANAMA

Research activities in Panama will continue to build from our strong research and field collaborations with STRI scientists. Panama's near-equator tropical zone (8–10°N latitude) and placement as a biological corridor between two continents create exceptionally species-dense, diverse habitats, both in plants and animals. Over 10,444 different plant species inhabit the small country, including more than 2,300 varieties of trees. Panama falls in the Intertropical Convergence Zone (ITCZ), where trade winds from the northern and southern hemispheres collide and, fueled by warm tropical air and ocean water, create a band of clouds

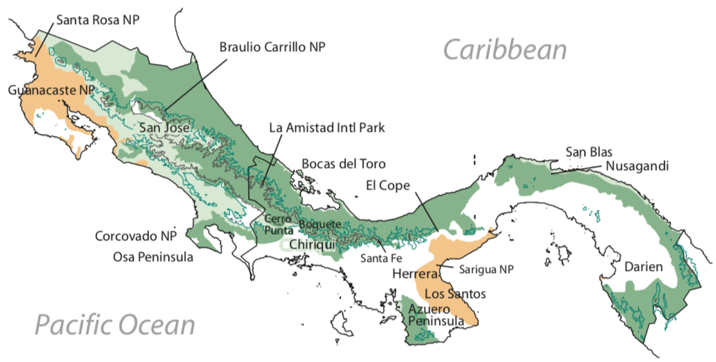

Figure 13. Forest zone in Panama and Costa Rica. Dry zones: light brown. Moist zones: light green. Wet zones: dark green. Green topographic line demarcates the lower montane zone at 800m elevation; black topographic line shows upper montane zone at 1500m. From Condit, R., R. Pérez, N. Daguerre. (2011). Trees of Panama and Costa Rica. Princeton, NJ: Princeton University Press. ISBN 978-0-691-14707-9.

and stormy weather that circles the earth. As a result, Panama has two seasons, wet and dry. The wet season is usually between May and November, with moisture flows moving west from Caribbean to the Pacific side. In December the ITCZ is pushed south by the trade winds, which creates the conditions of the dry season, which usually lasts until April. Panama's variability of gradients from dry to wet, and low to high elevation, along with variability in seasonal precipitation patterns, promotes diverse plant strategies to adapt, and in turn high density in diverse plant species.

Barro Colorado Island (BCI) Site—Barro Colorado Island (BCI), a 1,560-ha island (Lat. 9.154; Long. -79.848; Elev. 150m) in Panama, is a humid tropical forest with high biodiversity, around 300 species in 50ha. BCI is the best example of undisturbed tropical moist forest in Panama. The climate has a severe dry season from December to the end of April. Several deciduous species drop their leaves during this period. Lianas are very abundant in this forest, accounting up to 30% of leaf area. The 50ha long-term forest monitoring plot was established in 1980. Every five years since 1980 all free-standing woody stems at least 10mm diameter at breast height were identified, tagged, and mapped. This first plot set the standard for the Smithsonian's ForestGEO network, which now monitors the growth and survival of approximately 6 million trees and 10,000 species at 67 sites around the globe.

Parque Natural Metropolitano (PNM) Site—Established in 1992, the PNM canopy crane is located at the North Western edge of Panama City and the eastern edge of the Parque Natural Metropolitano (Metropolitan Nature Park; Lat. 8.99441, Long. -79.543) and is surrounded by 80-year old, lowland semi-deciduous forest. The crane is 50 meters tall with a radius of 51 meters, and can reach approximately 80 species of trees and lianas (Paton 2015 PNM Met report).

San Lorenzo (SLZ) Site [formerly Fort Sherman (FTS)]—Established in 1997, the FTS canopy crane is located approximately 11km South West from the city of Colon, in the middle of the Parque Natural San Lorenzo (formerly known as Fort Sherman; Lat. 9.280996; Long. -79.978162; Elev. 120m) and is surrounded by 300-year old, low-landtropical rainforest. The crane is 52m tall with a radius of 54m, and can reach approximately 240 species of trees and lianas. (Paton 2015 FTS Met report).

Agua Salud Site (forest and pasture catchments)—The Agua Salud site is located centrally in the Panama Canal Watershed (9°130 N, 79°470 W) in a steep, lowland, seasonal tropical setting. Two catchments in forest and pasture, with similar distribution of slope and topographic index, soil textures, and underlying bedrock geology, but distinct land uses/land covers, were instrumented by the STRI Agua Salud Project. Data on streamflow, infiltration rates, and water, energy, and carbon fluxes collected at these two catchments will be used to explore the role of preferential flow in the near-surface soil system in tropical ecosystems by incorporating preferential flow into the FATES-ELM framework.

BRAZIL

National Institute for Amazon Research (INPA) ZF2 site—Manaus activities will take place at the Experimental Station of Tropical Forestry (EEST in Portuguese) (2.45–2.66 S, 60.02–60.32 W), located ~50 km north of the city of Manaus along the ZF2 road (referred to as "ZF2" field site—**Figure 14**) in Amazonas State, Brazil. The ZF2 site comprises ~21,000 ha of forest, most of which is old-growth forest. Landforms include plateaus (90–105m elevation) and small valleys (45–55m elevation). Soils on plateaus are generally high clay texture, while soils from the upper slopes are sandy clays, lower slopes are loamy sands, and soils in the valleys are white sand dominated. Soil organic matter content, moisture, pH and biogeochemistry vary significantly with elevation along topographic gradients. The forest has a high diversity of tree species averaging ~350 species/ha with a mean canopy height of ~30m.

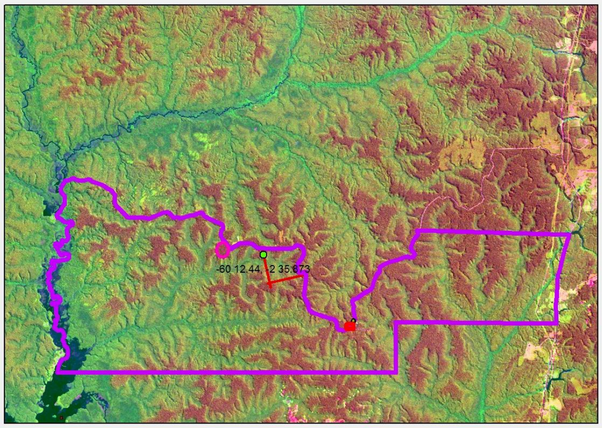

Figure 14. The ZF2 field site (purple boundary) located ~50km north of Manaus, Brazil. Location of the transect plots in red lines (each 20x2, 500m, 5ha, in size), and the field station (at ZF2 km 23) red rectangle. The magenta oval represents a ~1.5km path constructed for a boom lift (JLG 800AJ) to access tree

The ZF2 field site has extensive research infrastructure and a field station and has been the center of many decades of research activities by a large number of Brazilian and international researchers. For this project, two permanent forest "transect plots" (20 x 2500m; ~6000 trees > 10cm diameter) established in 1996 and re-inventoried eight times, will provide baseline information for forest dynamics over multiple hillslope profiles. The east-west transect plot will be the site for RFA1 hillslope research. The site also includes two eddy covariance towers on a plateau and valley forest about 2km southeast of the hillslope plot. The eddy covariance tower on the plateau was established in 1999, and is the longest running tower in the tropics. A large set of remote sensing products are also available for the ZF2 site, including lidar and drone flights. Our INPA partners (see letter of collaboration) will facilitate logistics support, including an excellent field station that comfortably houses up to 50 students and researchers.

MALAYSIA

Lambir Hills Site—Lambir Hills National Park in Sarawak, east Malaysia, on the island of Borneo (4°11' N, 114°01' E) includes 6,800ha of lowland mixed dipterocarp forest with the highest tree species richness recorded in the Palaeotropics. Rainfall averages ca. 3,000mm per year with no dry season (all months have >100mm). All research at Lambir Hills is overseen by the Sarawak Forest Department (see letter of collaboration). In 1991, a 52ha plot was established to monitor all trees ≥1cm diameter at breast height following the standardized protocols of the global ForestGEO network. The plot has been censused five times provided detailed information on the growth, mortality and recruitment of the species, functional traits on selected species, and detailed soil nutrient surveys. Soils are heterogeneous across the 52ha plot, providing an ideal landscape to explore how soil fertility regulates forest composition and dynamics. The plot will be used specifically for RFA2 in the development and testing of a nutrient-enabled version of FATES.

Figure 15. Lambir Hills crane. Credits: Japanese Canopy Biology Program. Photo: C. Ziegler

In 2000, a consortium of researchers from several Universities in Japan established an 85m tall canopy crane with a 75m long rotating jib (**Figure 15**). The crane was constructed in the center of a 4ha (200 x 200) plot to provide access to all levels within the forest canopy and understory. The canopy height in area of the crane is 30–40m with some emergent trees above 50m in height. Extensive research on canopy biology has been conducted using the crane, including studies of canopy physiology, plant phenology and reproductive biology, among other topics. The canopy crane site will be used widely in RFA1, including for detailed studies of plant hydraulic, photosynthesis, and carbon and mortality dynamics.

AUSTRALIA

Daintree Rainforest Observatory—The Daintree Research Observatory (DRO) is located in a tropical rainforest in Queensland, Australia, and is operated by the James Cook University. Located in a UNESCO world-heritage park, the forest is pristine and dominated by native species to the region. A canopy crane (Figure) at the DRO provides unparalleled access to the canopy. A drought study is in place, covering ~50% of the crane footprint for the last four years. NGEE-Tropics has established an active relationship with James Cook University scientists that work at the DRO (Susan Laurance and Lucas Cernusak, see letter of collaboration), including data set collections in November 2018 and May 2019 (Pivovaroff et al. in prep). The site will be used specifically for RFA1, targeting detailed hydraulic and carbon and mortality dynamics in the trees in response to the drought treatment.

FRENCH GUIANA

Paracou Site—The Paracou site in French Guiana is the location of the GuyaFLUX tower. The station is located in the coastal part of French Guiana approximately 50km NW of the European Space Center at Kourou, at latitude 5°18′N and longitude 52°53′W. The site is part of a private domain of about 40,000ha, owned by the Centre National d'Etudes Spatiales, France. The core area, which is approximately 500ha, is covered with old growth forest with exceptional richness (over 750 woody species). A series of 16 permanent plots (fifteen 6.25ha plus one 25ha) have been censused (DBH>10) every 1-2 years for more than 35 years. Nine of the plots were logged and subjected to human-induced disturbance in 1986. The site has a long history of research and including a large quantity of plant trait observations, as documented by the BRIDGE project (see http://www.ecofog.gf/Bridge/index.html) as well as numerous papers describing plant hydraulics databases assembled for this area (Marechaux et al. 2015, Bartlett et al. 2012).

5.5 DATA SYNTHESIS AND MANAGEMENT FRAMEWORK AND PHASE 2 TASKS, DELIVERABLES

The primary objective for NGEE-Tropics' Data Synthesis and Management Framework is to provide support for team members to share and preserve their data for use within the project that ensures a lasting publicly available legacy of NGEE-Tropics data, while complying with the CESD and DOE Office of Science Digital Data Management Requirements. Data generated by the NGEE-Tropics project will need to be properly managed. This includes data measured/observed in the field, data generated by simulations, and data products. The NGEE-Tropics Archive is designed to provide curation, QA/QC, and archiving and public release of project data. Data also need to be stored in a long-term repository (ESS-DIVE) using standardized formats to preserve the data legacy of NGEE Tropic beyond the lifetime of the project and enable data reuse. The details of our data management plan are outlined in Appendix A.

The FATES modeling efforts need meteorological driving datasets that are generated through consistent QA/QC and gap-filling protocols for intercomparison of cross-site simulation results. In addition, key data for benchmarking such as carbon fluxes, sapflow, and soil moisture, need to be quality checked, processed, and synthesized from different sites prior to use.

Phase 2 Approach

By working with RFA teams and building common infrastructure, we will help obtain existing datasets, perform QA/QC and transformations of data as needed, implement synthesis-product-generation pipelines, and manage the underlying data. To accomplish this, computational and data scientists will work closely with the RFA teams to build a framework that will support key project synthesis efforts.

Management, sharing and archival of data collected by the project: Data generated by NGEE-Tropics that require data management include data from the project's sensor deployments, other field measurements, remote sensing data and products, simulation inputs and outputs, and other data synthesis/analysis products. We will continue to maintain the NGEE-Tropics Archive built in Phase 1 for managing and publicly releasing our data. Most NGEE-Tropics data, including the data associated with publications will be initially stored in the Archive, with the exception being large-scale simulation datasets, which will be stored on NERSC. We will publicly release NGEE-Tropics data packages that we have authorization to distribute, as per our data management plan (see Appendix A).

In partnership with field data collectors, we will build off activities in Phase 1 to standardize reporting of metadata from sensor and sampling campaigns (FRAMES templates), that improve the usability of the data and enable automated data parsing and processing. We will also work closely with the ESS-DIVE team and the ESS Cyberinfrastructure working groups to evaluate and develop community data and metadata standards for the data types generated by NGEE-Tropics. Standardization of sapflow and soil moisture data files will be a high priority to enable automated parsing of these datasets for the model-data testbeds.

We will use DOE's new data archive ESS-DIVE as the long-term archive for the project's datasets (Varadharajan et al. 2019). Data packages from the NGEE-Tropics archive with digital object identifiers (DOIs) will be mirrored to the ESS-DIVE archive utilizing the web services provided by ESS-DIVE.

***Development of data products and testbeds*:** A core effort of the data team in Phase 1 has been the development of model driver datasets for the three testbed sites in Panama. The generation of the site-specific model drivers from meteorological data (rainfall, temperature, relative humidity, net radiation, etc.) is extremely important for the modeling effort, and the data products are actively being used in several FATES simulations for these sites. To maintain these drivers with new data, we will create one updated version of the drivers for each of the three Panama sites. Similarly, we will iteratively improve the preliminary meteorological drivers created for Manaus that were based on the data we acquired from LBA. Any improvements to the drivers will be created in close coordination with the modeling team, through iterative cycles. Finally, we will conduct assessments of the extent of model-driver availability and quality for additional sites at LH, DRO, and Puerto Rico.

We will continue to support and perform other QA/QC of priority datasets following on our efforts in Phase I. In particular, we will conduct QA/QC for new soil moisture data acquired for the core sites. We will also partner with LBA to acquire, and QA/QC data critical data on groundwater tables that are required to benchmark simulations in Manaus.

Finally, we will coordinate with the modeling team to build model-data testbeds. In particular, the data team will provide scripts in Jupyter notebook format to convert meteorological data to model drivers in netCDF format. Scripts will also be written to parse validation data (sapflow and soil moisture) that are provided by the RFA teams in standardized formats. These scripts will be combined with relevant data files as part of the model-data testbeds at core Panama sites (BCI, SLZ, PNM).

Data Synthesis and Management Deliverables

- Data packages curated in NGEE-Tropics archive with basic review of metadata submitted
- Enabling public release of datasets with associated data DOIs, as per our data management plan
- Metadata in FRAMES templates for primary sensor data streams (e.g., sapflow, soil moisture, dendrometry) in collaboration with RFA teams
- NGEE-Tropics data packages mirrored onto ESS-DIVE
- Updated site-specific meteorological drivers for Manaus K34 tower
- Updated version of site-specific meteorological drivers for the three core Panama sites at BCI, San Lorenzo (SLZ) and Parque Metropolitano (PNM)
- Quality assessment of meteorological drivers for Lambir Hills, Daintree, and Puerto Rico
- Acquisition and QA/QC of additional soil moisture and water table data in collaboration with LBA
- Scripts and assembled datasets for the model-data testbeds at core Panama sites (BCI, SLZ, PNM)

5.6 ANTICIPATED PHASE 2 OUTCOMES

Research carried out in Phase 2 will result in a number of transformative outcomes, while also setting the stage for a high-impact completion of NGEE-Tropics in Phase 3. First, research carried out under RFA1 will result in major advances in our understanding of how drought and temperature stress to trees exceed key physiological thresholds to produce reversible and/or irreversible damage and ultimately whole-tree mortality. Next, under RFA2 we will gain an understanding of differential forest functional assembly along competitive water and nutrient availability gradients, and following disturbances such as drought, wind storms, fire and land-use. Under RFA3, we will advance development of coupled tropical forest-climate interactions in E3SM-FATES, and explore large-scale forest-atmosphere questions such as precipitation recycling and the timing of the onset of the wet season in the Amazon basin, and how these are influenced by landscape hydrology, plant functional traits, and disturbance. Many of these outcomes are synergistic, requiring coupled advances within and among our RFAs and WPs. These outcomes are also synergistic with the roadmap of E3SM, including the use of FATES by the E3SM team for numerical experiments using E3SMv2, and the plan for land model development (e.g. land use and fire) building on the framework of FATES and targeted for E3SMv3/v4. By exploring the use of fully coupled simulations to address science questions in Phase 2 of NGEE-Tropics, we will enable the capacity to tackle a number of high-impact Earth system experiments in Phase 3. By the completion of our NGEE-Tropics research program, we will provide credible projections of tropical forest interactions with Earth system processes for the latter half of the 21st Century, and provide a foundation for expanding this work globally for all forests. Reliable projections for future risks to global forests are important for many stakeholders, and NGEE-Tropics' research will enable robust delivery on this challenging outcome.

6 MANAGEMENT PLAN AND TEAM INTEGRATION

Management of NGEE-Tropics activities will be led by Lawrence Berkeley National Laboratory (LBNL). The leadership structure (**Figure 16**) reflects the integrated and multidisciplinary character of our Phase 2 research objectives and deliverables. NGEE-Tropics investigators come from five DOE national laboratories (LBNL, BNL, LANL, ORNL, PNNL), the National Center for Atmospheric Research (NCAR), the Smithsonian Tropical Research Institute (STRI) and the U.S. Forest Service (USFS). In addition, collaborators around the world further enhance the NGEE-Tropics research portfolio (see Appendices C and D for collaborator list and letters). Research teams are multi-institutional within each RFA. Some individuals will contribute effort to more than one RFA work package, helping to foster integration within and across RFAs.

An important achievement in Phase 1 was the development of a strongly integrated and cohesive leadership team, particularly given the unique challenges of our distributed team members and international field sites. Aspects of our successful Phase 1 management structure will be retained in Phase 2, but adapted to reflect our proposed science activities, organized into three Research Focus Areas and their associated Work Packages. The NGEE-Tropics **Executive Committee** (EC), with Jeff Chambers (LBNL) as chair, oversees evolving project vision, scientific and modeling priorities, decides on scientific components, and consults with the Scientific Advisory Board on project direction. EC members are the NGEE-Tropics Director (PI), Chief Scientist, Modeling Framework Lead/Co-Lead, Data Management Lead/Co-Lead, Institutional Points of Contact, RFA Leads, and Project Manager. The Director assumes full responsibility for oversight of science activities, integration across components, and modeling and data management frameworks. The EC is responsible for ensuring progress toward Phase 2 goals and deliverables (including infrastructure support), the health and safety of team members, data management, and record maintenance of program plans and research project descriptions. The EC will hold monthly calls to review overall project status and to address operational issues. When possible, decisions are made by EC consensus.

Project Roles and Responsibilities

NGEE-Tropics Director Jeff Chambers (LBNL) holds ultimate responsibility for scientific integration, deliverables, and all decisions made by the leadership team. The Director is the point of contact for BER and has primary responsibility for building and sustaining partnerships with non-DOE institutions and collaborators. With the EC, the Director is responsible for budget, resource allocation, oversight, program review, establishing RFA and WP leads, and resolution of scientific, operational or policy disputes. The director and EC members will provide DOE with quarterly and annual progress reports that summarize milestone status, personnel actions, budget updates, and scientific highlights. The Director will hold monthly telephone calls with BER Program Managers.

The **Scientific Advisory Board** (SAB) is comprised of unfunded outside experts in Earth system and tropical forest science. The SAB will provide strategic advice to the Director and EC on research direction, vision, priorities, and opportunities; independently evaluate scientific progress and plans; and help facilitate external relations and partnerships. Ten distinguished members served on the Phase 1 SAB. With Phase 2, some SAB members will rotate out. We plan a 7–12 member SAB that will represent globally important tropical forest regions, and reflect NGEE-Tropics Phase 2 science priorities. In accordance with our SAB charter, the EC and the SAB Chair will nominate candidates for new membership and present the nominee(s) to the Director for approval. The SAB will meet with the EC twice a year, once face-to-face during our NGEE-Tropics Annual Meeting.

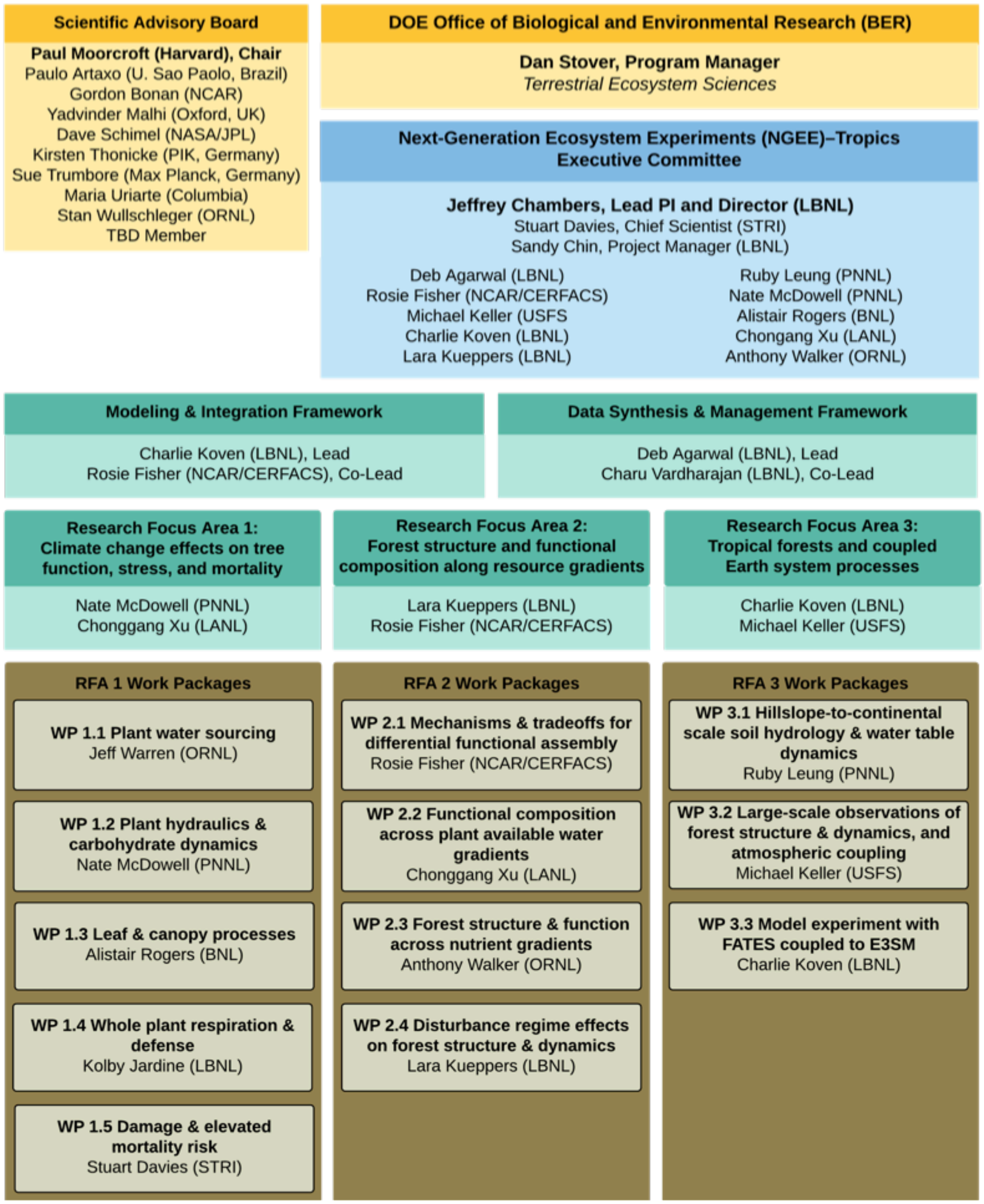

Figure 16. Phase 2 organizational structure for NGEE-Tropics.

Chief Scientist Stuart Davies (STRI) will contribute to the scientific vision of NGEE-Tropics, represent NGEE-Tropics to the larger scientific community, cultivate national and international partnerships, and use his pantropical expertise and ideas to expand cross-Lab tropical forest science capacity.

Modeling Framework Lead Charlie Koven (LBNL) will lead the NGEE-Tropics trait-enabled, demographic modeling approach; set priorities and deliverables for the modeling team; coordinate FATES model evaluation, development and application; and coordinate with E3SM and other DOE modeling activities such as for NGEE-Arctic. The **Modeling Framework Co-Lead** Rosie Fisher (NCAR/CERFACS France) will partner with the Lead to achieve modeling objectives.

Data Management Lead Deb Agarwal (LBNL) will lead the data synthesis and management system that supports NGEE-Tropics objectives—data acquisition and QA/QC; data product development; refining data sharing and archiving protocols; reporting data metrics and progress; and coordinating with ESS-

DIVE and other DOE data management activities (e.g., NGEE-Arctic and AmeriFlux). **Data Management Co-Lead** Charu Varadharajan (LBNL) will partner with the Lead to achieve data management goals. Borrowing from NGEE Arctic's successful data coordination model, we will also assign **Institutional Data Representatives** at each partner intitution. Each Data Rep will serve as a liaison between researchers at each institution and the Data Management Team to coordinate and support timely data submissions.

Institutional Points of Contact (POCs) will serve as the primary points of contact for their institutions: Jeff Chambers (LBNL), Alistair Rogers (BNL), Chonggang Xu (LANL), Anthony Walker (ORNL), Nate McDowell (PNNL), Rosie Fisher (NCAR), Stuart Davies (STRI), and Michael Keller (USFS). Institutional POCs will manage institutional budgets and project plans for all activities involving their Lab, implement Environmental Health and Safety (EH&S) protocols, develop institutional capacity, and ensure timely delivery across milestones for our RFAs.

Research Focus Area (RFA) Leads: Each RFA will be co-led by two members of the EC—one empiricist and one modeler—to ensure data-informed modeling and model-informed data collection. Co-Leads will be: RFA1: Nate McDowell (PNNL) and Chonggang Xu (LANL); RFA2: Lara Kueppers (LBNL) and Rosie Fisher (NCAR/CERFACS); RFA3: Charlie Koven (LBNL) and Michael Keller (USFS). They will set and manage priorities, milestones and deliverables for their respective RFAs and Work Packages. RFA Leads will also be responsible for integration among work packages within their RFAs and across the three RFAs. RFA Leads will hold monthly meetings for each RFA, and routinely report RFA progress to the EC, including through written quarterly and annual reports.

Work Package (WP) Leads (see Org Chart above) will be responsible for carrying out specific research activities, monitoring tasks and meeting milestones within their respective Work Packages. WP leads will attend relevant monthly RFA meetings to report and discuss WP progress, plans, challenges, and issues.

Project Manager Sandy Chin (LBNL) will track project requirements, coordinate proposals and subcontracts, track milestones and deliverables, develop budgets and forecasts, develop project progress reports and dashboards, synthesize presentations, facilitate and organize research meetings, symposia and workshops, and oversee all outreach/media for the project (e.g., website, collaboration tools, social media, brochures, newsletters, seminars, lectures, special sessions, etc.).

Team Interactions and Integration: As with Phase 1, we will host monthly All-Hands calls to all team members and collaborators, giving particular encouragement to early careers, to present research results, to share updates and news, and to enhance bi-directional information flow across activities. Additionally, we will hold annual, in-person All-Hands meetings (unfunded collaborators welcome) to present annual progress, identify future strategic directions and opportunities, and strengthen team interactions through formal and informal discussions. The EC will also meet with the SAB at the annual meeting. Based on progress made towards milestones, requirements for the next year, and SAB input, the EC will assess each area's efforts, and produce written recommendations for next year's priorities. The Modeling Team will host bi-weekly FATES modeling calls and run free FATES tutorial workshops for the modeling community at least once a year.

Reporting Progress and Communication with Program Managers: We will provide quarterly and annual progress reports to DOE that summarize status on milestones and deliverables, personnel actions, budget updates, and scientific highlights, and hold monthly calls with BER Program Managers. Early careers will also be given opportunities on these calls to present their work to BER Program Managers. If issues arise that may lead to a change in deliverables, a delay in performance, or a reportable incident (e.g., for safety), we will raise these promptly by phone or email.

NGEE-Tropics Interaction with E3SM and ELM: NGEE-Tropics software engineers and scientists will maintain regular interactions with E3SM through the E3SM-NGEE liaisons, partially funded by E3SM. Earlier interactions were maintained through the support of the Climate Model Data Validation (CMDV)-Land project. These interactions ensure cross-project communication, planning, maintenance, feature developments, and scientific support of the coupled ELM and FATES models. **E3SM-NGEE-Tropics Liaisons** Jennifer Holm and Ryan Knox (LBNL) will coordinate NGEE-Tropics process model developments within FATES for testing and application to extra-tropical and global scales in E3SM. Liaisons will coordinate use and development of code, code testing in project-specific external models, and NGEE-Tropics data as regional benchmarks for FATES and E3SM. The NGEE-Tropics liaisons will participate in regular NGEE-Tropics modeling calls, All-Hands meetings, and other team meetings, and will organize coordinating calls with NGEE-Tropics team members as needed. The liaisons will meet monthly with other projects' E3SM liaisons, report relevant NGEE-Tropics science and modeling updates to BER Program Managers on a quarterly basis, and share relevant E3SM model development updates with the NGEE-Tropics Modeling Leads and other key modeling stakeholders.

Project Resilience and Responsiveness: Every year we will revisit the science plan, funding allocations and research teams. We expect that progress will vary across objectives, and that priorities may shift. As a result, the NGEE-Tropics Director, in consultation with the EC, may need to make appropriate funding reallocations. The ability to wind down unproductive avenues of research and initiate new ones is essential to project success. Depending on project needs, NGEE-Tropics may add or subtract investigators or change priorities.

Development of Scientific Expertise and Leaders: We will continue in Phase 2 to provide a rich environment for training young scientists in tropical forest research, and to enable our more senior personnel ongoing expansion of their expertise in tropical forest ecosystems. The EC will also continually assess succession planning, developing talent and leadership opportunities for early career scientists to ensure an inclusive and global community of next-generation tropical science leaders. Phase 1 activities have supported and continues to support the training of over 35 undergraduates, graduate students, and postdoctoral scholars, including several postdocs who have transitioned into career scientist or faculty positions, some of whom still participate in or collaborate with NGEE-Tropics.

7 DATA/SOFTWARE/INFORMATION MANAGEMENT AND COMMUNITY OUTREACH

7.1 DATA/SOFTWARE/INFORMATION MANAGEMENT

Details regarding NGEE-Tropics Data/Software/Information Management plans can be found in Appendix A. The plans are designed to meet project requirements of NGEE-Tropics as well as digital data management requirements of DOE Office of Science and BER. Data will be made available typically within 3 months to NGEE-Tropics personnel. Data will be made available to the public within 12 months after the end of the data acquisition period for the proposed performance period of the award. The 1-year period of exclusive use allows for completion of QA/QC checks, calibrations, and processing required to prepare it for use, and publication of papers by the NGEE-Tropics team.

7.2 COMMUNITY OUTREACH

Collaborations and Partners: In Phase 2, the Director, supported by the Chief Scientist and the SAB, will strengthen existing domestic and international partnerships developed in Phase 1, as well as develop new ones aligned to Phase 2 goals and strategic opportunities. Key contributing partners (see letters) will continue to participate in Phase 2: **Smithsonian Tropical Research Institut**e (STRI), collaborators in Puerto Rico (**USFS, LTER, CZO, TRACE**), and Manaus (**INPA**). Funded partners **NCAR** and **USFS** will participate in Phase 2 as well. We are engaged with several DOE-funded projects who have identified specific areas for collaboration in Phase 2 : **E3SM, NGEE Arctic, ESS-DIVE, AmeriFlux, ILAMB, Rubisco SFA, IDEAS-Watershed; Early Career PIs, TES University PIs**—see letters.

As in Phase 1, we will co-locate NGEE-Tropics field sites with established field sites that have a history of long-term observations valuable to our objectives, as well as well-established field and logistical infrastructure and support. This will enable deployment of NGEE-Tropics field instrumentation and measurement campaigns in a manner that is cost-effectiveness and safe. To this end, we will continue existing and develop new collaborations with institutions and research networks in Puerto Rico, Panama and Brazil, and ForestGEO and other partners at other pantropical locations (e.g., Lambir Hills,Malaysia; Daintree, Australia)—see letters.

We will encourage collaborators to participate in NGEE-Tropics meetings (face-to-face or virtual) or to send students or postdocs as visiting scientists to collaborating laboratories. We will organize "Tropical Research Gatherings" at the annual ESS PI Meetings involving TES-awarded University PIs, to build and engage DOE's community tropical research community through sharing of research plans and exciting science updates. Additionally, as we successfully did in Phase 1, we will lead and organize sessions at scientific conferences such as the American Geophysical Union, Ecological Society of America, and Association for Tropical Biology and Conservation annual meetings, as well as host research and training workshops to engage the larger science community in our Phase 2 science plans and to further develop the E3SM-FATES user community.

We will continue to reach out to the international community of scientists who conduct tropical forest research in and out of the U.S. through opportunities to actively collaborate, archiving services for data generators, and hosting and serving data and data products of value to tropical forest scientists.

Website, Social Media, Newsletter: In Phase 2, we will leverage the successful NGEE-Tropics website launched in Phase 1 as a communication and outreach tool. We also plan to offer a social media presence using Twitter and other platforms to disseminate news and updates quickly and easily. Following NGEE Arctic's successful communication model, NGEE-Tropics will launch a quarterly newsletter to communicate science, modeling, data progress, highlights and productivity to our stakeholders (including our DOE program managers) and the greater pantropical researchers community.

Sharing Best Practices: Early in Phase 1, we engaged the **NGEE Arctic leadership** to take advantage of their experience and advice on handling large-scale, multi-institution collaborations, which was invaluable. We will continue to seek their advice, or share our own lessons-learned, regarding project management, model development and coordination with E3SM, data management, safety, optimizing collaborative productivity, and supporting relationships with collaborators and the larger community. NGEE Arctic PI Stan Wullschleger also serves as a member of our SAB.

Mentoring/Training: NGEE-Tropics has and will continue an active mentoring and training role with graduate students from collaborating institution INPA (Manaus, Brazil). INPA Masters and PhD students being advised by NGEE-Tropics team members Kolby Jardine, Jeff Chambers, Jeff Warren, and Brent Newman include: ***Raquel F Araujo***–PhD project on canopy dynamics with high temporal and spatial resolution UAS imagery. Now a postdoc at STRI, supervised by Stuart Davies; ***Bruno Gimenez*** –PhD project on environmental and physiological controls over tree transpiration. Now a postdoc at STRI, supervised by Stuart Davies; ***Israel Sampaio*** and ***Rafael Oliveira***–MS projects on environmental, physiological, and biochemical controls over stomatal conductance; ***Valdiek da Silva Menezes***–MS project on xylem morphology and sapwood active area; ***Leticia Cobello***–MS project on diurnal patterns of stem CO_2 efflux and its relationship to transpiration and temperature; ***Tayana Barro****zo*–MS project on photosynthetic potential and its association with isoprene emissions and chlorophyll fluorescence in response to high temperature in the fast growing tropical pioneer species; ***Gustavo Spanner***–Hydraulic redistribution and tree transpiration; ***Jardel Rodrigues***–Deep soil vertical drainage and biogeochemistry.

8 KEY PERSONNEL

Key personnel have been selected to provide a unique combination of skills and expertise deemed necessary to achieve Phase 2 goals. Additional personnel information is available in Section F. Curriculum Vitae.

Asterisk (*) next to name denotes Executive Committee member.

Lawrence Berkeley National Laboratory

***Jeff Chambers**—NGEE-Tropics Director—Responsible for decisions made by the Executive Committee (EC); ensures scientific integration and deliverables; serves as point of contact for BER; responsible for building and sustaining partnerships with non-DOE institutions and collaborators; oversee budget, resource allocation and program review; select and oversee RFA and WP leads; resolve scientific, operational, and/or policy disputes. All responsibilities involve EC consultation. FTE Y1-0.25; Y2-0.25; Y3-0.25; Y4-0.25

***Sandy Chin**—Project Manager—Track project requirements, milestones and deliverables; coordinate proposals and subcontracts; develop budgets, forecasts, progress reports and presentations; organize meetings, symposia and workshops; oversee all outreach/media (website, collaboration tools, social media, etc.); EC Member. FTE Y1-0.75; Y2-0.75; Y3-0.50; Y4-0.50

***Charlie Koven**—Modeling Framework and RFA3 Co-Lead—Lead trait-enabled demographic modeling approach; set priorities to ensure timely deliverables; coordinate FATES model evaluation, development and application; coordinate with E3SM and other DOE modeling activities; manage priorities and deliverables for RFA3 and associated WPs; WP3.3 Lead; serve on EC. FTE Y1-0.25; Y2- 0.25; Y3-0.25; Y4-0.25

***Lara Kueppers**—RFA2 Co-Lead—Manage priorities, research activities and deliverables for RFA2 and associated WPs; responsible for integration among work packages within RFA2 and with RFA1 and RFA3; serve on EC. FTE Y1-0.25; Y2-0.25; Y3-0.25; Y4-0.25

***Deb Agarwal**—Data Management Lead—Lead data synthesis and management team: data acquisition and QA/QC; data product development; data sharing and archiving protocols; coordination with ESS-DIVE and other DOE data management activities; serve on EC. FTE Y1-0.04; Y2-0.04; Y3-0.04; Y4-0.04

***Charu Varadharajan**—Data Management Co-Lead—Work with data management lead to meet NGEE-Tropics data management objectives; serve on EC. FTE Y1-0.25; Y2-0.25; Y3-0.25; Y4-0.25

Robinson Negrón-Juárez—Research scientist—Responsible for WP2.4 scientific tasks on wind disturbance effects; and WP3.2 scientific tasks on large-scale coupled simulations; coordinate LBA data collaboration; Met and Flux data processing for Amazon (Manaus); QA/QC Hydrology data for Manaus + other sites; Institutional data rep. FTE Y1-0.75; Y2-0.75; Y3-0.5; Y4-0.5

Gilberto Pastorello—Computer Research Scientist—Coordinate LBA Data collaboration; met drivers & fluxes for Manaus and Panama; assess model drivers for Daintree, Lambir Hills, Puerto Rico; QA/QC fluxes across Amazon in coordination with Ameriflux. FTE Y1-0.25; Y2-0.25; Y3-0.25; Y4-0.25

Kolby Jardine—Research Scientist—RFA1 scientific activities; WP1.4 Lead. FTE Y1-0.5; Y2-0.5; Y3-0.5; Y4-0.5

Tom Powell—Postdoc (in Year 1); Research Scientist (In Years 2-4)—WP2.2 scientific activities, FATES simulations across plant available water gradients, hypothesis testing for functional assembly and coexistence) PD: FTE Y1-1.0; RS: FTE Y2-0.75; Y3-0.5; Y4-0.5

Ryan Knox—FATES software developer/E3SM-NGEE-Tropics Liaison—Responsible activities related to integrating code into ELM/E3SM which will involve coordination with NGEE-Tropics and ELM team members, ensuring that FATES API releases are synchronized with changes in E3SM and capability is maintained, introduce plant nutrient competition and allocation in FATES and couple with BGC code in ELM, and interactions in relevant meetings. FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

Greg Lemieux—FATES Software Developer—FATES software engineering for model performance, software documentation, user community support. Only funded in FY22 and FY23. FTE Y3-0.5; Y4-0.5

Jennifer Holm—E3SM-NGEE-Tropics Liaison—Responsible for coordinating E3SM and NGEE-Tropics model development and integration roadmaps. (Funded by E3SM; no NGT funding)

Brookhaven National Laboratory

***Alistair Rogers**—Institutional POC, Work Package 1.3 Lead—plant physiology, model development, field work, serve on EC. FTE Y1-0.37; Y2-0.35; Y3-0.35; Y4-0.35

Shawn Serbin—Model implementation and evaluation, spectra-trait relationships, fieldwork. FTE Y1-0.26; Y2-0.25; Y3-0.25; Y4-0.25

Kim Ely—Institutional data rep, fieldwork. FTE Y1-0.25; Y2-0.25; Y3-0.25; Y4-0.25

Los Alamos National Laboratory

***Chonggang Xu**—Institutional POC, RFA1 Co-Lead, WP2.2 Lead—Mentoring postdocs and modeling on WP1.1, WP1.2 and WP1.5, serve on EC. FTE Y1-0.38; Y2-0.38; Y3-0.36; Y4-0.35

Brent Newman—Staff Scientist—Install, maintain and analyze hydrological and biogeochemical measurements. FTE Y1-0.28; Y2-0.26 ;Y3-0.24; Y4-0.22.

Rutuja Chitra-Tarak—Postdoc—Inverse estimate the rooting profiles (WP1.1), FATES-Hydro parameterization and evaluations (WP 1.2). FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

Turin Dickman—Institutional Data Rep—Data analysis and fieldwork. FTE Y1-0.2; Y2-0.2; Y3-0.2; Y4-0.2

Oak Ridge National Laboratory

***Anthony P. Walker**—Institutional POC, WP2.3 Lead—Mentoring postdocs, and modeling on WP1.3, serve on EC.. FTE Y1-0.3; Y2-0.3; Y3-0.25; Y4-0.3

Jeffrey M. Warren—WP1.1 Lead, Institutional Data Rep—Mentoring postdocs, and field data collection on WP1.2. FTE Y1-0.2; Y2-0.2; Y3-0.2; Y4-0.2

Xiaojuan Yang— Staff Scientist—Data synthesis and modeling WP2.3. FTE Y1-0.2; Y2-0.2; Y3-0.18; Y4-0.2

Richard J. Norby—Staff Scientist—Supervise two PhD students, analysis of root trait measurements (WP2.3). FTE Y1-0.2; Y2-0.1; Y3-0.08; Y4-0.1

Melanie Mayes—Staff Scientist—Field measurements and analysis, mentoring post-masters' (WP2.3). FTE Y1-0.15; Y2-0.15; Y3-0.15; Y4-0.15

Lianhong Gu—Staff Scientist—Field measurements of solar induced fluorescence (SIF) (WP1.3). FTE Y1-0.05; Y2-0.05; Y3-0.05; Y4-0.05

Forrest M. Hoffman—Staff Scientist—Incorporate datasets into ILAMB (WP3.2). FTE Y1-0.15; Y2-0.15; Y3-0.12; Y4-0.15

Jitendra Kumar—Staff Scientist—Phenology product development from Venus satellite data (WP3.2). FTE Y1-0.15; Y2-0.15; Y3-0.12; Y4-0.15

Elizabeth Agee—Postdoc—Data analysis and modeling WP2.3. FTE Y1-1.0; Y2-1.0; Y3-1.0 (no NGT funding Y4)

Cynthia Wright—Postdoc—Data collection and analysis WP1.1 and WP1.2. FTE Y1-1.0; Y2-1.0; Y3-1.0 (no NGT funding Y4)

Pacific Northwest National Laboratory

***Nate McDowell**—Institutional POC, RFA1 Co-Lead, WP1.2 Lead—Oversee field campaigns, lab work, and activities associated with RFA1 (with Chonggang Xu) and WP1.2, serve on EC. FTE Y1-0.46; Y2-0.45; Y3-0.45; Y4-0.44

***Ruby Leung**—WP 3.1 Lead—Oversee WP3.1 activities, including modeling of hydrology and land use land cover change, analysis of hydrologic measurements and land use land cover data, and manuscript generation, serve on EC. FTE Y1-0.09; Y2-0.09; Y3-0.09; Y4-0.09

Maoyi Huang—Staff Scientist—Improve modeling of land use land cover change in the FATES model. FTE Y1-0.10; Y2-0.10; Y3-0.09; Y4-0.09

Yilin Fang—Staff Scientist—Improve modeling of soil hydrology and plant hydraulics that influence plant response to drought. FTE Y1-0.30; Y2-0.30; Y3-0.3; Y4-0.29

Alex Pivovaroff—PostDoc; Institutional Data Rep—Execute field campaigns in Panama and Australia and Malaysia and potentially Manaus, including installation of sapflow instrumentation. FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

Chang Liao—PostDoc—Implement, test, and evaluate a subgrid lateral flow parameterization in E3SM Land Model. FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

Heather Pacheco—Post Bach—Provide field assistance on all field campaigns, supervision of all laboratory work, leadership on laboratory analyses, assistance with data analyses. FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

National Center for Atmospheric Research

Jackie Shuman—Institutional POC—Responsible for updating the SPITFIRE module and creating a new wind disturbance and mortality module within the FATES vegetation model Framework (WP2.4). FTE Y1-0.78; Y2-0.75; Y3-0.73; Y4-0.70

***Rosie Fisher**—Modeling co-Lead, RFA2 Co-Lead, WP1.2 Lead—Oversee testing coexistence hypotheses in FATES and improving trait/testbed infrastructure. Note: Rosie Fisher will be hard funded by NCAR for 1.5 years (FTE FY1-1.0 FY2-0.5), and then supported by NGEE-Tropics via subcontract to TBD institution, likely CERFACS, at FTE Y2-0.5; Y3-1.0; Y4 1.0

Smithsonian Tropical Research Institute

***Stuart Davies**—Chief Scientist, WP1.5 Lead—Contributes to the scientific vision of NGEE-Tropics; WP1.5 Lead and co-Lead WP 2.3. Contributes to other WPs in RFA 1 & 2. Leads collaboration with new field site in Lambir Hills, Malaysia. FTE Y1-0.4; Y2-0.4; Y3-0.4; Y4-0.2

Daniel Zuleta—Postdoctoral fellow—Lead field surveys and data analysis for annual mortality surveys across 12 ForestGEO plots under WP 1.5. FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

Bruno O Gimenez—Post-doctoral fellow—Leaf-level physiological analyses in WP 1.4. FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

Alfonso Zambrano—Field Technician—Oversees maintenance and data collection of sap flow systems in plots in Panama, maintenance and data collection and Eddy flux system on BCI, associated data quality control. FTE Y1-1.0; Y2-1.0; Y3-1.0; Y4-1.0

Raquel Araujo (unfunded)—Post-doctoral fellow—Involved in drone-based assessment of branch damage and mortality in WP 1.5.

Gabriel Arellano (unfunded)—Scientist—Contributes to the analysis and synthesis of tree damage and mortality data in WP 1.5. No NGT funding.

Helene Muller-Landau (unfunded)—Scientist—Contributes to a range of WPs through development of tropical model testbed, quantifying sources of model uncertainty, improve understanding and modeling of vegetation dynamics for tropical forests under natural disturbance regimes.

Ben Turner (unfunded)—Scientist—Contributes to the analysis and synthesis of soil nutrient studies under WP 2.3, and related WPs.

Joe Wright (unfunded)—Scientist—Develops methods to predict and test shifts in plant trait distributions in response to environmental perturbations. Oversees implementation of hydraulic trait measuements in core Panama sites. Contributes to several WPs in RFA 2 related to coexistence of functional diversity.

United States Forest Service

***Michael Keller**—Institutional POC, RFA1 Co-Lead, Work Package 3.2 Lead—Amazon and Pantropical forest structure analysis and product development. Contribute to modeling of forest regeneration in Puerto Rico. FTE Y1-0.25; Y2-0.24; Y3-0.22; Y4-0.19

Antonio Ferraz—Lidar remote sensing, forest structure analysis, data product development. FTE Y1-0.50; Y2-0.50; Y3-0.50; Y4-0.50

Marcos Longo—Forest structure analysis, statistical modeling, data product development. FTE Y1-0.50; Y2-0.50; Y3-0.50; Y4-0.50

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