Using GEDI to improve biomass estimates and understand recent biomass change in the tallest, highest biomass forests in the world.

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Introduction

At the global scale, the greatest uncertainty in forest biomass estimates (in units of carbon mass per land area) is in the highest biomass systems. Because of the strong relationship of tree height to biomass, these high biomass systems coincide with tall forest canopies. Yet, these tall forests are in trouble. The global number of trees on the planet has fallen by ~46% (Crowther et al 2015), and it is the largest trees that have experienced the largest reductions at all latitudes (Lindenmayer et al 2012). For instance, *Sequoia sempervirens* originally covered 8900 km^2, mostly in California, but now only cover 457 km^2 (Koch et al. 2004, Sillett et al 2015b, 2020). In increasingly fragmented tropical rainforests, half of the large trees (≥ 60 cm diameter) are at risk of loss in just the first three decades after isolation (Laurance et al 2000). Among the largest trees on earth, *Eucalyptus regnans* in Australia are predicted to decline from 5 in 1997 to less than one tree per hectare by 2070 (Lindenmayer et al 2012). These important tall forests are getting increasingly rare, and we do not yet even know how to properly value them. With GEDI, we can for the first time understand both their biomass and how they are changing.

Two unique ecosystems have given rise to some of the tallest trees on the planet - temperate coastal and tropical rainforests. Our group has experience with these forests and has produced extensive ground-based data on their biomass and structure. In the temperate zone, the tallest forests are found in coastal environments where rainfall is plentiful, temperatures not extreme, and soils relatively fertile. Prime examples, documented by the work of CoIs Sillett and Koch, include the coniferous forests of western North America (Sillett et al. 2018b, 2019b, 2020) and angiosperm forests of southern Australia and Tasmania (Sillett et al. 2010, 2015a). In the tropics, forests of exceptional stature are found in parts of the Amazon, the Congo basin, and Malaysia (Feldspauch et al. 2020, Shenkin et al. 2019). The conditions supporting extremely tall tropical forests are not well understood, possibly because of the greater influence of stochastic disturbance events (Espirito-Santo et al 2014). Tropical forest biomass estimates represent the largest uncertainty in the biotic carbon cycle, which is making future climate prediction difficult (Friedlingstein et al 2014). Large tropical trees store a disproportionate amount of aboveground carbon, and the density of large trees is perhaps the most important predictor of aboveground biomass in the tropics (Silk 2013). At the same time, the biggest errors in Amazonian biomass estimates are in tree height (Feldpauch et al 2012) and wood density (Baker et al 2004). New technologies are enabling the detection of canopies of exceptional height in Amazonia and in Malaysia (Shenkin et al. 2019), but the best way to estimate biomass in these tall forests is still uncertain. Our team's research experience in giant forests is exemplified by our direct access to

Figure 1 – Climbing one of the world's tallest trees (left) and the tallest tropical tree (right). Center shows lidar of the tallest tropical tree from Co I Shenkin et al 2017.

the trees. We have climbed the tallest tropical tree to accurately measure its height to compare to lidar (Fig. 1, right, from CoI Shenkin et al 2017) and the tallest conifers to the understand the biophysical constraints on tree height (Fig. 1, left, from CoI Koch et al 2004) and to quantify aboveground biomass with exceptional detail (Sillett et al. 2010, Sillett et al. 2015a, 2015b).

Despite their grandeur, much is still unknown about how much carbon tall forests hold and how they are affected by climate change. Recently it has been hypothesized tall trees may be getting taller in some areas and suffering increased mortality (or at least top dieback) in others (McDowell et al 2020). GEDI's nearly global coverage of tall forests provides the opportunity to tackle these unknowns. We propose to use our unique and extensive ground-based measurements in temperate and tropical forests to refine GEDI algorithms and improve biomass estimates of these tall forests and determine how they are changing. Specifically, we will test the following hypotheses.

H1 – The integration of ground-based data on tree structure and allometry with GEDI will improve GEDI estimates of biomass in tall conifer forests

H2 – The integration of ground-based data on tree structure, wood density estimated from multispectral data, and GEDI will improve GEDI estimates of biomass in tall tropical forests.

H3 – Tree canopies have changed stature over the past 20 years due to climate change associated increases in water use efficiency in some areas and rising vapor pressure deficit in others.

Background on Tree Stature and Climate Change

Are trees changing stature due to climate change? – The foundational objective of the proposed research is to improve GEDI biomass estimates in tall forests by integrating our extensive ground-based data and multispectral remote sensing. Building on this, we will also explore an exciting, novel hypothesis that old growth forest canopies have changed stature over the past 20 years (becoming taller in certain areas and shorter in others). Together these research activities will address key Question #2 - *What role will the land surface play in mitigating atmospheric CO_2 in the coming decades?*- because we will learn the net change over time of biomass (gain minus loss) in key non-disturbed systems that is most likely linked to climate change. There are separate arguments that forest canopies are getting taller versus shorter. We will now go through both arguments. We recognize up front that while these arguments are for individual trees, GEDI measurements will allow characterization of changes in forest canopy height, each pixel being unlikely to capture true tree height.

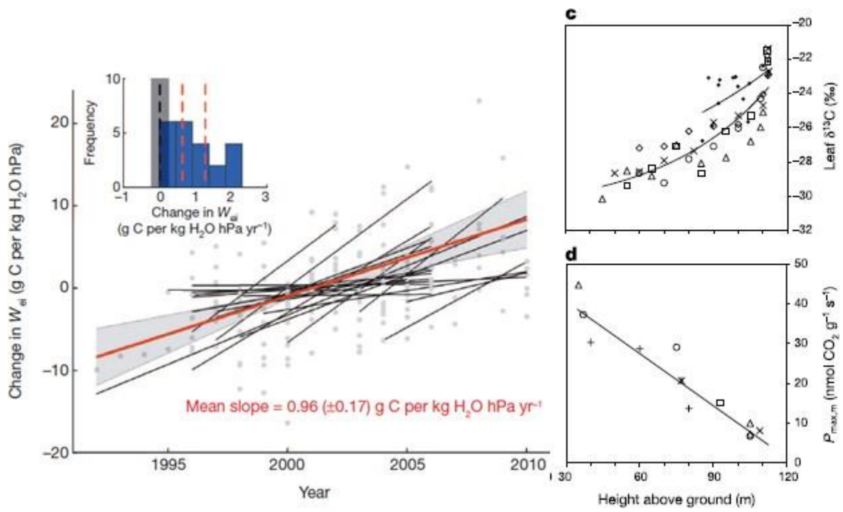


Figure 2 – Eddy covariance data showing that WUE has increased over the past 20 year (Keenan et al 2013). Foliar carbon isotope composition (d13C, ‰) increases with height d, Light-saturated photosynthetic rate per unit mass decreases with height (Koch et al 2004).

Trees are growing taller. Due to documented increases in water use efficiency (WUE) – the ratio of CO2 assimilation to water loss - trees may be increasing in height and size. Keenan et al. (2013) shows a substantial increase in WUE in temperate and boreal forests of the Northern Hemisphere over the past two decades, which they find is correlated with a strong CO_2 fertilization effect (Figure 2.) This causes a partial closure of stomata to maintain a near constant CO_2 inside the leaf even under continually increasing atmospheric CO_2 levels.

Our previous studies of the limits to tree height suggest that as WUE has increased over the past 20 years, mainly through reductions in evapotranspiration (ET) (Keenan et al. 2013), the tallest trees theoretically could grow taller. A tree's maximum height is largely a function of how it can transport water to its highest leaves. CoI's Koch and Sillett have done the groundbreaking work quantifying this in redwood trees showing how leaf physiology changes with tree height until it reaches upper thresholds (Fig 2) (Koch et al. 2004, Koch and Sillett, 2009). With increasing height in trees, a suite of chemical, physiological, and morphological changes is observed in branches and leaves that indicates increasing water stress and associated constraints on leaf growth and photosynthesis. Elevated CO2, because it reduces stomatal conductance, can lessen leaf-level transpiration while also stimulating photosynthesis, combined changes that increase WUE. Whether this is driving increased height growth in redwoods is unknown, but we do know that whole-tree growth, even in redwoods > 1000 years of age, has increased markedly during the past half century (Sillett et al. 2015b, 2019b), a period of rapid increase in atmospheric CO_2. Individual redwoods that are within 95% of the maximum known tree height have also grown taller over the past 20 years (Koch and Sillett 2009, Sillett et al. 2020). At the cellular level, growth in plants requires sufficient turgor pressure and carbohydrate supply. Leaf turgor pressure decreases with increasing height in redwood (Koch et al. 2004) and other tall conifers (Woodruff et al. 2004), and photosynthesis is more constrained by water stress in leaves at greater heights (Koch et al. 2004, Ambrose et al. 2010).

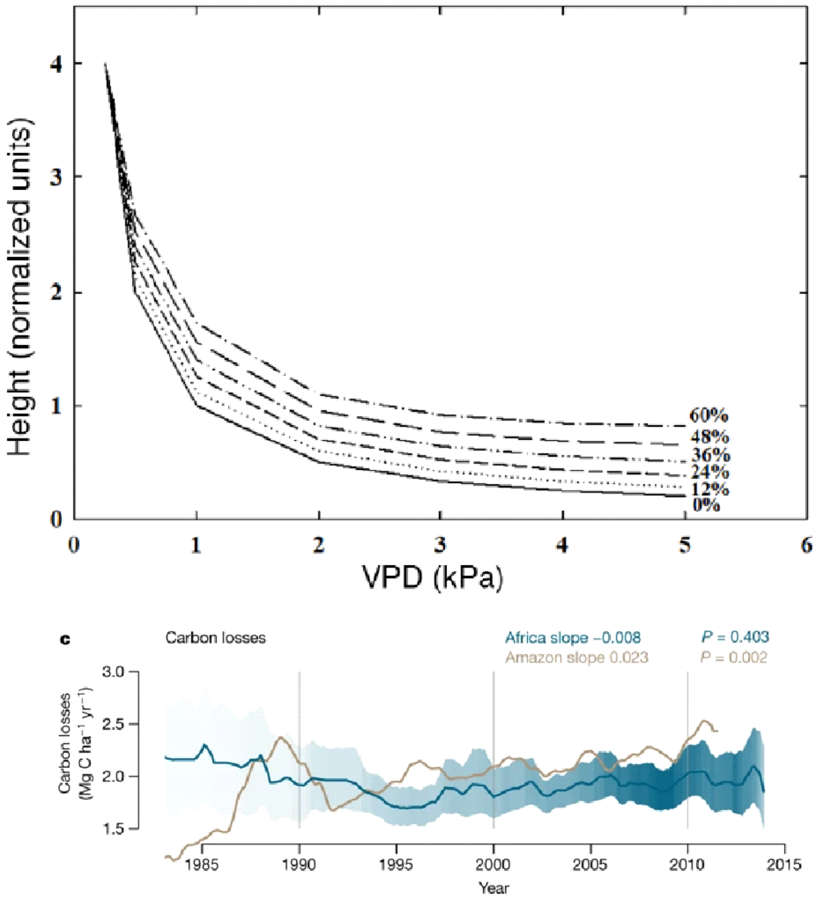


Figure 3 – (top) McDowell et al 2020 (Science)- Rising VPD forces declines in potential plant stature. Predictions of plant height in response to rising VPD from the hydraulic corollary to Darcy's law. (bottom) Hubau et al 2020 (Nature) – Plot based estimates of an increase in mortality in Amazonian forests but not in the Congo basin.

Trees heights are decreasing. A second line of ecophysiological reasoning proposes that increased vapor pressure deficit (VPD) associated with climate warming is driving increased mortality of tall trees and should result in lower average canopy height. A recent Science paper (McDowell et al. 2020, building on McDowell et al. 2015) suggests that as VPD rises, potential maximum tree height is reduced because of increased hydraulic stress (Fig. 3), making short stature advantageous with rising VPD. Because most plants cannot reduce their size (beyond limited reductions in leaf area or crown dieback), forests respond through increased mortality of taller individuals, which are replaced by smaller ones (McDowell et al. 2015), as observed in many studies (Bennett et al. 2015).

Taller or Shorter? The balance of CO_2 stimulation of photosynthesis and WUE vs. increased VPD (and altered soil moisture) will likely determine global patterns of forest mortality and height change. We propose that there is regional variation in the relative strength of these influences. Sites where we have extensive and long-term ground-based data on tree height and plot-level biomass are in regions where we expect this balance (to date) to have had contrasting influences, and it is these regions where we will use GEDI and other lidar products to test predictions about change in canopy height.
An example of contrasting patterns of change in tall forests is seen in the tropics; a recent Nature paper found that tree mortality has been increasing in the Amazon but not in Central African forests (Hubau et al. 2020). Figure 3 shows that over a 20-year period, the Amazon basin had a significant increase in tree mortality of big trees while African forests did not. Therefore, Amazonia follows the McDowell et al. 2020 hypothesis, but Central Africa does not. We hypothesize that broad meteorological trends are driving this process. Since it is the big trees that have died, the entire size structure of the forest would have changed in a measurable way. Here we propose to compare GLAS (Geoscience Laser Altimeter System - 2003-2009) to GEDI to verify these trends. We will compare biomass and vertical structure estimated from GLAS to that estimated by GEDI across these two continental regions and see if we find results similar to the recent empirical results.

Preliminary theory - We hypothesize that forest canopies are getting taller (and also higher in biomass) in certain regions (e.g., Congo basin, redwood forests) and shorter in others (e.g., Amazon basin). The expected geographic variation (Fig. 4) arises from underlying variation in key meteorological determinants of tree height. Increased VPD is a general consequence of climate warming, but how it impacts tree growth depends on water availability. Forests with a large surplus of water are characterized by much greater annual precipitation (PPT) than potential evapotranspiration (PET), i.e. PPT >> PET. A smaller water surplus means that PPT does not greatly exceed PET (i.e., PPT ≥ PET). We expect that warming-driven increase in VPD (and the consequent increase in PET) has not negatively impacted trees and forests where PPT >> PET. Here, increased VPD has led to higher evapotranspiration but not increased water stress and tree mortality that reduces canopy height. In contrast, in forests where

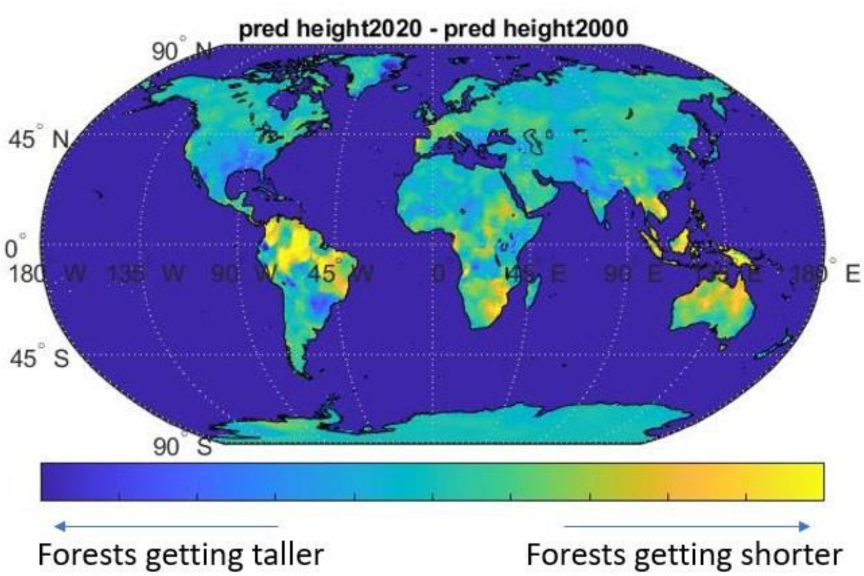


Figure 4 – Our estimate of change in mean canopy stature with blue indicating predicted increases and yellow predicting decreases.

the difference between PPT and PET is smaller increased VPD is more likely to have driven mortality of taller individuals and reduction in canopy height. Redwood forests have likely experienced little negative impact of rising VPD because they are in relatively cool coastal regions where PPT >> PET, and only minor warming has yet occurred. The mild increase in VPD here can be accommodated by the large water surplus. That said, we know from our past research that high VPD periods (seasonally and daily) do drive reductions in leaf-level stomatal conductance and branch transpiration, and these effects are greater in taller redwoods (Ambrose et al. 2010). Therefore, the McDowell et al. (2020) perspective is important – hydraulic pathlength matters, but tree mortality and top dieback impacts are not yet evident. Continued warming and VPD rise may eventually impact redwoods negatively, yet the vigorous growth of trees in these forests in recent decades (Sillett et al. 2015b, 2019b) indicates that the balance of rise of temperature, VPD, and CO_2 has thus far been beneficial and may have increased canopy height.

In contrast to redwood forests, we expect that the balance of VPD and CO_2 drivers of growth have increased tree mortality and reduced average canopy height in Amazonia. For instance, severe droughts in 1998, 2005 and 2010 have increased mortality of the largest trees (Doughty et al 2015, da Costa et al 2010, Briennen et al 2015). Here, warmer temperatures mean that a small temperature increase produces a larger increase in VPD (and PET) than in the cooler redwood forests. This places greater stress on the hydraulic systems of tall trees, one that stomatal regulation may not be able to compensate. However, the Congo basin has different drivers than the Amazon according to our preliminary theory (Fig 4) and could explain the Hubau et al 2020 (Fig 3b) observation.

As a starting point, we suggest averages of tree height and change in canopy height can be expressed by conceptual equations where PPT is mean annual precipitation (mm), PET is potential evapotranspiration (mm) and VPD is mean annual vapor pressure deficit (kPa) from Abatzoglou et al 2018:

Eqn 1 - Predicted height (pred_height): $\propto$ (PPT - PET) - VPD
Eqn 2 - Predicted height change: $\propto$ $pred\_height_{2020}$ - $pred\_height_{2000}$

We recognize this model needs further refinement because, for instance, the equation could incorrectly predict tall trees in cold environments (low PET, low VPD) even if they don't have high PPT. As a goal of this project, we will further refine the model adding, for instance, temperature and PPT thresholds. However, we note that height in redwoods, across the north to south range of the species, conforms to the above conceptual model with some exceptions, for instance, where very tall trees are found in fairly dry environments because their microsite is wet (along stream channels that give higher effective PPT).

Preliminary empirical results - We know from direct tape measurements that heights of individual tall redwoods have increased over the past 20 years (Koch and Sillett 2009, Sillett et al. 2020), but height change of the forest canopies where they are located has not been studied. Other repeat studies of tree height using lidar have shown a more mixed result in tropical forests. For example, Figure 5 depicts the results of LVIS lidar that shows height growth in some regions but not in others. These regional studies demonstrate the importance of taking a broad continental approach by comparing GEDI to GLAS. Only then can we know if canopies are increasing height versus reducing height. It is important to remember that lidar satellites like GEDI do not "see" these individual tree tops because of poor spatial resolution but would see the canopy around them, which may also have increased in height on average**.** For this reason, our analysis will be limited to canopy and not tree structure. Using a broader spatial resolution lidar sensor will also give us a better estimate of the carbon importance of an increase or decrease in tree height. We will not limit our analysis to canopy height but compare structure throughout the canopy. For instance, if tall trees are replaced by shorter gap specialists, there will be a potential signal at the top of the canopy (fewer tall trees), but also in the bottom (more LAI in the subcanopy) (as we demonstrate in Fig 11).

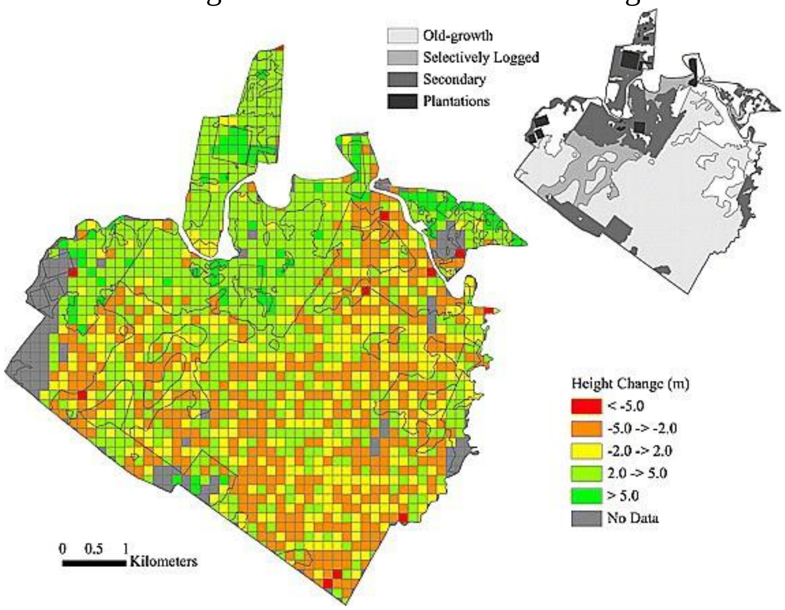


Figure 5 – In La Selva tropical forest repeat lidar over a 7-year period shows regions of growth and shrinkage (figure adapted from Dubayah et al. 2010).

Change detection - Comparing GEDI to GLAS - We recognize that both GEDI and GLAS have large vertical uncertainties in canopy height. However, with millions of canopy heights available, a power analysis indicates that we should be able to see a statistical difference given moderate height canopy (not individual tree) growth (~20 cm according to the power analysis), and thus test whether the growth matches our theoretical expectations. Here we propose to compare GEDI to GLAS to see how tall forests have changed over the past 20 years. GLAS has as much as a 4m error in its measurement of canopy height (Simard et al 2013). While this may seem to prohibit detection of small height changes over time, large sample sizes can overcome unbiased errors. The power analysis (Figure 7) shows that 2.5M samples are needed to detect a

1cm change in height, 630k samples to detect a 2cm change, and so on. Only 25k samples are needed to detect a 10cm change in height. Our expected changes in height vary across regions (Fig 4), but they often exceed 10cm. We are therefore confident that, despite the large errors in canopy height measurements in GLAS data, we will be able to detect biologically significant changes in tree height within regions across time. We more fully describe potential errors in this comparison below.

Expertise and plot networks in tropical and tall coniferous forests. Our team members have established networks of permanent plots in high-biomass temperate coniferous forests of western North America. Old-growth *Sequoia sempervirens* forests protected in parks and reserves include the tallest trees and greatest biomass forest known (Koch et al. 2004, Sillett et al. 2015b, 2020). Our plot network includes 19 one-hectare plots in tall forests (11 *S. sempervirens*, 5 *Sequoiadendron giganteum*, 3 *Pseudotsuga menziesii*) as well as several smaller plots in second-growth forests. Several individual trees per plot have been crown mapped, including 100s to 1000s of measurements of diameter and length of every branch, to develop extremely accurate estimates of aboveground woody and leaf biomass and robust allometric equations that can be applied to unmapped individuals (Van Pelt et al. 2016, Sillett et al. 2019a). Together trunk diameter and crown size predict > 95% of the variation in aboveground biomass based on thousands of individual measurements per tree. At the plot level, we have estimated aboveground biomass as high as 4340 Mg ha^{-1} and biomass increments up to 19 Mg ha^{-1} yr^{-1} in tall redwood forests. Each 1 ha plot has dimensions of 31.6 m x 316 m, meaning up to 12 GEDI footprints could potentially be identified within each. The permanent plots are the basis for 5-yr re-measurements of all vegetation and annual mortality checks to quantify aboveground biomass, leaf area, and growth increments. We have previously acquired aircraft-based LiDAR (10-20 points m^{-2}) for these plots, and it is available for comparison to GEDI. Our team and collaborators also

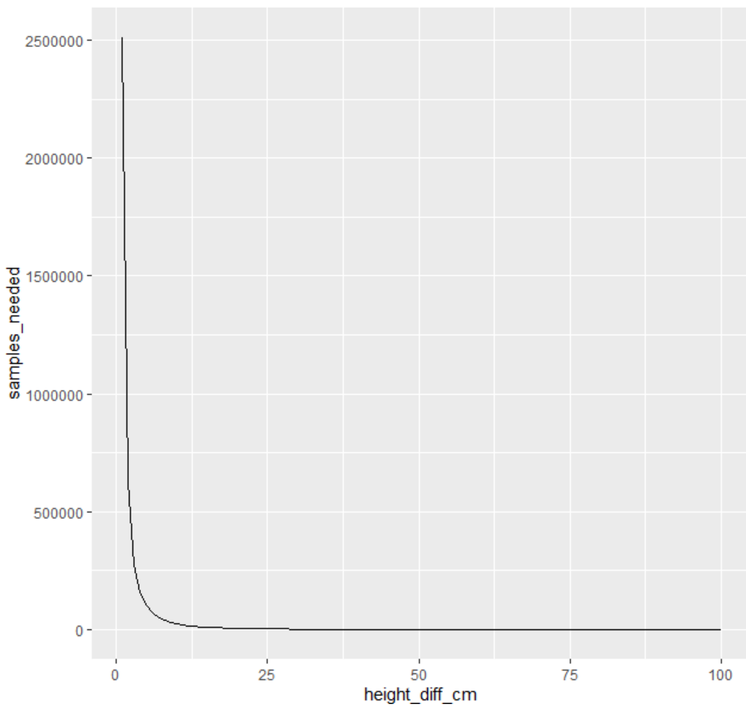
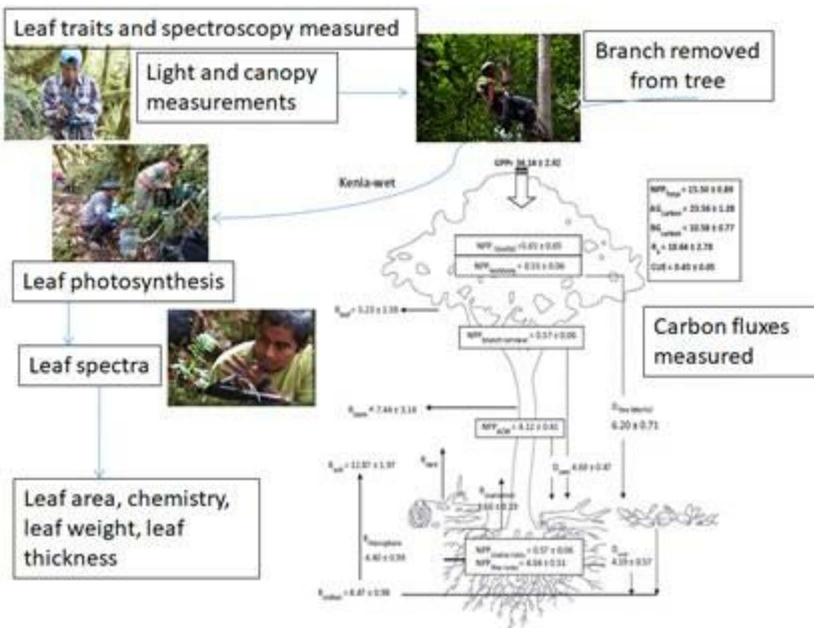


Figure 6 - The number of samples needed to detect a given change in canopy height with a power of 0.8. Standard deviation of GLAS height measurements are estimated to be 4m.

have established plots in forests dominated by another tall conifer, *Picea sitchensis*, in Washington State (Kramer et al. 2019). Here 36 plots (30-m radius) are centered on individual tall trees that were located with LiDAR. Within each plot, the focal tree crown was climbed and intensively mapped, and all neighboring trees within 30 m were measured for trunk diameter and crown size. We will leverage these detailed ground-based studies to evaluate GEDI biomass estimates and identify sources of error.



And in tropical forests – Our group has long term experience measuring tropical forest carbon cycling and biomass (Doughty et al 2015 Nature, Malhi et al 2015), including using lidar to study tropical trees (Malhi et al 2020) and the tallest known tropical tree (Shenkin et al 2019). In tropical forests, we have detailed estimates of tree height, biomass, wood density for every tree from 180 (35 with traits and spectral properties) 1 ha plots across the key tropical biomes of Amazonia, the Congo basin and Borneo (Fig 7). We also work closely with RAINFOR and AFRITON networks that have 1000+ 1 ha tropical plots. We will use GEDI, our ground-based data, and state of the art machine learning algorithms to improve allometric equations and biomass predictions at these sites. In 35 of these plots, we measured leaf functional traits and leaf spectroscopy (400-2500nm). The sampling campaigns took advantage of existing 1-ha forest dynamics plots where every tree > 10 cm in diameter was tagged, measured, and identified to species. In each of the plots, we collected leaf samples from all of the species necessary to account for 80% of the plot basal area, facilitating our ability to calculate community-weighted means of trait distributions such as LMA or wood density. We have scanned many of these plots with terrestrial LiDAR and some with aircraft lidar (Asner et al 2017), allowing us to derive precise biomass estimates, as well as to explore tree architecture and forest structure in great detail. Overall, our work will greatly improve biomass predictions in the regions of the greatest uncertainty.

Methods for hypothesis testing

H1 – The integration of ground-based data on tree structure and allometry with GEDI will improve GEDI estimates of biomass in tall conifer forests

H2 – The integration of ground-based data on tree structure, wood density estimated from multispectral data, and GEDI will improve GEDI estimates of biomass in tall tropical forests.

Part 1 improve biomass predictions - GEDI estimates footprint-level aboveground biomass density (i.e. AGBD, Mg/ha) using a data-driven approach. The current L4A biomass model aims to build an empirical relationship between GEDI waveform height metrics and AGBD, not with a single global model but multiple candidate models stratified by plant functional type and region. It requires assemblies of field AGBD data and its corresponding airborne lidar used to simulate GEDI waveforms, as demonstrated in Dubayah et al. 2020. This proposal aims to further improve GEDI's AGBD product not only through a geographical expansion of GEDI's cal/val database, but by refining field AGBD estimates over areas of largest uncertainty (i.e. tropical and tallest trees). While some forest inventory plots do not necessarily have corresponding airborne lidar for GEDI's simulation and calibration, they are of great value as an independent reference to validate GEDI's performance. We anticipate to develop a harmonized AGBD dataset over these areas by combining field data and GEDI's estimates.

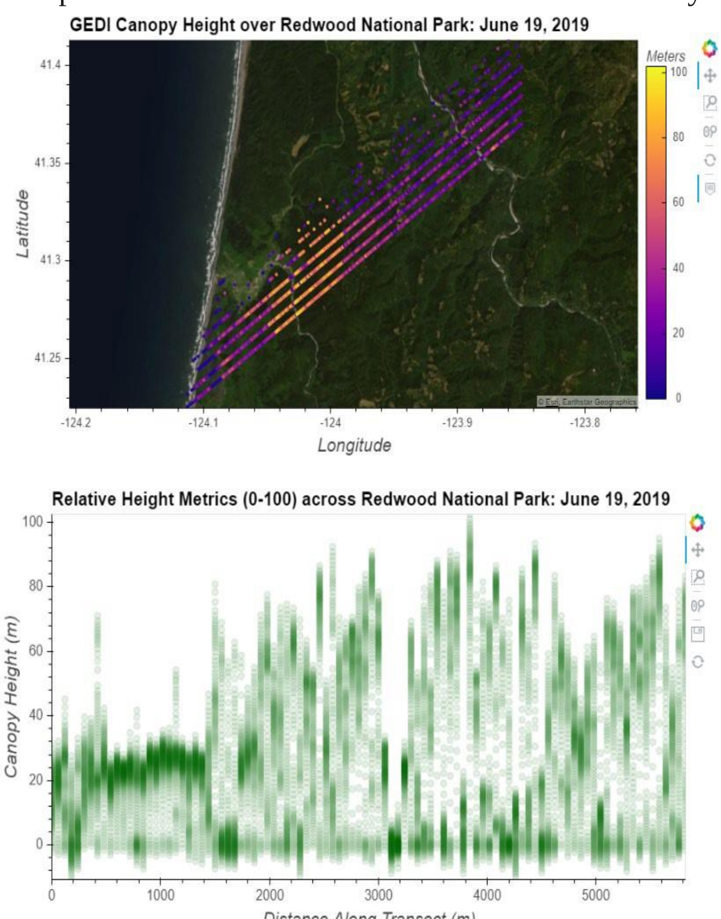


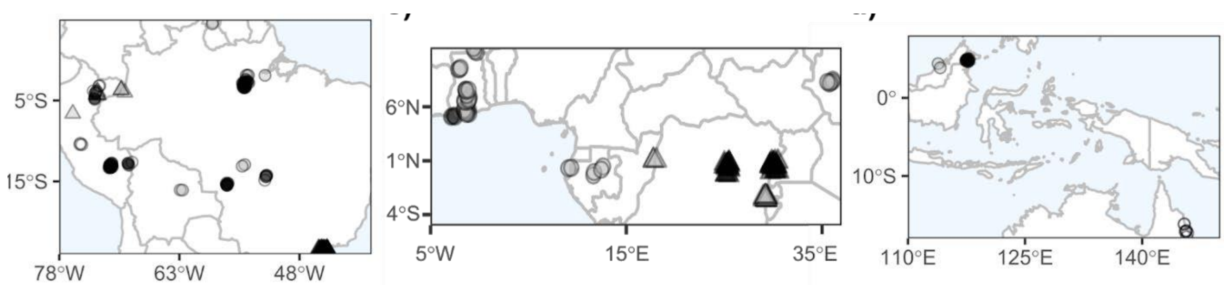
Figure 8 – (top) GEDI returns for *Sequoia sempervirens* forest in California containing trees > 110 m tall. (bottom) Measured heights along a transect in the area (credit: NASA LP DAAC).

Improving tall conifer forests biomass predictions - We will improve the L4A biomass model for tall conifer forests by building an empirical relationship between 19 plots in tall forests for which leaf area and aboveground biomass and growth increments were quantified recently (2014 to 2017) via intensive measurements and GEDI waveforms for the same locations using Real Earth Coordinates. With these coordinates, it should be possible to select GEDI returns occurring inside plot boundaries (~12 per plot). From these we can derive potential predictors in a likelihood framework to determine which individual predictor or set of predictors correlate best with measured per hectare quantities. If the fit is good, we can apply the resulting equation to tall forests in the vicinity of the plots for biomass (and other quantity estimation).

In Figure 8 we have shown relatively accurate height predicted by GEDI returns. We can apply equations to much of the forest depicted, nearly all of which is tall. We will first estimate tall forest biomass across thousands of hectares in WA, OR, and CA. To develop equations for nearby shorter stature forests, we will calibrate GEDI with plots in second-growth forests, and will combine this, when necessary, with National Forest and BLM inventory plots where available. If we obtain decent results using the old-growth forest plots, we will apply them as widely as possible using the known distribution of similar forest including across several National and State Parks.

Improving tropical forest biomass predictions

H2.1 - *Validating biomass and tree height against a large network of tropical forest 1 ha field plots.* We will improve the L4A biomass model for tropical forests (broadleaf evergreen tropical PFT) for different tropical forest regions that have different structural constraints. For instance, we know tropical trees have very different structures in the East versus West Amazon, the Congo basin and Borneo. With our 1 ha plot network (N=180), we have representative forests from each of these regions (Fig 9-below) and we will develop empirical relationships between GEDI waveform height metrics and AGBD for each of these regions separately. Every tree in each of the 1 ha plots is identified for wood density, measured for DBH and tree height. Most importantly, these plots (see below) are widely distributed throughout the tropics (and not in over-represented forests of Panama, Puerto Rico, or Hawaii).



Here we propose to greatly expand GEDI's cal/val database to include all the GEM network plots (including some RAINFOR/Afritron plots). If GEDI biomass/height estimates are inaccurate, we will create new algorithms based on our ground validated dataset.

H2.2 - *Adding a hyperspectral satellite wood density prediction with ground validated wood density and spectral properties* - Uncertainty in tropical forest wood density can lead to large uncertainties in tropical forest biomass prediction (Baker et al. 2004). Here we propose to use our leaf spectroscopy (400-2500nm) and leaf trait database from Peru, Brazil, Ghana, Australia and Borneo (N=35 with spectral data, N=180 plot wood density data in 1 ha plots) to develop a better spectral tool for empirically derived wood density prediction. In each of the plots, we collected sunlit leaf and wood samples from all of the species necessary to account for 80% of the plot basal area, facilitating our ability to calculate community-weighted means of trait distributions such as LMA or wood density at spatial scales relevant to DESIS (30m). There are solid theoretical reasons that we could predict wood density with hyperspectral satellite data.

Leaf traits, like leaf chemistry or leaf mass per area (LMA), are important indicators of a tree's life history strategy (Wright et al., 2004; Wright et al., 2010). For instance, light-demanding species with rapid growth and high mortality rates are predicted to have low LMA, wood density, and tree height (Wright et al., 2010) and other studies have correlated LMA and wood density (Ishida et al. 2008). LMA has been accurately predicted with the partial least squares regression technique for leaf (Doughty et al 2011 and 2017), aircraft and satellite data (Asner et al 2016).

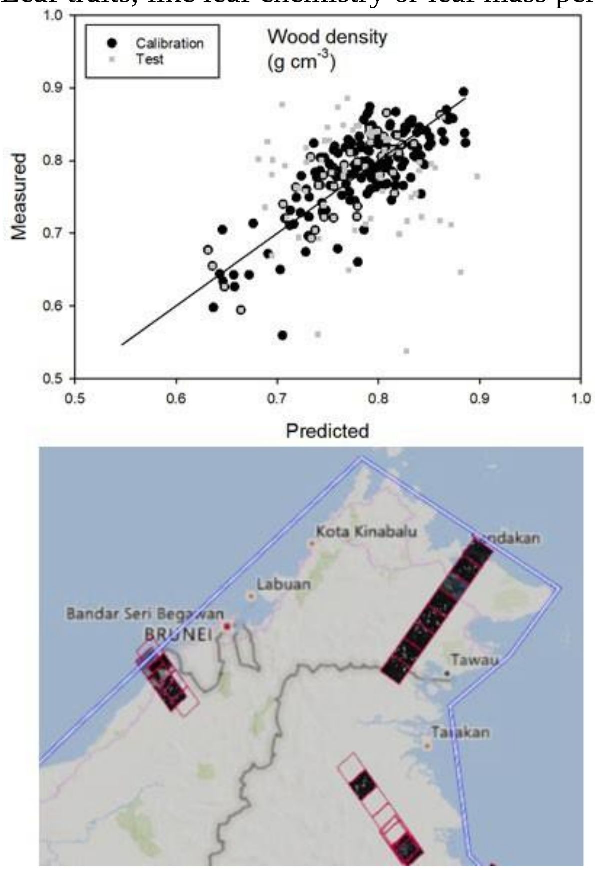


Figure 10 – (top) Predicting wood density with a handheld spectrometer from Doughty et al 2017. (bottom) Data from DESIS near our Borneo filed plots. Red zones basic quality criteria (cloud cover less than 50% and solar elevation angle greater than 30 degrees). In the map below, the red squares which show imagery are the scenes which meet the basic quality criteria.

At each GEM plot we have detailed information on tree species and we will use the largest wood density database to date (8412 taxa) (Chave et al 2009) to estimate species specific wood density combined with DESIS hyperspectral data to create an algorithm predicting wood density verified with our 1 ha plot network. DESIS has 235 spectral bands between 400-1000nm. In previous work, we have demonstrated the ability of hyperspectral leaf spectroscopy to accurately predict wood density in Borneo and Peru (Doughty et al 2017 and 2020) and at the aircraft scale (Jucker et al 2018). Fig 10 shows prediction of wood density with a handheld spectrometer and the PLSR technique using spectral bands 400-1100 nm which is of similar spectral bands to DESIS. We will ground validate wood density predictions where DESIS data overlap with our plot network (DESIS is still sparse (Fig. 10 bottom), but will greatly increase over the next few years). Then, again constrained by DESIS availability, we will create regional maps of wood density that can be combined with GEDI for more accurate biomass predictions. Currently, GEDI is not constrained by empirically derived wood density, leading to great biomass uncertainty in tropical forests.

H3 - How are forests changing? (comparing GLAS to GEDI) - We hypothesize that canopies are increasing in stature due to increases in water use efficiency in blue areas of fig 4 and reducing their stature due to increases in VPD in yellow areas of fig 4. We further hypothesizethat changes in stature over a 20-year period will be > 20 cm on average over large geographic areas. We will not limit our analysis to canopy height but will compare structure throughout the canopy. For instance, if tall trees are replaced by shorter gap specialists, there will be a potential signal at the top of the canopy (fewer tall trees), but also in the bottom (more LAI in the subcanopy) (as we demonstrate in Fig 11). We recognize that both GEDI and GLAS have large vertical uncertainties in tree height. However, with millions of canopy heights available, a power analysis indicates that we should be able to see a statistical difference given moderate height growth (~20 cm according to the power analysis), and thus test whether the growth matches our theoretical expectations. If trees have changes in stature, this is a major finding that could help us better understand the global carbon cycle and better predict future climate. Further, we propose to quantify the net change in biomass due to structural changes across the planet between the GLAS and GEDI period which will help achieve NASA goal #2.
Here we propose 3 specific predictions within Hypothesis 3:

1. **The GEDI – GLAS difference for the Amazon is less than that difference for the Congo.**

That is: $(\text{GEDI-GLAS})_{\text{Amazon}} < (\text{GEDI-GLAS})_{\text{Congo}}$. We hypothesize that average lidar differences between GLAS and GEDI will be different between African and Amazonian tropical forests due to the documented changes in mortality rates (Hubau et al 2020). For this section, we will compare lidar returns at different vertical profiles for Amazonia and compare them to Central Africa. There is much regional variability but with strong filters and thousands of data points, we will carefully select our datasets for comparison. For example, we show heavily filtered data in Figure 11 showing a possible height reduction (as large trees die and are replaced

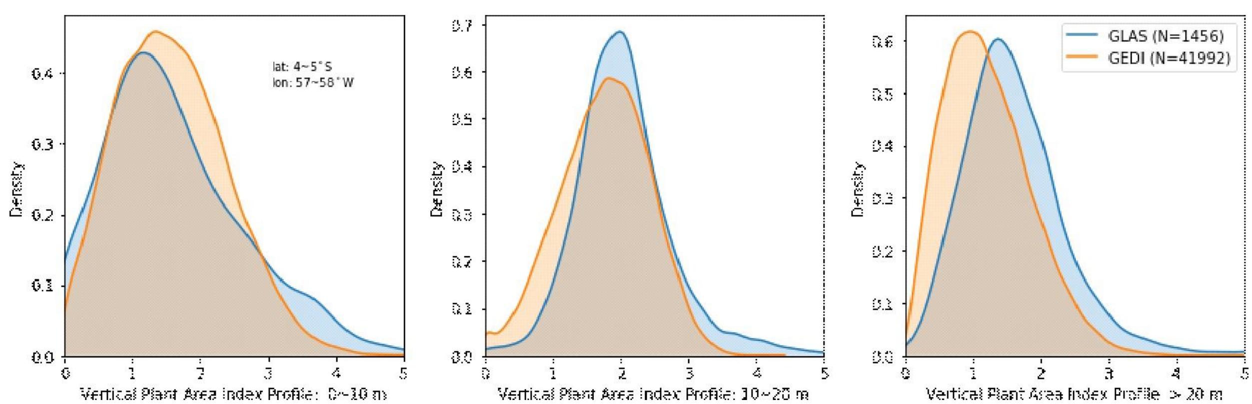


Figure 11– A preliminary comparison of GLAS to GEDI L2B data products over a section of the Amazon between 2005 to 2019 divided into three vertical height bins.

by shorter trees) of the Amazon between 2005 and 2019 as predicted in (project PI - Doughty et al 2015, Brienen et al 2015 and Hubau et al 2020). Interestingly, despite a similar total LAI value, the vertical structure of the forest has changed between 2005 to 2019. It shows a slight decrease in LAI > 30-m, an increase of LAI from 0~10m in height and little change between 10~20m. This is consistent with an increase in mortality of large trees in the Amazon as predicted by increased VPD (McDowell et al 2020) or droughts (Doughty et al 2015, Briennen et al 2015) followed by an increase in smaller stature gap specialists like Cecropia. To the best of our knowledge this result is real and not a sensor artifact because Co-I Tang extensively checked GLAS LAI profile versus LVIS (GEDI's airborne prototype) and they have good agreement (Tang et al 2016).

Much further verification and filtering of data are necessary to confirm this fascinating result because GLAS with larger footprints may give variable height returns when shot over slopes. We will carefully screen for any deforestation or potential logging in these areas using the Hansen et al 2013 landcover change database. There are many technical issues to comparing GLAS to GEDI that we address below in the error analysis section. Overall, we are measuring relative changes which is easier than absolute changes.

2. **The comparison of GEDI and GLAS canopy heights for tall conifer forests will show a height increase.**

That is, $(\text{GEDI-GLAS})_{\text{tall conifers}} > 0$. We hypothesize that tall conifers have gotten taller in certain regions (as defined by Fig 4). Because, we have actual ground-based data with tape measures documenting these changes over the past 20 years, in particular regions we can ground validate these results with confidence. Here, we will measure absolute changes in tree height. This is more difficult than relative changes (like above), but because we have some ground validated tree height data, we are confident in our ability to do this.

3. **The comparison of GEDI and GLAS will show that changes in canopy height vary regionally in the tropics.**

That is, from Figure 4: $(\text{GEDI-GLAS})_{\text{Yellow}} < (\text{GEDI-GLAS})_{\text{Blue}}$ - - Here we will generally test our conceptual model regarding the importance of water balance and vapor pressure deficit in determining where changes in tree stature have occurred over the past 20 years.

Approach to Errors, Uncertainties, and Instrument Calibration - Analysis of errors and uncertainties is an integral component of our research activities. One major uncertainty is the change detection analysis between GLAS and GEDI given their difference in instrument configurations (e.g. possible systematic error caused by different footprint sizes and sampling density). They may also be attributed to varying measurement accuracies at different acquisition conditions (e.g. random error dominated by solar noise and cloud contamination). It is thus imperative to first identify origins of these possible biases and then correct them. A detailed evaluation of GLAS performance is very challenging since the mission ended in 2009, and we therefore rely on reported accuracies from previous results and apply different QA criteria to create a subset product of higher data fidelity. We will also work with the GEDI science team to evaluate and factor in GEDI measurement errors in our analysis throughout the proposal. We expect this will be an iterative process as GEDI continues its algorithm update and data generation. We will calculate the expected change value of canopy height and vertical foliage profile and its uncertainty for targeted area by propagating measurement error and sampling variance aggregated from footprint-level estimations. An inverse-variance weighted average, for example, will be calculated from all intersected footprints using the raw observation and associated measurement error. The weighted variance, together with the sampling variance, will then be used to calculate confidence intervals of the aggregated estimation for our sites.

Error analysis - For all hypotheses, we will use 70% of the data to develop our algorithms and then calculate statistics on the remaining 30%. This way users of the developed product will have a much better sense of accuracy and the potential limitations of our estimates.

Achieving specific NASA goals - If this proposal is funded, we will create data products that will help better estimate the biomass of terrestrial carbon stocks in all tropical biomes and tall forest temperate conifer systems. NASA's specific goals for this call are listed below and we specifically answer how our proposal will address each.

1. *What is the aboveground carbon balance of the land surface?* Tall forests have the largest biomass uncertainties and we will bring ground data and expertise in these particular forests (tall conifers and tropical forests). We will reduce errors in uncertainty of aboveground carbon estimates for these key forests.
2. *What role will the land surface play in mitigating atmospheric CO2 in the coming decades?* Terrestrial ecosystems are sequestering carbon but a great uncertainty in this estimate is how canopy stature has changed over time due to climate change. Comparing GLAS to GEDI is a unique, robust methodology for determining if canopy structure is changing. Understanding these changes and their biomass implications will help us understand what role the land surface will play in the carbon budget in the coming decades.
3. *Proposals should address regional scales or larger.* We will address the pan tropics and some key tall conifer forests of the world.
4. *Innovative analyses using GEDI data products in combination with data products from other sensors* – We will predict wood density with DESIS hyperspectral data that will be calibrated with our unique tropical forest wood density/leaf spectroscopy dataset.

Project deliverables - We estimate a minimum of six, high quality publications as an outcome of this proposal (two addressing each of the above sections). More fundamentally, we will greatly improve biomass predictions of key ecosystems and possibly improve our understanding of the "missing" terrestrial carbon sink.

We are well suited to this project. Dr. Hao Tang has extensive experience processing both GLAS and GEDI data, and leads the development of GEDI L2B data product. Dr. Scott Goetz is the GEDI science PI and Dr. Shenkin has extensive knowledge of lidar and tree height in the tropics. Drs. Koch and Sillett are leading researchers quantifying height, biomass, and annual biomass increments in the most productive conifer forests. Drs. Doughty, Malhi and Shenkin are leading tropical forest researchers. Dr. Doughty has extensive experience predicting wood density with remote sensing in tropical forests.

Overall, our proposed project is a mix of the fundamental and the exciting. Our team has some of the best ground-based data for improving GEDI biomass predictions in critical tall, high biomass conifer and tropical systems. We also have the GEDI experience and therefore are confident in our ability to combine the two to improve GEDI predictions. We are also proposing to, for the first time, measure how canopy stature has changed over time. We have all the expertise and relevant datasets to do this.

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