Project Background

African forest elephants (*Loxodonta africana cyclotis*) face severe threats from poaching and deforestation with estimated population losses ranging from 62-81% in central Africa from 2002-2013 (Maisels et al., 2013; Poulsen et al., 2018). With the demand of ivory remaining high in global markets, the possibility of extinction is well established (Poulsen et al., 2018). However, forest elephants are poorly studied due to the dense and untraversable nature of African tropical forests. Specifically, forest elephant's ecological role in the Afrotropics is severely understudied in comparison to their cousins, the African savanna elephants (*Loxodonta africana africana*), whose role as a keystone species has been understood for decades (Bond, 1994). It is hypothesized that forest elephants have a large effect on habitat heterogeneity, or the variability of forest structure and function, from damage to the understory and the opening up of dense forests, however this has yet to be shown on a large scale (Maicher et al., 2020). We propose a new method of quantifying African forest elephant's ecological impact using lidar (light detection and ranging) to evaluate changes in habitat heterogeneity with varying elephant densities on both a national scale in Gabon and on a regional scale in the Afrotropics (Figure 1).

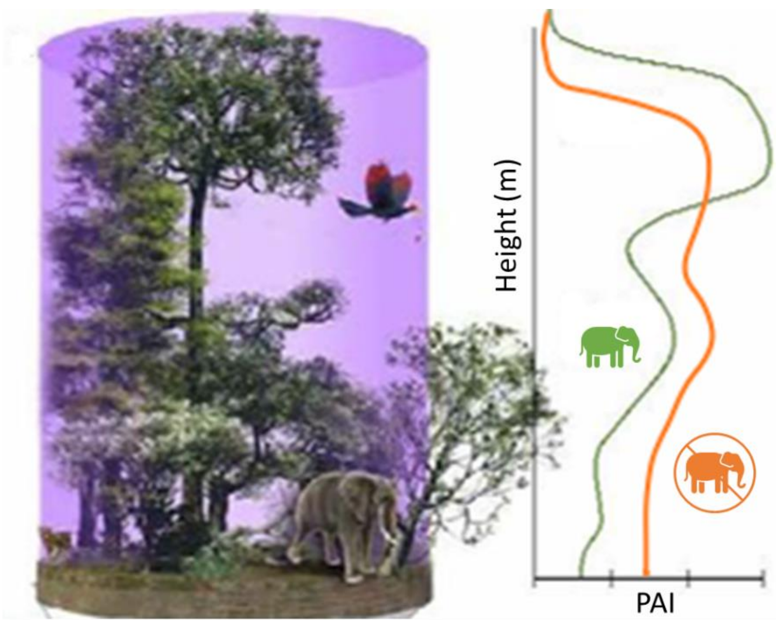

Figure 1. A comparison of canopy structure in forests with and without elephants using lidar. Proposed vertical structure profiles (right) show less plant area index (PAI) in the understory through elephant destruction and higher overall canopy height in forests with elephants (green) than without (orange).

African forest elephants are active seed dispersers and significantly impact nutrient cycles such as carbon, nitrogen, potassium, and sodium through plant digestion, defecation, urination and the ingestion of mineral rich water and soil (Doughty et al., 2016; Sienne et al., 2014; Blake et al., 2009). As generalist browsers, forest elephants inflict significant damage to their environment by trampling, upheaving, and ingesting vegetation. Consistent destruction of small saplings allows large woody trees to succeed (Terborgh et al., 2016). Unlike Amazonia, African rainforests have less diversity in the understory, but higher diversity of large trees that dominate the canopy layer, which points to the substantial impact of megaherbivores on forest structure (Terborgh et al., 2016). Additionally, Berzaghi et al. (2019) with contributions from our research group, discovered that changes in vegetation structure from elephant disturbance have significant effects on carbon stocks; if elephants were to become extinct in the African tropics, it is estimated that aboveground biomass would be reduced by 7%. Maicher et al. (2020) found the opening of forests through forest elephant damage not only significantly changed vegetation composition and structure in the Afrotropics, but also increased species richness of butterflies and light-attracted moths. These findings solidify the notion that forest elephants can play a vital role in influencing habitat heterogeneity locally. However, the spatial scale at which Maicher et al. (2020) observed these trends was limited to Mount Cameroon. A similar investigation is needed on a much larger spatial scale to validate these claims and instill greater confidence in their results, especially since Mt. Cameroon National Park is home to a mere 118 elephants (African Elephant Status Report, 2016).

Habitat heterogeneity is the variability of ecosystem structure and function which leads to increased levels of biodiversity (MacArthur and MacArthur, 1961). To measure changes in vegetation structure in areas with varying elephant densities on a large spatial scale, the use of remotely sensed data is essential. Lidar will provide needed information on how megaherbivores influence microscale shifts in habitat.

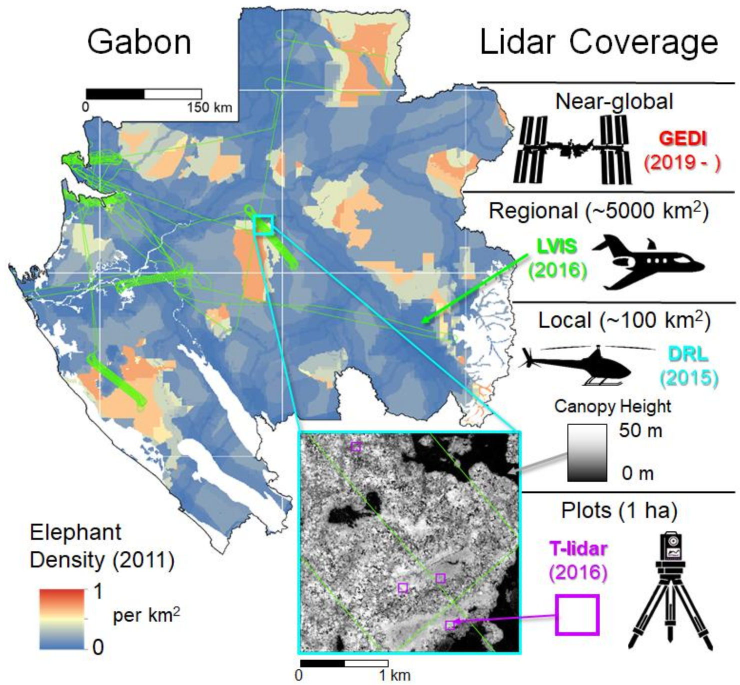

Figure 2. Elephant densities (Maisels et al., 2013) and lidar coverage from TLS, DRL, LVIS, and GEDI campaigns in Gabon.

Lidar sensors are used to measure forest structural properties, such as cover and canopy height. These sensors send out pulses of energy, digitize the energy signal reflected off the ground and vegetation, and then convert that signal to a 3D representation of topography and vegetation. The relative distribution of returned energy provides information about vertical sub-canopy structure and distribution of plant biomass. Lidar has proven effective in predicting arboreal mammal ranges in Panama (McLean et al., 2016), leaf area index in Costa Rica (Tang et al., 2012), and suitable bird habitats in the Neotropics (Goetz et al., 2010), yet this technology has never been used to determine forest elephant impacts at a national level. Our team has extensive experience working in tropical forests (Doughty et al., 2015), using remotely sensed lidar to characterize forest structure (Hansen et al., 2020), and modeling forest elephant impact (Berzaghi et al., 2019; Saatchi et al., 2011). The Global Ecosystem Dynamics Investigation (GEDI) mission uses a lidar instrument on the International Space Station to measure vegetation structure at a 25m spatial resolution between 51 degrees North and South latitude (Dubayah et al. 2020). With the addition of consistent, near global lidar, large scale investigations of habitat heterogeneity can be conducted.

This study aims to quantify the role forest elephants play as ecosystem engineers and to determine their impact on habitat heterogeneity using lidar (Figure 2). Utilizing elephant location data from the Wildlife Conservation Society, bio-logged tracking data from the Save the Elephants Foundation, and four types of lidar for forest composition and structure, we will address urgent questions regarding how elephants impact canopy structure and carbon storage. Specifically, our research questions are:

1. Which, if any, lidar technologies can identify elephant transitory trails?
2. How do forest elephants impact habitat heterogeneity?
3. What changes in Afrotropical canopy structure have accompanied elephant population change over the last 20 years?

Not only will these findings address important questions related to ecological function, but they will expand our understanding of forest elephant's influence on carbon storage. Furthermore, environmental policy makers will be armed with needed information on the importance of biodiversity for ecosystem services without the need of costly and time-intensive field work.

Methods

The cryptic nature of forest elephants combined with overall cost, danger, and logistical difficulties of conducting field work in Gabon makes acquiring elephant data formidable. Currently, the best method of estimating elephant impact is by walking along transects through the forest counting dung and recording vegetation metrics, however with new technologies we can rectify this problem. Through our close collaboration with Dr. Fiona Maisels, the survey and wildlife monitoring adviser for central Africa at the Wildlife Conservation Society (WCS), we have the most comprehensive African forest elephant occurrence dataset available (Maisels et al., 2013; Figure 2). Dr. Stephen Blake of Save the Elephants Foundation is another collaborator of ours, allowing us access to satellite movement data from 34 elephants starting in 1998 from the Forest Elephant Telemetry Programme (Wikelski and Kays, 2019). Lastly, we work closely with Dr. Katherine Abernethy of the National Centre for Research in Science and Technology in Gabon (CENAREST), who has provided us with on the ground knowledge of elephant trail locations in Lope National Park, Gabon, for validation.

Surveying environmental impact from forest elephants using lidar has never been done before. To accomplish this research goal, multiple spatial scales will be investigated using terrestrial, airborne and spaceborne lidar (Figure 2). First, we will test the accuracy to which lidar can be used to determine elephant transitory trails. Forest elephants create paths through the dense tropical forests to navigate between rivers, bais, and fruiting trees which are anywhere from 0.5-2 m wide (Blake et al. 2004). Lope National Park, Gabon, has the highest density of forest elephants in the world (Maisels et al., 2013), geolocated elephant trails, and overlap from four lidar datasets (Figure 2). This analysis will use terrestrial lidar (TLS; Wilkes et al. 2017), Airborne discrete return lidar (DRL; Silva et al. 2018), NASA's Land, Vegetation, and Ice Sensor airborne lidar (LVIS; Blair et al., 1999), and NASA Global Ecosystem Dynamics Investigation lidar (GEDI; Dubayah et al., 2020) in combination with WCS elephant data, elephant telemetry data, and a known elephant trail database. Identifying elephant trails remotely is not only a fundamentally interesting question in remote sensing application, but a potential break-through advancement in conservation; it would provide needed information on elephant behavior, movement patterns, and establishment as a key stone species.

Next, a survey of Gabon's habitat heterogeneity from elephants will be completed using all available elephant data, LVIS, and GEDI lidar. To characterize the variability of Gabonese forests, canopy height (CH), height of median energy (HOME), vertical distribution ratio (VDR; Goetz et al. 2007), and canopy cover (CC) metrics will be extracted from LVIS and GEDI lidar for Gabon's national parks (Figure 2). These metrics will be compared in parks with varying elephant densities, but with few other disturbances to isolate variation in vertical structure caused by elephants. Elephant impact was identified in preliminary results of LVIS returns across high and low elephant areas of Lope (with distance to road, slope, and canopy cover constrains) indicating the feasibility of identifying an elephant signal on a larger extent (Figure 3). Further analysis will include a generalized additive model with variables such as distance to river, distance to road, slope, and human influence to account for external influences on structure.

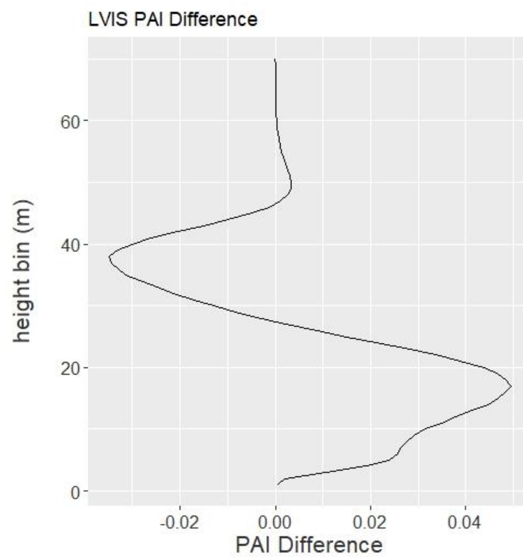

Figure 3: Difference in PAI between elephant high and low density areas of Lope National Park, Gabon.

Finally, a regional analysis of Afrotropical canopy structure over the last 15 years will ensue. This investigation will utilize elephant population data from the African elephant database and WCS, GLAS (Geoscience Laser Altimeter System; 2003-2009) spaceborne lidar, and GEDI lidar (2019-present). Due to significant losses of elephants in many national parks throughout the region (Minkebe National Park lost an estimated 25,000 elephants from 2004-2014; Poulsen et al. 2018) it is possible to determine how the rapid destruction of elephants is affecting forest structure and function to better prioritize conservation efforts.

Table 1. Elephant present and absent study areas.

Country	Protected Area	Area (km^2)
Elephant Present		
Gabon	Lope	4,486
	Loango	1,510
	Ivindo	3,864
CAR	Dzangha	3,861
Cameroon	Lobeke	1,029
DRC	Salonga	25,141
Elephant Absent		
DRC	Kuhuzi-Biega	6,138
	Virunga	6,356
	Okapi	12,787
Equatorial Guinea	Rio Muni Region	24,635
CAR	Chinko Drainage	19,000
Gabon	Minkebe	11,956

Using the most recent elephant population data from the IUCN and WCS, select parklands with and without elephants were identified for this analysis (Table 1). Vertical structural data such as canopy cover and canopy height will be compared from 2004-2021 in each study area. Although GEDI and GLAS have substantial uncertainties, the use of millions of points should allow us to identify a statistical difference in canopy structure as small as 20 cm (determined from a power analysis; Figure 4). A GEDI research proposal was recently awarded to Christopher Doughty (PI) and colleagues to investigate whether climate change is changing mean forest heights, which will in turn process all GLAS and GEDI data for the Amazon and African tropics (20-GEDIST20-0020). These data will then be subsetted to protected areas with elephants and those that have experienced massive declines (Table 1) by the FI with the assistance of Hao Tang, Patrick Burns, Scott Goetz, and other lidar experts from the GEDI Science Team. Figure 4 demonstrates the ability of determining understory, mid-canopy, and high-canopy structural differences across large spatial areas (Amazon forests) between the two instruments. This is critical as we hypothesize that forest elephants will impact the understory and possibly other canopy regions as well.

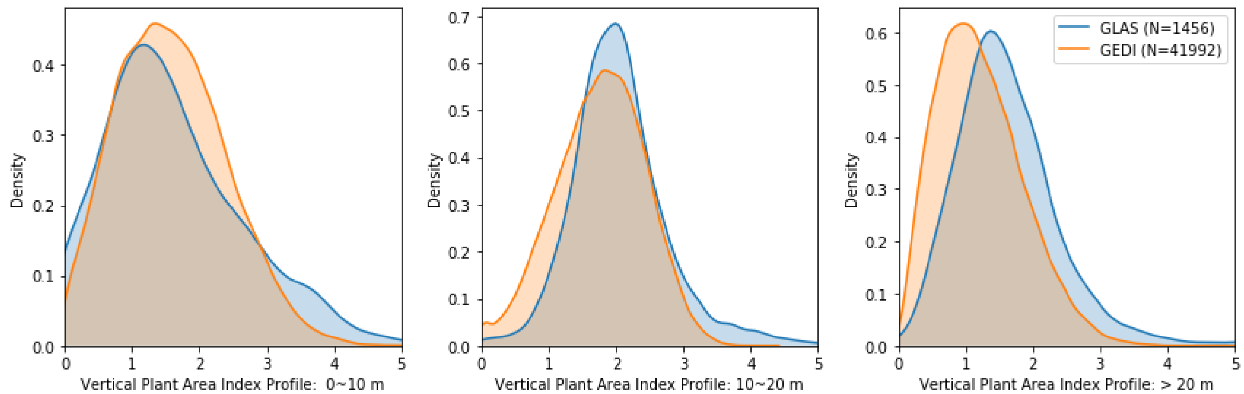

Figure 4. Changes in canopy structure in the Amazon from 2005-2019 using GLAS and GEDI L2B data (Doughty GEDI grant 20-GEDIST20-0020)

Earth System Science Impact

Not only does this research have potentially large impacts in quantifying the effects of defaunation, but if forest elephants are discovered as significant ecosystem engineers in Congolese forests, their protection could be integrated into carbon credit trading schemes. These findings can be used by REDD+ to provide additional carbon credits to countries investing in elephant protection. Our collaborator, Fabio Berzaghi, along with many others on this research team (Marcos Longo, Stephen Blake, Christopher Doughty) found that African forest elephants increase the carbon storage of the tropical forests (2019). The modeled results from this investigation can be validated by this proposed study using global canopy structure metrics and detailed forest elephant location data. Additionally, we have already had significant interest in the possibility of incorporating forest elephants into carbon credit trading by the World Bank, which would only be enhanced by the findings of this study.

Furthermore, we are developing an educational app based on our collaborator Fabio Berzaghi's research that turns carbon emissions from personal travel into a "forest elephant protection" metric. However, findings from this study would greatly improve this metric. Instead of offsetting carbon emissions from travel by planting trees, this app quantifies elephant protection into stored carbon in the tropics and suggests donation amounts to elephant conservation organizations. Using the public's immense interest in saving elephants and the World Bank's interest in the connection between elephants and carbon, we are confident this app will disseminate the findings of this study to society. Although these efforts to incorporate our research into mobile apps and international organizations are critical, they are not included in this proposal, but are examples of the broader societal impacts this project would support.

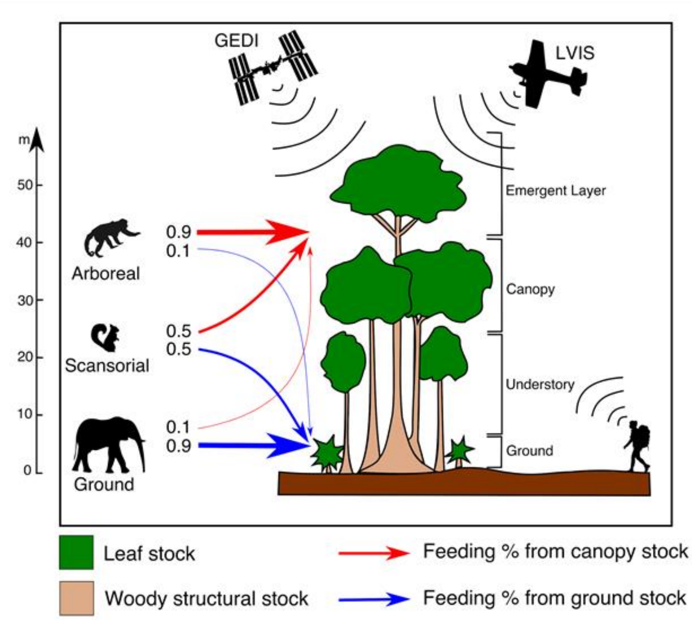

Figure 5. Tropical forest structural layers depicted with lidar (right) in comparison to Madingley biodiversity cohorts (left).

Not only does this research assist in education and carbon credit trading, but it influences ecological forecasting initiatives. Modeling biodiversity and ecosystem services across large scales is necessary for predicting how climate change will impact fauna, but also for discovering how the ecosystem will change with defaunation (Nasi et al., 2011). Our research team works closely with the creators of the Madingley model (Figure 5), a novel ecological model that represents all life on Earth (Purves et al., 2013), enabling users to examine feedbacks and trophic cascades that other ecological models cannot (Harfoot et al., 2014). The addition of forest elephants as ecosystem engineers in the Madingley model is currently funded through a NASA Biodiversity and Ecological Forecasting grant (SLSCVC 2018). The research proposed in this study would amplify the ongoing Madingley model work, however would not directly incorporate model simulations as that work is being carried out by other members of our team.

Project Timeline

Table 2. Planned publications and project timeline.

Publication Title	Required Data	Release Date
Detecting forest elephant transitory trails using lidar in Gabon.	DRL lidar, LVIS lidar, WCS elephant data, elephant trail data, Movebank elephant data	Spring 2022
An application of lidar in evaluating habitat heterogeneity in Gabon.	GEDI lidar, LVIS lidar, WCS elephant data, IUCN elephant database	Spring 2023
Changes in tropical canopy structure from forest elephant losses in central Africa.	GEDI lidar, GLAS lidar, WCS elephant data, IUCN elephant database	Spring 2024