

LIDAR-based Analysis of Mangrove Forest Structure & Carbon Stocks of The Republic of Palau.

by

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Executive Summary

This study assesses the mangrove carbon stocks of the Republic of Palau, using existing in-situ data, aerial lidar, and RGB imagery. Palau's fringing mangrove forests have been expanding relatively uninterrupted since the end of World War II. This presents a challenge for Palau as development pressures increase demand for shoreline access and land reclamation. While carbon offset protocols incentivize resource conservation there are not any that support the status quo. As a good steward of its resources, Palau uses environmental fees to support conservation, but excessive fees may dissuade tourism. This study assesses Palau's mangrove carbon stocks to support innovative payments for ecosystem services (PES) in lieu of carbon offsets.

Palau's mangroves generally do not qualify for avoided conversion, afforestation, REDD+, or improved forest management carbon offsets as its mangroves are partially protected, healthy, and aren't used as an extractive forest products resource base. One could argue the nation's mangroves are at risk of conversion, but meeting protocol standards necessitates proving significant degradation. Deforestation rates serve as a benchmark demonstrating reductions in degradation and deforestation resulting from conservation actions. This arbitrage is quantified as a carbon offset in metric tons of carbon dioxide emissions avoided. Remote sensing analysis indicates low levels of mangrove degradation in Palau, calling into question the potential for avoided conversion offsets (Dendy et al. 2022; The Nature Conservancy 2023). However, creative conservation finance models could provide buyers opportunities to option Palau's current carbon stocks and future carbon sequestration. This requires sound estimates of existing stocks and a means to efficiently assess annual carbon accretion to value future carbon sequestration.

There currently is not a robust low-cost and efficient means to regularly assess mangrove cover change and spatially relate carbon density remotely. This limits efficient valuations of proposed development areas, associated cost-benefit analysis, and PES. This study evaluates existing in-situ data from a 2011 US Forest Service (USFS) mangrove carbon stock analysis and explores techniques to assess carbon stocks remotely using limited field data. The primary in-situ data consists of biomass and carbon stocks data derived from fixed-radius plots of live mangrove trees, dead downed woody debris, and soil samples from the state of Airai, Palau. The existing in-situ data is evaluated against the nation's first complete aerial lidar point cloud and RGB imagery dataset which was acquired in 2021 by the Palau Automated Land and Resource Information System (PALARIS) office. A lidar-derived digital mangrove canopy surface, ground elevation, and carbon density model of the USFS study site was used to estimate carbon stocks.

Analysis revealed a ratio of 5:1 to 6:1 belowground to aboveground carbon in the study area. However, efforts to correlate belowground carbon using aboveground mangrove tree height derived from lidar were not successful. Further plot level data, elevation, and species validation points will be needed to derive a localized allometric equation for Palau's primary mangrove species. However, volumetric estimations of carbon (C) using ESRI's ArcPro software supported some carbon stock analysis. A pixel-based grid calculation tool and a bathtub volume estimation tool revealed 144.8k Mg C and 146k Mg C respectively across the study area. Unfortunately, due to a lack of time, ground control points, and other reference data, a national estimate using these tools wasn't possible. However, a planar estimate using the mean carbon density of all plots revealed carbon stocks of ~3.3 million Mg C nationwide. This number should be used conservatively as sediment accretion drives the vast majority of mangrove carbon stocks. The

gradient of sediment across the country's mangroves is not known and could alter this estimate substantially.

The estimates made here could be enhanced with further study of the underlying gradient and depth of the coralline and sandy bottom underlying Palau's mangrove sediment. It is suggested to collect sediment depth using a simple probe. This would support the creation of a digital elevation model of the coralline/sand floor. Efforts to create a digital elevation model (DEM) were unsuccessful owing to the complexities of mangrove root and trunk structures. Seawater also inundated the study area when the lidar data was collected, limiting the reliability of ground return elevations in the creation of a digital elevation model (DEM). It is suggested that field measurements of sediment elevations be taken concurrently while probing sediment depth. The volume between the coralline/sand floor and DEM could be used to estimate sediment volume. A nationwide 2016 study installed sediment measurement rods that support annual sediment accrual monitoring (MacKenzie et al. 2016). Further soil core analysis and sediment depths would support the interpolation of below-ground carbon stocks. This could be combined with regular drone surveys to collect photogrammetry, hyperspectral species analysis, and species photo validation surveys to assess aboveground biomass and carbon stock change more accurately. Some measurements could be implemented by each state's protected area network (PAN) offices and collected on an annual to 5-year basis per carbon offset protocols. Taken together, they would generate a highly accurate estimate of Palau's carbon stocks. This could be achieved at a low cost and in a repeatable manner that could easily incorporate community involvement.

Palau has a strong record of demonstrating conservation leadership, banning shark fishing in 2009, instituting innovative approaches to fishery management of its northern reefs in 2013, closing 502,538 km² of its seas to foreign fishing vessels in 2015, reissuing a ban on hawksbill turtle harvests in 2018, and conserving 44.18% of its terrestrial and 100% of marine area in some form or another (SPREP 2023). Certainly, a buyer is willing to prolong this stellar record by funding a trust to finance the permanent protection of Palau's 4612+ hectares of mangroves.

Statement of purpose

This study attempts to assess the structure and carbon stocks of the Republic of Palau, located in the Western Pacific Ocean. In the last twenty years, the nation established the world's first 100% closure of commercial tuna fishing, a ban on shark fishing, and has conserved vast swaths of reefs, mangroves, and terrestrial forest systems. Palau faces new fiduciary challenges sustaining its conservation policies which have been exacerbated by the global pandemic. Recently, Palau's congress introduced a bill to re-open the Palau National Marine Sanctuary (PNMS) for commercial fishing (Tia Belau 2022). The proposal to close PNMS is a response to declining tourism revenue resulting from the closure of the nation's borders, which successfully prevented a public outbreak of COVID-19 until January 2022 (WHO 2023).

Tourism represents 47.73% of the nation's GDP and 82% of Micronesia's gross tourism receipts (World Data 2020). The \$100 visitor environmental fee charged upon ticket booking is distributed to fisheries protection \$10, the protected areas network \$30, airport security \$25, general fund \$22.5, and \$12.5 to State governments (Kesolei 2018). Mean arrivals were 118K from 2010-2019, 41K before the border closure, and 3.4K visitors in 2021 (PVA 2022). This represents a mean loss of \$473k in conservation funding. Revenue from the sale of fishing permits and royalties yielded \$16.5M from 2011-2014, compared to 37.5M for vessel day scheme (VDS) permits in the three years after the creation of the PNMS in 2015 (Heaton 2022). Revenue from VDS was \$7.5M in 2015 and \$8M for 2020 and 2021. In addition, Palau received \$25-111M in commitments and grants associated with the creation of the PNMS (Reklai 2021; 2022)

This study aims to provide the Palau Conservation Society (PCS) with a baseline assessment of mangrove carbon stocks. This will provide PCS with the data needed to seek payments for ecosystem service (PES) and help the nation retain a thriving natural system while diversifying government revenue sources. The PES mechanism is the most realistic form of conservation support as Palau's mangroves have been expanding since the end of the Japanese occupation at the close of WWII (Dendy et al. 2022). The nation's mangroves are not considered degraded nor are they managed as forestry resources (Dendy et al. 2022). Despite the expansion of the nation's mangrove complexes, Palauans sometimes view these systems as an obstacle to development (Kludge 1993)

As a former PCS employee, I became immersed in the community and cultivated enduring relationships with business and government leaders of the nation. I built an intimate knowledge of the nation's mangroves and realized a potential conflict may emerge as development pressures grow. I also grew concerned as the main carbon registries do not offer a protocol for the preservation of relatively unmanaged healthy natural systems. I decided to undertake graduate studies to find ways to ensure mangroves can persist without being detrimental to the economic prospects of the country.

The main protocols employed by carbon registries broadly focus on forest restoration, enhanced forest management, and avoided conversion. None of these three protocols apply to Palau as the nation's mangroves are not in a degraded or deforested state, nor are they managed as a commercial forestry resource. One could argue they are at risk of conversion as new pressures emerge to develop coastal access, resorts, and commercial real estate. However, this may be difficult to prove according to avoided conversion protocol requirements as the pace of development within mangrove areas has been minor since the end of WWII (Dendy et al. 2022). Further, Palau does not qualify for the United Nations Reduced Environmental Degradation and Deforestation (REDD+) protocol. This leaves few tools for nations that have been good stewards of their forests and do not harvest or otherwise degrade their mangrove resources. I realized there was a need to ensure Palau has the means to preserve mangrove systems without becoming a burden to economic prosperity.

In pursuit of the Masters of Environmental Management and Coastal Environmental Management degree (MEM-CEM) at Duke University, students undertake a Masters Project (MP) that encompasses the skills they have assembled during their studies. The objective of my MP is to conduct a carbon stock assessment to better understand the potential value of PES payments for Palau. This will provide the nation with the data needed to compare the financial benefits of preservation in real dollars.

Background

Palau's reputation as a conservation pioneer has led to numerous international conservation groups and universities visiting to collect data and establish ongoing research relationships with the nation. The establishment of the nation's independence on October 1st, 1994, emerged after the United States exited United Nations Trusteeship over the region (Kludge 1993). However, the special arrangements of free association made with each Pacific nation ceded autonomy in exchange for technical support and capitalization of a Compact Trust Fund. As part of this arrangement, the nation of Palau is provided extensive funding under the Compact of Free Association (DOI 1996).

The Palau Automated Land Resource Information Service (PALARIS) undertook the nation's first aerial light detection and ranging (LIDAR) survey in 2021 which covered the entire archipelago (UNDP 2021). This represented a significant opportunity as PALARIS created a 1m resolution digital elevation (DEM), and 0.25M resolution RGB imagery collection. To date, there have been three studies of total ecosystem biomass and carbon stocks of Palau's mangroves including two US Forest Service (USFS) and a recently published ninety-three years forest cover change detection study of Palau's main island, Babeldaob (Kauffman et al. 2011; Donato et al. 2012; MacKenzie et al. 2016; Dendy et al. 2022). Up to now, mangrove analysis was limited by the 2015 10M spatial resolution DEM created by the US geological survey (USGS), Pacific Islands Ocean Observing System, and the National Oceanic and Atmospheric Administration (NOAA) (USGS 2015; Dendy et al. 2022).

I visited Palau in April 2022 to request access and establish a data-sharing agreement to acquire the nation's lidar point cloud, RGB imagery, and newly created DEM from PALARIS. The lidar point cloud was used to construct a canopy model of the USFS study area to assess carbon stocks of the 2011 USFS study site. The study site is located in Airai state on the southern terminus of the nation's largest island, Babeldaob. The Airai state study area is located on the shoreline of Papago International Resort and hosts a mangrove complex of ~110 hectares.

Babeldaob is oriented north to south at 40km in length and runs east to west reaching 17km at its widest point, with a land area of 330km² and hosts 3800-3900 ha of mangroves (Dendy et al. 2022). The next largest mangrove stands are found on Peleliu island (588 ha), and the islands of Ngermid (154.2 ha) and Meyungs (39.5 ha), in Koror state for a total of 193.5 ha.

The nation has a cumulative area of mangroves of approximately 4,600 ha depending on the method of calculation. For this study I used the 2007 NOAA National Center for Coastal Ocean Science (NCCOS) IKONOS derived habitat map, "emergent vegetation" habitat class as the primary basis of mangrove habitat area estimation. Several polygons were misclassified as "unconsolidated" along the northern end of the Melekok estuary on the west side of the causeway, and just northeast of the causeway along the

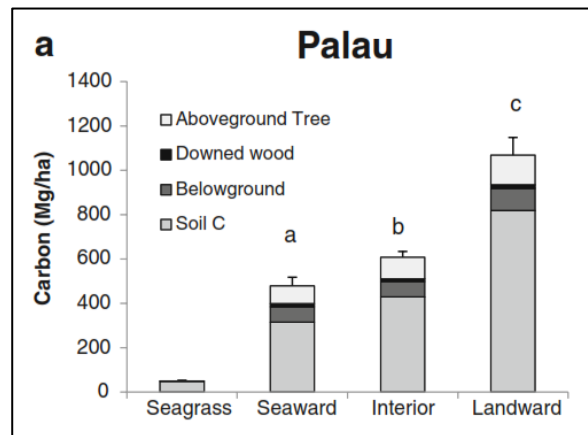


Figure 1 Total above ground carbon stocks of Palau's mangrove complexes (Reprinted from Kauffman et. al. 2011)

coastline extending to Ngekeklaui. Two minor mangrove areas of less than two hectares were misclassified as “unclassified,” were not reclassified as “emergent vegetation/mangrove” as they were discovered at the end of the study. These areas are located at the southern end of Meyungs Island, in Koror State, west of the Australian diplomatic compound, and in the middle of Ngeremeduu Bay, in Ngatpang State.

The scope of this study is limited to previously collected 2011 USFS study field data derived from three 125m transects composed of eighteen 7m fixed area plots. The plot level data included dead downed and woody debris (DWD) plots, and soil core sample data. The USFS study determined ecosystem stocks as they pertained to the three transects positions along a 144cm gradient from the terrestrial shoreline to the mangrove/seagrass ecotone (edge). The plot level information ranged from 479 Mg C/ha at the mangrove shoreline edge to 1,068 Mg C/ha at the landward boundary as seen in Figure 1 (Kauffman et al. 2011). This study is based on the original measurements taken within the 15 plots to the west of the Papago boardwalk. The easternmost plot at the end of each transect was omitted from the study by the original researcher due to sediment disruption that may have occurred during boardwalk construction. This data is then extrapolated using a LIDAR-derived canopy surface elevation model across the study area. I then compare planar, volumetric, and zonal statistical methods to gauge the continuity of below and aboveground carbon stocks.

Methods

2011 In-situ data

The 2011 USFS study design encompassed three transects, buffered 13m inward from the mangrove and seagrass ecotone (low transect), mid-slope moving in a landward direction (mid transect), and at the top of the slope buffered 13m seaward from the terrestrial shoreline (high transect) see figure 2. Each 125m transect was composed of six 7m radius subplots placed 25m apart. All trees with an elevation greater than 1.3m were measured at a diameter at breast height (DBH) of 1.3m to derive basal area, stand density, diversity, and biomass. Dead downed and woody debris were sampled within each of the six plots across the three transects using the planar intercept technique and ranged in size classes from 0–0.64 cm, 0.65–2.54 cm, 2.55–7.5 cm, and ≥ 7.6 cm diameter with specimens ≥ 7.6 cm diameter partitioned into sound and

rotten classes. The USFS study noted Illachetomel Peat classified soils in the proximity of the mangroves which were sampled at the center of each plot across the three transects using 5.14cm PVC pipe. Sampling depths were set to 0–15 cm, 15–30 cm, 30–50 cm, and 50–100 cm.

Where soils exceeded 100cm, values were substituted using the 50-100 cm data up to 200cm (Kauffman et al. 2011). As mentioned earlier, a total of 15 of the 18 plots were used for each transect, omitting the most easterly plot of each transect due to potential soil disruption.

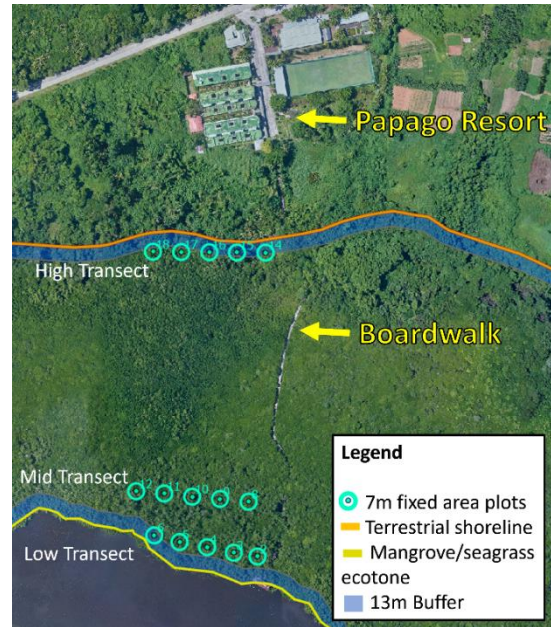


Figure 2 Study area current and Kauffmann et.al. 2011.

Study Site

The study area is situated downslope of the Papago Resort and Hotel in the state of Airai, on the island of Babeldaob, Palau. No GPS locations were taken of the plot locations by the initial study. However, the researchers provided a JPEG image with the approximate plot locations. This was georeferenced in ESRI's ArcPro to approximate spatial relation to mangrove canopy height and density.

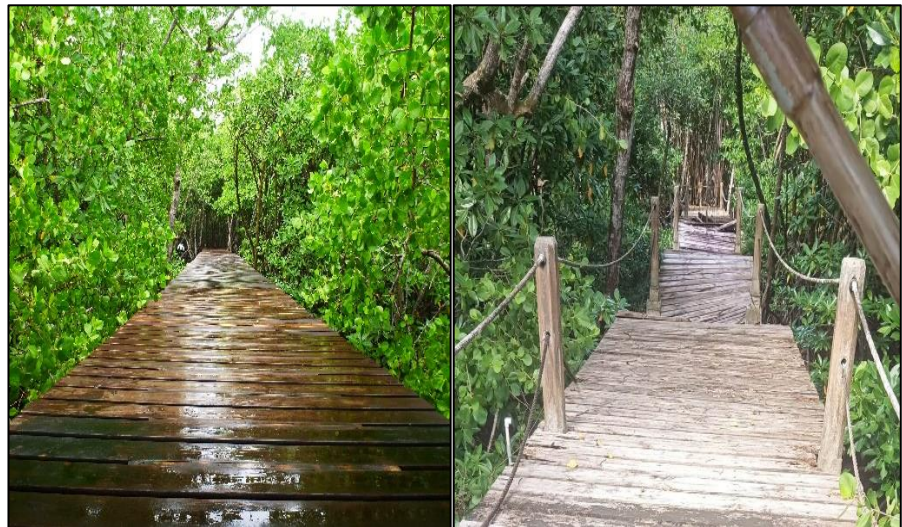


Figure 3 Papago boardwalk in 2013 (left pane) and in disrepair in 2023 (right pane)

When the study was conducted there was a well-maintained boardwalk from the terrestrial shoreline edge to the mangrove /seagrass ecotone. Over the past ten years, the boardwalk has fallen into a state of disrepair, and the resort has been closed since the 2020 COVID-19 pandemic (figure 3). The boardwalk is now too treacherous to access, complicating future site

monitoring. Access to study sites is further limited by Palau's semidiurnal tidal range which necessitates a longer period of study on a given day.

Allometric Equations

I had initially intended to visit Palau a second time and acquire new plot data to compare against the 2011 USFS study. While the DBH measurements and species documentation from the Kaufmann 2011 study were thorough but did not include GPS coordinates or hypsometer measurements (tree height) of any plots. This necessitated a great deal of experimentation to determine how I could make a comparative assessment of carbon stocks. I lacked critical benchmark elevations and coordinates from the original study and was unable to return to Palau in time to acquire field measurements based on the georeferenced plot locations.

This necessitated locating a geospatial lidar analysis method that does not require field measurements to estimate carbon stocks. The allometric equations used in the original study did not require elevation data but functioned upon DBH. This required finding an allometric equation that does not require DBH and functions based on elevation data provided by the lidar point cloud. I was able to locate a study conducted in Brazil that undertook intensive field measurements to formulate a relationship between ground-truthed lidar elevations and in-situ biomass measurements (Salum et al. 2020). *Rhizophora mucronata* and *Rhizophora apiculata* are the dominant species in Palau. Collectively these genera are referred to as *Rhizophora* spp. (RHSP). Salum et. al. developed an allometric equation that presented an opportunity to use as an analog to estimate biomass with the lidar point cloud. However, I was unable to develop a corollary equation given the short duration of this study and the need for a large sample set of in-situ data and validation points. However, this should be considered in future research. Such equations could be used in combination with drone-based photogrammetry to construct digital surface elevation models. This would support efficient remote carbon stock analysis regularly, enabling low-cost monitoring protocols.

Digital Elevation Model (DEM)

Palau's mangrove complexes have remained largely undisturbed since the close of WWII and are relatively mature, dense stands. Mangrove prop-roots, aerial roots, pneumatophores (snorkels), foliage, branches, and tides constrain the penetration of lidar to the muddy surface below. This results in incredibly low lidar true ground return density and little confidence that the ground returns represent the actual muddy surface. Without an accurate representation of the ground surface, there is some difference between canopy height and the DEM. This implies estimates of biomass and carbon will have some inherent error. This is further compounded by the fact that Palau does not have a localized geoid model, though PALARIS is in the process of creating one. The current geoid is based on the EGM2008 model. I evaluated the accuracy of the new lidar-derived PALARIS DEM and tried to generate a localized DEM specific to the mangroves. I visually evaluated the error associated with the lack of lidar beam pulses penetrating the mangroves to be significant. This made creating a new DEM based on ground returns too error-prone to be meaningful. This required setting a fixed surface elevation based on ground truthing.



Figure 4 Papago resort boathouse, located at the eastern terminus of the boardwalk from the resort. There are 6 concrete piers in total, all of which measured at least one 2.2m lidar point and an average of 2.18m

Lidar Point Elevation Validation

To verify the lidar point elevation differences I hired a field assistant to measure the true height of hard surfaces and the height of the muddy ground beneath the water's surface. There is a boathouse located at the end of the boardwalk in the study area (figures 4 and 5). The field assistant measured the actual height from the mud to the top of six concrete piers that remained from the old dock piers, and to the top of the boathouse floor and roof peak. The measurement from the top of the piers from the ground had a mean value of 1.78m and half of the piers measured 1.8 meters in height (figure 6). The height from the ground to the peak of the boathouse roof was 6.83m compared to a lidar return maximum value of 7.35m and a range of 6.69-7.35m (figure 6). This is consistent with expectations as holes have begun to rust through the roof which could further influence values (figure 5). The actual height from the ground to the top of the boardwalk and boathouse floor was 2.5m compared to the lidar returns of 2.9m (figure 6).



Figure 5 Papago boathouse roof, holes in the roof led to a range of lidar return values.

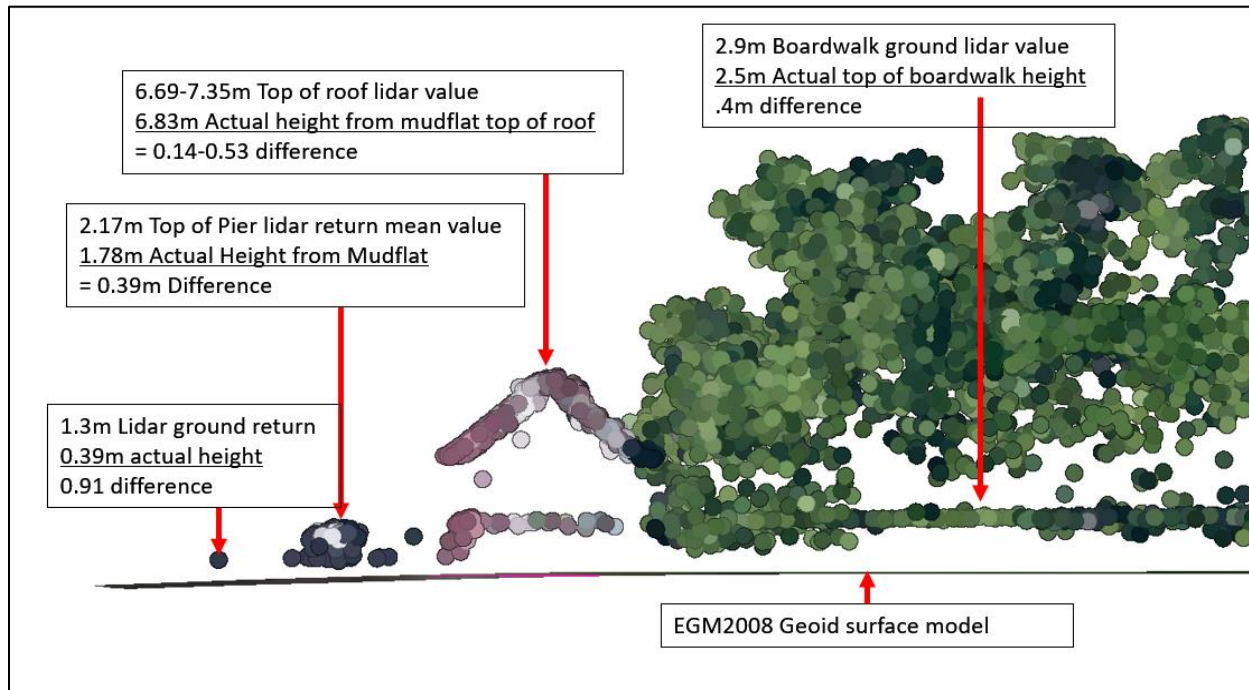


Figure 6 Lidar return values compared to actual heights of the Papago boathouse roof and floor, boardwalk, and concrete piers.

These values indicated there was at most 0.4m of water present at the time of the lidar flight. There is water visible in the imagery taken simultaneously with lidar measurements, but some environmental features appear to be showing like mudflats near the mangrove edge. This could either be the result of pneumatophores or seaweed reflecting lidar returns. Figure 7 demonstrates the mud flat likely present in

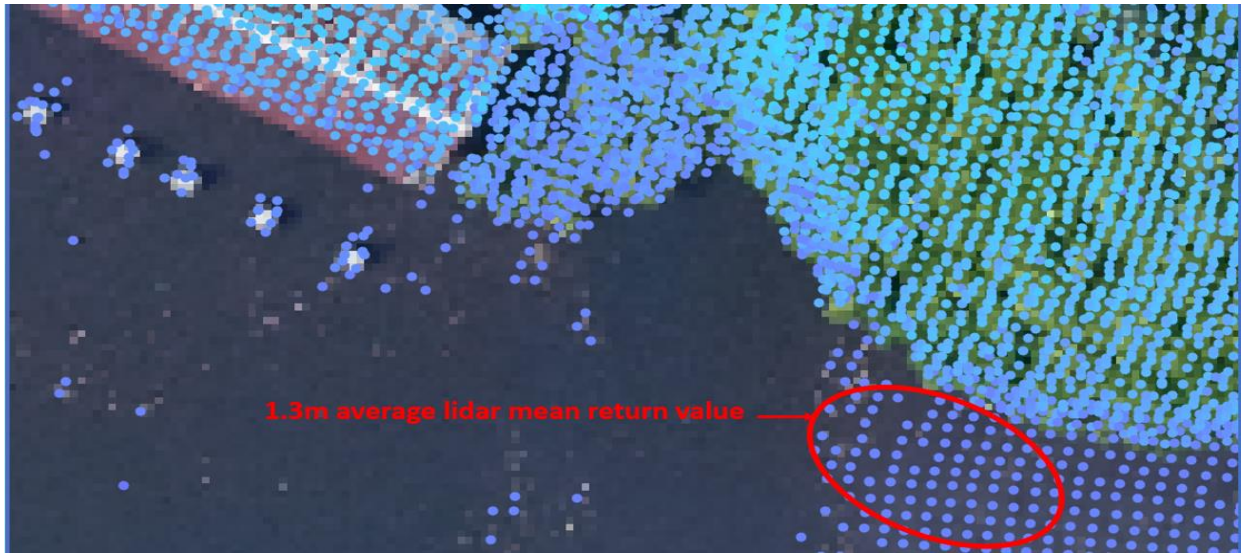


Figure 7 Lidar returns likely reaching the mudflats below water or are reflecting off pneumatophores, shown below in figure 8.

the lower right of the image below. This closely aligns with images of this area during low tide as shown in Figure 8, which was taken at a different tidal period. At the time of the lidar flight, there was an outgoing tide with a tidal range of 1.32m. The data was acquired at 1:55 pm local time and high tide occurred at 11:35 am at 1.65m and low tide at 7:06 pm at 0.33m. Because no in-situ sea-level elevation validation data was available, it is not possible to determine what the true tidal height was at the time of lidar acquisition. However, based on the observations illustrated in Figure 7, there was water present. However, the lidar approximated the mudflats to be 1.3m in elevation as can be seen through a visual comparison of Figures 7 and 8. Based on this, I deduced that there was at least 0.4m of water present at the time of data acquisition.



Figure 8 Mudflats east of Paggao resort boat house align with lidar return values shown in Figure 7. LIDAR pulses are likely reflecting off pneumatophores, indicating a minimal difference to the ground.

Canopy Model

The Palau lidar point cloud was subset in ArcPro GIS to the study area setting the map to WGS 1984 UTM zone 53N. The lidar data was deemed to be well-filtered upon receipt as no significant noise or anomalies were present across the study area. A study area polygon was created using the PALARIS-provided NOAA habitat map to select emergent habitats which represented mangrove areas. The area of interest was selected and then buffered by 50m on the exterior of the polygon. I then used it as a clipping mask to improve processing speed by reducing the lidar points included in raster creation. Then a LAS dataset was then generated and used to create several rasters at elevations ranging from 0.4m to 1.7m using a cell size of 1m x 1m constituted of first returns only. Rasters were created for each 0.1m increment from 0.4-1.7m to refine the best approximation of true canopy extent. This was determined by visually inspecting the RGB imagery that was concurrently acquired with the lidar cloud.

Because there is not a highly accurate geoid for Palau, the zero value appeared to be significantly below the water surface. Extensive effort was made to approximate ground level (see Digital Elevation Model) with 0.9m assumed to be the true ground level in terms of the original dataset at the farthest seaward extent of the mangrove. However, when creating rasters at values lower than 1.7m, the canopy began extending over the water surface. This was due to the triangulation connecting mudflat and seagrass returns with true mangroves. To ensure an accurate representation of the canopy, 1.7m was chosen as the final elevation to begin the canopy model. The 1.7m raster showed the best alignment with what was known to be true ground level and aligned well with the mangrove ocean terminus. Next, the PALARIS-provided shoreline polygon was adapted to clip the raster at terrestrial-mangrove ecotone. Taken together, the seaward mangrove buffer, 1.7m raster, and terrestrial shoreline clipping mask ensured an accurate mangrove extent would be calculated for the digital surface model.

Correlating Lidar Elevations and Carbon Stocks

The digitized 7m fixed-radius location polygons were used as a boundary to determine the first returns lidar point elevations within each plot. The digitized 7m fixed-radius location polygons were used as a boundary to calculate the first return maximum lidar point elevation. The maximum elevation was then determined within the 7m radius. The 2011 USFS study provided a carbon stock value for each 7m plot across three classes: live trees, downed woody debris (DWD), and soil carbon (BGC). The mean mangrove carbon stocks and maximum elevation for the first lidar return lidar elevations within each plot were then correlated in Microsoft Excel to determine the R-value associated with each class. This was followed by correlating live tree carbon stocks to DWD; live +DWD + BGC. Finally, true ground height was subtracted from each class to determine if this affected the correlations.

Results and Discussion

Digital Elevation and Mangrove Canopy Model

There was little confidence that an accurate DEM could be constructed due to the large degree of elevation variation between lidar ground returns. The presence of at least 0.4m of seawater at the mangrove's seaward edge indicated some water inundated the mangrove interior. However, there was no practical way to determine the extent or height of the water within the mangrove leading to the terrestrial-mangrove shoreline demarcation point. This was further complicated by the low lidar ground return density, the presence of mangrove pneumatophores, stilt roots, prop roots, and thick understory. Lidar pulses classified as ground returns numbered 55.6k (Figure 9) but only 45 represented elevations corresponding to known water height. This could mean returns disappeared into the water column or that few returns made it to the interior, to begin with.

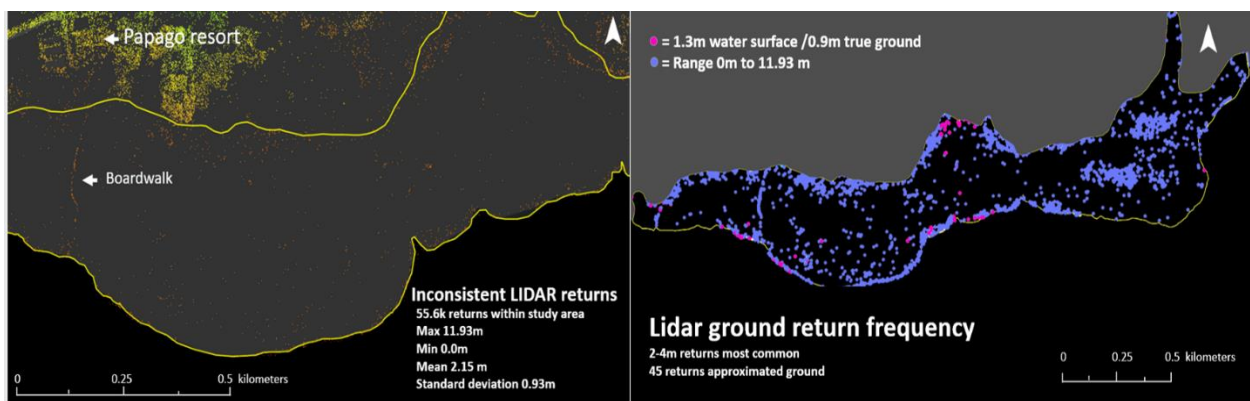


Figure 9 LIDAR ground return penetration within the study area indicated few returns represented true ground.

This made it difficult to create a more accurate DEM to set as the baseline to subtract the canopy model and assess mangrove volume. Gauging density within the mangrove stand was also unclear making it difficult to confidently correlate lidar point density with carbon stocks. Side profiles of the mangrove point cloud demonstrated scant lidar penetration (figure 10). This limited efforts to predict carbon as it relates to canopy mangrove volume and lidar point density.

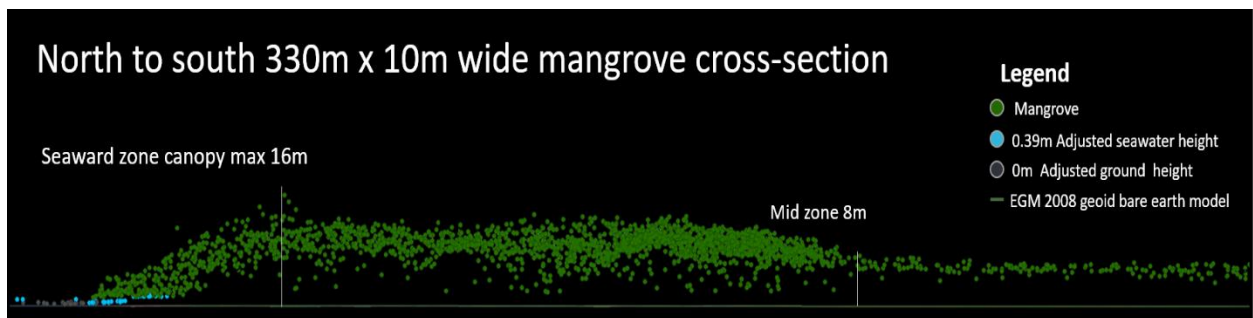


Figure 10 Mangrove complex north to south running 330m long x 10m cross-section of all lidar returns from the terrestrial shoreline to seaward mangrove edge demonstrates minimal lidar penetration to the most likely ground surface.

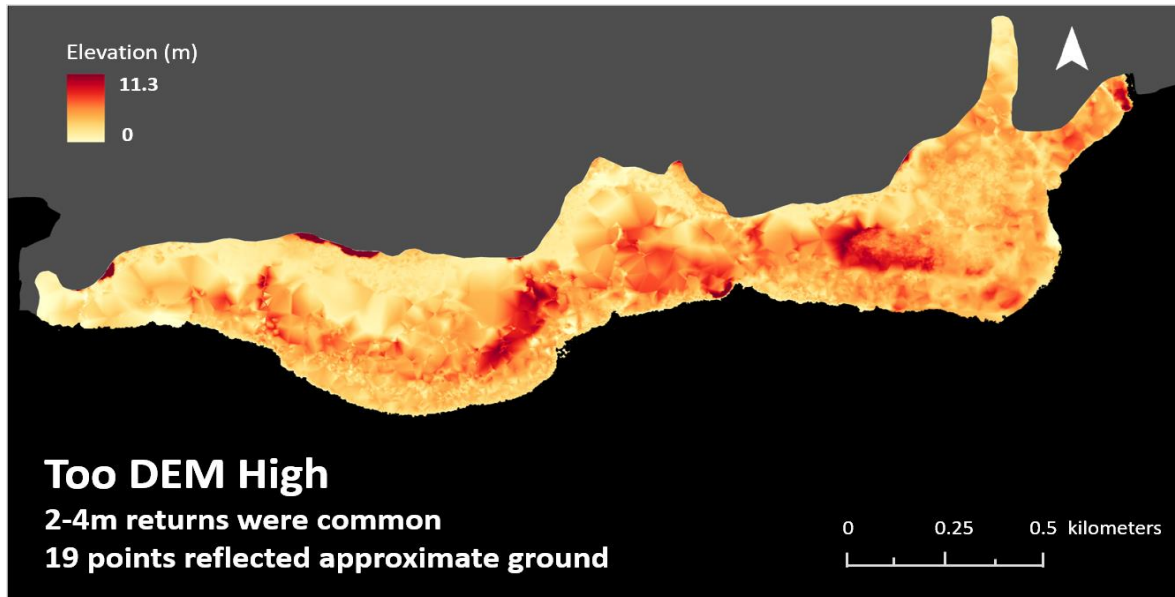


Figure 11 Digital Elevation Model (DEM) illustrates the dramatic range in elevations that likely represents the structure of mangrove pneumatophores, arching prop roots, stilt roots, and buttressed trunks rather than a flat muddy surface.

The DEM constructed using the ground returns that penetrated through the canopy clearly illustrates the erratic elevations as a heat map (figure 11). Physical visits to the study area made it known that the surface is uniformly flat. The high elevations within the heat map are likely representative of mangrove structures like arch/prop roots, buttressed trunks, pneumatophores, and canopy to some extent. The effects of this structure on lidar penetration are substantial as some LIDAR pulses do not penetrate while others are lost on the return to the sensor (figure 12).

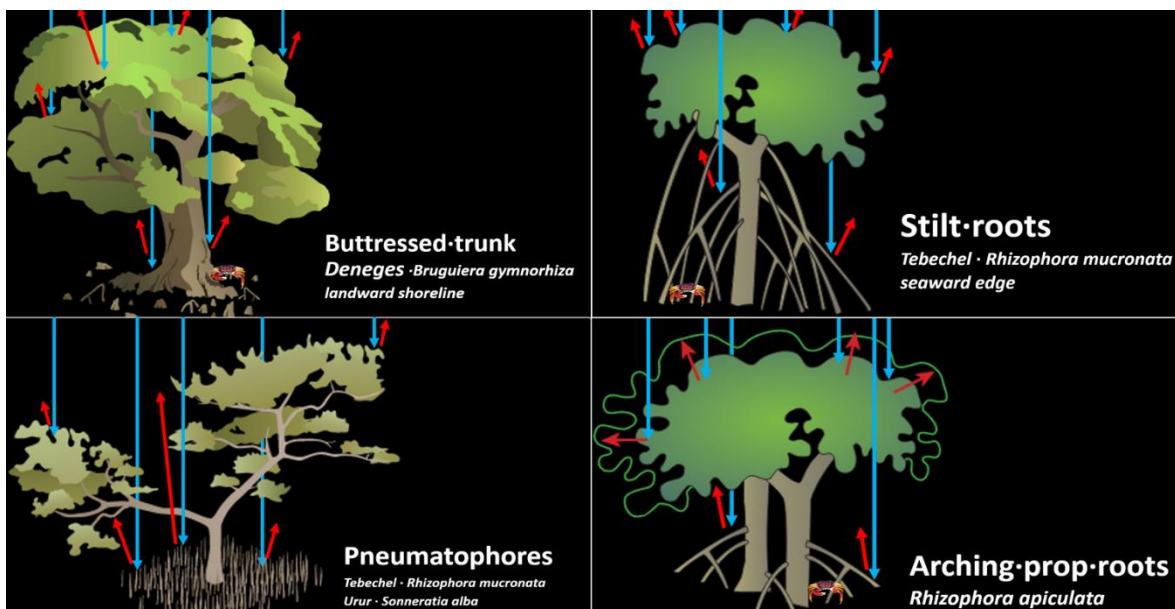


Figure 12 illustrates the incoming LIDAR pulses (blue arrows) and return pulses (red arrows) intercepting the mangrove structure. Species are noted by the Palauan name followed by Latin species names. Mangrove clip-art source: Vector.io

The final canopy model assumed that the ground began at 0.9m at the mangrove seaward extent. The mudflats registered at approximately 1.3m in the actual lidar elevations, meaning there was at least 0.4m of water present at the time of the lidar mission. There was a high degree of variation in what was classified as a ground return and what represented true ground, moving into the mangrove interior. Based on visual inspection of the RGB imagery, I determined the most likely maximum elevation of the ground at the terrestrial-mangrove shoreline was 1.2m actual or 1.6m using the lidar elevation. However, because I was not able to ground truth elevation validation points, this cannot be assumed to be absolute. The 2011 USFS study measured the elevation gradient using a base station and GPS. They determined the gradient from the mangrove-seagrass ecotone to the terrestrial-mangrove ecotone was to be 144cm over the 330m distance (Kauffman et al. 2011). Based on this there was at least 0.3m variation in elevation between the mangrove seaward edge and terrestrial shoreline in terms of the 1.3-1.6m ground returns. This implies that at a minimum there was 0.15m variation in what appeared to be ground returns from the terrestrial shoreline to the mangrove seaward edge. This indicates there could be a range anywhere from a 0.144m to 0.3m error in ground returns. The maximum mangrove height was 30.6m, or more likely, a maximum true canopy height of 30.17m as illustrated below (figure 13). The inherent difficulty determining what is true ground within the mangrove complex has an inherent error of approximately 1-2%. Thus, any estimate of carbon stocks based on canopy returns would have a minimum error of 1-2%. While this may not substantially impact a general carbon stock assessment it highlights the complexity of using lidar to build an accurate DEM. Without a true baseline to calculate the volume above the DEM using first returns is inherently inaccurate. This is significant as the ratio of belowground to above-ground carbon estimated in the 2011 study ranged from 5:1 to 6:1. A more accurate DEM could be augmented with simplified soil depth measurements taken by driving a probe until it struck rocky coralline and sand substrate. A series of these measurements could then be interpolated to generate a more accurate DEM.

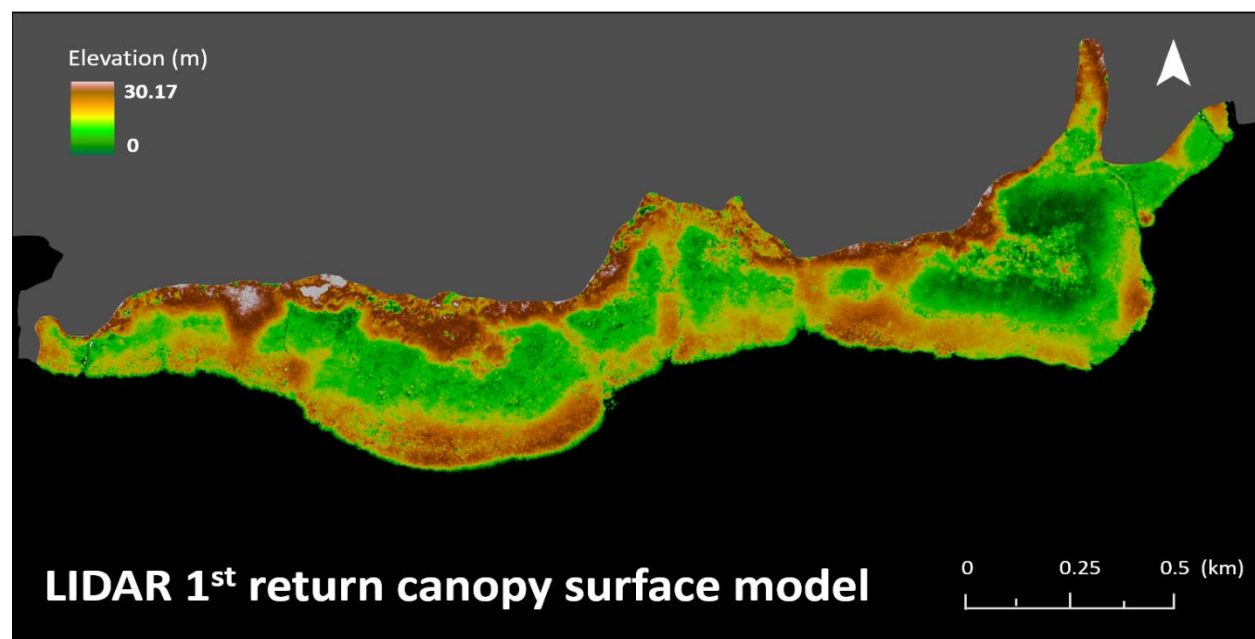


Figure 13 LIDAR 1st return canopy model. Cell size 1m. Elevations truncated by 0.4m based on estimated ground level of 0.9m.

Canopy Elevation and Carbon Stock Correlation

Due to the difficulty of relating lidar density to carbon stocks, I attempted to correlate canopy elevation with carbon stocks. The relationship between live tree aboveground carbon and the maximum lidar return heights within the 7m fixed area plots yielded an R-value 0.1331 as demonstrated by Figure 14. There was no difference in correlation before or after adjusting 0.4m of presumed seawater to reflect true ground. Then I added downed woody debris (DWD) to live tree carbon, which led to an increase in correlation to R-value 0.1399. This was followed by correlating the sum of total ecosystem carbon: live tree, DWD, and soil carbon, and resulted in an R-value of 0.7055, a significant increase as can be seen in the top panel of Figure 15.

This process was then repeated for the mean elevation within each of the plots with respect to live tree, DWD, soil carbon, and total ecosystem carbon stock values. This demonstrated a slight increase in correlation between live tree carbon and mean elevation with an R-value of 0.1482. The sum of live tree carbon and DWD amounted to an R-value of 0.1382. Finally, total ecosystem carbon was related to the mean lidar return height resulting in an increase of 0.1727 over the maximum lidar return height or an R-value of 0.8792.

Finally, each transect was calculated separately regarding the live tree, DWD, and soil total ecosystem carbon, and the Maximum and Mean lidar elevations. There was a trivial difference in the correlation of values with regard to the low, mid, and high transects, likely due to the sparse number of data points. Correlation between lidar first return elevations and carbon stocks would be an efficient means of remotely assessing mangrove carbon stocks. While stronger correlations were evident for the mean compared to maximum lidar elevations, in-situ data is still necessary to accurately assess total carbon stocks.

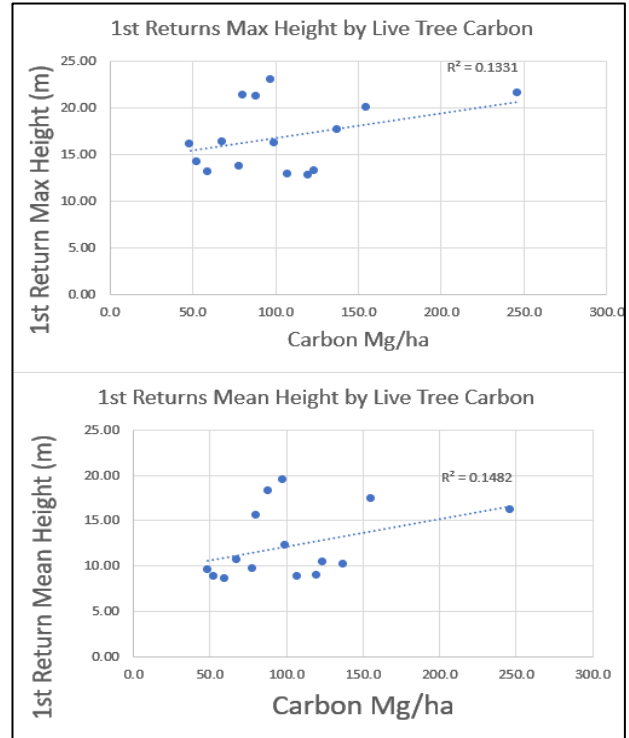


Figure 14 Maximum lidar point elevation (top panel) and Mean lidar elevation (bottom panel) by live tree carbon stock within each 7m fixed-radius plot.

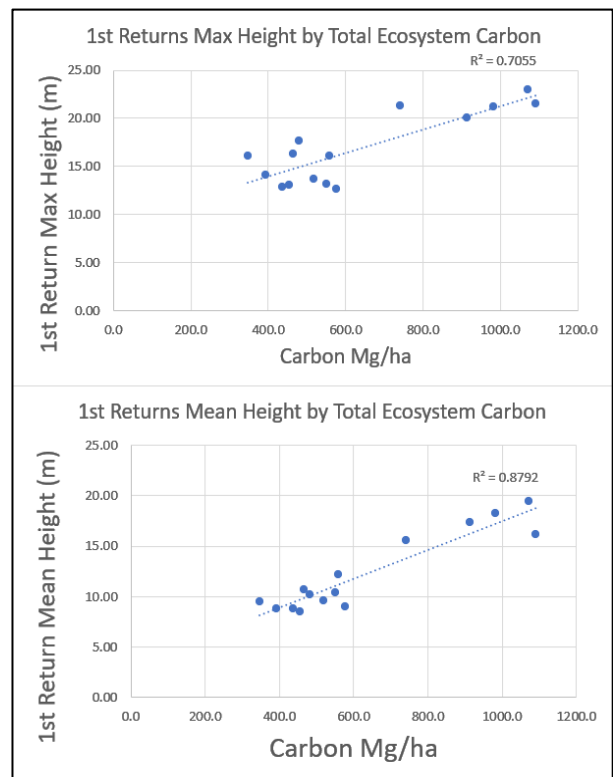


Figure 15 Maximum lidar point elevation related to total ecosystem carbon stocks (top panel) and mean lidar point elevation related to total ecosystem carbon stocks (bottom panel)

Carbon Stock Analysis

Three methods were used to analyze carbon stocks. First, a planar assessment was conducted based on the mean carbon stocks of all 15 plots from the 2011 study. The mean aboveground carbon value of 118.09 Mg C/ha of the high, mid, and low transect plots was multiplied by the 2011 study site's 110.62 hectares area (figure 16). This resulted in a mean of 13,061 Mg C over the study area or 543,234 Mg C across the nation's 4612 hectares of mangroves. Total ecosystem carbon resulted in 79,512 Mg C for the study area and 3,306,635 Mg C nationally (figure 17).

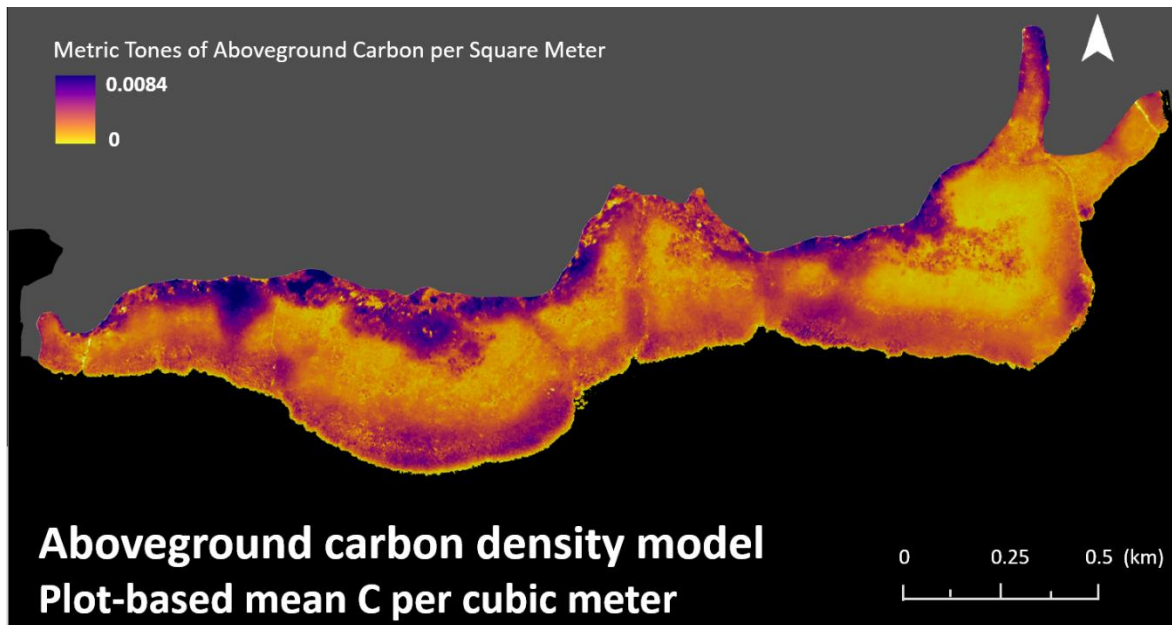


Figure 16 Pixel-based (raster) map representation of plot-based aboveground carbon density per square meter pixel.

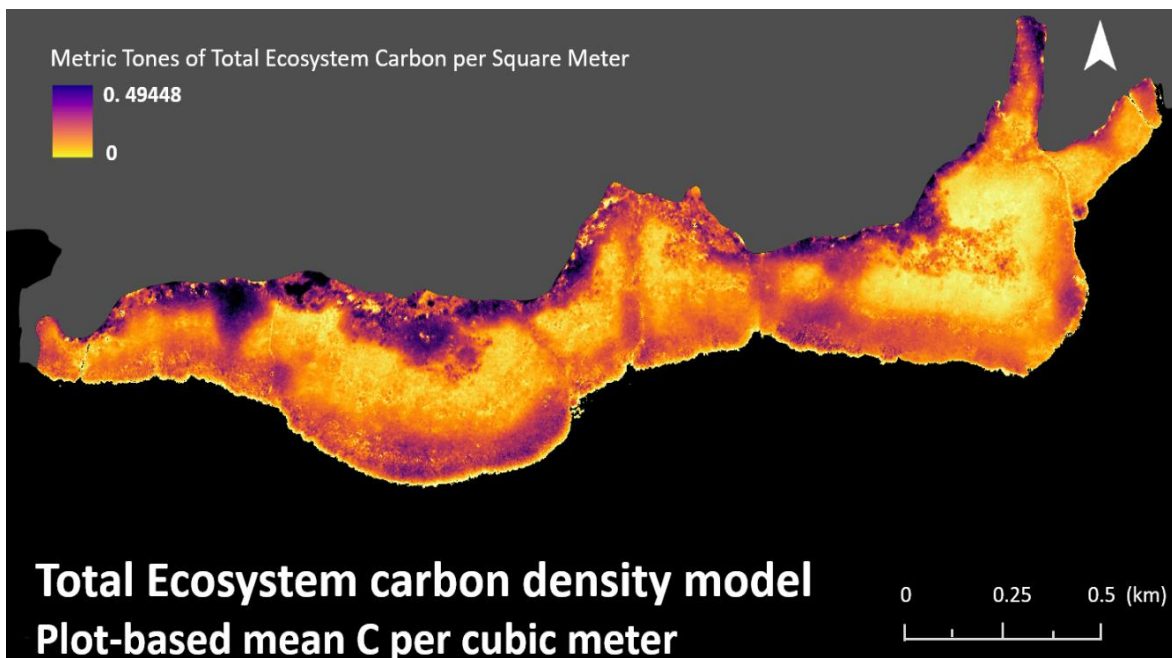


Figure 17 Pixel-based (raster) map representation of plot-based total ecosystem carbon density per square meter pixel.

The second and third methods were also based on the mean plot-based carbon stock per hectare. However, the per hectare value was allocated based on the volume of each plot and then broken down to a mean carbon value per cubic meter. The volume of the study area was calculated by setting the canopy model as the upper digital surface and 0.9 m as the ground in the ArcPro surface volume tool. This resulted in a study area mangrove complex aboveground volume of 8,687,568 cubic meters. The mean carbon per cubic meter of all 15 plots was used as the minimum unit and multiplied by height across the study area. This resulted in an aboveground carbon stock of 24,313 Mg C and total ecosystem carbon of 142,391 Mg C for the study area. A per cubic meter minimum unit was also calculated using the maximum canopy heights within the 15 plots and resulted in a lower aboveground carbon stock of 17,940 Mg C and total ecosystem carbon stock of 106,376 Mg C. It appears the value per cubic meter was diluted by the maximum height. While this calls into question the accuracy of the chosen minimum unit, I was unable to determine how to adjust for this.

The third approach used the “zonal statistics as table” tool to calculate the cumulative height of each pixel within the study area. This yielded 8,837,282 cubic meters cumulative value across the 110.62-hectare study area. This is a remarkably close assessment of the volume estimation tool and differs by just 149,714 cubic meters. Given the uncertainty of the accuracy of the maximum canopy elevation within the plots, only mean height was used to calculate carbon stocks. This resulted in 24,730 Mg C aboveground carbon and 144,845 Mg C for total ecosystem carbon across the study area.

While the tools used appear to be accurately assessing mangrove volume, a more refined DEM would greatly enhance accuracy. Not only could a ground-truthed DEM result in greater aboveground volume estimates but it could also be used to extrapolate the gradient of belowground carbon from the terrestrial edge to the seaward edges of the mangrove. The 2011 study found mean carbon stock values of 909.94 Mg C/ha at the “high” landward transect, 493.95 Mg C/ha at the “mid” transect, and 398.32 Mg C/ha for the seaward transect.

If the soil depth were known across a range of transects originating from the landward edge to the seaward edge, perpendicular to the mangrove extent, they could be correlated to carbon density given the established carbon values. Such an estimate could be enhanced by additional plots across a wider range of terrain variation. The three transects from the 2011 study did not fully capture the side profile of most areas of the mangrove that tend to be lower in the middle of the complex. Greater plot density would increase profile accuracy and help correlate above-ground carbon, yielding a more accurate carbon stock analysis. Given enough data and accurate elevations, an allometric equation could then be developed based on the correlation between above and below-ground carbon stocks. This would significantly enhance the accuracy of national carbon stock assessment and reduce the burden of fieldwork. This could be further augmented with permanent plot markers and sediment estimation (SET) rods to gauge carbon sequestration annually to every five years to facilitate carbon protocol reporting integrity. Over time, allometric equation values could be refined to account for sequestration accuracy as the canopy and ground elevations accrue vertically.

Why do carbon stocks matter?

This study intentionally chose to avoid estimating the impacts of sea level rise (SLR) on carbon stocks given the great degree of variability and complexity of SLR modeling. Rather the focus was on ensuring an accurate baseline of ground level and canopy height. This enables better volumetric assessments of

mangrove complexes which can then be combined with SLR, shoreline erosion, and annual carbon sequestration values. While determining a general carbon stock is valuable from an ecosystem service accounting perspective, accurate annual values increase the reliability of conservation finance models. Palau does not meet the requirements of avoided conversion, REDD+, or enhanced forest management carbon protocols. However, that does not mean they cannot seek carbon-based compensation.

Palau mangrove belowground to aboveground carbon ratios translates to a factor of 6-7 Mg C/ha. By comparison terrestrial temperate forest carbon approximates 2.7 Mg C/ha and tropical forests reach 4.44 Mg C/ha (Hawken 2017). This results in a premium of 1.56-2.56 Mg C/ha over tropical forests and 3.33-4.33 Mg C/ha over temperate forests. Given Palau's limited land area, this makes their mangrove forests a critical carbon store and a national asset that has underlying financial value. This value can be derived in the form of increased real estate if reclaimed, or as a resource that foreign investors or institutions could opt to retain in the mangroves' preserved form. Palau is entitled to develop their resource base as they see fit to support the economic development of its citizens. Accurate carbon stock assessments inform the trade-off in carbon emissions from development associated with reclamation in mangrove areas. If an accurate carbon stock value is known for a proposed development, the nation can compare the economic and social benefits of that development to an alternative conservation finance option.

There is a finite area of lands and wetlands that can be restored or allowed to regenerate for the purposes of carbon sequestration to mitigate the effects of a warming climate and offset monetization. Recently the Wall Street Journal estimated that the carbon emissions associated with 900 US companies amounted to 9 billion tons of carbon dioxide equivalents (1 CO₂-e or CO₂-eq.) or 1 metric tonne of CO₂. This is significant when one considers the WSJ estimated the available supply of offsets is only 705 million tonnes (The Wall Street Journal 2022 n.d.). The Nature Conservancy's oceanwealth.org mangrove restoration website estimates globally restorable mangroves at 812,003 hectares (The Nature Conservancy 2023). Hence there is a scarce supply of restorable mangroves globally. Until a viable direct air capture technology emerges at scale, restoration is the best means to draw carbon from the atmosphere. Society is otherwise left dependent on consumer behavioral change and low-carbon technologies to reduce emissions to a level that allows natural systems to normalize atmospheric carbon. No shortage of imagination should be applied in generating new carbon protocols to allow nations to benefit from managing their resources responsibly for future generations. Bloomberg New Energy Finance estimates that carbon offset values will increase exponentially over the next 27 years. They project \$11-\$215 per tonne of CO₂ equivalent by 2030 and declining to \$47-\$120 per tonne by 2050 with respect to the voluntary offset market (Bloomberg NEF 2022a).

Palau chose to minimize the impacts of development on the nation's mangrove ecosystem and they should be rewarded for being a good steward of their environment. Ignoring this sets up a perverse incentive. Carbon offset certifying bodies focus on projects that generate additionality, or the increase of carbon stocks because of a project that would not otherwise have occurred. This places Palau in an inconvenient situation as they have sequestered carbon in their mangroves for decades without a financial return. There are very few ecotourism operations that focus on Palau's mangroves and to date no studies of the value of the nation's mangroves as they related to tourism revenues. Conversely, nations that have degraded their resources are incentivized to restore them by these protocols. This is after nations have already monetized their resource base at least once through development and degradation, resulting in at least a 2x economic return. While there are certainly negative externalities associated with resource exploitation and

development, the financial returns usually result in a larger tax base, infrastructure, and jobs that accompany development.

If Palau sought a buyer of carbon offsets, they would be forced to propose development projects that would threaten the integrity of their mangrove complexes to meet the standards of avoided conversion protocols. This is because Palau does not qualify for the UN's REDD+ program, enhanced forest management, or avoided conversion protocols as it does not harvest mangroves for fuel or construction beyond an artisanal scale. To limit the chances of setting up a perverse incentive to develop, innovation and market-based solutions to conservation are critical. This is especially true given the projected future value of carbon offsets.

An entrepreneurial administration could seek buyers of preservation credits such as Starbucks. Starbucks committed to generating more water than it consumes as part of its climate commitment (Starbucks Stories 2023). The nutrient filtration services provided by mangroves are analogous to this goal and serve as an example of how a private venture might become interested in buying offsets from Palau. While this is commonly known as payment for ecosystem services (PES), this term should not limit the creativity of the productization of ecosystem services.

Certainly, there will be companies that can more quickly meet their climate and sustainability goals through innovation and industrial efficiencies. These companies could become partners in conservation as they seek to increase market share by moving beyond compliance and shareholder expectations. Those companies seeking to differentiate themselves could purchase temporary or permanent options on Palau's carbon stocks to ensure future Palauans and visitors can see mangrove systems thriving in a natural state. Palau has already instituted a \$100 green fee for visiting the nation and cannot increase the fee too quickly or they risk impacting tourism arrivals. Corporate partners provide a way to ensure Palau can benefit from opting to inhibit development while not being significantly economically impacted.

Voluntary markets could fail and should be given the chance to; failure is essential to developing integrity and lasting change. The Chicago Climate Exchange carbon market failed but it also promoted creativity and innovation in conservation finance. Today 70 regulated markets exist that actively trade offsets including 30 compliance markets and numerous voluntary markets (World Bank 2023; Bloomberg NEF 2022b). Regulators are the authority tasked with prosecuting claims of fraudulent credits as they would pursue purveyors of fraudulent securities. The US Securities and Exchange Commission has brought suits against more than 100 crypto securities since September 2015 accused of defrauding investors (SEC 2023). Preventing innovation at the expense of ensuring every credit is fighting climate change perfectly is a myopic perspective. The root cause of unsustainability is consumption and consumer behavior, not the formation of a diverse and resilient carbon offset economy.

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