Aboveground Biomass and Carbon Storage Capacities of a Western Amazonian Primary and Secondary Growth Forest

Lindsay Finnell[1,3] and Bailey J. Nordin[2,3]*

[1] Drake University, Des Moines, IA, USA lindsay.finnell@drake.edu

[2] Columbia University in the City of New York, NY, USA bjn2122@columbia.edu

[3] Center for Amazon Studies School for Field Studies, Loreto, Peru

Abstract — **Amazonian tropical forests are critical to global carbon cycling and sequestration, and in direct danger from deforestation. In order to contribute to limited existing literature on the carbon sequestration potential of secondary forest ecosystems and their aboveground biomass (AGB), we established permanent 0.2-ha plots in a primary and a secondary forest near Iquitos, Loreto, Peru. We measured diameter at breast height (DBH), tree height, and wood density for trees ≥10 cm DBH and took the diameter of lianas at 30 cm shoot extension, then used published allometric equations to estimate AGB and compare it between forests. Trees within the primary forest plot had a significantly greater mean DBH and higher mean wood density, as well as a greater overall AGB than trees within the secondary forest. AGB was calculated to be 322.05 Mg/ha for the primary forest and 51.17 Mg/ha for the secondary forest. Sequestered carbon quantities were 151.36 Mg/ha and 24.05 Mg/ha, respectively. Higher estimates of stored carbon within the primary forest are attributed to old-growth trees with large DBH values and increased wood density, and discrepancies between our carbon estimates for the secondary forest and past estimates for the same site suggest the need to focus more research and attention on allometric equation use. The results of this study provide a potential incentive for carbon sequestration funding to be awarded to the primary forest property studied and establish a foundation for future estimations of the carbon storage capacities of tropical secondary forests.**

I. INTRODUCTION

Tropical forests play a fundamental role in the global carbon cycle by sequestering up to 40% of the world's terrestrial biomass-bound carbon (Pan et al. 2011). More than half of the carbon in tropical forests is found in the neotropics (Ngo et al. 2013). However, the carbon storage potential of these forests can be truncated by deforestation and ecological degradation. An estimated 1.6 to 2.4 Pg of carbon is released into the atmosphere from tropical forest clearing each year, representing 20-29% of global anthropogenic carbon emissions (Naughton-Treves 2004). In Peru, forests are being cleared at a rate of 0.4% per year, releasing enormous amounts of stored carbon (Naughton-Treves 2004).

After a forest has been disturbed, it will regenerate as a secondary forest and accumulate carbon in its aboveground and belowground tissues as it grows. Light-demanding ruderal species grow quickly and form wood with lower specific gravity than later successive, shade-tolerant species that require time to establish and are not a significant fraction of secondary forest composition (Ramanantoandro et al. 2016, Gao et al. 2015, King et al. 2006). Wood density is directly related to above ground biomass (AGB), and therefore secondary forests tend to have less accumulated biomass than primary forests. Carbon storage is often estimated as half of total AGB (Day et al. 2013, Chave et al. 2005), so it can be assumed secondary forests store less overall carbon than primary forests.

The proportion of tropical forests that are secondary is projected to increase continually due movement of populations toward urban centers (Thomlinson et al 1996). Abandonment of cleared sites may also contribute to increased secondary forest cover. This may be the case in regions of the Amazon whereland-use practices continue to be characterized by reliance upon fallow periods (e.g. Marquart et al. 2013, Naughton-Treves 2004). Though secondary forests contain an estimated 60% less biomass and 19% less total stored carbon than primary forests (Ngo et al. 2013), they exhibit slightly higher regeneration rates. Naughton-Treves (2004) found that the growth rate of secondary forests in the Peruvian Amazon was as high as 11.47 Mg/ha per year, compared to Chave et al. (2001)'s estimate of primary forest growth of 2-4 Mg/ha per year, indicating that tropical secondary forests should not be overlooked for their carbon storage potential.

Significant attention in the literature has been given to the C storage abilities of tropical primary growth forests (Chave et al. 2001, Baker et al. 2004, Ramanantoandro et al. 2016). To date, however, there has not been a comparable number of studies on the C storage potential of regenerating secondary forests in tropical areas. This is also the case in Amazonia specifically, partially because much of the existing literature on Amazonian AGB has been compiled based only on trees ≥ 10cm DBH, and secondary forests are often excluded from these calculations entirely, due to their low abundance of large trees (e.g., Baker et al. 2004, Chave et al. 2001). Further study of secondary forest carbon storage will help ensure they are properly valued for their ability to offset the effects of climate change and protected from further deforestation.

Proper evaluation of carbon storage in both secondary and primary forests could also improve the ability to use REDD+ incentives to protect tropical forests. REDD+ stands for "reducing emissions from deforestation and degradation" and aims to develop policies that add high financial value for carbon stored in intact forests (Kricher 2011). It serves as an international incentive to reduce deforestation. To help offset global carbon emissions, REDD+ is focused on maintaining carbon storage within the tropical forests of developing countries by reducing land use change of natural ecosystems (Pan et al. 2011). Forest concessions can apply for REDD+ funding based on calculations of their total carbon storage capacity. To ensure the equitable distribution of REDD+ funds, it is imperative that the carbon storage of different ecosystems is accurately estimated.

In this study, we estimated and compared AGB and carbon storage capacities for a section of primary *terra firme* forest and a section of secondary *terra firme* forest in the Northeastern Peruvian Amazon (Loreto, Peru). With the objective of refining carbon estimates and improving the local understanding of land-use history, we established a permanent plot system to measure biomass at two locations: the Universidad Cientifica del Peru Conservation Concession (UCP), a primary forest sites, and SFS Center for Amazon Studies (CAS), a secondary forest site. We also hope to contribute to the information bank needed to garner REDD+ funding at these two sites.

Given that the trees at the two sites are found within a primary and secondary forest of different ages with significant differences in species composition, we expected that the AGB of each site would reflect these differences. We predicted that the trees at UCP would have greater DBH and greater average height than those at CAS. Since faster growing, pioneer tree species found more commonly in secondary forests disturbed recently like those at CAS may have less dense wood than older, slower-growing trees in the primary forest at UCP, we also predicted greater wood densities and more overall AGB to be found at UCP.

II. METHODS

Study Site

We established permanent forest plots at two locations in the Amazon Basin: secondary broadleaf *terra firme* forest at CAS that was cleared for mixed agricultural purposes 16-20 years ago, and primary *terra firme* forest at UCP that has never been cleared for agriculture. CAS is located at km 54 of the Iquitos-Nauta road within the Loreto region of Peru (18 M 668840 9535047), and UCP is located two hours up the Itaya River from the town of Cahuide (Iquitos-Nauta Road km 57) (18 M 651648 9528215) (Figure 1). CAS has 69.5 forested hectares; 22.0 are 15-20 year-old secondary regrowth and the remaining 47.5 are older forest (>20 years-old) (L. Marshall, unpublished data). UCP has an estimated 10,500 hectares of forested area (H. Portocarrero, personal communication). Data collection at both sites took place between the 5th and 15th of November 2018, which is roughly the end of the dry season and the beginning of the rainy season in Loreto.

Field Data Collection

At each location, we established a 20 x 100-m plot composed of five contiguous 20 x 20-m subplots, according to RAINFOR field manual standards (Phillips et al. 2016). These 20 x 20-m subplots are the replicate unit for plot-level variables (tree density and AGB) in this study.

Within each of these subplots, measurements were taken and recorded for three variables: diameter at breast

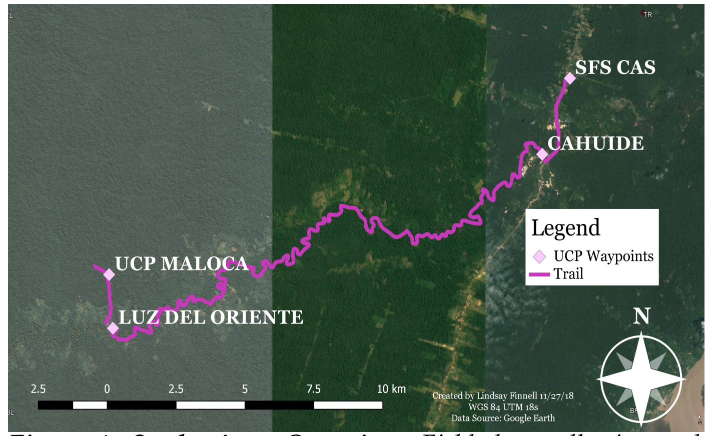

Figure 1. Study Area Overview: *Field data collection took place at School for Field Studies Center for Amazon Studies (SFS CAS) and Universidad Cientifica del Peru's conservation concession (UCP). The route from CAS to UCP includes a short drive, a boat ride up the Itaya River, and a hike of nearly 2 km, shown in purple. Aerial imagery sourced from Google Earth (2018).*

height (DBH) in cm, height in m, and wood density in g/cm3. DBH was taken for each tree ≥ 10 cm, and for each liana ≥ 10 cm diameter at any point below 2.5 m vertical height using a standard DBH tape. A clinometer was used to estimate height for each tree. We measured the angle in degrees from observer's eye level to the top of the tree *(a)* and the angle from eye level to the ground *(b)*, and a Bosch GLM80 laser rangefinder to measure the horizontal distance from tree to person measuring height *(x)* in meters. Wood density was measured by drilling into each tree and collecting the wood shavings in a marked bag. At each tree drilled, the hole was measured for depth and width in order to calculate the green volume of wood extracted. The dry weight of the wood was determined by weighing the wood shavings after drying them at 104°C for a minimum of 24 hours. All trees were measured for DBH and height, but due to time constraints, only 48 out of 83 trees at CAS and 67 out of 150 trees at UCP were measured for wood density. In final AGB calculations, a site average density was used for the trees that were not directly measured for wood density, as recommended by Chave et al. (2005).

AGB Calculation

Tree height was calculated in meters using the following trigonometric equation:

$$\textit{tree height} = x(\tan(a) + \tan(b))$$

Wood density was estimated by calculating the green volume of the drilled hole as a cylinder, then dividing the resulting number by dry weight. AGB for each non-palm tree was calculated in kg using the following equation from Chave et al (2005):

$$ABGest = \exp(-2.557 + 0.940 * \ln(\rho(D^2)H))$$

where ρ = wood specific gravity, D = DBH, and H = total tree height. This equation was chosen based on Chave et al. (2005)'s analysis of allometric equations to measure AGB, since in our study region, evapotranspiration exceeds rainfall for less than a month per year (Rivas-Martinez 1994), thereby classifying our study sites within what Chave et al. defines as "wet" forest. AGB for lianas was calculated in kg using the following allometric equation:

$$\ln(\textit{total biomass}) = -7.114 + 2.276 * \ln(D)$$

where D = diameter at 30cm shoot extension. This equation is based on Gehring et al. 2004's evaluation of liana AGB for primary and secondary forests of the Amazon. AGB for all palms (Family: *Arecaceae*) was estimated in kg using the following equation:

$$AGB^{0.25} = 0.55512(dmf\, D^2\, Hstem)^{0.25}$$

where dmf = dry mass fraction, D = DBH, and $Hstem$= stem height. This allometric equation is based on Goodman et al. (2013)'s assessment of the allometry of Amazonian palms. We used Goodman et al.'s mean dry mass fraction, 0.370, for all palm stems. Tree, liana, and palm AGB were summed for both study sites to get an estimate of total AGB per plot.

Mean AGB values per hectare were then estimated by calculating the mean AGB for each 20 x 20-m subplot, and multiplying the high, low, and mean subplot values by 25. Our subplot estimates of AGB and hectare estimate of AGB were converted from kg/ha into Mg/ha and multiplied by the carbon conversion rate of 0.47 to obtain an estimate of carbon storage per hectare and the total carbon storage at each site (Day et al. 2013). A carbon mass fraction ~50% of total AGB has been used in other studies of Amazonian *terra firme* forests (Chave et al. 2005) Our Mg/ha estimates of AGB and carbon were converted into site-wide equivalencies of total carbon for both CAS and UCP by multiplying by the total forested area at each site. When calculating total location AGB for CAS, we used the UCP estimate of AGB for the areas of older forest at CAS and the CAS estimate for younger secondary regrowth.

Statistical Analysis

PAst3 (Hammer et al. 2001) analysis software was used to compare the mean values of DBH, height, and wood density using standard t-tests. Differences in DBH, height, and wood density between sites all had unequal variance. Trees surveyed were grouped into four DBH size classes: DBH ≥10 – 20 cm, DBH >20 – 30 cm, DBH >30 – 50 cm, and DBH >50 cm. Wood density was then compared between these size classes using an ANOVA test. Densities of trees and AGB per subplot were also compared between sites using t-tests. A p-value ≤ 0.05 was considered statistically significant.

III. RESULTS

In total, 228 trees (CAS = 83 and UCP = 145) were surveyed and tagged within our plots. Overall, trees of smaller size classes (DBH of 10-30cm) were more common at both sites, and more trees of larger size classes (DBH ≥ 30cm) were encountered at UCP (Figure 2). No lianas were surveyed at CAS, and 5 lianas fitting our DBH criteria were surveyed at UCP. Four palms were measured at CAS and 2 at UCP, and a total of 3 trees surveyed were not included in AGB calculations because they were either dead or leaning too severely to estimate height.

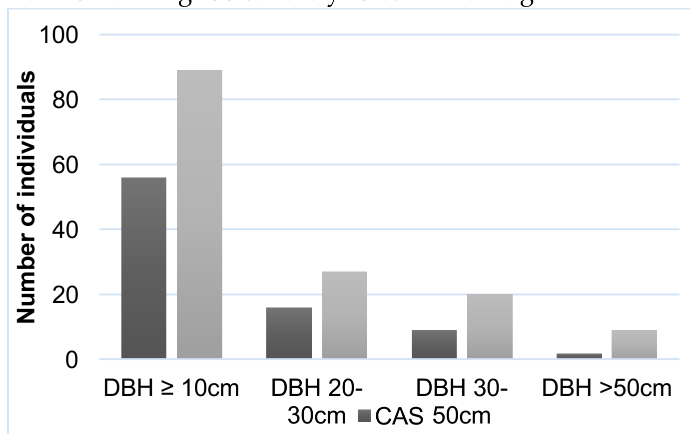

Figure 2. Size class distributions: *Number of individual trees surveyed in each DBH size class at both CAS and UCP. 188 out of 228 trees had a DBHof 10-30cm, and 29 out of the 40 trees surveyed with a DBH≥ 30cm were found at UCP.*

The trees measured at UCP were found to have, on average, a greater DBH (CAS = 18.9cm and UCP = 22.3cm; t-value = 2.231, df = 236.04, p-value = 0.027) and a higher wood density (CAS = 0.328g/cm^3 and UCP = 0.732g/cm^3; t-value = 9.953, df = 112.98, p-value = 3.89E^- 17) (Figure 3). No significant difference was found in wood density between size classes, however ($F_{3,110}$= 1.05, p- value = 0.373). Mean tree height also did not exhibit significant differences between CAS and UCP (t-value = 1.571, df =149.13, p-value = 0.118) (Figure 3).

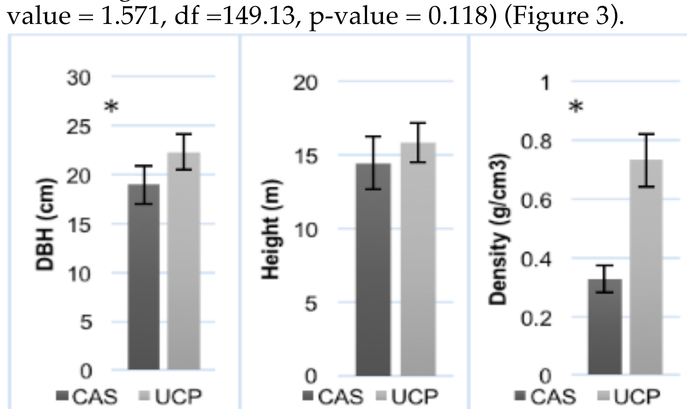

Figure 3. Mean DBH, height, and wood density: *Comparisons of mean values (± S.E.) calculated for tree DBH (cm), tree height (m), and wood density (g/cm^3) between CAS secondary forest and UCP primary forest plots. The asterisk indicates that significant differences were found between the two sites at the critical p-value of 0.05.*

The total AGB estimated within our 20 x 100-m plot at

UCP was greater than the total estimated at CAS (Table 1). Per hectare, the UCP primary forest plot was also estimated to store more AGB than the CAS secondary forest plot, with a mean AGB estimate of 322.05 Mg/ha (95% conf. interval: 236.04-408.06) (Range: 254.67-433.19Mg/ha) at UCP and 51.17 Mg/ha (95% conf. interval: 31.44-70.90) (Range: 37.71-61.75Mg/ha) at CAS. Carbon estimates for each forest in Mg/ha are also reported in the table, as well as estimates of the total AGB and total carbon stored in the forested area of each location. Density of trees at UCP was also higher per subplot, with a per hectare mean of 725 (95% conf. interval: 613.08-836.92), whereas the mean number of trees per hectare at CAS was 415 (95% conf. interval: 350.63-479.37).

Table 1. *Estimated AGB and carbon: Quantities of AGB and carbon estimated within the 20x100m plots, calculated quantities of AGB and carbon in Mg/ha, and the quantity of AGB and stored carbon calculated for the total area of CAS (69.5 forested ha) and UCP (10,500 ha).*

Site	Plot AGB (Mg)	Mean AGB (Mg/ha)	Total site AGB (Mg)	Plot carbon (Mg)	Mean carbon (Mg/ ha)	Total site carbon (Mg)
CAS	10.55	51.17	16,423	4.86	24.05	7,718
UCP	64.41	322.0	3,381,525	30.27	151.3	1,589,317

IV. DISCUSSION

The objective of our study was to contribute to existing literature on the AGB, carbon sequestration capacities, and regenerative potential of secondary *terra firme* forests in the Amazon basin. With these goals in mind, we tested the hypotheses that we would observe a greater mean tree DBH, wood density, and tree height within the primary forest at UCP, contributing to higher overall AGB estimates and carbon storage than at the secondary forest at CAS. With the exception of height, which did not vary significantly between sites, all the predicted differences were observed. We will first address the contributions of increased DBH and wood density to the biomass at UCP, followed by sources of variation concerning tree height and tree density, and finally, we will address the implications of the disparity between our AGB estimations for CAS and those of a previous study of the area as well as the implications of the greater carbon sequestration observed at UCP.

DBH

According to Chave et al. (2005), the variables most important to predicting the AGB of an individual tree are trunk diameter, wood density, and tree height, in that order. Therefore, it is reasonable to assume that the significantly higher mean DBH measured at UCP directly influenced the site's greater AGB estimate and carbon storage capabilities. Primary forests tend to have greater DBH measurements than secondary forests of the same forest type, simply because they have had more time to grow and accumulate biomass, although secondary forests are able to increase average DBH more rapidly (Ngo et al. 2013).

Though we did not measure every stem located within our plots, we have reason to believe that the trees surveyed did give us a close estimation of actual AGB. Based on studies conducted in Amazon forests, more than 80% of total AGB is found in trees greater than 10cm in diameter (Baker et al. 2014). In addition, trees less than 10 cm DBH only contribute an estimated 2% of total AGB; the remaining quantities can be found in lianas, dead wood, and leaf litter (Chave et al 2001). Thus, our decision to omit smaller stems from our field measurements is supported by existing literature as a time-efficient way to accurately sample a large area of land.

It is important to note the significance of especially large trees to AGB. Chave et al. (2001) found that trees greater than 70 cm DBH disproportionately contribute to AGB estimates, with roughly 2.5% of trees surveyed contributing 36% - 39% of biomass. Our results were not nearly as dramatic, perhaps because we only measured two trees with DBH greater than 70 cm, but those two trees (1.3% of trees surveyed) still accounted for nearly 6% of the total AGB at UCP. Though forests quickly regenerate and accumulate biomass after clearing, the carbon contained within old-growth trees of such huge stature cannot simply be replaced by the rapid carbon sequestration of saplings. The disproportionate biomass of ancient and enormous trees in old-growth forests emphasizes the importance of incentivizing the preservation of these forests through REDD+ funding.

Wood Density

Studies of forests in temperate regions report that DBH alone is sufficient to estimate biomass (Chave et al. 2005). Indeed, the only other existing biomass estimate for CAS was calculated using an allometric equation based solely on DBH (Marshall 2018, unpublished data). However, it should be emphasized that many temperate models are based on simpler forests with dominant tree species, whereas tropical forests are more complex and require models that utilize more variables to estimate AGB (Chave et al. 2005). In order to refine our AGB and carbon estimates, we chose a model that accounts for wood density and tree height in addition to DBH.

Wood density is a measurement that reflects the amount of biomass per unit volume of tree trunk and is significant in calculating AGB (Ramanantoandro et al. 2016). It has been concluded that fast-growing, light-demanding species have lower wood densities than slower-growing, shade-tolerant species; there is a trade-off between the volume of wood produced, facilitating rapid growth toward the canopy, and its resulting density, which provides structural support and protects against breakage (Baker et al. 2004, Ramanantoandro et al. 2016). Therefore, the greater wood densities observed at UCP suggests a species compositional difference within the mature forest, which probably contains more shade-tolerant, slow growth trees as opposed to the higher number of light-demanding pioneer species in a secondary forest such as CAS. The importance of individual tree wood densities in estimating AGB may not seem as significant in old-growth forests that are mainly composed of hardwood species with a narrow range in wood densities, but Baker et al. (2004) has shown that ignoring variations in wood density results in poor prediction of overall AGB. The landscape of this study is a mosaic of species and differing wood densities, and Baker's assertion here implies that, on the landscape level, it is important to account for the spatial variation of species composition and wood density.

For tropical trees, species compositions appears to be more important than size class in influencing wood density. Indeed, we found no correlation between DBH size class and wood density at either of our study sites. Thus, our study supports previous findings in Madagascar that tree diameter had no relationship to wood density within or between tree species, despite the variation of wood densities between species (Ramanantoandro et al. 2016).

Height

Since we did not observe a significant difference in heights between our two sites, our data tends to agree with the assertion that tree height on its own is not a good estimator of AGB (Chave et al. 2001). Though height on its own is not significantly important to AGB, when used in conjunction with DBH it becomes *D2H*, which Chave et al. (2001) asserts is the best estimator of AGB. Indeed, the standard error in estimation of biomass decreases from 19.5% to 12% when height is included in the equation (Chave et al. 2005); we therefore chose to measure and include tree heights in our study.

Our results support previous findings that after trees have grown to a certain height, they focus most of their energy on growing outward rather than growing upward (Da Silva Scaranello et al. 2012). This helps explain our lack of significant difference between tree height at CAS and UCP despite the greater DBH of UCP trees. It can be assumed that there is a threshold past which vertical growth does not confer greater benefits to trees, and that trees at CAS and UCP have both reached that point and have begun to invest more energy into increasing girth. Again, the old-growth trees at UCP have merely had a longer lifespan to accrue biomass and increase in diameter, resulting in greater total AGB.

Tree Density

We were not able to find much mention in literature of tree density differences between primary and secondary forests. This is indicative of a lack of available information concerning lower secondary forest tree density of trees ≥ 10 cm DBH. Perhaps the comparison of tree density between forest types is not worth scientific attention because it can be assumed that primary forests will contain more trees of larger size classes than secondary forests, based merely on time required for recruitment and growth.

Carbon Storage and AGB

Our carbon estimates of 151.36 Mg C/ha for UCP and 24.05 Mg C/ha for CAS are both slightly lower than average carbon storage values for primary forests found in the Peruvian Amazon by Nebel et al. (2001) (220.2 Mg C/ha) and previous estimates for the CAS property by Marshall (2018) (138.8 Mg C/ha). However, AGB and carbon storage estimates vary throughout the primary, wet tropical forests of Central and Western Amazonia, ranging from 74.5 Mg C/ha to 203.9 Mg C/ha in certain areas (Kauffman et al. 2009). Even within a given tropical evergreen forest, the total sequestered carbon values derived from AGB estimates can vary by as much as 117.5 Mg C/ha across a local landscape (Kauffman et al. 2009). UCP's carbon estimate, therefore, falls within a normal range for primary *terra firme* forests of the Amazon, and certainly warrants the area's continued conservation and consideration for REDD+ funding.

Just as the diversity of structure and composition among trees in tropical ecosystems represents a potential source of variation in calculating carbon quantities across the landscapes, the choice of equation used to estimate AGB can also affect the predicted quantities (Chave et al. 2005). This is in part because the broad applicability of each allometric equation is limited by the diversity and composition of the original data set used to derive it. For example, the Chambers et al. (2001) equation previously used to estimate biomass at the CAS site is known to consistently give the highest predictions of AGB of any Amazonian allometric equation, and was developed using only data from forest plots in the Central Amazon, where tree wood density is reportedly higher than in the Western Amazon (Baker et al. 2004). Local topographical variation within the CAS site might also account for some of the variation between our estimates and Marshall's, and sampling a larger area could produce more representative AGB values. Tree densities, for example, were different between the region we sampled and the area sampled in the previous study (our range was 325-450 as compared to 500-575 trees per hectare) (L. Marshall, unpublished data). Regardless, the AGB and carbon estimates derived using the Chambers et al. (2001) equation are likely an overestimate of actual values for the CAS property, as they were calculated without taking into account the unique wood density values and height/diameter relationships of this region that lead to variations in allometry across Amazonia.

It is important to note that even the Chave et al. (2005) equation we used tends to overestimate AGB to some degree (0-5%) when averaged across an entire site. Nonetheless, equations such as the one chosen for our study, which estimate AGB using forest type (dry, moist, or wet) as a predictive measure, represent a significant improvement over others because models without this measure reliably overestimate AGB by as much as 50% (Chave et al. 2005). We also believe that, had we used a different equation to estimate AGB that did not include wood density in the calculations, our AGB and carbon storage values would have been even greater overestimates. When we input our DBH and height measurements into the Chambers et al. (2001) used by Marshall (2018), our AGB and carbon estimates in Mg/ha nearly tripled (Our CAS range changed from 17.72-29.02 Mg C/ha to 56.74-121.20 Mg C/ha). While these increased values are still smaller than Marshall's estimate of 138.8 Mg C/ha for the CAS property, the parameters and assumptions of the equations being used explain some of this inconsistency. Differences in equation used also help contextualize the disparity between Marshall's (2018) total carbon estimate for the CAS property (9,650.2 Mg C) and ours (7,718.84Mg C). This indicates that in many cases AGB estimates are highly dependent on the allometric equation applied, and emphasizes the importance of applying an equation which allows for the use of more site-specific variables.

V. CONCLUSION

In order to improve AGB estimates for our study area, we recommend either calculating the individual wood density of every tree sampled or generating information on species composition in the area to improve the accuracy of wood density averages and thereby AGB estimations (Day et al. 2013). We also recommend the sampling of a larger area to account for local topographical variation, since our range of potential AGB values calculated from inter-subplot variation was relatively large (UCP range: 254.67-433.19Mg/ha, and CAS range: 37.71-61.75Mg/ha). Any additional carbon estimates generated for secondary forests of the region would contribute significantly to existing research.

The AGB and carbon storage estimations for the UCP primary forest concession place it within the range of other highly productive primary tropical forests of the Amazon basin. However, although our data supports the consensus that primary forests store more AGB and sequester more carbon than secondary growth forests through increased parameters such as tree DBH, height, and wood density, this does not indicate that mature forests should be the only conservation priority. While old growth forests like UCP tend to store more of their carbon above ground, secondary growth forests like CAS store only about 38.1% of forest carbon in AGB, with the rest being stored primarily soil (Ngo et al. 2013). Our carbon storage estimates for CAS, therefore, may be significant underestimates of total ecosystem carbon storage. More research on below ground biomass in Western Amazonia would contribute substantially to estimations of carbon storage in the secondary forests of the region. Moreover, existing research on regenerating tropical ecosystems states that secondary forests, which already act as substantial carbon sinks, increase their capacity to store carbon with increasing time since disturbance (Mukul et al. 2016). The potential carbon sequestration abilities of both primary and secondary *terra firme* forests of the Western Amazon, therefore, should not be undervalued.

AUTHOR INFORMATION

Lindsay Finnell, Drake University, Des Moines, IA, USA: lindsay.finnell@drake.edu

*Bailey Nordin, Columbia University in the City of New York, NY, USA: bjn2122@columbia.edu
(717) 830-4730
604 W 114 St, New York, NY 10027

ACKNOWLEDGMENTS

We would like to express the sincerest gratitude for the academic support, hard work in the field, and friendship of Dr. Laura Morales, Eliza Amber, Henry Hurt, Molly Sayles, Christian Perez, and Jose David Urquiza, as well as all of the staff and students at Universidad Cientifica de Peru and the Center for Amazon Studies. We thank the staff and students of The School for Field Studies, Peru Center for Amazon Studies for making this research possible.

REFERENCES

Baker, T., O. Phillips, Y. Malhi, S. Almeidas, L. Arroyo, A. Di Fiore, T. Erwin, T. Killeen, S. Laurance, W. Laurance, S. Lewis, J. Lloyd, A. Monteagudo, D. A. Neill, S. Patino, N. C. A. Pitman, J. N. M. Silva, and R. Vasquez Martinez. 2004. Variation in wood density determines spatial patterns in Amazonian forest biomass. Global Change Biology 10: 545– 562.

Chambers, J.Q., J. dos Santos, R.J. Ribeiro, N. Higuchi. 2001. Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. Forest Ecology and Management 152:73-84.

Chave, J., C. Andalo, S. Brown, M. A. Cairns, J. Q. Chambers, D. Eamus, H. Folster, F. Fromard, N. Higuchi, T. Kira, J. P. Lescure, B. W. Nelson, H. Ogawa, H. Puig, B. Riera, and T. Yamakura. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145: 87–99.

Chave, J., B. Riera, and M. Dubois. 2001. Estimation of biomass in a neotropical forest of French Guiana: spatial and temporal variability. Journal of Tropical Ecology 17: 79-96.

Da Silva Scaranello, M. A., L. F. Alves, S. A. Vieira, P. B. de Camargo, C. A. Joly, and L. A. Martinelli. 2012. Height-diameter relationships of tropical Atlantic moist forest trees in southeastern Brazil. Scientia Agricola 69: 26-37.

Day, M., C. Baldauf, E. Rutishauser, and T. C. H. Sunderland. 2013. Relationships between tree species diversity and above-ground biomass in Central African rainforests: implications for REDD. Environmental Conservation 41: 64–72.

Gao, Y., J. Cheng, Z. Ma, Y. Shao, and J. Su. 2014. Carbon storage in biomass, litter, and soil of different plantations in a semiarid temperate region of northwest China. Annals of Forest Science 71: 427-435.

Gehring, C., S. Park, and M. Denich. 2004. Liana allometric biomass equation for Amazonian primary and secondary forest. Forest Ecology and Management 195: 69-83.

Goodman, R. C., O. L. Phillips, D. C. Torres, L. Freitas, S. T. Cortese, A. Monteagudo, and T. R. Baker. 2013. Amazon palm biomass and allometry. Forest Ecology and Management 310:994-1004.

Hammer, O., D. Harper, and P. Ryan. 2001. PAST: Paleontological statistics software package for education and data analysis. Paleontologia Electonica 4: 9. <http://folk.vio.no/ohammer/past/>

Kauffman, J. B., R. F. Hughes, and C. Heider. 2009. Carbon Pool and Biomass Dynamics Associated with Deforestation, Land Use, and Agricultural Abandonment in the Neotropics. Ecological Applications 19:1211-1222.

King, D., S. J. Davies, S. Tan, and N. S. MD. Noor. 2006. The role of wood density and stem support costs in the growth and mortality of tropical trees. Journal of Ecology 94:670-680.

Kricher, J. 2011. Tropical Ecology. Pages 325, 556-57. A. Kalett, editor. Princeton University Press, Princeton, New Jersey.

Marquardt, K., R. Milestad and L. Salomonsson. 2013. Improved fallows: a case study of an adaptive response in Amazonian swidden farming systems. Agriculture and Human Values 30:417–428

Marshall, L. 2018. Carbon storage inventory of above-ground biomass in a Western Amazonian secondary growth forest. Unpublished work. Directed Research Report. SFS Peru, Spring 2018.

Mukul, S. A., J. Herbohn, and J. Firn. 2016. Tropical secondary forests regenerating after shifting cultivation in the Philippines uplands are important carbon sinks. Scientific Reports 6: 22483.

Naughton-Treves, L. (2004). Deforestation and Carbon Emissions at Tropical Fontiers: A Case Study from the Peruvian Amazon. World Development 32.1:173-190. Nebel, G., J. Dragsted, and A. S. Vega. 2001. Litter fall, biomass and net primary production in flood plain forests in the Peruvian Amazon. Forest Ecology and Management 150:93-102.

Ngo, K. M, B. L. Turner, H. C. Muller-Landau, S. J. Davies, M. Larjavaara, N. F. N. Hassan, and S. Lum. 2013. Carbon stocks in primary and secondary tropical forests in Singapore. Forest Ecology and Management 296:81-89.

Pan, Y., R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, and W. A. Kurz. 2011. A large and persistent carbon sink in the world's forests. Science 120: 9- 16.

Phillips, O., T. Baker, T. Feldpausch, and R. Brienen. 2001. RAINFOR Field Manual for Plot Establishment and Remeasurement. Amazon Forest Inventory Network 2016: 1-27. <www.rainfor.org/en/manuals.>

QGIS Development Team. 2017. QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.osgeo.org.>

Ramananantoandro, T., M. F. Ramanakoto, G. L. Rajoelison, J. C. Randriamboavonjy, and H. P. Rafidimanantsoa. 2016. Influence of tree species, tree diameter and soil types on wood density and its radial variation in a mid-altitude rainforest in Madagascar. Annals of Forest Science 73: 1113- 1124.

Rivas-Martinez, S. 1994. Iquitos Climate Data. Worldwide Bioclimatic Classification System Phytosociological Research Center. www.globalbioclimatics.org.

Thomlinson, J.R., M.I. Serrano, T. del M. Lopez, T.M. Aide, J.K. Zimmerman. 1996. Land-use dynamics in a post-agricultural Puerto Rican landscape. Biotropica, 28:525.