EFFECTS OF LAND USE ON CARBON STOCKS IN THE ECUADORIAN CHOCO

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Meryl LaRue. Effects of Land Use on Carbon Stocks in the Ecuadorian Chocó.

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This study aimed to investigate aboveground carbon stocks across three contrasting land use types (full sun cacao, shade grown cacao, and tropical forest) in Northwest Ecuador's Chocó Rainforest while assessing the relationships between biotic and abiotic factors and carbon stocks. In Ecuador, cacao farming contributes to high rates of deforestation. Shade grown cacao can be an alternative to full sun cacao that contributes to climate change mitigation goals with co-benefits through higher carbon storage, improving farmer livelihoods, and improving habitat connectivity. Previous studies have indicated that shade grown cacao can store more carbon than full sun cacao, but few studies focus on the impacts of shade grown cacao in the Ecuadorian Chocó region. This study examined aboveground carbon stocks (AGC) of tree plots across a gradient of land-use type and found that shade grown cacao stored more carbon than full sun cacao and statistically similar amounts to forest. This study also found that species diversity had a significant ($P < 0.05$) positive relationship with carbon stocks. High species diversity can contribute to higher carbon stocks because diverse plant communities have a wider variety of functional traits, allowing communities to utilize resources more efficiently and develop higher biomass and carbon stocks. Species diversity often decreases with human disturbance, so the variance in carbon stocks between land uses can be interpreted as an increase in carbon stocks along a gradient of lowest to highest level of human disturbance, which is evidenced by changes in species richness and diversity across land use types. Shade grown cacao can contribute to climate change mitigation goals while benefitting farmers and improving biodiversity.

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1. INTRODUCTION

1.1 Climate Change and Natural Climate Solutions

Climate change poses a formidable threat to human life and many of our planet's ecosystems. Global mean surface temperature has reached 1.1 ºC above pre-industrial averages and is continuing to rise, causing widespread adverse impacts on ecosystems and human communities (Calvin et al., 2023). Human activities such as land use change are major contributors to greenhouse gas (GHG) emissions that contribute to climate change, with land use and land cover change making up 12.5 percent of anthropogenic carbon emissions from 1990-2010 (Houghton et al., 2012). Deforestation specifically makes up 6-17 percent of global anthropogenic carbon emissions (Baccini et al., 2012). Limiting warming to 1.5 ºC is imperative to avoid reaching tipping points, or critical thresholds that when reached lead to rapid changes to or the collapse of an ecosystem (Hoegh-Guldberg et al., 2019). Reaching this goal is still possible, but most pathways will require active removal of carbon dioxide from the atmosphere in addition to reducing carbon emissions (Hoegh-Guldberg et al., 2019).

A proven method to remove carbon dioxide from the atmosphere is through management actions that rely on nature's existing abilities to uptake and sequester carbon, called natural climate solutions. Natural climate solutions are defined as "deliberate human actions (NCS pathways) that protect, restore, and improve management of forests, wetlands, grasslands, oceans, and agricultural lands to mitigate climate change" (Ellis et al., 2024). Through these actions, natural climate solutions enhance natural carbon removal through natural components of the carbon cycle such as photosynthesis and long-term carbon burial. For example, terrestrial ecosystems such as forests remove carbon dioxide from the atmosphere and store it in the form of biomass (Falkowski et al., 2000). When combined with dramatically reducing emissions from fossil fuels, natural climate solutions can mitigate climate change while providing ecosystem services such as biodiversity protection and improvements to air and water quality (Griscom et al., 2017).

1.2 Tropical Agricultural Management as a Natural Climate Solution

In the tropics, deforestation and forest degradation and responsible for 95 percent of carbon emissions (Bauters et al., 2015). Agricultural expansion is one of the main drivers of tropical deforestation and is thus a major contributor to tropical GHG emissions (Pendrill et al., 2022). In tropical countries, natural climate solutions have the potential to mitigate nearly half of recent national historic annual GHG emissions (Griscom et al., 2020). Improved management of agriculture, specifically, can be a valuable natural climate solution in the tropics. For example, planting trees on farms in the tropics has the potential to mitigate nearly 1000 Tg CO_2e yr^{-1} of emissions at less than $100 USD per Mg CO_2e (Griscom et al., 2020). In addition, avoided forest conversion in the tropics has the potential to mitigate nearly 3000 Tg CO_2e yr^{-1} of emissions at less than $100 USD per Mg CO_2e (Griscom et al., 2020).

1.3 Context in Ecuador

As of 2020, Ecuador had 14 Mha of forest cover (Global Forest Watch, 2026). Ecuador is one of the most biodiverse countries in the world and is home to parts of the Amazon and Chocó tropical rainforests. It is one of thirteen countries that comprise over 70% of the Earth's biodiversity despite making up less than 10% of its surface (Rivas et al., 2024). However, due to deforestation, 30% of Ecuador's natural ecosystems are highly fragmented, making Ecuador the country with the second highest number in the world of threatened species on the IUCN red list (Rivas et al., 2024). The ecosystems that have suffered the worst rates of deforestation in Ecuador are the Chocó lowland forests (Rivas et al., 2024). These high rates of deforestation are largely due to land-clearing for agricultural purposes (Rivas et al., 2024).

In northwest Ecuador's Chocó rainforest, agriculture has historically contributed to these high rates of deforestation due to the creation of the Ecuadorian Institute for Agrarian Reform and Colonization (IERAC) in 1964 (Perlin & Leguizamón, 2024). IERAC led a large-scale initiative in which families would be given titles to land that they settled if they could prove that they had cleared land to be used for agriculture (Perlin & Leguizamón, 2024). Now, cacao farming is the predominant type of agriculture practiced in La Zona, the area in northwest Ecuador where this study took place (Perlin & Leguizamón, 2024).

1.4 Aims and Objectives

This thesis aims to quantify the impact of land-use, biotic variables, and abiotic variables on aboveground tree carbon stocks in the Ecuadorian Chocó Rainforest. The objectives of this thesis are to:

1. Investigate AGC across three contrasting land-use types (full sun cacao, shade grown cacao, and tropical forest).

Understanding the difference in AGC between these land-uses will be crucial in determining how natural climate solutions can be implemented in this region. The Foundation for the Conservation of the Tropical Andes (FCAT), for example, is conducting a project that partners with local families to cover hundreds of hectares with shade grown cacao. Quantifying the impact of land-use on AGC will help determine the potential contribution of this project and future projects to climate change mitigation through carbon storage.

2. Examine biotic and abiotic factors and their relationship with AGC.

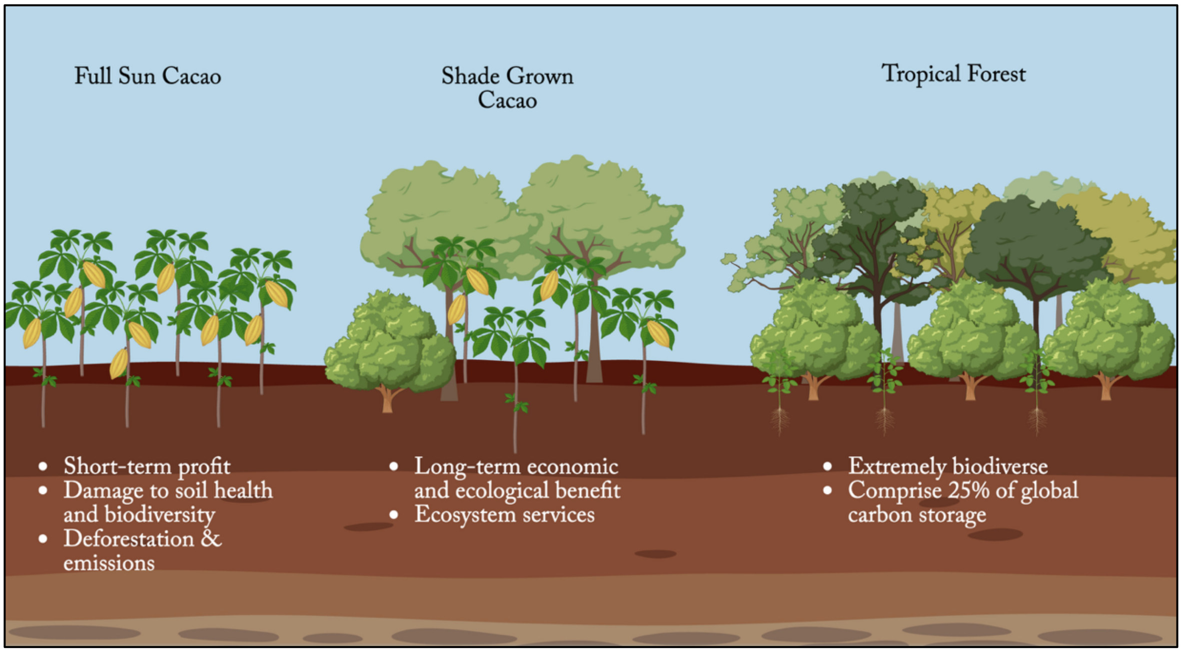
Species diversity and AGC are positively correlated (Obonyo et al., 2023). Quantifying the relationship of biotic factors such as species diversity with carbon stocks within this region will be crucial to understanding how natural climate solutions can be implemented that maximize ecosystem benefit and carbon storage. Some studies find a significant difference in carbon stocks with changes in abiotic variables such as elevation, whereas others find no significant difference (Phillips et al., 2019; Khadanga & Jayakumar 2020). Biotic and abiotic variables such as species diversity and topographic aspect could vary across land use types, and investigating their relationship with AGC could help us understand why there may be differences in AGC across land use types. Understanding the impact of biotic and abiotic environmental factors on carbon stocks within this region could also be useful for designing future natural climate solutions projects.

2. BACKGROUND

2.1.1 Land uses

The three contrasting land uses examined in this study were full sun cacao, shade grown cacao, and tropical forest. Figure 1 depicts the differences in diversity, composition, and human and ecosystem impacts between these land use types.

Figure 1. *Differences between full sun cacao, shade grown cacao, and tropical forests*



2.1.2. Full Sun Cacao

One of Ecuador's main agricultural exports is cacao, and Ecuador is the third largest exporter of cacao in the world (Caicedo-Vargas et al., 2022). Global demand for cacao has been increasing, leading to an increased prevalence of full-sun cacao monoculture farms (Andres et al., 2016). While cacao monocultures can maximize short-term profits, they also reduce soil health through increased soil erosion and degradation, contribute to biodiversity loss, and are more susceptible to climate change impacts, pests, and diseases (Andres et al., 2016). Intensifying cacao production has also led to deforestation and increased carbon emissions in many locations (Niether et al., 2020). Full sun cacao plantations store less carbon than shade grown cacao systems, and this difference is related to differences in tree density, species diversity, and tree size (Rajab et al., 2016). Thus, I hypothesize that the full sun cacao land use will store the least AGC because it will have the smallest trees and lowest species diversity.

2.1.3. Shade Grown Cacao

In Ecuador, shade grown cacao can promote ecosystem services and sequester carbon while providing human benefits. Worldwide, 0.29 to 15.21 Mg of carbon per hectare per year is stored in shade grown cacao systems (Jose & Bardhan, 2012). Shade grown cacao also has the potential to store 0.1–5.7 Gt of carbon dioxide per year (Roe et al., 2019). In addition to storing carbon, shade grown cacao systems provide ecosystem services such as biodiversity enhancement, water quality improvement, and soil health improvement (Cardinael et al., 2021). Shade grown cacao systems have substantially higher species diversity than full sun cacao plantations (Miharza et al., 2023; Rajab et al., 2016). They also exhibit vertical layering, which can increase carbon stocks through an increase in stem density as when trees that can survive at different light levels grow together, they can more efficiently utilize space and grow more densely (Pretzsch & Schütze, 2021). Shade grown cacao systems can also increase farmers' income and make cacao farms more resilient to climate change (Ghale et al., 2022; Igbatayo, 2023). Growing cacao under the shade of forest trees reduces physical stress on the cacao tree, meaning that cacao yield does not significantly decrease in shade grown systems (Miharza et al., 2023; Rajab et al., 2016). Despite shade grown cacao's high potential to sequester carbon and provide ecosystem services, it is relatively understudied in Ecuador. A research gap exists for its potential to store carbon within the Chocó Rainforest region of Ecuador. I hypothesize that the shade grown cacao land use will store significantly more carbon than the full sun cacao due to increased species diversity, which could lead to increased prevalence of larger species, and due to vertical layering and higher stem density.

2.1.4. Tropical Forest

Tropical forests make up a quarter of global vegetated terrestrial carbon storage and are home to 96% of all the tree species in the world (Poorter et al., 2015). Ecuador's Chocó Rainforest has been termed a "biodiversity hotspot" because it contains at least 1,500 endemic vascular plant species (Koenig, 2016). The theory of niche complementarity states that high biodiversity should lead to greater carbon uptake and storage because increasing diversity increases resource use efficiency (van der Sande et al., 2017). Many studies support the idea that high biodiversity can increase productivity and carbon storage in forests (van der Sande et al., 2017). Forests that are dominated by tall species with high wood density also have high carbon storage (van der Sande et al., 2017). Tropical forests also exhibit layering, which can reduce competition for light and increase the efficiency of trees' use of space, and can contribute to higher stem density (Laurans et al., 2014) (Pretzsch & Schütze, 2021). I hypothesize that the tropical forest in this study will store the most carbon due to its high biodiversity, its prevalence of tall species with high wood density, and its high stem density due to vertical layering.

2.2 Abiotic and Biotic Factors

2.2.1. Abiotic factors

Elevation can influence AGC because temperature changes along elevation gradients affect the metabolic processes that drive wood production (Mayor et al., 2017). In addition, as elevation increases, temperature decreases, shaping which species can survive at higher altitudes and the scale to which species can grow (Mayor et al., 2017). In Ecuador, AGC stocks can be lower in tropical montane forests at high elevation than in lowland forests at low elevations (de la Cruz-Amo et al., 2020). I hypothesize that plots at higher elevations will have lower AGC stocks than those at lower elevations due to decreased temperature contributing to different community biodiversity.

Slope aspect can also impact carbon stocks because topographical features can cause local variations in solar radiation received, moisture, temperature, and soil, which can influence the diversity and distribution of plant communities (Zhang et al., 2022). In the southern hemisphere, north-facing slopes are warmer and drier than south-facing slopes, which receive less solar energy and are more moist (Gxasheka et al., 2023). I hypothesize that south-facing slopes will have higher AGC stocks because cooler slope aspects have been shown to increase growth of woody plants due to increased moisture availability and reduced heat stress (Gxasheka et al., 2023).

2.2.2. Biotic factors

Increased canopy density can increase AGC stocks (Baul et al., 2021) (Xu et al., 2018). This is because canopy density is determined by other factors that are positively correlated with AGC stocks, such as DBH, height, and tree stem density (Xu et al., 2018). Canopy density is also associated with species diversity, which is positively correlated with AGC stocks (Xu et al., 2018).

Tree density directly increases carbon stocks, as increasing the quantity of trees per hectare increases the amount of carbon stored per hectare (Osei et al., 2022). I hypothesize that higher tree density will result in higher AGC stocks. Tree height is also directly related to AGB, and thus carbon stocks, so I hypothesize that higher canopy heights will result in higher carbon stocks (Chave et al., 2005).

Species richness can also impact AGC stocks because higher tree species richness could increase stand productivity through niche complementarity and reduced competition, leading to higher tree density and larger tree sizes (Liu et al., 2018). I hypothesize that increased species richness will result in higher AGC stocks because higher species richness increases the ecosystem's productivity and reduces competition among species due to increased interspecific variation in plant traits (Amyntas et al., 2023).

Shannon Index, a measure of biodiversity that considers species richness and evenness, can also impact AGC stocks because species diversity can increase ecosystem stability and resilience, which enables primary production, biomass accumulation, and increased carbon stocks (Obonyo et al., 2023). High Shannon Index is positively correlated with AGC stocks (Obonyo et al., 2023). Similarly to species richness, this can be due to niche complementarity (Lu et al., 2023). I hypothesize that increased Shannon Index will result in increased AGC stocks because increased diversity enables higher primary production and biomass accumulation due to increased ecosystem health and decreased competition among species.

3. METHODS

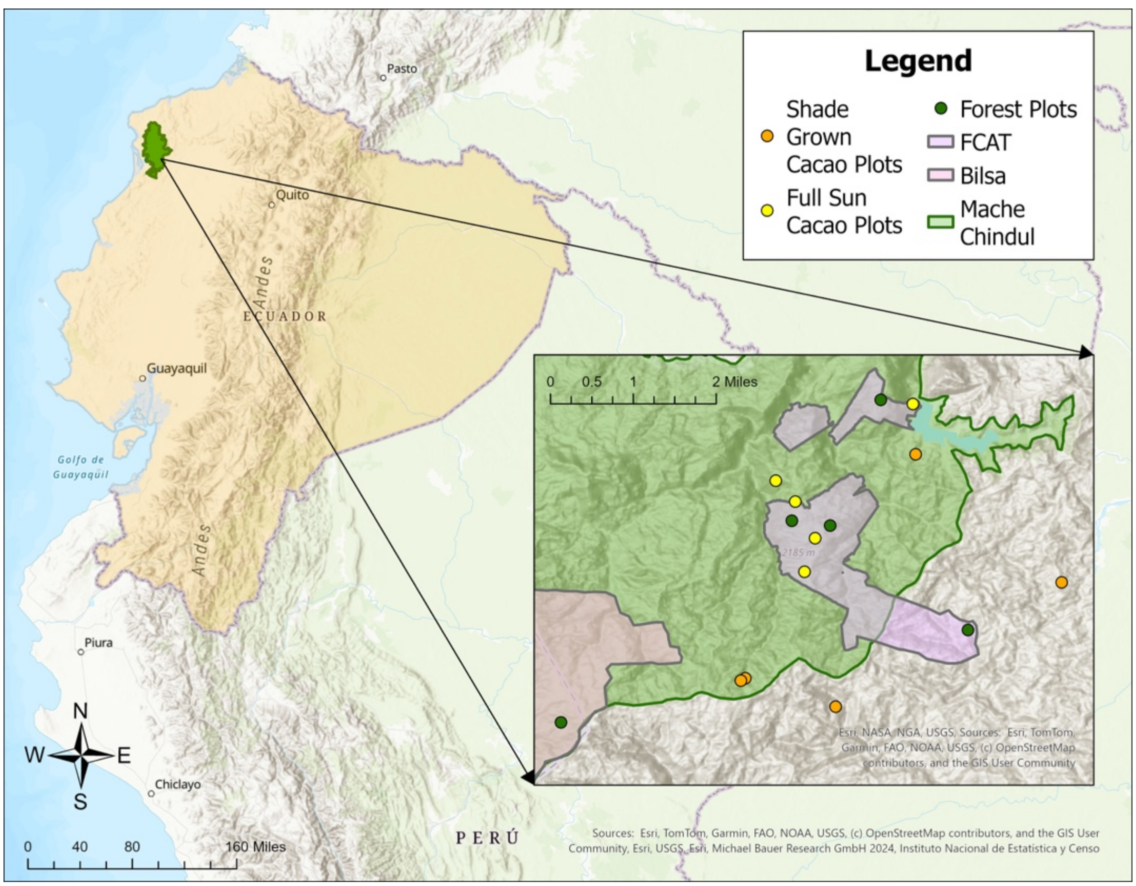
3.1 Study Site

I conducted this study in partnership with FCAT, an Ecuadorian NGO dedicated to the conservation and restoration of the Ecuadorian Chocó Rainforest. FCAT is located mostly within the boundaries of Ecuador's Mache-Chindul Ecological Reserve. The Mache-Chindul Reserve spans 121,376 ha and is quite unique because despite being designated as an ecological reserve, the area is home to a population of over 6,000 people (Perlin & Leguizamón, 2024). Many of these inhabitants depend on cultivating cacao to earn a steady income (Perlin & Leguizamón, 2024). As shade grown cacao can improve farmers' income and livelihoods while increasing habitat and biodiversity, FCAT recently implemented a project collaborating with 80 local families which has covered 442.77 ha of land with cacao shade grown cacao.

3.2 Field Methods

I examined plots along a gradient of land-use type, comparing shade grown cacao to full sun cacao plantations and forest. I sampled fifteen 20x20 m, or 0.04 ha plots, five for each land use type. The locations of these plots are depicted in Figure 2.

Figure 2. *Study site – Sampling Locations in Northwest Ecuador's Chocó Rainforest*



Four of the forest plots were located within FCAT's Reserve, while the fifth was in the nearby Bilsa Ecological Reserve. The five shade grown cacao plots were located outside of FCAT's reserve. Four of the full sun cacao plots were located inside of FCAT's reserve, while the fifth was located only in the Mache-Chindul Reserve. Three out of five of these cacao plots were actively managed. Two of the full sun cacao were abandoned full sun cacao plots that were no longer actively managed. Though these plots were dominated by cacao, some forest tree species were present. All plots examined in this study contained fully grown trees. I aimed to keep age as consistent as possible between plots. The trees in all examined plots were at least 12 years old, with many plots that included forest trees containing trees that were over 30 years old.

Plot locations were chosen based on tree age in order to keep age consistent between plots. In the full sun cacao and shade grown cacao plots, locations could not be randomly selected because we were limited to specific farms and specific locations within those farms that would be appropriate to sample in due to tree age. In the forest plots, locations could not be randomly selected either because we were limited by access to fine enough scale spatial data with which to randomly generate sampling locations. Instead, we randomized plot locations as best as possible by walking at least 50 m to an out of sight location from the forest paths (Moonlight et al., 2022). To establish the center of these plots, we attached flag tape to a stick and threw it after spinning in circles with our eyes closed.

In each plot, each tree with a diameter at breast height (DBH) greater than or equal to 10 cm was identified to the species or family level. This size threshold was chosen because it is the standard for the RAINFOR methodology, which has developed standard methods for tropical forest inventory sampling (Malhi et al., 2002). The DBH of each tree that met this size requirement was recorded. The height of each tree was measured using a Nikon Forestry Pro II Laser Rangefinder/Hypsometer tool on the 3-point setting. Five height measurements per tree were recorded and averaged to minimize error. In one plot, steep topography made it impossible to accurately measure the height of the tallest tree of that plot, so the height for this tree was estimated by substituting in the height of the second tallest tree in the plot. In each plot, canopy density was also measured with a densiometer. Four measurements were taken in each plot, one in each cardinal direction, 15-20 ft. away from the center of the plot (Strickler, 1959). These four measurements were then averaged to calculate the overall canopy density for the plot. Finally, a small wood core was taken for each species using an increment borer.

3.3 Lab Methods

I measured the green volume of the collected wood cores using the water displacement method. The cores were dried in an oven at 90 ºC for at least 48 hours, weighing at regular intervals until the wood samples reached a constant weight. Using the green volume and oven dried weight of each sample, a wood density value was calculated for each species encountered during this study.

I used the allometric equation developed for tropical wet forests by Chave et al., 2005 to calculate the biomass of each tree measured in this study, then used a carbon factor of 0.47 to convert biomass to AGC (IPCC, 2003). I then calculated the total AGC for each plot and land-use. In addition, I calculated the species richness, Shannon Diversity Index, and Simpson's Diversity Index of each plot and land-use type.

I also utilized ArcGIS Pro to calculate topographic aspect. Using a DEM of Ecuador and points I collected in the field marking the center of each plot, I calculated the topographic aspect of each plot.

3.4 Statistical Methods

To assess the relationship between land use and carbon stocks, I first used a Shapiro-Wilk test to assess the normality of my data. I concluded that my data were not normally distributed, so I then performed a Kruskal-Wallis test to determine whether there was a statistically significant difference in the relationship between land-use and carbon stocks. Finding a statistically significant relationship in this test, I then performed a post-hoc Dunn test to determine which land-use and carbon stock groups were statistically different from one another.

Then, to assess whether additional gradients existed within my plots, I performed several Kruskal-Wallis tests to determine whether there were significant differences in environmental, structural, and diversity variables across land use types. I conducted tests comparing the differences in elevation, aspect, species richness, Shannon index, plot tree density, plot canopy density, and maximum canopy height between land use types.

3.5 Modeling Methods

To determine which abiotic and biotic factors are correlated with carbon storage, I fit eight linear regression models to determine the correlation between carbon stocks and elevation, aspect, species richness, Shannon index, plot tree density, plot canopy density, and maximum canopy height in each plot. Because I only measured or calculated one value per plot for each of these variables, I opted to use a multiple linear regression model to assess the significance of the relationship between these variables and their influence on carbon. Before implementing the multiple linear regression model, I tested for multicollinearity in my variables. To accomplish this, I conducted Variance Inflation Factor (VIF) tests. High VIF scores indicate multicollinearity among variables, meaning that the variables are not appropriate to use in the same model. Using variables that exhibit multicollinearity in the same model could cause incorrect statistical results (Kim, 2019). Upon first assessment, I found that my variables exhibited high VIF scores and were thus not appropriate to use in the same model. I narrowed my explanatory variables to one environmental variable, one structural variable, and one diversity variable by running several VIF tests and choosing the combination of environmental, structural, and diversity variables that resulted in the lowest VIF scores for each variable. The final variables I chose to include in the model were aspect, tree density, and Shannon Index. I then executed a multiple linear regression model using carbon stocks as the dependent variable and aspect, tree density, and Shannon Index as the independent variables to determine the impact of environment, forest structure, and diversity on carbon stocks.

3.6 Limitations

One limitation of this study was that I used a generic allometric equation for wet tropical forests. To make the most accurate estimates of biomass, allometric equations developed for each species found in this study should have been used. Species-specific equations are preferable to use to calculate biomass because they are developed based on a single species of tree and can more accurately capture differences in that species' biomass due to its growth characteristics. However, it was not possible to use species specific equations for this study because after searching through multiple databases, I could not locate species-specific equations for the species present in this study. I was also unable to locate equations developed for the genera present in this study. Thus, I chose to utilize a generic allometric equation developed for wet tropical forests, which could have decreased accuracy in my biomass calculations. Generic allometric equations are widely used in carbon stock assessment studies because developing allometric equations is a destructive process, and thus allometric equations have not been developed for all locations and species (Martínez-Sánchez et al., 2020). Chave et al., 2005, where the equation used in this study was developed, has been cited over 5,000 times. Generic equations can underestimate or overestimate biomass, so it is possible that the biomass calculated in this study could have been higher or lower in reality (Martínez-Sánchez et al., 2020).

Another limitation of this study was that plot locations were not randomly chosen, but rather convenience sampling was used in an effort to maintain tree age as a fixed variable and capture variability in elevation. We were limited in our choices of appropriate sites to sample in due to tree ages and could not randomize sampling locations. There were very few full sun cacao and shade grown cacao farms that would have been appropriate to sample in because most farms in the region contained very young cacao trees that would not have been appropriate to compare to forest trees due to their age. We also needed to obtain permission from the owners of the farms to conduct research on their land. We thus chose sampling locations for full sun and shade grown cacao based on which farms had the oldest trees and based on the willingness of farmers to participate in the study rather than randomizing plot locations. While convenience sampling can introduce bias, it is utilized in similar field studies that examine carbon stocks in various agroforestry systems due to the necessity of farmer participation, capturing the variety in certain variables, or keeping certain variables consistent (McGroddy et al., 2015; Somarriba et al., 2013). In the forest plots, we attempted to randomize sampling locations by generating random points in QGIS. However, once we attempted to find these points in the field, we realized that the spatial data we had was not fine enough because the randomly generated points ended up being located outside of the forest. While full randomization was not possible, we were able to follow an alternative method presented by the *RAINFOR Field Manual for Plot Establishment and Remeasurement* to minimize bias in our choice of sampling locations (Moonlight et al., 2022).

In addition, the technique used to measure canopy density was a limitation of this study. Because I used a spherical densiometer to measure canopy density, there were some occasions where I obtained a higher canopy density measurement than I anticipated because the measurement locations in each cardinal direction happened to be directly under a cacao tree, but the canopy appeared to be more open than the measured value. Remotely sensed data could have improved these measurements, but remotely sensed data would introduce the added challenge of spatial resolution. NASA's Global Ecosystem Dynamics Investigation Lidar (GEDI), for example, has a resolution of 30 m, which would not be sufficient to use to analyze this study's plots as they are smaller than each pixel of the GEDI data. If these tools are available, future studies could consider utilizing a drone fitted with a LiDAR sensor to measure canopy density as this strategy would mitigate the issue of insufficient spatial resolution.

4. RESULTS

4.1 Relationship between land-use type and aboveground tree carbon stocks

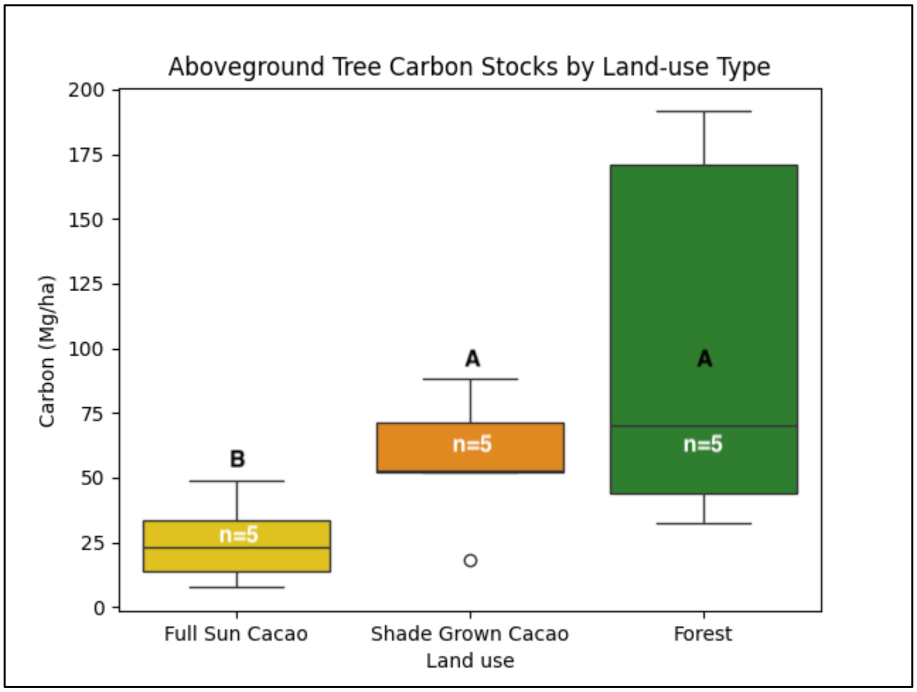
Carbon stocks varied significantly between land-uses (P=0.00007). On average, full sun cacao stored 25.28 Mg of carbon per hectare, shade grown cacao stored 56.49

Mg of carbon per hectare, and forest stored 101.68 Mg of carbon per hectare. The shade grown cacao land-use stored roughly 55% of the amount of carbon stored per hectare by forest, but 223% of the amount of carbon stored per hectare by the full sun cacao land-use. The standard deviation in Mg C per hectare was 74.13 for forest, 16.37 for full sun cacao, and 25.99 for shade grown cacao.

On average, each individual cacao tree in this study stored 0.03 Mg of carbon, whereas each individual non-cacao tree stored 0.21 Mg of carbon on average, meaning that the non-cacao trees found in this study stored seven times more carbon than the cacao trees. In addition, full sun plots were made up of 75% cacao trees on average, the shade grown plots were 36.5% cacao trees on average, and the forest plots had no cacao trees. Trees in the forest plots and shade grown cacao plots also had higher average DBHs, heights, and wood densities than those in the full sun plots.

Using a post-hoc Dunn test, I determined that in the relationship between carbon stocks and land-use type, there was a statistically significant difference ($P = 0.036007$) between shade grown cacao and full sun cacao, and between full sun cacao and forest ($P = 0.000047$), but there was not a statistically significant difference between shade grown cacao and forest ($P = 0.281423$). These differences are depicted in Figure 3. This suggests that in terms of carbon stocks, the shade grown cacao systems were statistically similar to forest, showing that the inclusion of shade trees on cacao farms can increase carbon stocks to a level comparable to forest habitat.

Figure 3. *Spread of carbon stocks across land use types*



4.2 Relationship between biotic and abiotic factors and aboveground tree carbon stocks

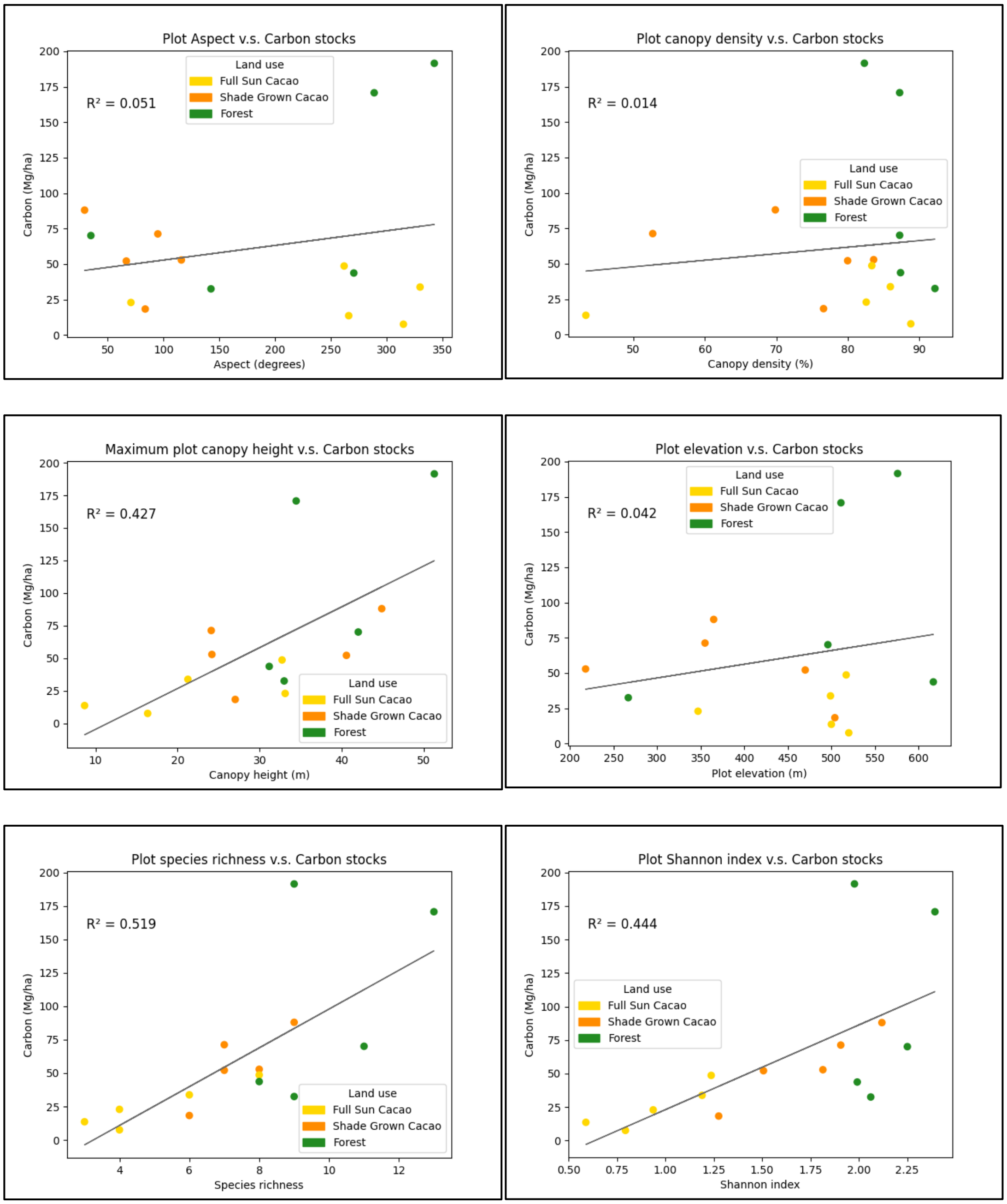
When comparing variations in abiotic and biotic variables across land uses, I found that there was not a statistically significant difference in elevation, tree density, canopy density, aspect, or maximum canopy height between land uses. However, there was a statistically significant difference in species richness and Shannon Index between land uses. The p-values from each KW test are displayed in Table 1.

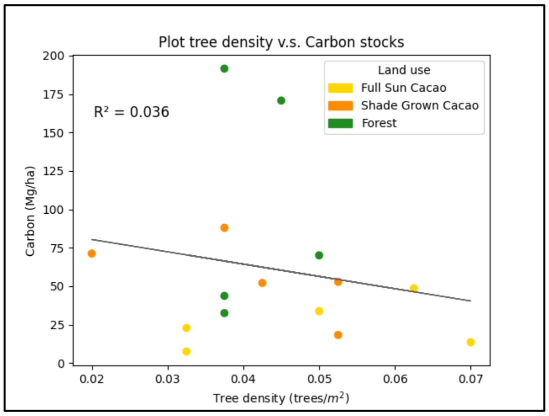
Table 1. *KW Results – Land use vs. abiotic and biotic variables*

Variable	**p-value**
Elevation	0.22091
Aspect	0.0871609
Tree density	0.829579
Canopy density	0.0552896
Max canopy height	0.0898153
Species richness	0.00982019
Shannon Index	0.00373503

When implementing linear regression models to compare these factors with carbon stocks, I found that elevation, tree density, canopy density, and aspect were not correlated with carbon stocks as evidenced by low r-squared values depicted in Figure 4. However, species richness, Shannon Index, and maximum canopy height were all moderately positively correlated with carbon stocks as evidenced by moderately high r-squared values depicted in Figure 4. As shown in Figure 4, species richness, Shannon Index, and maximum canopy height increased across land uses, with full sun cacao having the lowest values and forest having the highest.

Figure 4. *Linear regression models comparing carbon stocks to abiotic and biotic variables*





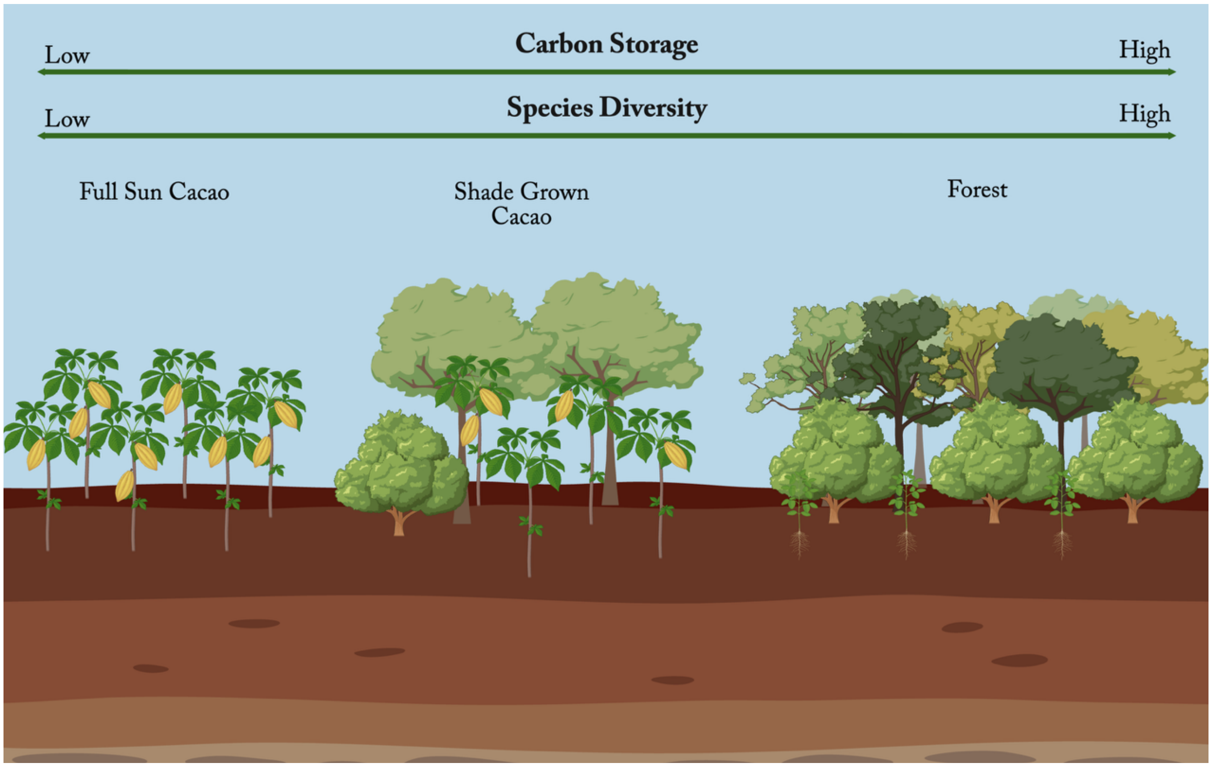
After running a multiple linear regression using Shannon Index, aspect, and tree density as independent variables, I concluded that these variables were responsible for nearly 60% of the variance in carbon stocks from the Multiple R-squared value given in Table 2. The F-statistic p-value was less than 0.05, meaning that the overall model is statistically significant and appropriate for the data. Shannon Index was the only variable with a p-value less than 0.05, meaning that it was the only statistically significant variable in terms of explaining differences in carbon stocks.

Table 2. *Results of Multiple Linear Regression Model*

Variable	**Significance**
Shannon Index p-value	0.00368
Aspect p-value	0.06471
Tree density p-value	0.93978
Multiple r-squared	0.5985
F-statistic p-value	0.01515

As depicted in Figure 5, the statistical results of this study demonstrate that carbon stocks and species diversity varied significantly across land use type, and that increased species diversity corresponded to increased carbon stocks.

Figure 5. *Carbon storage and species diversity across land use types*



5. DISCUSSION

5.1 Relationship between land-use type and aboveground tree carbon stocks

Shade grown cacao stores significantly more carbon than full sun cacao, and similar amounts of carbon to forest. At the same time, forest stores nearly twice the amount of carbon as shade grown cacao on average. This is primarily explained by cacao's limited storage of carbon as compared to forest and other fruit trees. While cacao trees can reach 20-25 m in height under natural conditions, they typically only reach 3-5 m in height in agricultural systems (Almeida & Valle, 2007). In this study, cacao trees had lower heights, diameters, and wood densities than other species on average. These variables are all directly related to biomass and thus carbon storage. The shade grown cacao plots stored more carbon than the full sun cacao plots because they had a higher proportion of larger and denser tree species with higher biomass, yet they stored less carbon than the forest plots because they incorporated 36.5% cacao trees, which are smaller and less dense than forest tree species and thus have lower biomass and store less carbon.

This trend is consistent with the findings of relevant literature. Other studies observed carbon stocks of 17 Mg ha-1 in monoculture cacao farms and 100 Mg ha-1 in shade grown cacao farms (Rajab et al., 2016). This was explained by the incorporation of shade trees, which comprised 57-78% of the total biomass carbon in the shade grown farms of this study (Rajab et al., 2016). Additional studies also found higher carbon stocks in shade grown cacao farms than in full sun cacao farms, which was explained by higher carbon storage in non-cacao trees (Schneidewind et al., 2019). Shade tree inclusion is the primary driver behind higher carbon stocks in shade grown cacao systems, and cacao trees themselves store very little carbon as compared to shade trees (Dawoe et al., 2016; Norgrove & Hauser, 2013).

5.2 Relationship between biotic and abiotic factors and aboveground tree carbon stocks

5.2.1 Abiotic variables

This study does not demonstrate any correlation between abiotic environmental variables and carbon stocks, nor does it demonstrate any significant variance in abiotic environmental variables across land-use types. This study shows that elevation does not significantly influence carbon stocks because the study was conducted over a narrow gradient of elevation. This study did not take place over a wide enough gradient for elevation to influence carbon stocks. Carbon stocks decrease with increasing elevation; however, this is true over wider elevation gradients than the gradient examined in this study. For example, one study concluded that temperature drives variation in AGC in secondary forests in the Ecuadorian Andes over a 3000 m gradient (Pinto et al., 2023). Another found that AGC decreased with elevation along a 2050 m gradient (Phillips et al., 2019). However, both studies took place in the tropical montane forests of Ecuador, whereas this study took place in the tropical lowland forests of Ecuador under a 399 m gradient. Another study also examined a 399 m elevation gradient and similarly did not find significant variance in biomass, suggesting that 399 m is an insufficient elevation gradient to observe differences in biomass and carbon storage (Torres et al., 2019).

Topographic aspect was not correlated with carbon stocks, there was no significant difference in aspect across land-use types, and it was not found to be significantly related to carbon stocks by the linear mixed effects model. This study demonstrates that topographic aspect does not significantly impact carbon stocks. Topographic aspect can be an important factor impacting tree growth, so it is reasonable to assume that it could affect carbon stocks (Fekedulegn et al., 2003). However, other studies indicate that in equatorial regions, there are no consistent differences in the response of vegetation to aspect (Holland & Steyn, 1975). It is likely that aspect did not influence carbon stocks in this study because it took place close to the equator, and thus aspect did not significantly impact solar energy received.

5.2.2. Biotic variables

Overall, forest structure variables did not impact carbon stocks in this study. Tree density, canopy density, and maximum canopy height did not differ significantly across land uses (P = 0.829579, P = 0.0552896, and P = 0.0898153, respectively), and they were not driving factors for changes in carbon stocks. While tree density has been shown to impact carbon stocks in other studies (Osei et al., 2022), it was not a driving factor in determining carbon stocks in this study due a lack of significant variation in tree density across land uses. It is possible that there was insignificant variation across land use types due to the rule of self-thinning. As forests grow, trees compete for resources such as light, water, and space, and forests eventually reach a density limit, which represents the forest's carrying capacity (Long et al., 2025). As forests continue to grow, this carrying capacity changes, and the maximum density of trees that can possibly be supported in a given area can decrease, leading some individuals to die and the forest to self-thin (Long et al., 2025). In addition, the Law of Constant Final Yield states that when forests reach high densities, biomass production eventually levels off and remains constant due to competition for resources (Cavalieri et al., 2022). It is likely that tree density did not vary across land use types because these plots were made up of fully grown trees and could have already reached their carrying capacity and constant final density and biomass.

Similarly, canopy density and maximum canopy height did not impact carbon stocks in this study due to a lack of variation between land uses. Maximum canopy height was moderately correlated with carbon stocks across plots, but it did not vary significantly across land uses. While average tree heights seemed to be different across land uses, the maximum canopy height likely did not vary because even full sun cacao plots tended to incorporate at least one other species of tree that was often much taller than the cacao trees, leading the maximum canopy height to be higher than the average height. Because of this lack of significant variation across land uses, these variables did not significantly impact carbon storage. Increased tree height can positively influence biomass and carbon stocks (Chave et al., 2005), but there was not enough variance in maximum tree height between land uses in this study for it to be a significant reason for carbon stock variance.

The variance in carbon stocks between land uses can be more accurately explained by differences in species richness and diversity. Species richness varied significantly between land uses and was positively correlated with carbon stocks. Species richness was correlated with carbon stocks likely because higher species richness reduces competition between species, resulting in higher productivity and larger tree size, which leads to higher biomass and thus higher carbon stocks (Liu et al., 2018). Additionally, higher complexity increases the efficiency of resource use in plants, which can increase biomass and thus carbon stocks (Mensah et al., 2018). Shannon Index also varied significantly between land uses, was positively correlated with carbon stocks, and was a significant positive predictor of carbon stocks in the multiple linear regression model. Similarly to species richness, it is likely that Shannon Index is related to carbon stocks because more diverse communities possess a greater variety of functional traits, allowing for more efficient utilization of resources, known as the complementarity effect (Sintayehu et al., 2020). In addition, human disturbances to ecosystems often reduce species diversity (Keck et al., 2025). The relationship between species richness, species diversity, and carbon stocks demonstrate that as land use diverges from natural forest due to human disturbance, carbon stocks decrease. The variance in carbon stocks between land uses can be interpreted as an increase in carbon stocks along a gradient of lowest to highest level of human disturbance, which is shown by changes in species richness and diversity across land use types. When planning future shade-grown cacao projects, species richness and diversity index should be prioritized if maximizing carbon stocks is a goal of the project because these variables are positively correlated with carbon stocks.

5.3. Implications for Natural Climate Solutions

These findings have wider implications for natural climate solutions because they demonstrate that implementing new shade grown cacao systems can be an impactful management strategy for increasing carbon storage in the Ecuadorian Chocó Rainforest while benefitting farmers and ecosystems in the long-term. Natural climate solutions are deliberate management actions taken to reduce or sequester GHG emissions. Strategically planting forest and fruit trees on existing full sun cacao farms to increase carbon storage, or converting degraded and abandoned farmland to shade grown cacao to increase carbon storage can be natural climate solution strategies in the Chocó Rainforest region of Ecuador to mitigate climate change by storing higher quantities of carbon than full sun cacao, and by providing co-benefits and improving farmer livelihoods by increasing cacao health and stability in the long term.

Shade grown cacao has significantly higher carbon stocks and is closer in carbon stocks to forest than full sun cacao, and it can also improve cacao farm health in the long term. Planting cacao under shade can drive more productive cacao yields long term by the reducing stress on cacao plants caused by radiation intensity and evaporative demand while also increasing system stability (Rajab et al., 2016). Shade grown cacao can also improve cacao health through natural pest control due to provision of habitat for pest predators and by increasing soil nutrients with litterfall and reducing soil erosion (Rajab et al., 2016). In full sun cacao systems, soil nutrients are rapidly depleted, and soils can become unproductive after about 30 years (Amponsah-Doku et al., 2022). However, shade grown cacao systems remain productive for longer than full sun cacao systems due to the natural fertilization provided by shade trees through litterfall (Amponsah-Doku et al., 2022). Shade grown cacao systems can also promote moisture retention and can decrease erosion because shade trees reduce the impact of heavy rainfall and intense sunlight on the soil of the system (Biloa et al., 2025). Shade grown cacao can also provide diversified income for farmers because fruit trees that can bring in additional income sources are often planted in shade grown cacao systems (Allen et al., 2024).

Numerous studies have investigated the economic viability of shade grown cacao for smallholder cacao farmers. Full sun cacao maximizes cacao yield in the short term, and shade grown cacao can produce lower yields of cacao beans when compared with full sun cacao (Solarte-Soto et al., 2025). However, it is possible to increase cacao bean yield while adding shade trees when the proper arrangement of trees is utilized in a shade grown cacao system (Waldron et al., 2015). In fact, removing all shade trees from a system may decrease cacao bean yield (Waldron et al., 2015). Moreover, shade grown cacao systems are likely to have more stable and productive cacao bean yields in the long term as compared to full sun cacao systems due to lower physiological stress on the plant (Rajab et al., 2016). Cacao agroforestry systems can also yield higher total revenues and necessitate lower total costs than full-sun monoculture cacao farms due to the addition of by-crops such as bananas or plantains and reduced need for fertilizers and herbicides, and they can have a higher return on labor than full sun monocultures (Armengot et al., 2016). Furthermore, the benefits of shade grown cacao on biodiversity can improve the stability of cacao crops. Full-sun cacao systems are less resistant to pests due to low biodiversity (Mattalia et al., 2022). In contrast, shade trees can increase a cacao system's resistance to pests by providing habitat for species that prey on the herbivore species that harm cacao plants (Bisseleua et al., 2013).

Many studies have evaluated whether cacao agroforestry systems could further generate income for farmers by generating carbon credits in the voluntary carbon market. In Ghana, there is substantial opportunity to develop REDD+ carbon crediting projects based on shade grown cacao, which can benefit smallholder farmers through additional income and diversified crops while contributing to Ghana's REDD+ efforts (Dawoe et al., 2016). In Peru, carbon crediting has been found to increase the profitability of shade grown cacao systems when carbon is priced at 7 USD/Tn CO_2 e with a maximum of a 70% increase in profitability when carbon is priced at 40 USD/Tn CO_2 e (Goñas et al., 2024). One study examining cacao agroforestry systems in the Chocó Rainforest of Ecuador finds that improving the efficiency of shade grown cacao systems combined with carbon credit payments and eco-label payments could help promote the implementation of shade grown cacao systems and ensure their success for farmers in the long-term (Waldron et al., 2015). Carbon credit projects could potentially be a feasible way to encourage shade grown cacao systems in this region. Additionality can be proven for new projects because numerous studies such as this one demonstrate a significant increase in carbon from full sun cacao to shade grown cacao systems.

Verra, the world's leading voluntary carbon crediting agency, currently has 23 projects in its registry designated as "agroforestry" using the Agriculture, Forestry, and Other Land Use (AFOLU) methodology. Two of these projects are cacao agroforestry, and both are located in South America. "Sustainable Agroforestry Cacao Meta" in Columbia, is an Afforestation, Reforestation, and Revegetation (ARR) project that is converting degraded land into shade grown cacao systems by planting new cacao and shade trees (BACAO SAS, 2025). "Shade Coffee and Cacao Reforestation Project" in Peru is another ARR project that is converting abandoned or degraded farmland into cacao and coffee farms with forest cover (Desmarais, 2025). Verra also has a third project in the pipeline for verification that would take place in Brazil. Plan Vivo, another leading voluntary carbon crediting agency, currently has 16 projects designated under their "agroforestry" methodology. Three of these projects, located in Indonesia, Madagascar, and Guatemala, involve integrating cacao with shade cover trees (Plan Vivo, 2026). These projects set a precedent that it is possible to generate carbon credits from shade grown cacao, showing that carbon crediting projects could be a viable way to encourage the expansion of shade grown cacao as an alternative to full sun cacao.

6. CONCLUSIONS AND RECOMMENDATIONS

Reaching the Paris Agreement goal of limiting climate change to 1.5 ºC above pre-industrial averages will require aggressive removal of carbon dioxide from the atmosphere. Natural climate solutions can contribute to this goal through management actions that rely on and enhance nature's existing abilities to remove carbon from the atmosphere and store it for long periods of time. This study examines the relationship between land use and carbon stocks in the Ecuadorian Chocó Rainforest, and it examines the relationship between abiotic and biotic factors and carbon stocks. This study concludes that shade grown cacao stores significantly more carbon than full sun cacao. Shade grown cacao stores less carbon than forest, but not significantly so in this study. In addition, this study finds that increasing species richness and diversity significantly increases carbon stocks, and it recommends that future shade grown cacao implementation projects prioritize high species richness and diversity to maximize carbon storage. Restoring forest is a clear way to increase carbon storage in previously deforested land and increase biodiversity, but shade grown cacao should also be utilized as a natural climate solution through the planting of fruit and forest trees on existing full sun cacao farms and the conversion of abandoned and degraded land to shade grown cacao as an alternative to full sun cacao, due to its ability to store significantly higher quantities of carbon than full sun cacao while diversifying farmers' income, increasing biodiversity, enhancing long-term stability and productivity of cacao crops, and providing numerous ecosystem co-benefits such as water quality improvement and soil health improvement. Shade grown cacao also has the potential to generate additional income for smallholder farmers through carbon crediting projects.

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