RC AGROFOREST BASELINE CARBON REPORT

Ilhéus, Bahia, Brazil
2023

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Executive Summary

The implementation of agroforestry systems can help reverse climate change while simultaneously providing the world with climate-positive food, ingredients, and timber. Agroforestry systems can also increase farmer income and create habitat for biodiversity. The present study aims to measure carbon removal in agroforestry systems at “Resgate Climático” farm, a pioneering agroforestry association in Brazil. In order to monitor carbon sequestration in future years, we begin now with a baseline carbon stock measurement, measuring both below ground (Soil Organic Carbon) and aboveground living biomass. We measure carbon stock in one agroforestry system with 0.854 hectares. The system studied was planted in 2022 and it combines fruits with precious wood timber species, palm trees, bananas and natural regeneration.

The results showed that the “Resgate Climático” (RC) or “Climate Rescue” (in English) Agroforestry System (AFS) has a mean of 29.70 CO2 tons of CO2 eq./ha in the ABG component, which means that it has a high potential to increase the aboveground carbon stock in the next years of the project lifetime.

The Arapyaú Institute, when surveying the stock of aboveground carbon, observed that the average value between some properties was 242 tons of CO2 eq. per hectare in “Cabruca” agroforestry systems. That said, we also proved the importance of the soil in stocking carbon, mainly in the beginning of an AFS project. At the present moment, while the agroforestry systems are young, about 80% of the total carbon is in the belowground biomass.

The carbon stocked in the agroforestry system was equal to 157.03 tons of CO2 equivalent/ha. Multiplying these values by its respective area we have 134.1 tons of CO2 equivalent sequestered in the RC agroforestry system.

These results already suggest that the implementation of agroforestry systems by Resgate Climático and other farms has enormous potential in helping mitigate climate change. As the agroforestry systems develop, they reduce net GHG emissions while also providing other ecosystem services and high-quality foods.

01 | Introduction

Global warming has been a scientific consensus since the 1990s when the United Nations Framework Convention on Climate Change (UNFCCC) was created, and the Kyoto Protocol was established as an international treaty that committed state parties to reducing greenhouse gas emissions. The Kyoto Protocol implemented the objective of the UNFCCC to reduce the onset of global warming by reducing greenhouse gas concentrations in the atmosphere. Before that, in 1988 the Intergovernmental Panel on Climate Change (IPCC) was created by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The objective of the IPCC is to provide governments at all levels with scientific information that they can use to develop climate policies.

Climate change is an urgent and potentially irreversible threat to human societies and all life on Earth and the hu- man-made CO2 emissions have not slowed down in recent years. In recognition of this, the overwhelming majority of countries around the world adopted the Paris Agreement at the 21st Conference of the Parties (COP21) in December 2015, the central aim of which includes keeping the global average temperature rise this century as close as possible to 1.5 degrees Celsius above pre-industrial levels.

The UNFCCC supports a complex architecture of bodies that serve to advance the implementation of the Convention, the Kyoto Protocol and the Paris Agreement. It provides technical expertise and assists in the analysis and review of climate change information reported by Parties and in the implementation of the Kyoto mechanisms.

It also maintains the registry for Nationally Determined Contributions (NDC) established under the Paris Agreement, a key aspect of the implementation of the Paris Agreement.

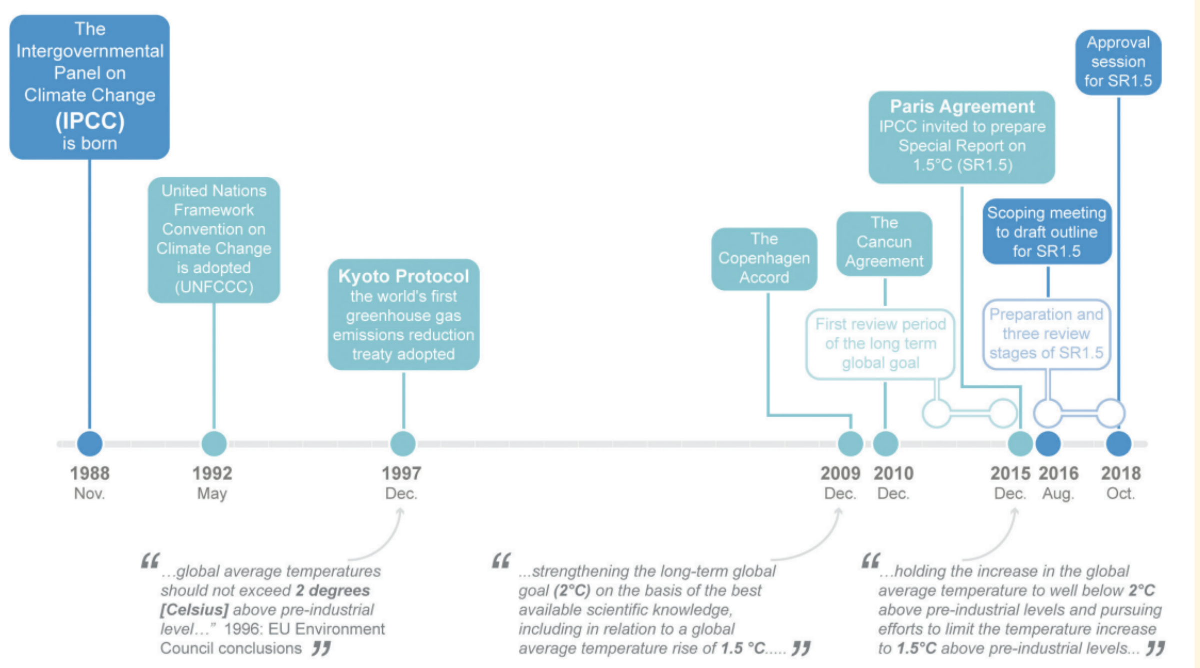

Figure 1 - Relevant events of international climate negotiations (IPCC Report, 2018).

Human-induced warming has already reached about 1°C above pre-industrial levels. By the decade 2006–2015, human activity had warmed the world by 0.87°C (±0.12° C) compared to pre-industrial times (1850–1900). Given that global temperature is currently rising by 0.2°C (±0.1° C) per decade, human-induced warming reached 1°C above pre-industrial levels around 2017 and, if this pace of warming continues, would reach 1.5°C around 2040.

While the change in global average temperature tells us about how the planet as a whole is changing, looking more closely at specific regions, countries and seasons reveal important details. Since the 1970s, most land regions have been warming faster than the global average, for example. This means that warming in many regions has already exceeded 1.5°C above pre-industrial levels. Over a fifth of the global population live in regions that have already experienced warming in at least one season that is greater than 1.5°C above pre-industrial levels.

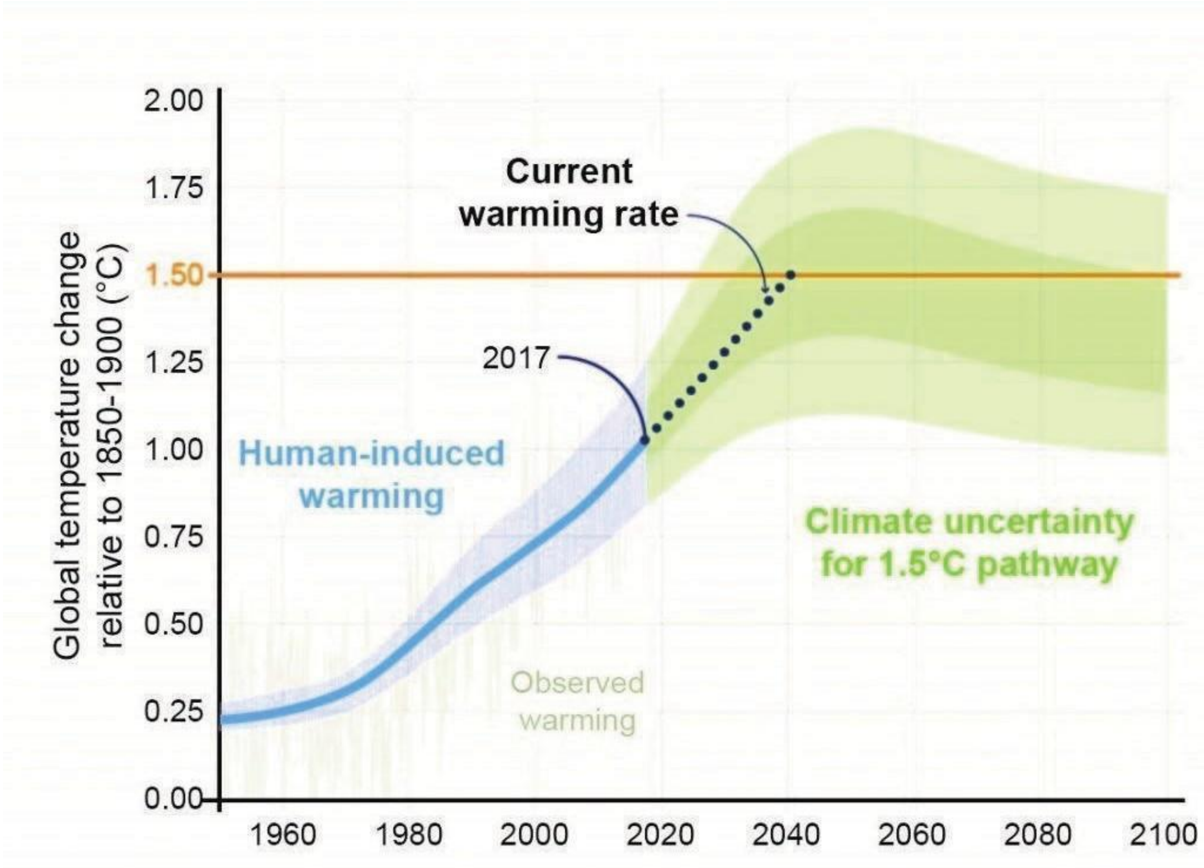

Figure 2 - Human-induced warming (IPCC Report, 2018).

The Kyoto Protocol applied to seven greenhouse gasses listed: carbon dioxide (CO2), Methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), nitrogen trifluoride (NF3). Nitrogen trifluoride was added for the second compliance period during the Doha Round. Carbon dioxide emissions are the primary driver of global climate change and it is widely recognized that to avoid the worst impacts of climate change, the world needs to urgently reduce emissions and increase the sequester of it.

The Brazilian strategies to mitigate climate change include the reduction in deforestation in the Amazon and the Cerrado, restoration of grazing land, change in agricultural practices, reduction in energy consumption (energy efficiency, alternative energy sources, etc), stabilization of the share of renewable energy sources in the energy matrix, increased use of biofuels, etc. This presents challenges at the federal, state and municipal levels for Brazil, for both public and private sectors.

There is also a growing interest in the role of different land-use systems in stabilizing atmospheric CO2 concentration. Primary attention has been given to forests, which account for 45% of terrestrial carbon stocks and are responsible for 17% of annual emissions through deforestation. It is, however, notable that trees in other land systems such as farmlands have great potential for sequestration because of their spatial extent. Recent initiatives have emphasized the importance of improving and understanding the ecosystem functions and services of agroforestry systems, mainly within carbon sequestration and biodiversity issues.

02 | RC Agroforestry Systems

Agroforestry is a general term for systems that integrate cultivated trees and agriculture. There are different kinds of agroforestry, including silvopastoral (trees and animals), agrisilvicultural (trees and agriculture), and agrosilvopastoral (trees, agriculture, and animals). These can all be great options for increasing carbon sequestration and thus reducing or even eliminating the overall carbon footprint of agriculture.

In addition to the climate regulation function (through carbon sequestration), trees in agroforestry contribute to soil protection, water regulation, enhancement of local climate conditions, soil carbon sequestration, reduced impacts on natural forests and other environmental benefits (Kerr et al. 2022) as biodiversity habitat.

Lastly, not only does agroforestry help mitigate climate change, it also helps farmers prepare for it. Agroforestry systems outperform traditional exposed agriculture in extreme weather events such as drought, floods, heat, and frost. This is because the climate inside forests is naturally more moderate than outside.

For cocoa cultivation we can list some adaptation and mitigation strategies aligned with the climate vulnerability of the south Bahia region:

1) The use of improved genotypes;
2) The use of polyculture systems (e.g. consortium, agroforestry and afforestation);
3) Higher density of planting;
4) Intelligent and ecological management of spontaneous plants.

In this context, the agroforestry projects executed by the association Resgate Climático (RC) presents a valuable strategy for mitigating climate change and ensuring resilience in the face of imminent global warming through the establishment of cocoa production intercropped with native and exotic trees and fruits with different ecological and economic functions. RC is working to mitigate climate change and produce agroforestry cocoa and other products while increasing quality. The present study aims to estimate the potential of the RC agroforestry project to sequester carbon.

a. System Analyzed

The present study focuses on analyzing the sequester of carbon in the RC agroforestry systems with cocoa as the main crop. RC is located in the municipality of Iheús/BA (figure 3). This is one of Brazil's established agricultural producing regions, especially for cocoa. Under these conditions, soil in the region has become degraded. Ilhéus has a tropical climate. In Ilhéus there is a lot of rain even in the driest month. This climate is considered to be Af according to the Köppen-Geiger climate classification. In Ilhéus, the average annual temperature is 23.9 °C | 75.0 °F. The annual rainfall is 1325 mm | 52.2 inches. When carrying out a carbon inventory it is important to know because of the Carbon Stock difference in the litter and soil components in each season of the year. Due to the decomposition process of the litter in the soil being accelerated by water, the tendency is that in rainy seasons organic carbon will be more concentrated in the soil, while in dry seasons the tendency is greater organic carbon concentration in the litter. That said, it is important that all subsequent carbon inventories are carried out around the same time of the year as this baseline report inventory, which was in February. RC farm is located in the Atlantic Forest biome.

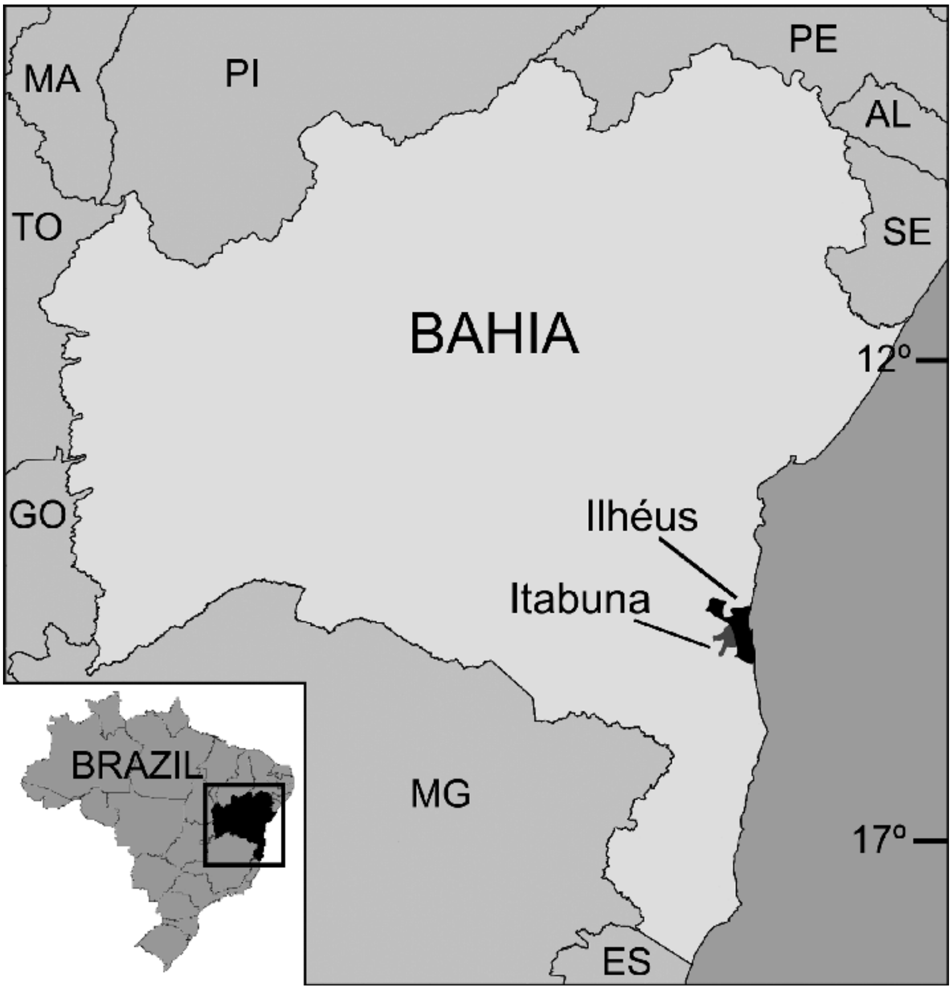

Figure 3 - Location of Ilhéus municipality.

The land cover situation of the city where RC farm is located is shown in figure 3.5. To analyze the changing in land cover in this region, 6 years were analyzed and compared, between 2015 and 2021 (figure 3. 5 shows the tree cover loss of the city of RC farm between 2015 and 2021). In this analysis it is possible to check the diminishment of forest areas over the region and the increase of farming lands. The land cover situation of the RC farm region study was based on Global Forest Watch.

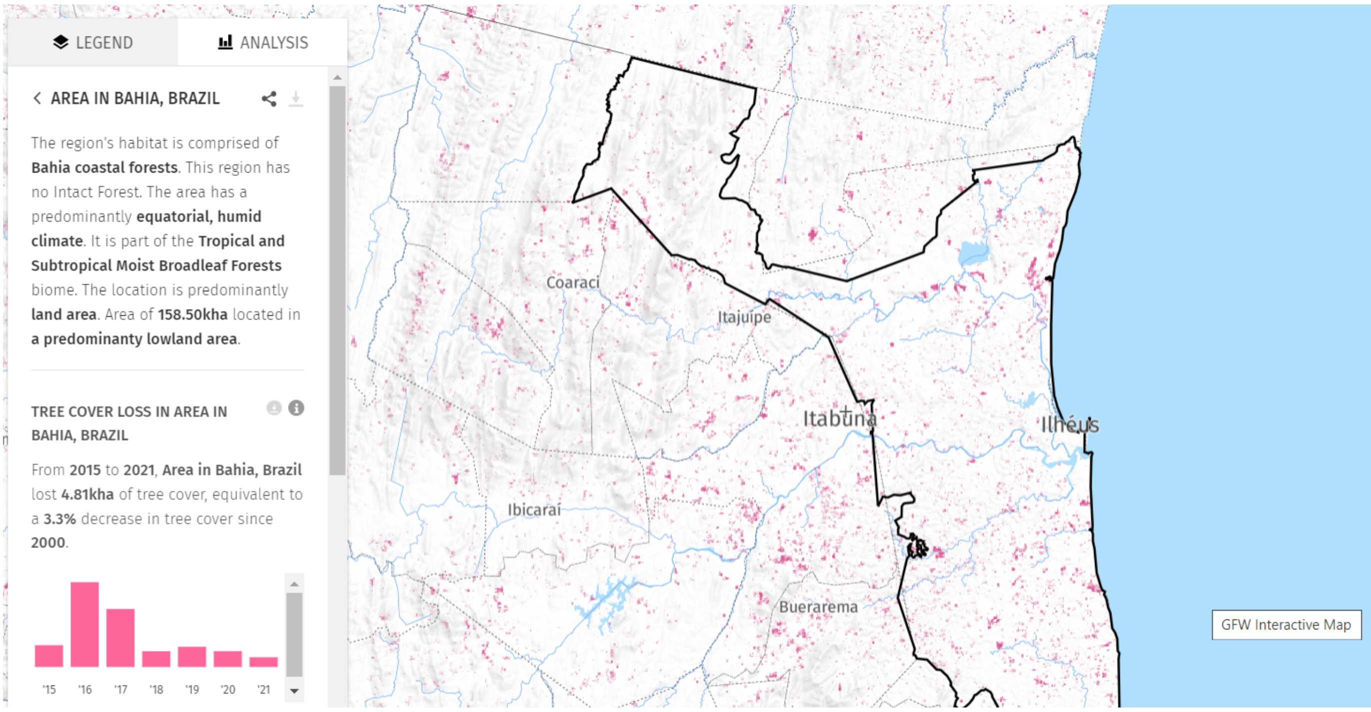

Figure 3.5 - Tree cover loss between 2015 and 2021 in the RC farm region. 3.3 % of the whole area of interest is not forest anymore and from 2015 to 2021, Ilhéus lost 4.81kha of tree cover.

Both for plot stratification and for effectively inventorying carbon, it is important to understand the history of use and management of different stands. Management, fertilization, planting and stand information are listed below:

Agroforestry System (AFS) information:

- Total area - 0.854 hectares;
- Area name - “Talhão G”;
- Avocado, banana and timber trees (Khaya grandifoliola, Cedrela fissilis, Handroanthus serratifolius, Hymenaea courbaril, Cordia trichotoma, Inga edulis, Spondias pinnata, Bowdichia virgilioides) planting date - July/2022
- Cocoa Planting Date - it will start in july/2023
- Organic Compost Application - 0 tons;
- Pure Manure Application - 2 tons;
- Cover Crop Seeding - some plants of feijão guandu (*Cajanus cajan*), gliricídia (Gliricidia sepium) and margaridão (*Tithonia diversifolia*) distributed in the area
- Land use before planting - cassava cultivation and then initial natural forest regeneration

System	Spacing between cocoa/banana plants inline [meters]	Spacing between cocoa/banana lines [meters]	Spacing between trees inline [meters]	Spacing between trees lines [meters]
RC AFS (Talhão G)	3	6	3	6

Table 1 - Spacing of RC’s Agroforestry System.

Figure 4 - Satellite imagery of RC farm location. The Agroforestry System area considered in the carbon estimation is shown in the opaque green polygon with a red border.

03 | Courageous Land Agroforestry Carbon Measurement Methodology

The methodology we used was developed by Courageous Land. The estimation of the total carbon stock in the agroforestry system of RC was divided into three steps: Stratification, Sampling and Data Interpolation.

a. Stratification

Stratification is the process in which the land is divided into smaller areas considering key variables that are relatively homogeneous and considering one variable that is heterogeneous (which can be, for example, above and belowground biomass). This process is extremely important because it makes the project less expensive. The cost of laboratory analysis and hours of labor can be high and stratification helps reduce sampling needs while maintaining scientific rigor.

The stratification process is divided into 3 steps:

I. Reconnaissance;
II. Selection of sampling parameters;
III. Choose a strata location.

I. The reconnaissance of the farm is crucial because it allows the methodology's applicant to visually analyze the land and check the heterogeneities. This step of the stratification is necessary to produce pre-sampling maps (preferably using a GIS) to guide the applicant when choosing the strata position.
Another important output of the reconnaissance step is the judgment for the best size plot. The plot's area must be big enough to capture all the key sampling parameters of each plot, making the heterogeneities explicit.

II. The selection of key sampling parameters is made after the reconnaissance of the land. At this point, the applicant already has auxiliary maps and notes about the local

heterogeneities. These heterogeneities can be related to orography, number and mortality of trees, presence of shrubs and others. This step is aimed at dividing continuous data (for example above and belowground biomass) into discrete categories. And as this grouping step can be subjective, it is indispensable to rank the key factors into the importance of their effect on separating the area into homogeneous categories.
Once the ranking list is done, the key differences of each stratum must be documented to reinforce the reason for being classified into distinct strata. GIS maps and pictures of the land can be used as evidence.

III. After the stratification is completed, it is necessary to choose the location of the plot, randomly or systematically within each stratum. In the RC project, the plots are permanent, which means that the next carbon measurements will be taken in these areas.

The random location can be achieved using GIS sampling techniques and the systematical approach of locating the plots can be done manually based on step II. Figures with the plot's location are indispensable in the report.

It is important to note that there is no maximum or a minimum number of strata during the stratification process once the heterogeneities of the key factors are captured by each stratum.

b. Sampling

The capacity of the land (above and below the ground) to capture carbon differs in different biomes (Scharlemann et al. 2014; Mukul et al. 2020) and within each biome, each tree (Brown and Iverson 1992; Chave et al. 2005; Parron Padovan et al. 2017) and soil types (Paradelo et al. 2015) have different characteristics implying different carbon sequestration capacities.

Thus, the sampling of every component (trees, shrubs and soil) must be based on peer-reviewed articles. And, preferably, from literature where the study was made in places close to where the methodology is being applied due to the local similarities, such as soil, climate and the land's species. The idea behind following peer-reviewed articles' methodologies of measurement is to correctly apply the biomass equations provided by them.

For aboveground living biomass specifically, the applicant can find species-specific equations for certain components of the project area or use general equations of a group of species (e.g. tropical forests or palm trees located in Atlantic Forest biome) that fits into the project needs.

Once the biomass of each component is known, it is necessary to get the amount of carbon corresponding to the biomass of each plant. Following IPCC guideline (IPCC 2006), the carbon fraction of the plant's biomass is equal to 47%, thus, the biomass values are multiplied by 0.47 to get the amount of carbon (kg of C) stored.

However, the CO2 equivalent is the desired unit and to achieve this, it is needed to multiply the carbon content (kg of C) by 44/12 to get the mass of CO2 equivalent (United Nations Framework Convention on Climate Change (UNFCCC) 2013).

For the soil carbon component, two measurements must be taken: Bulk density and percentage of soil organic carbon (SOC) at a depth of 20 cm. The bulk density sample is collected from the center of the soil plot and sent to the laboratory. To get the soil carbon stock, about four samples were taken from distinct points within the plot's area and then mixed inside a clean bucket to capture all the local nuances.

For example, if the soil plot's area has one tree and a line of a crop, it is suggested to get one sample from below the tree's canopy, another from the soil between the line of crop and the tree and, the last one, from the crop's line, avoiding biases due to very small scale nuances like organic matter accumulation due to a land's slope.

c. Data Interpolation

Once the aboveground biomass and its carbon content is measured, plus soil organic carbon is measured, it is possible to discover how much carbon is being stored per unit of area. To achieve this it is necessary to interpolate the data from the plots to the whole area represented by them.

The interpolation can be done with numerous techniques but the most straightforward is the Inverse Distance Weighting (IDW) (eq. 1) (Isaaks and Srivastava 1989), where the interpolation is made based on the distance between the plot samples and unsampled location and nearby observations have heavier weight (Collins and Bolstad 1996; Hartkamp et al. 1999).

IDW needs an input called inverse distance weighting power (P). Changing P implies different outputs, leading the applicant to test a set of values of P to be able to choose correctly which one brings spatial interpolation with smaller errors.

$$\mathrm{IDW}(L_1) = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{d_i^P}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i^P}\right)} \quad (1)$$

From equation 1, zi is the value of position i, di is the distance between the location L1 (the place where we want to estimate the interpolation value) and the position i, P is the inverse distance weighting power and n is the total number of data collected from the plots.

$$\text{RMSE} = \sqrt{\frac{\Sigma\left(Y' - Y\right)^2}{N}}$$

$$\text{MAPE} = \frac{1}{N}\Sigma\left|\frac{Y' - Y}{Y}\right| * 100$$

$$\text{nSEE} = \frac{1}{\underline{Y}}\sqrt{\frac{\Sigma(Y' - Y)^2}{N}}$$

(2) (3) (4), respectively.

Where Y’ is the model’s output and Y is field data for the same location, Y is the mean of all Y values and N is the number of data measured in the field.

04 | Results

a. Stratification

The reconnaissance of the RC agroforestry system was done in February 2023, when the orography aspects, the tree density and mortality were considered to capture heterogeneities in the system.

For the aboveground living biomass, 4 permanent plots of 15x15 meters were deliberately located to capture all the heterogeneities within the AFS. For soils, circular permanent plots with 5 meters of diameter were set inside the aboveground plots because it was considered that the key variables to stratify the ABG are very similar to the BLG once the system' plots are all managed equally. The main vertex of each plot was georeferenced with GPS and the cardinal position of that vertex was always southwest. After the materialization of this vertex in the field, a measuring tape was stretched 15 meters to the north and 15 meters to the east with the aid of a magnetic compass.

Coordinates of the main vertex of each plot:
P1: 14°34'42.4"S; 39°05'36.2"W
P2: 14°34'41.9"S; 39°05'37.5"W
P3: 14°34'43.5"S; 39°05'39.3"W
P4: 14°34'43.7"S; 39°05'41.4"W

b. Carbon Estimation

Once the stratification step is complete, it is then necessary to calculate the carbon content in each plot.

I. Aboveground stock of CO2

In order to estimate the aboveground living biomass, it is necessary to measure what is necessary to achieve the total biomass for each plot following the literature. Thus a set of equations were used with different inputs. For cocoa, for example, the equation needs the diameter at 30 centimeters (d30) and the total height (alt) (equation 5) (Somarriba et al., 2013), for palm trees, the diameter at breast height (DBH) was used (equation 6) (Velasco, 2009), for general trees, the DBH, tree height (h) and wood density (WD) were used as input (equation 7) (Alves et al. 2010), for shrubs (used as hedgerows) the height (h) and crown diameter (CD) were used as inputs (equation 8) (Conti et al. 2019) and for bananas, the DBH was used as input (equation 9) (Walter Steenbock et al., 2013).

Equations 5 to 9 were used to estimate the biomass
(B) for each plant groups separately, which is necessary to get the total biomass of each plot, to then interpolate to the whole agroforestry area.

Equations:
$\text{Log } B = (-1.684 + 2.158 * \text{Log}(d30) + 0.892 * \text{Log}(alt))$ (5)
$B = (\exp(-1.497 + 2.548 * \ln(DBH)))*0.6$ (6)
$B = \exp(-2.977 + \ln(WD * DBH^2 * h))$ (7)
$B = \exp(-0.37 + (1.903 * \ln(CD)) + (0.652 * \ln(h)) * 1.403)$ (8)
$B = \exp(-3,98414 + 2,20132*\ln(DBH)$ (9)

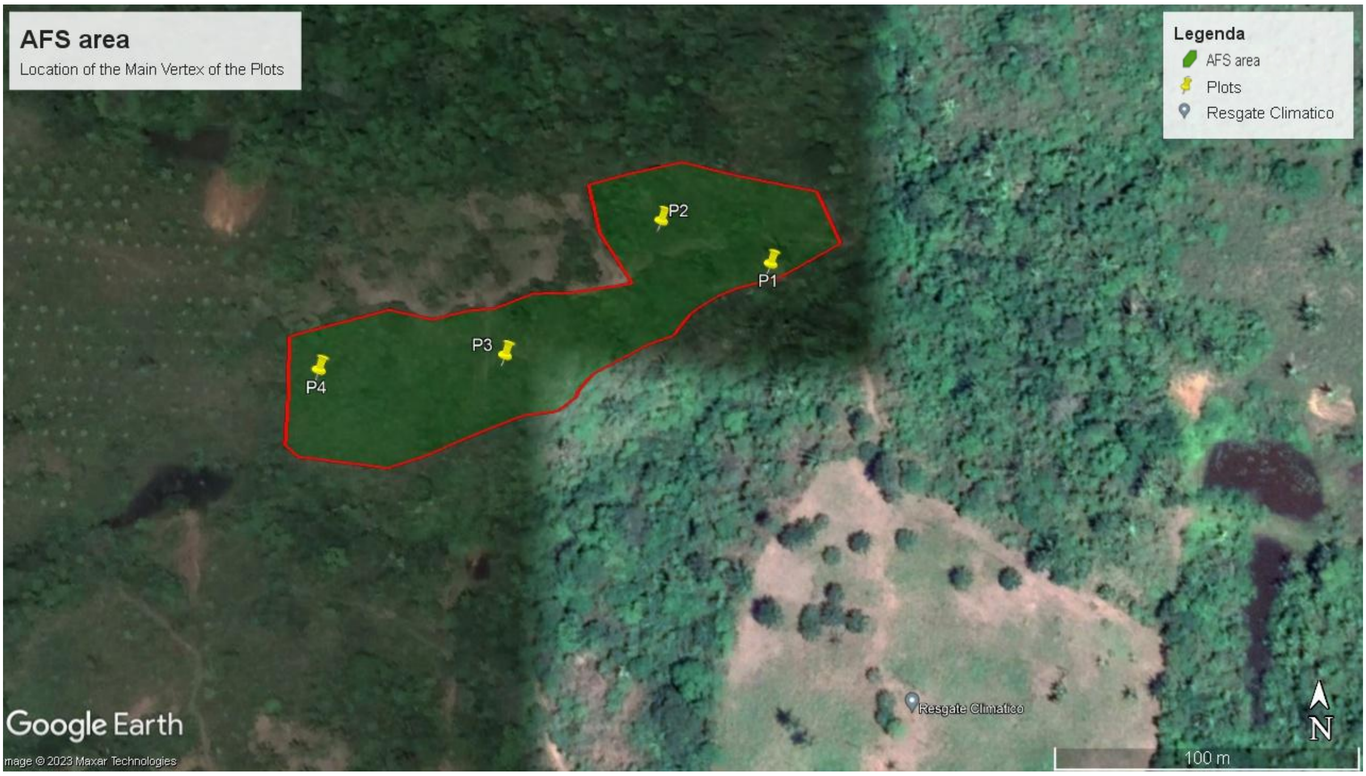

Figure 5 - Agroforestry system studied at RC farm with the (15x15 meters) plots' main vertex (southwest) location.

All the plants were measured following the methodology of peer-reviewed articles (Somarriba 2013, Velasco 2009, Alves et al. 2010 and Conti et al. 2019) to get the biomass equations (equations 5 to 9) and transform to carbon content [CO2 equivalent] for each group of plants in the different plots (Figure 6).

From Figure 6, it is possible to visualize the differences between the carbon stocked by each component in the plots of the systems analyzed. For an individual of a given tree species to enter the inventory, it must have at least 5 cm of DBH (Diameter at Breast Height). As the planting was still very recent, no individual of the planted species reached the inclusion factor and, therefore, they were not counted here (only one banana). Furthermore, no shrubs were found in the plots. Therefore, this explains why in plots 1, 2, 3 and 4 of the RC AFS, aboveground carbon is 100% allocated in trees and palms from natural regeneration.

With the aboveground carbon sequestration calculated for the plots, it is time to interpolate this data into the boundaries used for the AFS. Four values of inverse distance weighting powers were tested (equation 1) during the leave-one-out cross-validation (LOOCV): 1.5, 2, 2.5 and 3.0. The values chosen were 2 for the AFS, the errors were smaller than the other interpolations' errors using the remaining power values, indicating fewer errors. In the maps of the data interpolated are shown the tons of CO2 equivalent/hectare (figure 7).

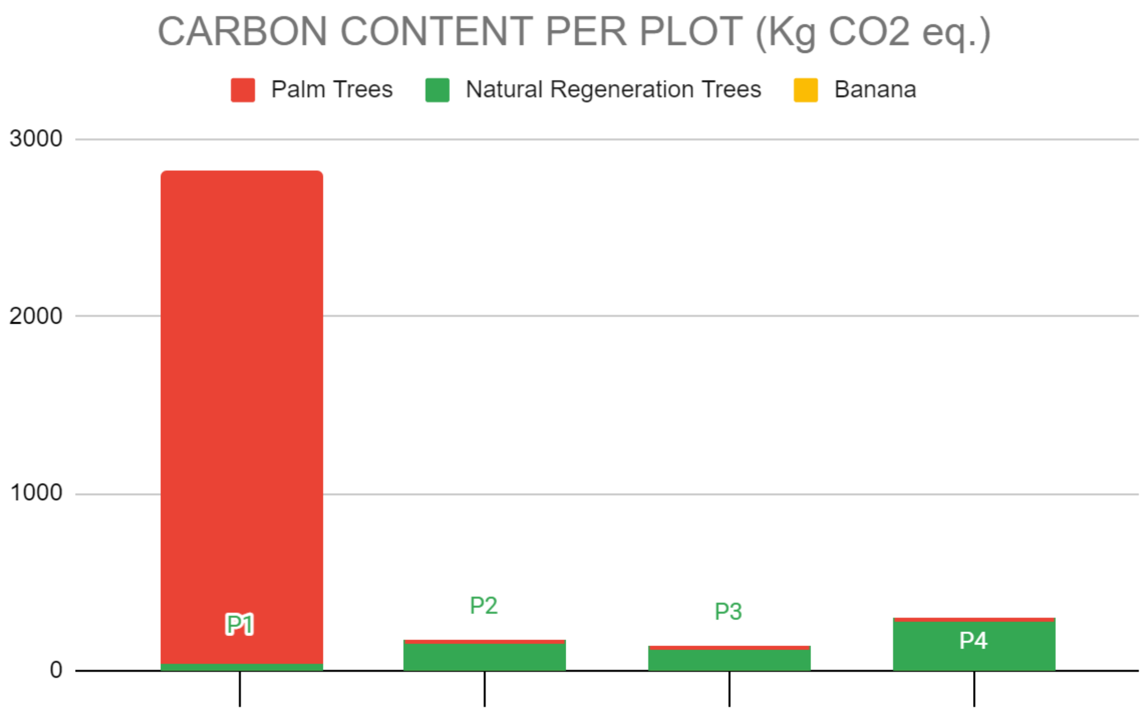

Figure 6 - Total aboveground stock of Co2 equivalent in each plot (P1, P2, P3 and P4) of the AFS analyzed [Kg CO2 eq. per plot]. The colors red, green and yellow represent the components of palm trees, natural regeneration trees and bananas, respectively.

In order to understand the agroforestry system efficiency in removing carbon, it is crucial to calculate the means of aboveground carbon stocked (table 2 and figure 7), and the total weight of CO2 equivalent (mean of the CO2 equivalent multiplied by its area).

CARBON CONTENT (Kg CO_2 eq.)				
Plant group / Plot	P1	P2	P3	P4
Banana	0	0	0	2,10
Natural Regeneration Trees	52,75	159,94	126,79	284,06
Palm Trees	2761,41	0	0	0
Cocoa	0	0	0	0
Planted trees	0	0	0	0
TOTAL PER PLOT (Kg CO_2 eq.)	2814,16	159,94	126,79	286,17
Kg CO_2 eq./hectare per plot	125073,96	7108,62	5635,00	12718,48
Ton CO_2 eq./hectare per plot	125,07	7,11	5,64	12,72
Mean CO_2 equivalent per hectare [tons of CO_2 eq./ha]	29,70			
AFS total area (ha)	0,854			
Total Weight of CO_2 equivalent [tons ofCO_2 eq.]	25,36			

Table 2 - ABG carbon content calculations.

Data Interpolation

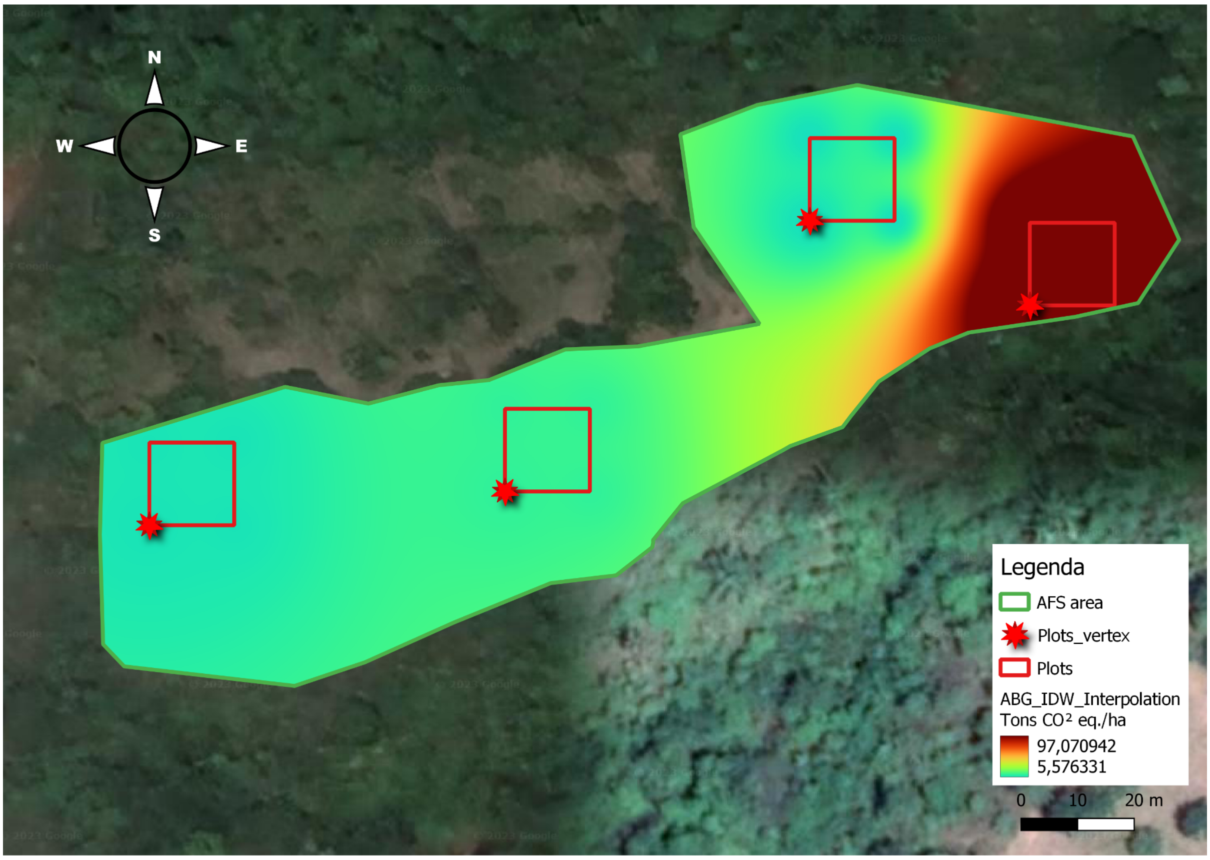

Figure 7 – Stock of Co2 equivalent [kg of Co2 eq./ha] from aboveground component of the RC AFS. [Map Software QGIS 3.22. Datum: UTM SIRGAS 2000 24S]

II. Soil Organic CO2 equivalent stock

To calculate the belowground stock of carbon dioxide, it is necessary to have the bulk density and the percentage of carbon in the ground. To access this data, some soil samples must be collected, some for the bulk density analysis and others for the carbon percentage analysis. Once the laboratory analysis is done, it is necessary to use the data for the percentage of carbon in the soil (%C) and bulk density (BD) (g/cm3) to get the Soil Organic Carbon (SOC) stock, then, we apply equation 10 and get the CO2 equivalent.

$$CO_2 \text{ Stock (tons of } CO_2 \text{ equivalent /ha)} = \%C \times BD \times \text{Soil Depth} \times 44/12$$
(10)

The soil depth is equal to 20 cm.
The stratification variables used in the belowground system are the same for the aboveground once the variables used in the stratification step for ABG can also distinguish areas with similar soil structures.

Four soil samples within each soil plot were collected, mixed and sent to the laboratory to determine the percentage of carbon. One sample was used to get the bulk density in the first 20 cm below the ground (located in the center of the soil plot) (table S2 in supplementary material). Thus, each plot has one value of carbon percentage and one for bulk density, totaling 4 data for each variable.
The same methodology used in the ABG component to select the best interpolation model is used for BLG. However, for the soil component, it is necessary to apply equation 10 first, and then calculate the error metrics.

The same four values used as inverse distance weighting powers in ABG carbon interpolation were tested in the cross-validation. The value chosen was 2.0.

The map of CO2 stock below the ground is shown in figure 8. Note that the AFS have a huge variation in their data, going from 82.92 to 174.08 tons of CO2 equivalent. It occurs due to the very local differences, especially because of the percentage of carbon (table S2).

CARBON CONTENT (Kg CO_2 eq.)				
Plot	P1	P2	P3	P4
CARBON CONTENT PER PLOT (Tons CO_2 eq./ha)	183,88	118,58	91,99	138,81
Mean CO_2 equivalent per hectare after interpolation [tons of CO_2 eq./ha]	127,33			
AFS total area (ha)	0,854			
Total Weight of CO_2 equivalent [tons of CO_2 eq.]	108,74			

Table 3 - Mean, area and total weight for the belowground component for the RC Agroforestry System.

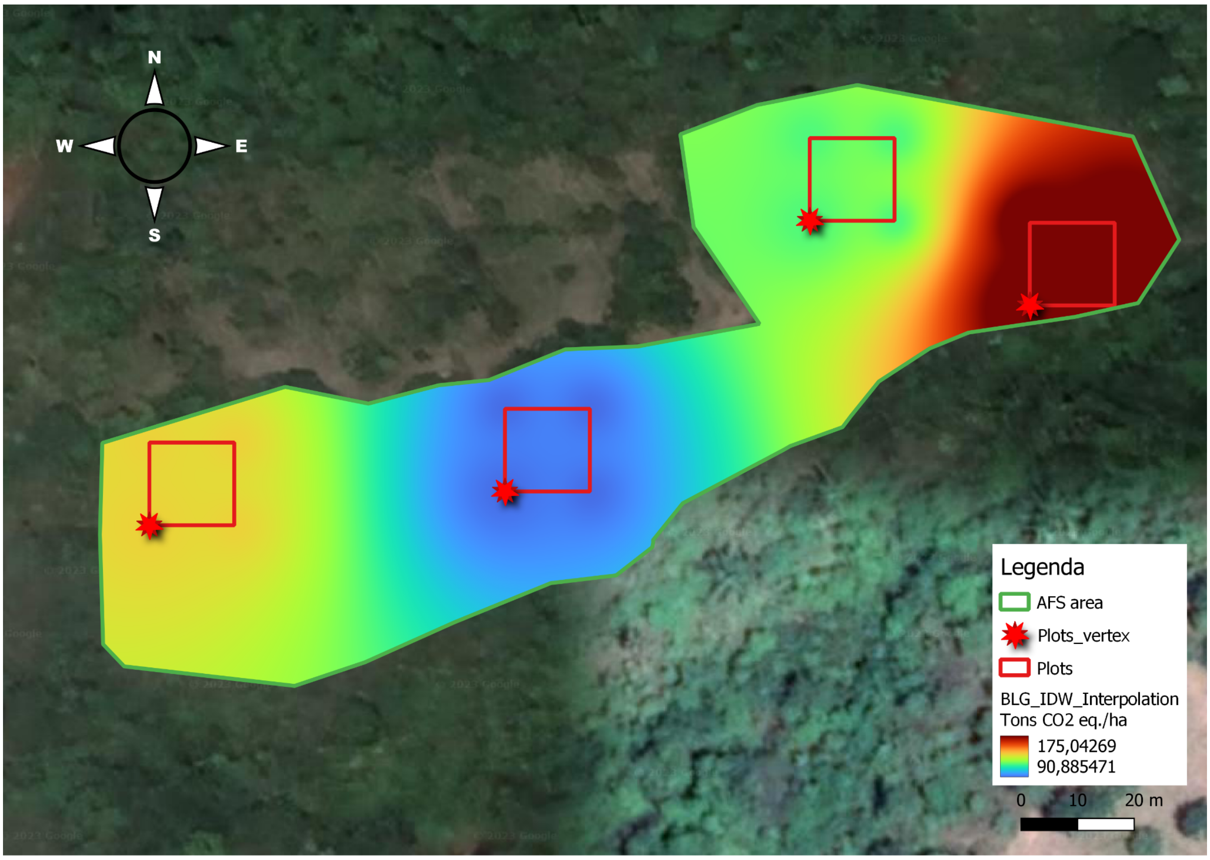

Figure 8 – Stock of Co2 equivalent [kg of Co2 eq.] from below the ground component of the RC AFS. [Map Software QGIS 3.22. Datum: UTM SIRGAS 2000 24S]

At this point, with the ABG and BLG carbon content measured it is possible to add these two components (tables 2 and 3) and quantify the total stock of CO_2 equivalent measured in the RC agroforestry system (table 4 and figure 9).

System	Mean CO2 eq. per hectare [BLG] (tons of CO2 eq./ha)	Mean CO2 eq. per hectare [ABG] (tons of CO2 eq./ha)	Mean CO2 eq. per hectare [ABG + BLG] (tons of CO2 eq./ha)	Area (ha)	Total Weight of CO2 eq. (tons of CO2 eq.)
RC ASF	127,33	29,70	157,03	0,854	134,10

Table 4 – Mean of Co2 equivalent for belowground (BLG) and aboveground (ABG) components, the area, and total weight of Co2 equivalent (from ABG + BLG) for the Resgate Climático Agroforestry System.

The efficiency of the soil in stocking carbon is higher than in the aboveground living biomass in the beginning of an agroforestry system project lifetime. Approximately 20% of the RC AFS total carbon was stocked by the ABG component, while 80% is due to the soil.

Approximately 134.1 tons of CO2 equivalent was stocked by the agroforestry systems. It is important to be clear that the amount of carbon shown in figure 9 is the mean CO2 equivalent per hectare calculated from the interpolation and multiplied by the AFS area.

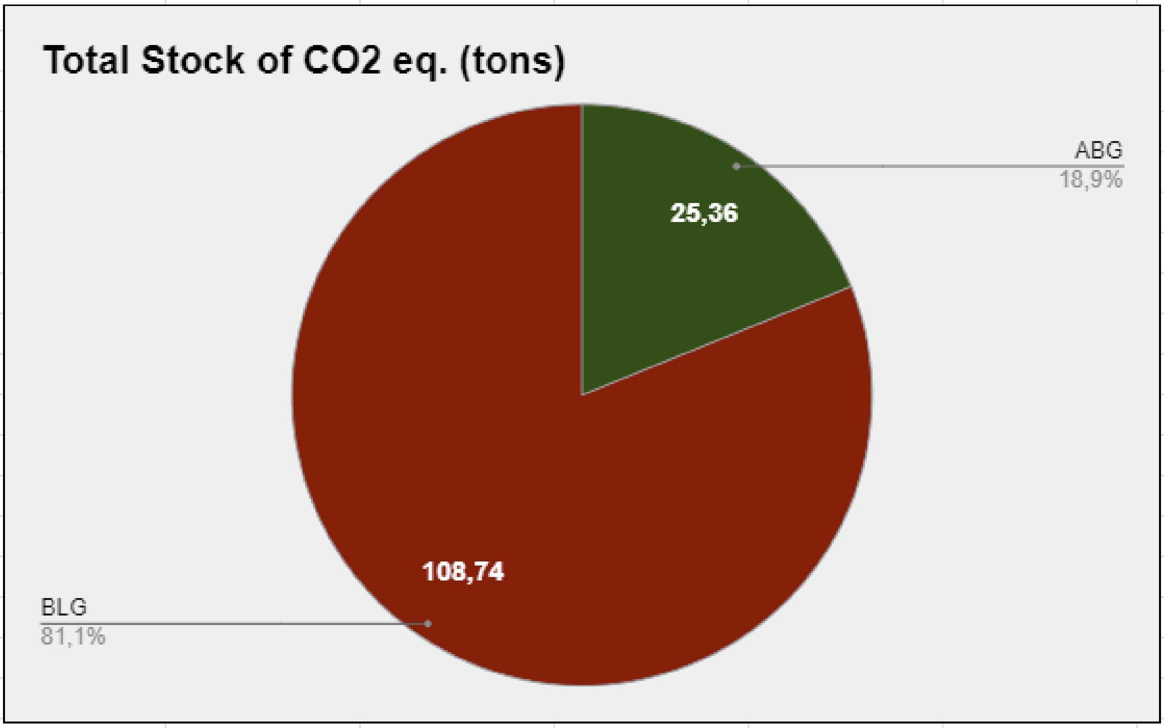

Figure 9 - Total weight of Co2 equivalent for RC AFS. The green color represents the ABG component stock and the brown color represents the BLG component stock.

05 | Final Considerations

The CO2 eq./ha stored in the cocoa plants themselves in RC's agroforestry system has not yet been accounted for because these plants will be planted in july/2023 and a lot of the bananas do not yet have the minimum diameter to be included in the equation (inclusion factor of 5 cm). Arapyaú studies showed that, on average, cocoa accounts for about only 40% of the total aboveground carbon in "Cabruca" systems. Beyond that, these "Cabrucas" systems are older than RC AFS, which shows that as RC's agroforest matures, the numbers will continue to rise. Cocoa plants themselves aren't the key carbon fixer in agroforestry systems, the trees are.

Beyond the comparison between similar studies about the carbon sequestration capacity in agroforestry systems with cocoa, it is also interesting to compare the capacity of capture between monoculture and more complex systems (like agroforests). Studies of monoculture and non-organic cocoa systems in the Kulawi valley in Central Sulawesi, Indonesia state, showed that the living aboveground biomass of the cocoa monoculture systems stored about 38,86 tons of CO2 eq./ha. These areas were 25 years post-implementation, with the spacing 3 m x 3 m (Abou Rajab et al., 2016). The RC Agroforestry System is only one year post-planting and already has 157.03 tons of CO2 eq./ha stored, with the spacing of 3 m x 3 m between cocoa and tree lines, which is higher than 25 years old monoculture and we just accounted the carbon stock in the natural regeneration trees because the trees planted were not with the minimum diameter yet.

In the current study, the soil component has 108.74 CO2 eq./ha (AFS implemented in 2022), in a depth of 20 cm. In agroforestry systems associated with Inga densiflora, in Costa Rica, in the layer between 0 and 40 cm, 408.06 tons of CO2 eq./ha was found (Hergoualc'h et al. 2012), while in 30 cm of depth in agroforestry systems in Peru, 370 tons of CO2eq./ha was measured in a system aged 15 years. Given these references and noticing that the depth analyzed in these systems are greater, which implies more carbon being quantified which does not mean the system necessarily, stock more carbon. Thus, we expect RC's system to sequester large amounts of carbon in the years to come as the systems mature.

When we think about another commodity like coffee, that it's another possible crop to grow in AFS, studies related to carbon sequestration in monoculture and non-organic coffee systems in Minas Gerais state had shown that the soils could capture from 183.33 to 333.66 tons of CO2eq./ha. These results showed that even younger, the agroforestry system of RC had shown a huge capacity of stocking carbon in the soils, being capable to sequester more than older agricultural systems.

The percentage of total carbon from ABG and BLG components differs from some peer-reviewed papers. Our study showed that about 20% of the total carbon stocked was captured by the ABG component, which is in line with some studies (Andrade et al. 2014; Ehrenbergerová et al. 2016; Nair 2012; Andrade and Zapata 2019). However, others show a lower amount of carbon stocked by the ABG component in agroforestry systems, with about only 10% (Ávila et al. 2001; Schmitt-Harsh et al. 2012; van Noordwijk et al. 2002; Häger 2012; Soto-Pinto et al. 2000; Hernández Vásquez et al. 2019; Dossa et al. 2008).

06 | Conclusion

The present study shows that RC Agroforestry System baseline carbon stock is 134.1 tons of CO2 equivalents, in which 25.36 are from ABG component and 108.74 from BLG component.

The adoption of ecosystem-based strategies (a type of management that increases the resilience and reduces the vulnerability of people and the ecosystem to climate change) is crucial to avoiding exceeding the limits of irreversible climate change effects. Beyond organic management, the implementation of agroforestry provides biodiversity, the addition of more organic matter to soils and creates more resilient crops in extreme events, while still being economically attractive (Kerr et al. 2022).

Resgate Climático has shown the potential of increasing carbon stock in plantations by adopting agroforests. This strategy can help to mitigate climate change while still providing cocoa, timber, fruits, superfoods and spices that all the world loves.

Agroforestry Project Development: Associação Resgate Climático

Agroforestry Carbon Measurement Methodology Development: Courageous Land (CL)

Guidance, supervision and review (Forest Engineer at CL company): Rafael Ciraqui

Thank you!

07 | References

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