Impact of shade-grown coffee and cocoa agroforestry in watersheds of the Dominican Republic

A STUDY BY THE NATURE CONSERVANCY'S NATURAL CLIMATE SOLUTIONS PROTOTYPING NETWORK

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Executive Summary

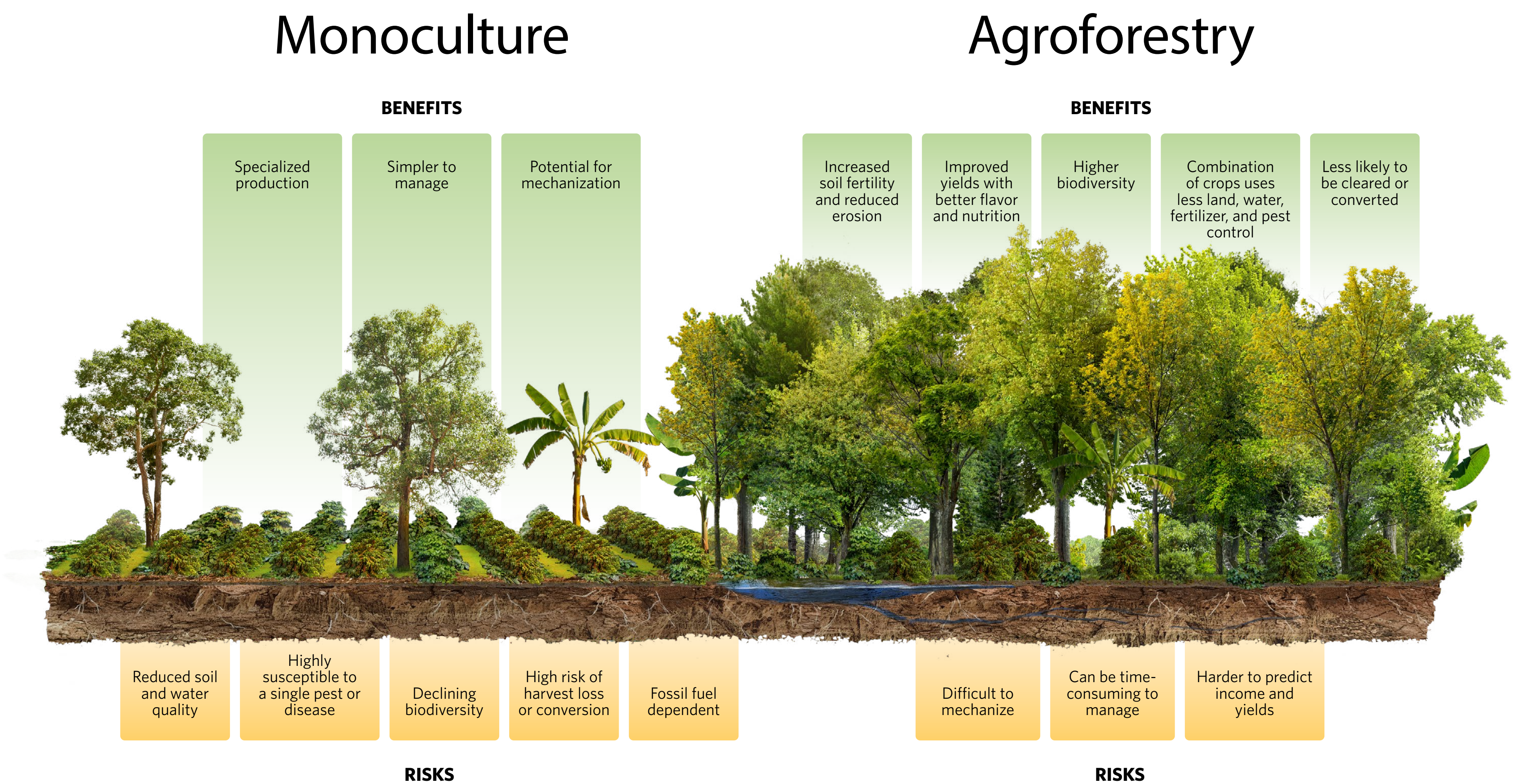
Coffee and cocoa agroforestry projects in the Yaque del Norte and Santo Domingo watersheds have proven to be quite successful in improving water quality and other measures of ecosystem function.

Agroforestry involves the intentional integration of trees onto cropland. As those trees grow, they sequester and store carbon, contributing to efforts to fight climate change. To assist the Dominican Republic government and the Yaque del Norte and Santo Domingo Water Funds in measuring how agroforestry impacts carbon, The Nature Conservancy (TNC) used remote sensing and field data collection to study the carbon stored in these agroforestry systems.

Our study provides the first estimates of carbon in Water Funds agroforestry sites, and can best be viewed as a baseline to use to measure carbon increases over time. Coffee and cocoa agroforestry sites are already storing an impressive amount of carbon per hectare given their young age (2 to 9 years old). High levels of variability make it challenging to draw conclusions about how much additional carbon agroforestry stores per hectare. However, when compared to pastures, coffee (80.70 +- 16.8 tCO_2e/ha YDN; 125.1 +- 31.2 SD) and cocoa agroforestry (44.9 +- 15.0 SD tCO_2e) had consistently more carbon storage. Many of the Water Funds agroforestry sites are only a few years old, with small, newly planted shade trees, which are poised for rapid growth over the next several years. Soil carbon in the 15-30 cm layer is also starting to show a trend towards a higher percentage of soil organic carbon in Water Funds-style agroforestry sites.

The carbon in all of our sample plots was driven by shade trees. In Water Funds agroforestry, shade trees are valued primarily for their non-carbon benefits, including the breadfruit, mango, lemon, and other food they produce, as well as the homes they provide for animals, for their ability to improve soil health and structure, and the large amount of water they filter as it travels from rainfall to rivers. In many ways, these carbon benefits come without any tradeoffs – and this is quite different from most other ways to reduce and remove carbon emissions. The figure below lists some of the benefits of adding shade trees.

We provide here a protocol that can be used by others to continue to collect carbon data in the field and to analyze it using free, open-source software. Over the coming year, we will compile a field manual that can be shared with others, including Water Funds beneficiaries who are eager for ways they can help to understand and measure the results of their investments. Our methods largely follow, and are compatible with, the Dominican Republic FREL (Forest Reference Emissions Level) report.



Our study reaffirms the importance of investing in continued Water Funds agroforestry interventions for their multiple benefits and to ensure the long-term storage of additional carbon. The Water Funds have built trust and respect in the communities in which they work, and are in continuous contact with farmers. As climate change continues to force those who work and own the land to adapt to storms, droughts, and other impacts, these farmers, and all those who have integrated trees into their ranches and farms, are demonstrating that sustainable land management is possible without sacrificing yield or socioeconomic benefits. Agroforestry as practiced by the Water Funds is beneficial for the environment, the farmers, and their communities. With our study, its carbon benefits are just beginning to be understood as well.

Introduction

Like many other small island states, the Dominican Republic is vulnerable to climate-related impacts: hurricanes, heatwaves, prolonged droughts, as well as disruptions in the water supply (Melendez-Ackerman et al., 2022). These impacts threaten the people and nature of the country. In forests and agricultural systems, the impacts of climate change can also reduce productivity, and therefore, producers' incomes. Climate change has added a new concern to watersheds where a long history of unsustainable land use practices has, in many cases, reduced soil fertility and quality, and affected the availability of water for human consumption.

In 2015, *The Nature Conservancy* (TNC), together with a group of local public and private stakeholders, established two Water Funds to contribute to water governance and channel financial resources to support the restoration and conservation of the Yaque del Norte, Nizao, Haina, and Ozama river basins that supply the cities of Santiago and Santo Domingo. After nearly a decade, landscape-scale and community-based interventions have led

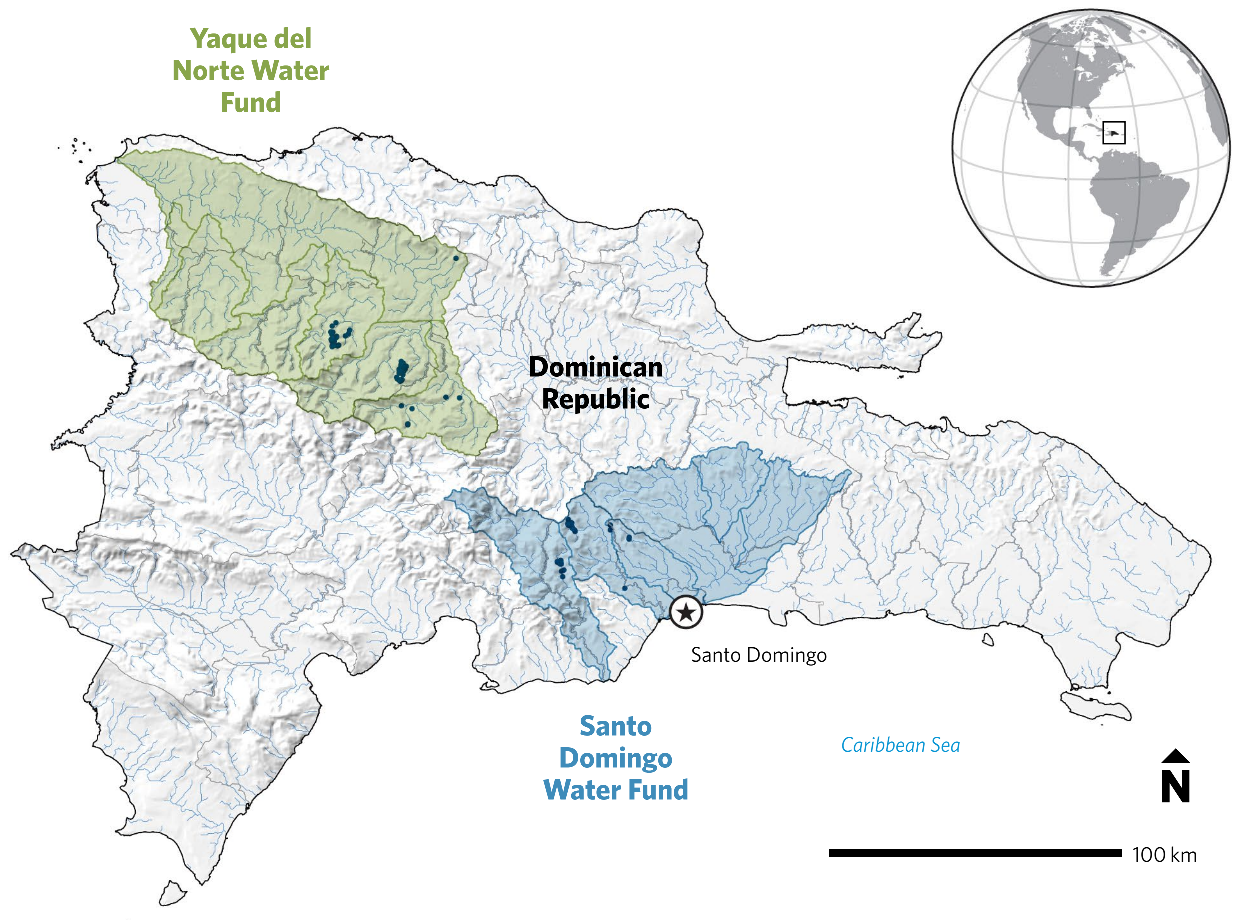


Figure 1. Location of the Yaque del Norte (above) and Santo Domingo (below) watersheds within the Dominican Republic.

to impressive improvements in water quality and quantity (see: https://fondodeaguayaque.org/, and https://fondoaguasd.do/). These interventions have also generated benefits for biodiversity, as well as more predictable and in many cases higher economic benefits for farmers and ranchers.

The Water Funds worked from the beginning to establish trust in these communities and to offer assistance without asking for much in return. Unsurprisingly, they were quickly able to expand throughout the subbasins. By the beginning of 2024, the two Water Funds had worked with more than 414 agricultural producers to improve the condition of more than 1,179 hectares of land (TNC, 2023). Since these programs are community-based, they adapt to the needs of each owner. Its proven track record of success has generated constant interest from new landowners who wish to enroll their lands in the Water Funds.

While the main objective of the Water Funds projects was to reduce surface runoff at the micro-watershed level, these projects also maintain or improve biodiversity, improve income and livelihoods of beneficiaries, and remove carbon from the atmosphere, thus contributing to the fight against climate change. These projects are examples of "natural climate solutions", ways to protect, better manage, or restore forests, farms, grasslands, and wetlands to reduce or remove carbon pollution from the atmosphere (Griscom et al., 2017). In recent years, there has been a worldwide surge of interest in natural climate solutions, and in understanding the magnitude of their carbon benefits. Executive Decree 541-20 of the Dominican Republic establishes the Measurement, Reporting, and Verification System for Greenhouse Gases (MRV) and requires that projects with carbon benefits, such as Water Fund interventions, report them. These benefits are tracked in order to contribute to the global accounting of greenhouse gases under agreements such as the Paris Agreement on climate change.

STUDY JUSTIFICATION

Quantifying the benefits of carbon from agroforestry systems, whether through satellite remote sensing or other remote images or through collecting data on the ground, is a significant challenge. There are still important knowledge gaps. There are no scientific publications that provide precise and quantitative estimates of carbon storage or sequestration in tropical agroforestry, such as the shade-grown cocoa and coffee practices used in the Dominican Republic. Similarly, although this report will address promising techniques using satellite data interpretation, current technology still does not allow for accurately calculating carbon reserves and land changes through remote sensing.

In an effort to address this and other knowledge gaps in agroforestry, peatland restoration, and blue carbon restoration projects, *The Nature Conservancy* (TNC) launched the *Natural Climate Solutions Prototyping Network* in 2022. Funded by the *Bezos Earth Fund*, the *NCS Prototyping Network* invited TNC programs to apply for funding and technical assistance. The proposal presented by the TNC program in the Dominican Republic was one of the 15 projects selected through a rigorous selection process. In 2023, a new scientist was hired to work on this project, as part of a larger team of TNC based in the USA that designed and carried out the work presented in this report.

The central objective of this project was to answer the question: What is the carbon mitigation impact of agroforestry restoration work implemented by the Water Funds in the Dominican Republic? Despite the limited availability of data, this project also considered the carbon benefits associated with reforestation and silvopastoral projects within the Water Funds areas. This report describes the methodology used, the results obtained during the field seasons of 2023 and 2024, and the lessons learned and recommendations for future initiatives derived from this work. We point out here, and we will reiterate throughout this report, that even if their carbon benefits are ignored, Water Funds projects provide enormous benefits. It is never appropriate to consider carbon as the only, or even the most valuable benefit of community-focused projects. The benefits for water, biodiversity, and livelihoods are well documented. Given that the carbon benefits of these initiatives have never been measured before, and now the law requires reporting on them, the intention of this report is simply to add an additional justification to continue and expand the work of the Water Funds in the Dominican Republic.

WATER FUNDS CONTEXT

The Yaque del Norte and Santo Domingo Water Funds work at a community level, directly with farmers, ranchers, or forest owners, to offer various types of interventions. "Intervention" refers to a change in land management and use compared to before enrollment in the program, which is offered at no cost to the owner/farmer/rancher. These interventions are illustrated in Figure 2 and are described in more detail below:

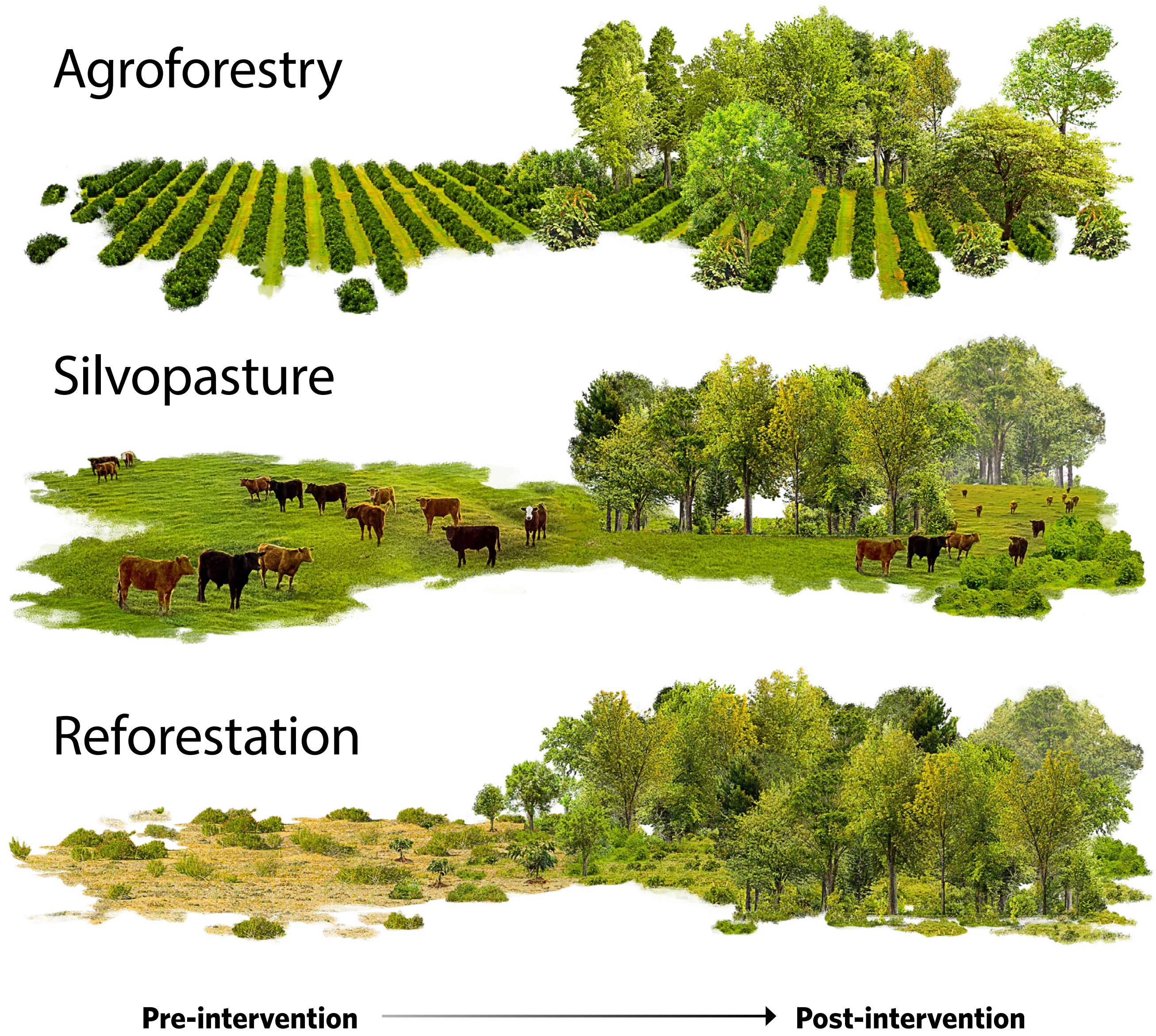
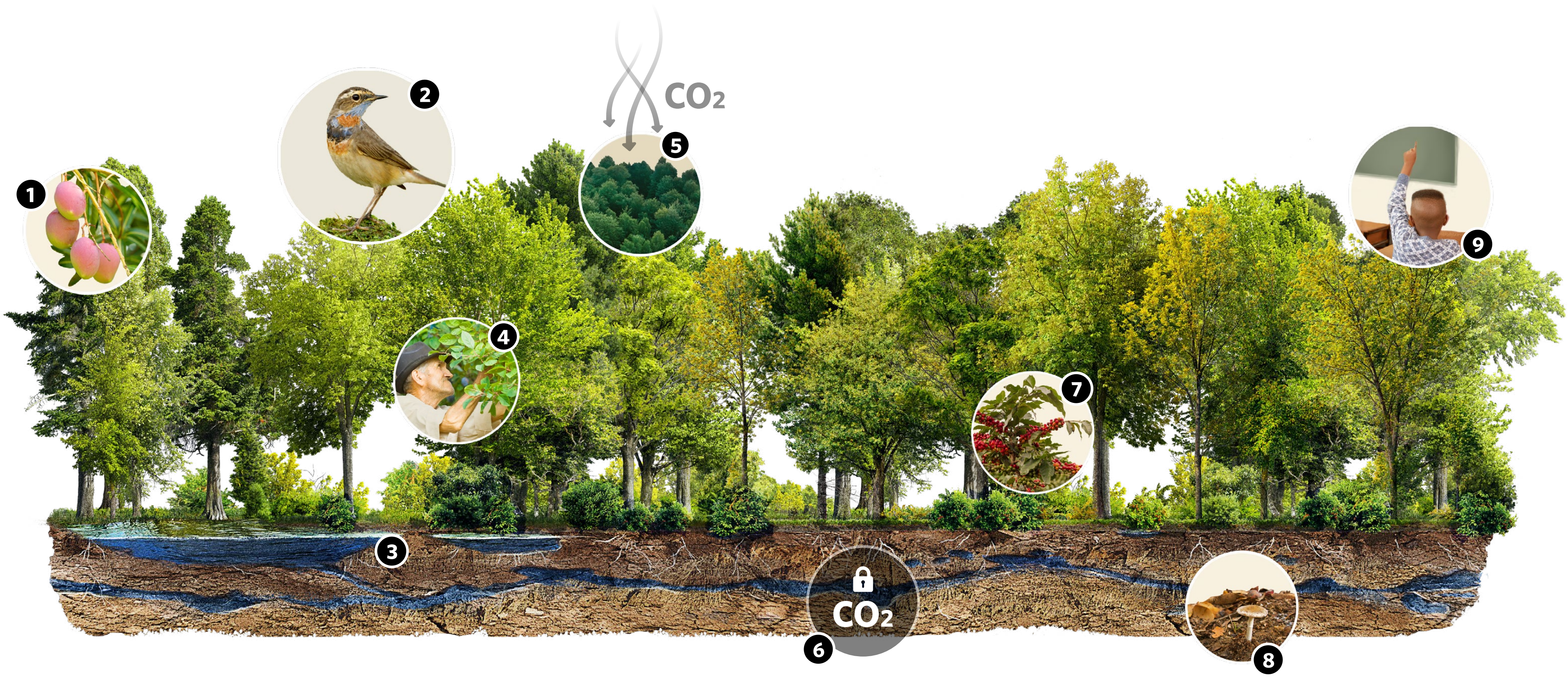


Figure 2. Different types of intervention within the Water Funds.

- **Agroforestry:**
  - Shade-grown coffee - A few years ago, in some areas of the Nizao and Yaque del Norte river basins, coffee production decreased considerably due to rust disease. As a result, owners considered converting their lands to livestock farming or other intensive agricultural uses. The Water Funds intervention replaces the ailing coffee plants with a new variety that has proven to be more resistant to coffee rust. At the same time, shade trees of various native species are planted, as well as other fruit trees of commercial interest such as mango, avocado, breadfruit, orange, and lemon, as well as native species such as cedar and mahogany.
  - Shade cocoa - In the basins of the Haina and Ozama rivers, a similar technique is used to replace areas of livestock or short-cycle crops (more harmful due to the slope of the soil) with cocoa plantations that include bananas to provide temporary shade during the first year of establishment.
  - In Figure 3, some of the benefits of agroforestry are illustrated.

- **Reforestation:** A mixture of coniferous and broadleaf species is planted on marginal lands such as abandoned agricultural lands, or along streambanks, to restore forest cover, improve infiltration, and reduce sediment runoff.
- **Silvopasture:** Much of the land used continuously for cattle grazing is degraded, resulting in lower productivity. Silvopasture, as practiced by the Water Funds, includes a combination of site-specific activities. These include rotating livestock through smaller paddocks delimited by living fences, planting protein-rich grasses and forages to reduce the amount of feed brought to the site, and planting of trees that serve as both forage and shade for the livestock. These are often combined with manure management, composting, and technical assistance to reduce the ecological impact of livestock farming.
- **Forest conservation:** A conservation agreement with the landowners to prevent land use change and logging of forest patches (for wood or to convert them into land for agriculture, livestock, or real estate development). Some forests are pine plantations close to logging, while others are forests with a diverse mix of species.

Although we have described previous interventions as specific pathways to natural climate solutions, it is worth noting that one of the strengths of Water Funds is that they adapt to the needs of each farmer and rancher. For example, a farmer could have shade-grown coffee planted in a part of his land, but also receive technical assistance and training to build and use organic waste composting on his estate or farm. For the purposes of this report, we focus on agroforestry systems, as it was one of the focal areas of the Natural Climate Solutions Prototypes Network. Readers may also be interested in the results of our programs in Brazil, Guatemala, and Ecuador, which are available on the NatureBase website.



1

Food security: Food for families to sell or consume.

2

Homes for wildlife: Protection for biodiversity.

3

Water quality: Sediment and other pollutants are filtered from water, increasing water quality.

4

Socioeconomic benefits: Nearly all of the farmers who adopt agroforestry practices continue using them.

5

Carbon sequestration: Trees remove pollution from the air, including carbon dioxide.

6

Carbon storage: Trees store carbon in their trunks, branches, and roots, and in wood.

7

Crop resilience: Shade and improved soil health increase the resilience of crops to climate change.

8

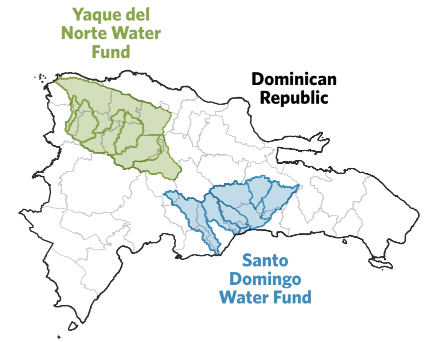
Soil health: Stronger root systems reduce erosion, hold moisture, and provide a source of nutrients and carbon to the soil, increasing soil health.

9

Community benefits: Local communities benefit from food, fiber, and wood for cooking and for furniture.

Figure 3. Description of the different benefits that agroforestry systems provide to communities and nature.

Methods



AREA OF STUDY

The interventions of the Water Funds occur in four watersheds: that of the Yaque del Norte (Yaque del Norte Water Fund - FAYN), and those of the Nizao, Haina, and Ozama rivers (Santo Domingo Water Fund - FASD). Within each basin, these sites are concentrated in a specific set of subbasins (see figures 4 and 5).

In the FASD basins (see figure 4), there are shade-grown coffee, shade-grown cocoa, reforestation, silvopasture, and forest conservation sites. On the other hand, in the FAYN basin (see figure 5), there are shade-grown coffee, reforestation, silvopasture, and forest conservation sites.

Thanks to the excellent record keeping by the Water Funds and TNC since the beginning of these projects, we have a map of all the plots under intervention. The Ministries of Agriculture and Environment also shared Geographic Information System (GIS) files of cocoa and coffee farms, and of forests, which we used in our experimental design.

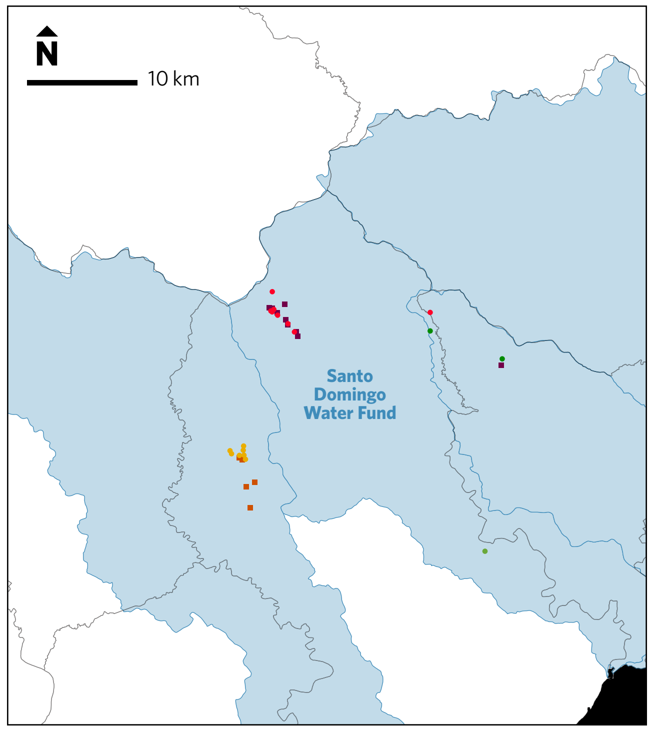


Figure 4. Spatial distribution of the sample plots located in Santo Domingo. Or consult the interactive map.

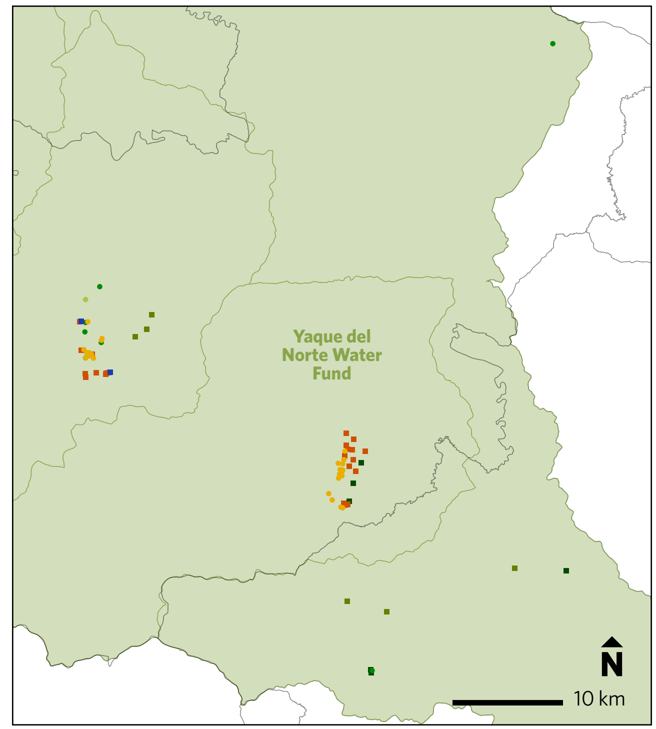


Figure 5. Spatial distribution of the sample plots located in Yaque del Norte. Or consult the interactive map.

EXPERIMENTAL DESIGN

To establish the experimental design, we considered four categories or types of Water Funds interventions: shade-grown coffee agroforestry (SAFCafé), shade-grown cocoa agroforestry (SAFCocoa), forest conservation (Conservación de bosque), and reforestation (Reforestación).

Each of these categories needed an appropriate control (reference). In the case of agroforestry systems, we assumed that randomly selected cocoa or coffee farms that were not registered in the Water Funds would be the most appropriate reference. (However, as pointed out below in the results and discussion sections, this assumption was most likely incorrect). Table 1 shows the number of sample plots of each type within the Water Funds. We randomly selected our intervention plots, and then matched each intervention plot with a reference field plot with the same type of soil cover (for example, cocoa plantation), type of soil, relatively similar elevation, and less than 2 km from the intervened plot. See: (pairing protocol).

Although the study focused on agroforestry, we also measured some plots of the other types of intervention. The reference sites for silvopasture intervention plots and reforestation were grasslands. Although these were not measured in the field, the 2018 FREL (Forest Reference Emissions Levels) report from the Dominican Republic provides estimates of carbon stocks in grasslands across the country (Ministerio Medio Ambiente, 2019). For forest conservation, we considered that the appropriate reference was a forest that had recently been subjected to logging, although an alternative approach would be to compare it with a plot where the forest had recently been cleared for development, grazing, or agriculture.

Type of intervention	Intervention plots	Reference plots	Total plots
SAF Coffee	33	27	60
SAF Cocoa	8	9	17
Forest conservation	9	6	15
Reforestation	3	6	9
Silvopastoral	0	2	2

Table 1. Summary of the number of plots in each watershed by type of intervention, as of July 2023.

FIELD PROTOCOLS

For this study, several field protocols were considered. We evaluated the proposals from the Food and Agriulture Organization of the UN (FAO), the REDD+ Cookbook (Japan), and the field protocols of Colombia and Peru (FAO, 2020; Hirata et al., 2012; Honorio Coronado and Baker, 2010; The Nature Conservancy, 2019). We also evaluated the protocols of various carbon offset registries, but it was considered that they had too little details and relied too much on modeling for our study. In general, we follow the FREL methodology of the Dominican Republic, with some modifications (Ministerio de Medio Ambiente y Recursos Naturales Unidad de Monitoreo Forestal Proyecto de Preparación de REDD+, 2017; Ministry of Environment and Natural Resources, 2017). Additionally, to perform the carbon estimations, we used the i-Tree ECO softwarefrom the U.S. Forest Service.

The detailed methods for field data collection and the data entry forms can be found in our Guide for Data Collection (TNC, 2023). Photographs were taken in most of our sampling plots to complement the data collection on aerial and soil carbon. In figure 6, a diagram of our field plots is shown.

Within each plot, we set up three subplots measuring 10 m x 10 m. We measured the diameter at breast height (DBH), the height of the tree,

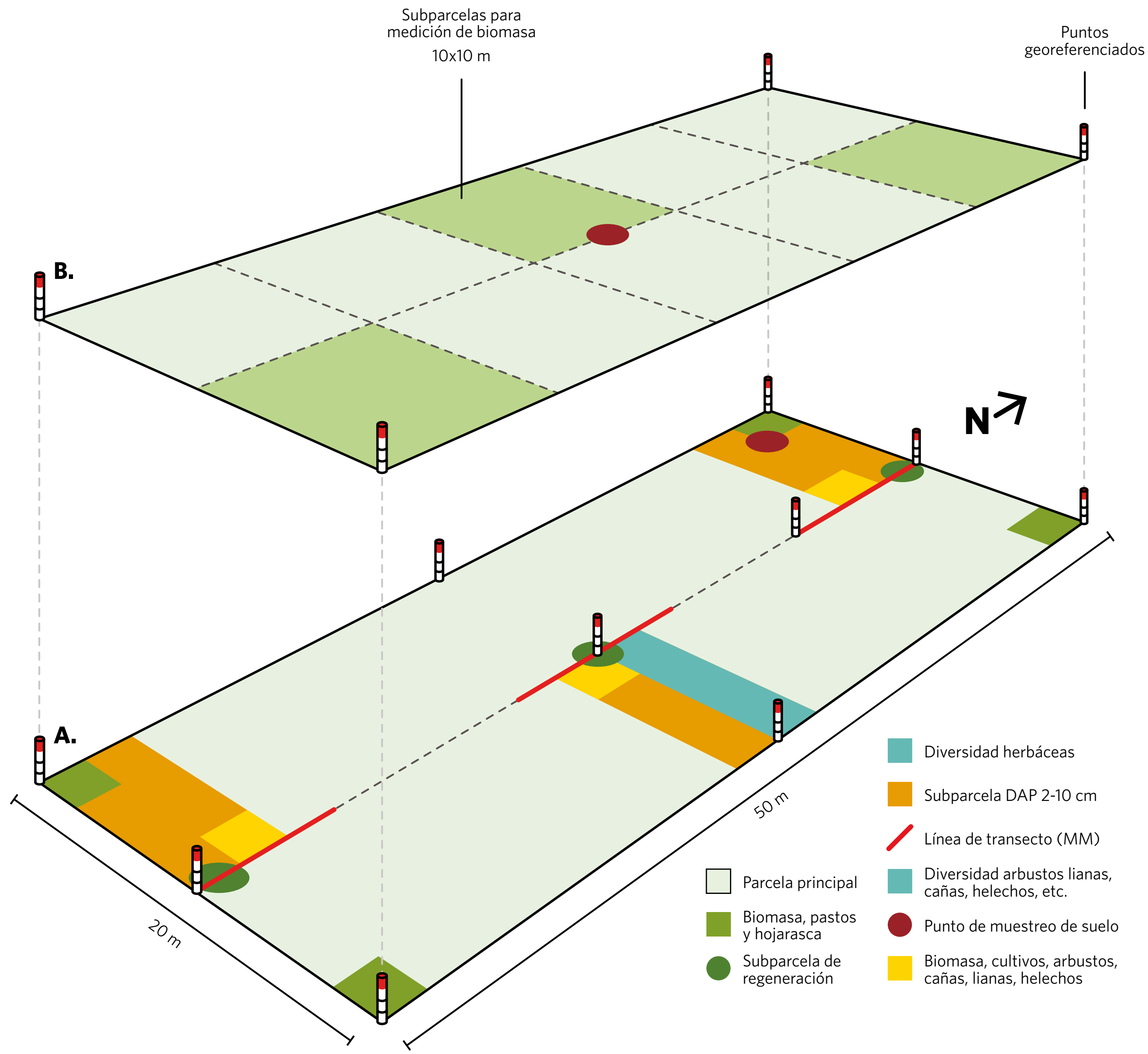


Figure 6. Design of the sampling plot from A. the FREL manual of the Dominican Republic, and B. modified plot design, with three subplots for data collection with the forest inventory.

the species, the condition of the canopy, and any branching or leaning of the trunk of each tree (crop or shade) present in those subplots. This differs from the FREL methods, which measure each tree in the entire plot, but use an average tree height and do not measure the diameter of smaller trees and shrubs. Some modifications to the FREL protocol were considered mainly for logistical reasons, as the time in the field to conduct the inventory was limited. Additionally, the topography of the sites made it difficult to establish a 20m x 50m plot with the same precision that we could achieve with a 10m x 10m plot (errors at the parcel level would influence the tree/crop density; any error in the total size of the plot would result in an error in the calculated density). Additionally, we decided not to measure litter, as it represents an average of 2 to 3% of the total carbon in the coffee and cacao plots of FREL.

Other adaptations were made due to the requirements of iTree. Each tree with a diameter of less than 2.54 cm (1 inch) was assigned the minimum diameter value of 2.54 cm in iTree. This means that we are very slightly overestimating the carbon stored in the smaller diameter trees. Another variation of the FREL method was to use the iTree database of allometric equations and wood densities to calculate the carbon stored in each tree. For many of the species in our field plots, there are no allometric equations available in the iTree database, GlobAllomeTree, or other sources, so we rely on the iTree database of wood densities at the genus level instead of the species level.

Soil samples were collected at each of the four corners of the plots, at two depths: 0-15 cm and 15-30 cm. We used a custom-designed tool to take soil samples, after finding that conventional soil probes did not work well in our field sites. The samples were placed in a plastic bag identified for each depth, and transported to different laboratories; for the samples from Yaque del Norte, the Food Safety and Industrial Analysis Laboratory (LIAAI) was chosen, and for the Santo Domingo plots, the laboratory of Junta Agroempresarial Dominica (JAD). Relative densities could not be recorded for half of our samples in the Santo Domingo basin. In order to allow comparisons between both basins, we report here the percentage of soil organic carbon, instead of the tCO_2e/ha.

CALCULATION OF CARBON STOCKS

To estimate the carbon reserves contained in the trees, we used the iTree Eco software developed by the U.S. Forest Service to convert the measured diameters and height of each tree into a carbon reserve per tree. Our intention in doing so, and in providing detailed methods here, is to allow others to replicate these methods with their own fieldwork using open source software. It is worth noting that the iTree staff from the Forest Service provided very helpful technical assistance, even in Spanish, and regularly offers office hours to address concerns via teams, as well as recorded training courses.

To ensure that the results were based on accurate climatic data, we processed and sent to the software developers, hourly precipitation data from the year 2019, corresponding to the meteorological station located in Los Montones, in the Yaque del Norte basin. With pre-processing and primary quality control, the data from this station has been added to iTree and is available to all platform users. The data was assigned to the Cibao Internacional weather station UTM coordinates (784600-99999).

Although the iTree software is quite robust, it also presents several restrictions that make data preprocessing quite cumbersome. The most common restrictions we found were, for example, with empty fields, with incorrect spelling or other aspects in the field data such as the minimum DBH value to be able to incorporate the data into the system.

To convert our data from the FREL field sheets to the iTree format, we use a script in R to convert the data into a format readable by iTree. Next, we import the data into an iTree Eco project (complete inventory). At this point, some manual data correction was necessary to eliminate field plots with missing data, and to choose a similar tree species when the exact species we measured was not part of the iTree database (in those cases, we used the genus instead of the species). The detailed methods of iTree, including screenshots so that others can replicate our methods, are available in our draft user handbook. It is expected that this manual will be finished by early 2025.

The analysis of the remaining data was carried out using the statistical programs IBM's SPSS and SAS Institute's JMP.

REMOTE SENSING

We use PlanetScope satellite images to detect changes in tree canopy cover and vegetation indices between 2017 and 2023. We hired TamaGroup SAS, based in Germany, to measure changes in land use at three scales: 1) national level, 2) within the watersheds of the Water Funds, and 3) in the intervention sites within each watershed. TamaGroup uses its own machine learning model ("convolutional neural network" or CNN) that was trained to distinguish between the classes of agricultural land use, canopy (including forests and agroforestry), grasslands, urban land, bare soil, and bodies of water. A description of the model training process can be found here (TamaGroup, 2024). Given the visual similarity between agroforestry areas and forests, it was not possible to distinguish between these two types of land cover and we refer to both as "canopy". Using an existing data layer of protected forests, we considered that any "canopy" within these protected areas was forest, and any "canopy" within a layer of coffee and cocoa farms was agroforestry. The regular meetings between TamaGroup and The Nature Conservancy allowed us to compare the data and refine the model. The final results include a layer of the changes in land use between 2017 and 2023 that is available upon request to any interested party.

We have also used a drone to collect images of a handful of places, and we plan to carry out more flights throughout the next year. The TNC office in the Dominican Republic has the DJI Mavic 3 Multispectral drone, which has a 4 x 5 MP multi-spectral camera, a 20 MP visible light camera, and the ability to cover up to 200 hectares per flight.

Results

LAND USE AND LAND COVER (LULC) CHANGE

The Dominican Republic has several types of remote sensing data, including canopy height (Potapov et al., 2020), a GIS land cover layer generated by the government, and global satellite datasets such as those generated by Sentinel-2. The Norwegian government has also made available the NICFI dataset, which uses Planet satellite data with a resolution of less than 5 meters. In our study, we also contracted TamaGroup to use data from the Dove satellite with a resolution of 3.7-4.0 meters to detect changes in vegetation cover at various scales, as shown in Table 2.

We explore various ways to use this data to map or estimate the carbon found in the agroforestry systems of the Water Funds. Unfortunately, when comparing the Normalized Difference Vegetation Index (NDVI) of Sentinel-2, it was not possible to differentiate between agroforestry systems and forest canopy. The NICFI data, although very high resolution, also do not allow us to see individual trees or the difference between the crop canopy and shade trees in agroforestry systems.

Area of interest	Canopy increase [ha] (%)	Canopy decrease [ha]	Canopy change overall [ha]	Total area [ha]
Dominican Republic	+401,301 (7.4%)	-217,053	+184,248	5,401,688
Yaque del Norte	+42,787 (5.4%)	-18,025	+24,762	778,433
Santo Domingo	+51,659 (10.4%)	-33,272	+18,387	492,578
YdN intervention sites*	+79 (9.1%)	-44	+35	871
SD intervention sites*	+130 (12.0%)	-109	+22	1,085

Table 2. Summary of land cover change in the Dominican Republic at the national level, at the watershed level, and at the intervention sites of the Water Funds within each watershed between 2017 and 2023.

Note: The land use classes include: agriculture (row crops), agroforestry (agricultural areas within the government data layer of coffee and cocoa farms in the Dominican Republic), bare soil, canopy (continuous presence of trees, but not in a protected forest area or in the coffee and cocoa farms layer), forest (within protected forest areas), grasslands, urban, and water. *Note that the results corresponding to the intervention zones of the Water Funds (AOI3 YN and SD) should be used with caution. For example, some of our Water Funds intervention sites were intervened before 2017 or during 2023, outside the range of the years covered by this study.

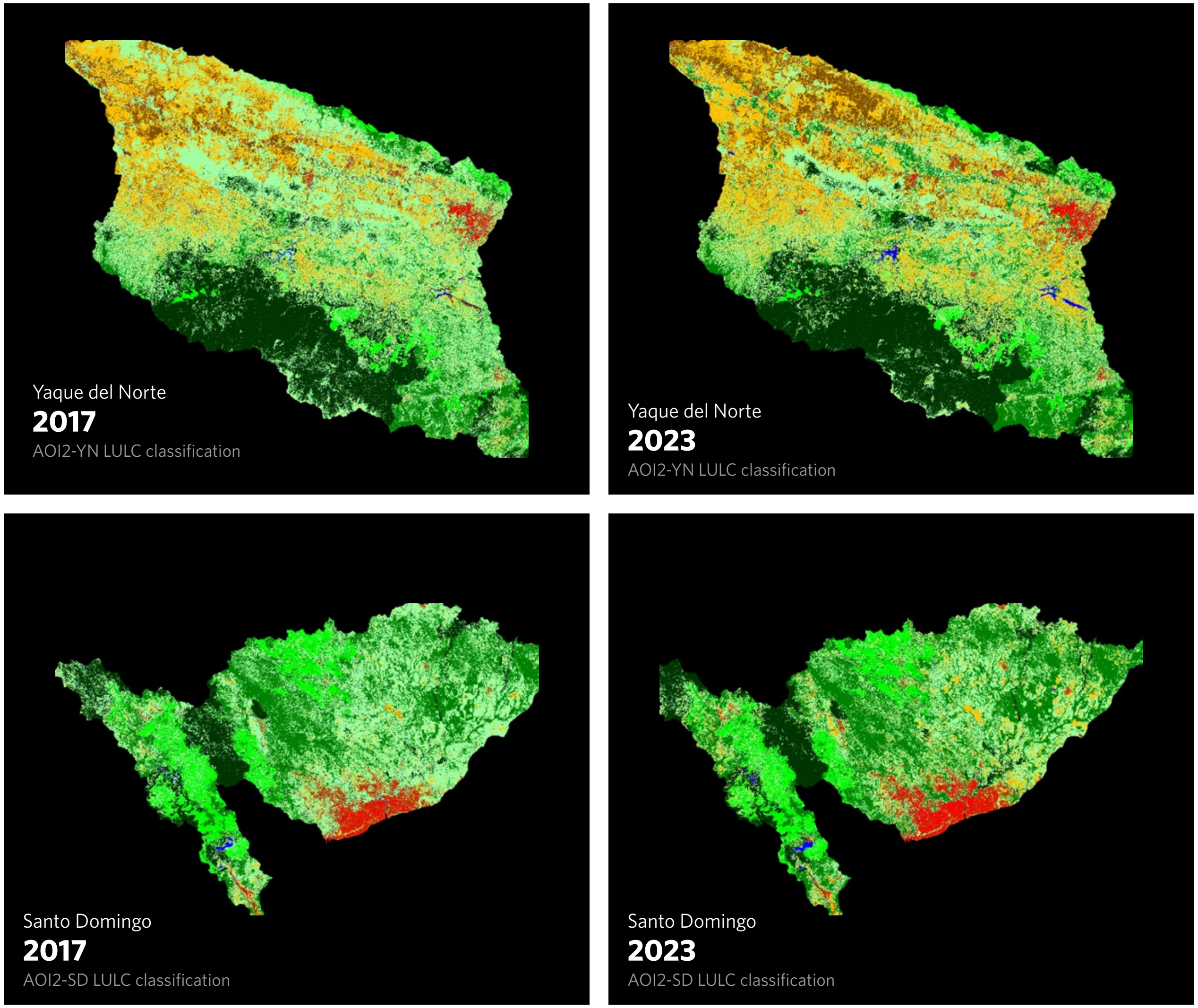


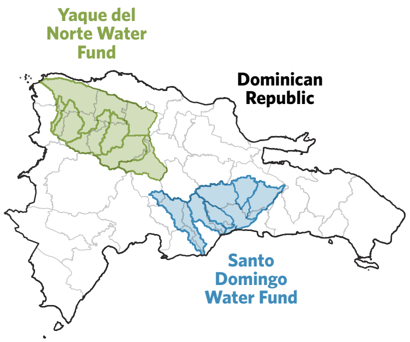
Figure 7. Comparison of land cover in 2017 and 2023 in the Yaque del Norte, Nizao, Haina, and Ozama watersheds. Note that the canopy class contains a mixture of agroforestry and forestry pixels.

Land cover

Agriculture
Agroforestry
Bare soil
Canopy
Forest
Pasture
Urban
Water bodies

PlanetScope's higher resolution data was used to measure the increase and decrease in canopy cover. In all the scales analyzed, the forest cover increased over time. However, like others (UNFCC, 2022), we were unable to accurately identify agroforestry compared to other types of canopy cover such as forest plantations or natural forests. Whether spectral indices or visual comparisons are used, additionally, the analysis was limited by the relatively dry conditions of 2017 compared to the relatively wet conditions of 2023.

Despite the young age of the agroforestry intervention sites, the inability to identify these systems suggests that their development and functionality resemble those of more mature and established forests, which is an encouraging finding. Despite the high resolution of our satellite data, drones, LiDAR data, or some combination of both may be needed to accurately map and track the growth of agroforestry systems. This topic is discussed in more detail in the "Discussion" section. Likewise, the GIS data provided by TamaGroup showing each pixel in 2017 and 2023 (see Figure 7) and a layer of land use change, allow us to focus on the areas within the Water Funds intervention sites that appear to have gained or lost canopy since 2017. This will allow verifying the data and correcting the results of the intervention sites of the Water Funds.



Coffee

Cocoa

	Coffee								Cocoa			
	INTERVENTION				REFERENCE				INTERVENTION		REFERENCE	
	Yaque del Norte		Santo Domingo		Yaque del Norte		Santo Domingo		Santo Domingo		Santo Domingo	
ABOVEGROUND CARBON (% of in crops versus shade trees)	Crop 5.4%	Shade 94.6%	Crop 4.6%	Shade 95.4%	Crop 3.1%	Shade 96.9%	Crop 7.4%	Shade 92.6%	Crop 34.5%	Shade 55.5%	Crop 19.5%	Shade 80.5%
ABOVEGROUND CARBON (tCO_2e/ha)	80.70 (16.81)		125.17 (31.15)		130.11 (31.06)		67.27 (22.93)		44.88 (15.024)		165.47 (75.05)	
SOIL ORGANIC CARBON (%)	0-15 cm: 4.32 (0.51)	15-30 cm: 2.54 (0.19)	0-15 cm: 1.46 (0.14)	15-30 cm: 1.09 (0.22)	0-15 cm: 3.67 (0.31)	15-30 cm: 2.15 (0.18)	0-15 cm: 1.59 (0.03)	15-30 cm: 1.53 (0.07)	0-15 cm: 1.43 (0.18)	15-30 cm: 1.40 (0.15)	0-15 cm: 1.29 (0.11)	15-30 cm: 0.94 (0.16)

CARBON STORAGE IN AGROFORESTRY

Table 3 shows the average carbon stocks in trees and crops above ground and in the soil. It was to be expected that in our results there would be high variability between the plots, even within the same class (for example, the coffee intervention sites in the Santo Domingo basin). An unexpected finding was the high number of shade trees in our reference plots. We observed that the density of shade trees was quite similar in our intervention plots compared to the reference plots. Given that most of the aboveground carbon in any field plot was found in the shade trees, the abundance of shade trees in the reference plots contributed to the lack of significant differences with the intervention plots. In effect, we designed a study to compare carbon stocks in coffee

Table 3. Carbon stocks in coffee and cocoa intervention and reference plots in the studied watersheds.

Note: The values are means, with standard errors in parentheses. The sample sizes are found in Table 1, except that 12 of the Yaque del Norte soil samples are excluded here due to a labeling issue.

or cocoa based on differences between land management in the intervention plots and the reference plots, but we ended up with a very different study; one in which we compared young Water Funds agroforestry intervention plots to older reference agroforestry plots.

Age was also an important confounding factor in this study. All our intervention sites were established in 2015 or later. Since most of our reference plots are owned by farmers who are not part of the Water Funds, we do not know the age of all our reference plots. However, when conducting our field sampling, we were able to ask the majority of farmers in the Nizao, Haina, and Ozama sub-basins in which year they had established their plantations, and some indicated that it was since the 1990s or early 2000s.

When analyzing the age of the trees in the reference plots, no significant or consistent effect was observed. However, in the oldest sites, shade trees can be much more than ten years old and, therefore, be considerably larger and influence the results. Additionally, the results were also affected by outliers, such as newly planted or very young intervention plots where shade trees were only a few years old, or the case of a reference plot of cocoa in the Santo Domingo basin where a single huge shade tree dominated the plot.

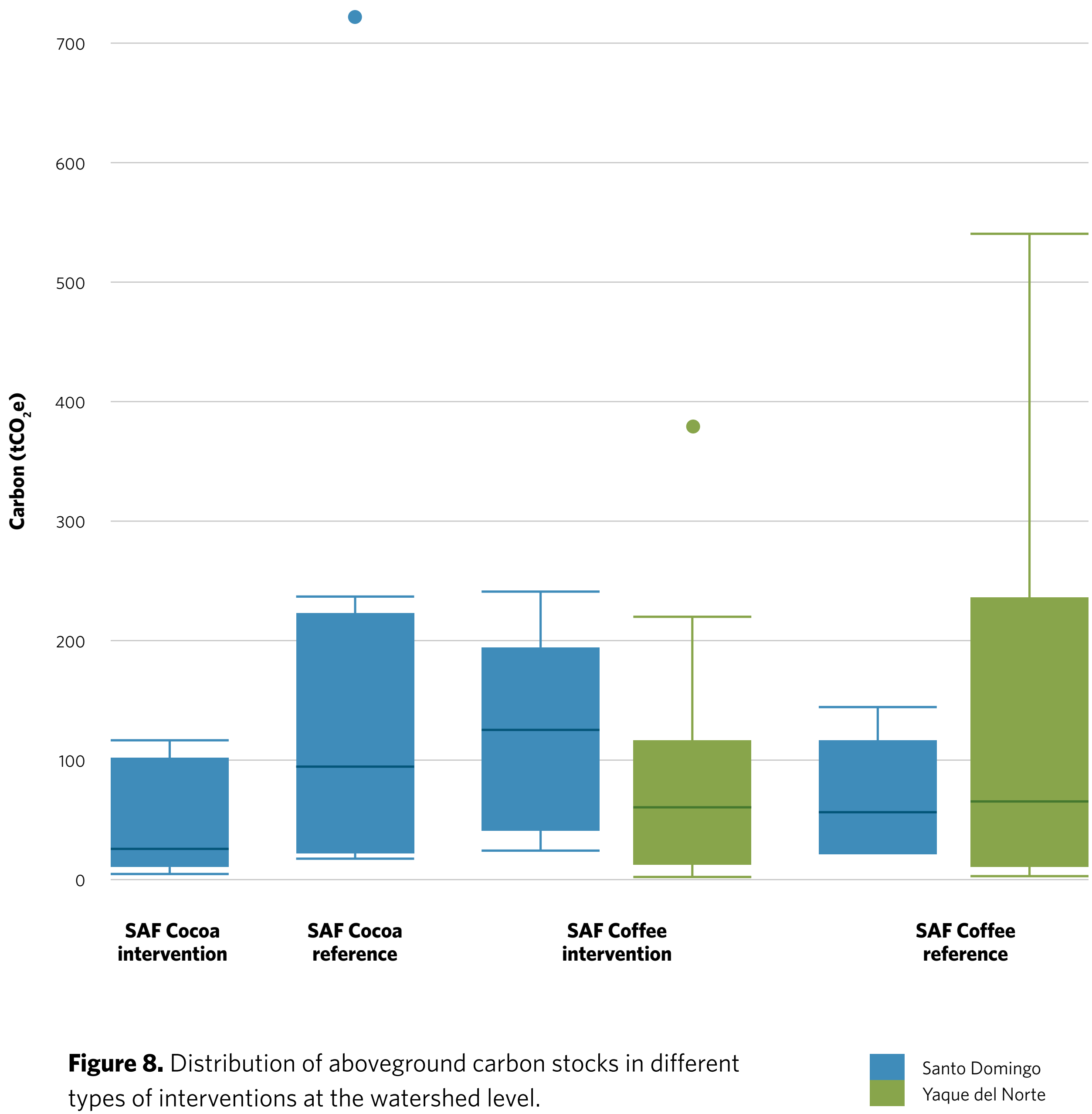


Figure 8. Distribution of aboveground carbon stocks in different types of interventions at the watershed level.

Figure 8 presents a diagram with the average of aboveground carbon reserves, illustrating more effectively the range of this type of carbon and the impact of outliers. It is anticipated that our intervention plots, some of which were established as recently as 2021 and 2022, will significantly increase carbon reserves in the coming years as their shade trees mature.

The results of the Yaque del Norte and Santo Domingo basins are also quite different from each other. For example, coffee plantations in the Yaque del Norte Water Funds sites had an average carbon storage of 81 tCO2e/ha, while coffee plantations in the Santo Domingo Water Funds sites had an average carbon storage of 125 tCO2e/ha - despite both being young coffee plantations established by the Water Funds. This difference highlights the influence of specific regional factors that affect carbon sequestration in coffee plantations. To deepen our analysis, it is recommended to carry out complementary studies that explore in detail the soil and climatic characteristics and coffee management practices in each watershed. This additional information would allow us to more accurately identify the factors responsible for the differences observed in aboveground carbon stocks. Understanding these specific factors in each basin would also help Water Funds optimize coffee management strategies and maximize both yield and carbon sequestration potential at the local level.

Although our study did not end up being a powerful, balanced, and matched design of intervention and reference, we measured large carbon reserves in all of our sites. We suggest that the most appropriate way to use our data is as a means to understand the current amount of carbon stored securely in the Water Funds sites. Applying our average carbon reserves per class to all hectares of agroforestry interventions in the Water Funds, we found that there are 4,256 tCO_2e/ha currently stored in the 53 hectares of coffee agroforestry sites in the Yaque del Norte, and 32,813 tCO_2e/ha currently stored in the 588 hectares of coffee and cacao agroforestry sites in Santo Domingo. This carbon storage occurs without trade-offs in performance or socioeconomic factors, as described in the discussion section later on. It will be important to continue measuring the same plots over time, if possible, using this set of data as a reference. The carbon stocks in the intervention sites of the Water Funds can be compared with an appropriate counterfactualfactual -- baseline actions taken if the Water Funds did not exist -- such as the average amount of carbon in pasturelands, or in short term row crops managed more intensively.

It is important to consider that our data may also reflect the success of initiatives such as Water Funds, which influence even farmers who do not participate in the program. In all the basins studied, farmers are adopting shade trees as an important part of their management. A key difference in Water Funds sites is the continuous communication and technical assistance provided by Water Funds staff. In a longer-term study, it could be expected that the rates of abandonment of agriculture and land conversion would be lower in the plantations that are part of the Water Funds.

The land use change maps from our study provide a solid reference base that will be used to track land conversion rates and patterns over time. Having large carbon stocks per hectare has a certain value, but if the land is not kept forested or in agroforestry, much of that carbon is lost once the land is cleared, burned, or harvested.

The carbon storage in agroforestry plots of coffee and cacao was highly variable, ranging from 1.5 tCO_2e/ha in a young coffee agroforestry plot with only a handful of newly planted Cedrela odorata (Spanish cedar) trees, to 724.9 tCO_2e/ha in a cacao farm chosen as one of our reference sites, which contained a single enormous hardwood responsible for 3/4 of that carbon reserve.

CARBON SEQUESTRATION IN AGROFORESTRY

The preliminary results of carbon sequestration in Yaque del Norte are presented in Table 4. For this watershed, we provided the iTree team with hourly precipitation data for the year 2019. Note that iTree calculates carbon sequestration rates per individual tree, which are then added up for each plot and averaged across plots for each type of intervention.

These figures are similar to those of other commonly accepted global data sets. Next year we hope to provide iTree with a similar precision weather data set for the subbasins where the Santo Domingo Water Fund operates, which will allow us to also generate carbon sequestration values per hectare for agroforestry systems in that basin.

Type of intervention Yaque del Norte	SAF Coffee Intervention	SAF Coffee Reference
Carbon sequestration (tCO_2e/ha/year)	11.4 (1.2)	12.9 (1.8)
N	25	22

Table 4. Carbon sequestration in the Yaque del Norte basin. Mean ± (standard error).

SOIL CARBON

In table 3, the results of soil carbon are shown. There seems to be a slight trend towards a higher percentage of soil organic carbon in our intervention sites, although, again, the variability is quite high and there are no significant differences. Even so, it is surprising to see differences, given how young most of our intervention sites are. We have obtained funding to continue analyzing this data on soil carbon, looking for spatial patterns or other explanatory variables. We also hope to be able to compare our results with those of other agroforestry projects in the Natural Climate Solutions Prototypes Network of TNC, such as those in Brazil, Ecuador, and Guatemala. The observation of an increase in soil carbon over time would be a clear indication of the carbon benefits, as soil carbon is believed to be a relatively stable carbon reservoir, especially in deeper depths. These initial data are encouraging, and we hope that the Water Funds and other entities continue monitoring these sites over time.

Discussion

AGROFORESTRY

We suggest that this study serve as a rigorous reference for measuring carbon gains over time in agroforestry interventions. This study serves as a complement to other efforts of the Water Funds and the government of the Dominican Republic to measure the environmental benefits derived from forests and other types of land cover. The Water Funds had been recording water, biodiversity, socioeconomic, and other benefits from their interventions, but until now, they did not have data on carbon benefits. Similarly, although the 2018 FREL carefully cataloged carbon reserves in a series of land cover types, it did not specifically include agroforestry systems.

This study provides the first estimates of carbon reserves in agroforestry intervention sites of the Water Funds. As a whole, all these elements can be used in a political context to model the amount of additional carbon storage that could be expected from converting a certain number of hectares of grasslands into agroforestry or, conversely, the loss of carbon if agroforestry systems are converted into grasslands or agriculture.

We discovered that the agroforestry interventions of the Water Funds have shade tree densities similar to those of coffee and cocoa plantations many years old. And even very young agroforestry areas appear, either through satellite images or vegetation indices, quite similar to forested areas. The photos of our agroforestry intervention fields show a complex and diverse system that produces significant amounts of food and income, while also hosting wildlife and infiltrating and slowing down the movement of rainwater. Perhaps it is not surprising, then, that farmers enrolled in the agroforestry program are happy with the results and they maintain their participation over the years.

Due to the small size of the sample, divided into several watersheds and two types of crops, and the wide range of ages of coffee and cocoa plantations, we observed an extremely high amount of variability in carbon in all our field sites. Although this is not unexpected, it complicates statistical comparisons. In some reference sites, higher amounts of carbon were observed than in the intervention sites, while in other cases this trend was reversed. The average data was affected by some plots with an unusually low number of shade trees or with one or two exceptionally large diameter trees within the studied plot. A clear pattern of higher carbon content in the soil or surface was not detected at the intervention sites. It will be necessary to continue collecting data over time to determine if the intervention sites, as they age, exceed the amount of carbon in the reference sites. In both intervention and reference sites, most of the carbon is found in the shade trees, suggesting that the choice of a resilient range of native species and ensuring the health of these shade trees over time are very important for maintaining carbon reserves and sequestering more carbon over time.

The reference plots in cacao agroforestry systems store almost four times more carbon than the intervened ones. This notable difference can be attributed to a combination of factors, including the size of the sample, the age of the crop, and the soil and climatic conditions, as well as a plot with a shade tree outlier. Although the random sampling design used in the study ensures the representativeness of the samples, a larger sample size could reduce variability and provide more accurate results. The age of the crop is also a determining factor, since older cocoa trees store more carbon. It is recommended to analyze the average age of the plots in each group to evaluate their influence. Finally, the soil and climate conditions, such as soil fertility, water availability, and climate, can significantly affect carbon storage.

OTHER TYPES OF WATER FUND INTERVENTIONS

Reforestation

Reforestation plays a crucial role in mitigating climate change by sequestering carbon dioxide (CO_2) from the atmosphere, while also improving soil health and biodiversity. The estimation of the values of carbon stored by this activity is essential to quantify both the contribution of this activity to the achievement of national and global climate goals. Reforestation was not the focus of our study, however, we were able to gather information from a reforestation plot near Santo Domingo and two other plots in Yaque del Norte. Carbon stocks ranged from 32.9 tCO_2e/ha in a 6-year-old site for the first case to 213.2 tCO_2e/ha for an area with a longer history of reforestation in Yaque del Norte. Estimates of carbon sequestration are more available for reforestation than for agroforestry (Cook-Patton et al., 2020).

Forest conservation

Forests play a crucial role in regulating the global climate by acting as natural carbon sinks. Through photosynthesis, trees absorb carbon dioxide (CO_2) from the atmosphere and store it in their biomass (trunks, branches, leaves) and in the soil. The forest conservation sites are areas designated to conserve the ecological integrity of ecosystems and their ecosystem services, including carbon storage. Forests contain so much carbon that when they are converted to another land use, there is a portion of the lost carbon that is essentially unrecoverable on a meaningful time scale, even if the site is reforested (Goldstein et al., 2020).

In the Dominican Republic, Law No. 57-18 on the forestry sector is the regulatory framework that governs and promotes sustainable forest management. Said law also provides that the Ministry of Environment and Natural Resources is the competent authority to approve and oversee the implementation of forest management plans on both public and private lands.

Although forest conservation was not the focus of our study, we measured carbon in nine forest plots in the Yaque del Norte. We compared the plots of the Water Funds (176.3 tCO_2e/ha) with the recently logged forests (169.4 tCO_2e/ha) in the same watershed. Over time, it will be important to continue measuring forest protection sites to understand: 1) if protected forests store more carbon than harvested plots, 2) determine the type of forest management that best balances carbon and wood production in the Dominican Republic, and 3) communicate the benefits of forest protection to a wide range of audiences.

Silvopasture

In the framework of this study, no samples of aerial or underground carbon were taken in silvopasture; however, in YN, it was possible to carry out the forest inventory in 2 reference plots. During the forest inventory conducted in the YN basin, information was collected from 2 silvopastoral plots; the first showed an aboveground carbon value of 65.82 tCO_2e/ha, while the second showed a value of 290.83 tCO_2e/ha. Silvopastoral interventions, as promoted by Water Funds, should produce carbon benefits in multiple ways. Living fences are planted as part of this intervention, with two potential carbon benefits: 1) reduction of carbon loss, as the need to cut down trees or shrubs to create posts for fences is reduced, and 2) increase in carbon reserves, as carbon is stored in these trees as they grow.

Silvopastoral activity sometimes involves planting protein-rich grasses, which reduces the carbon needed to cultivate, harvest, and transport feed for livestock. The trees planted to provide shade also increase the carbon stock in these sites, and most species have edible leaves, which again provides more food for livestock and reduces the need for external inputs. In the majority of cases, manure is dried in situ, reducing the need for fertilizers and increasing pasture yields, thus reducing carbon emissions from external fertilizers and feeds.

If livestock is able to survive on less land, carbon emissions are reduced again by decreasing the need for additional land use conversion. These carbon benefits add to the demonstrated and considerable water quality benefits measured by the Water Funds. Although silvopastoral systems are not the widespread practice of livestock production in the Dominican Republic, we do not want our lack of quantitative measures of its impact to diminish the importance of this activity. It is worth noting that there is a waiting list of farmers who would like to register to receive plants and technical assistance to establish silvopastoral systems on their properties, a situation that we hope can be remedied with additional funds and trained personnel to address this need.

Other interventions

This study focused on agroforestry systems that constitute the majority of the fieldwork carried out by the Water Funds. However, the Water Funds carry out other interventions that complement their portfolio of projects and that we define below:

- **Riparian restoration.** Restoration of the natural habitat found in the area of contact between land and water along the banks of a river or watercourse.
- **Good agricultural management practices.** Change in the management of agricultural lands to achieve multiple positive environmental outcomes.
- **Creation of artificial wetlands.** Construction of wetlands at specific points to emulate the natural water purification functions and reduce the entry of organic contaminants into water bodies.

POLICY IMPLICATIONS

Water Funds are platforms to capture and channel financial resources for conservation, as well as the promotion of environmental education and governance of the water sector. With less than a decade of operations, the benefits in water quality and biodiversity are already noticeable.

The work of the Water Funds is aligned with the main public policy instruments in environmental matters such as: The Sustainable Development Goals (SDGs 6, 11, 13, 15 and 17); Law 64-00 on environment and natural resources; Law 1-12 on National Development Strategy in its axis 4; Law 57-18 sectoral on forest resources. Similarly, there is great affinity with the National Climate Change Adaptation Plan (CNCC, 2016) and the National Communication for the United Nations Framework Convention on Climate Change (in its third version) and more recently, the decree 541-20 of the Executive Power that creates the National System for the Measurement, Reporting and Verification of Greenhouse Gases, the National Greenhouse Gas Inventory System, and the National Registration System for Greenhouse Gas Mitigation Actions.

Although Water Fund beneficiaries do not necessarily value carbon, they do value other benefits such as strengthening their productive capacities, training, and reducing soil erosion by reducing surface runoff, and consequently, sediment transport. So it is very likely that they will maintain their lands in their current use instead of clearing additional land, changing their use for development, or using intensive agricultural methods that ultimately degrade water and soil.

The strong commitment and continuous presence over almost a decade has generated interest in additional communities that now hope that the Water Funds can link them to some agroforestry or silvopastoral projects.

With this study, the Water Funds consolidate their position as leaders in natural resources management at a landscape scale by having data that allows them to identify areas with high conservation rates that could receive additional investments to enhance conservation efforts.

STUDY LIMITATIONS

Statistically speaking, the fact of only having a single year of field data collection makes it difficult to establish comparisons between our different types of intervention. However, this first step allowed us to establish a field protocol and data collection that will allow us to make measurements and calculations of aboveground biomass and soil organic carbon. It is worth mentioning that, during the forest inventory, the team faced various challenges in the field to locate the reference plots. These challenges were mainly due to the team's lack of familiarity with the area and the difficulty of accessing some sampling points due to their remote location. It will probably continue to be difficult to establish this type of controls in the future, however, having field personnel who know the area well proved to be very helpful in establishing the study's reference points.

When the initial experimental design was developed using power analysis, the goal was to include randomly choose samples, as well as to establish a sample size robust enough to obtain low experimental errors. However, the variability existing among the planting dates of the project plots adds another variable that was important to consider from the beginning of the study. It is fundamental to consider the age of agroforestry systems as a key stratification factor in the design of sampling, since younger crops will have smaller DBH than more mature crops. This involves dividing the total population of agroforestry systems into subgroups (strata) according to their age, ensuring adequate representation of each stratum in the final sample. This will allow for a more precise identification of the differences in carbon capture between systems of different ages and evaluate the statistical significance of these differences.

This is also important to take into consideration because the use of i-Tree ECO is primarily tied to the DBH and the total heights of the trees, and it is logical to think that younger trees, although of the same species, will have a smaller DBH and will be shorter than mature trees and, therefore, will capture or sequester less carbon.

The difference in carbon capture between young and mature agroforestry systems is the result of a complex interaction between biological, soil-climatic, and management factors. The appropriate sampling design, consideration of relevant factors, and rigorous statistical analysis are essential for understanding and quantifying these differences accurately.

Not having a baseline of previous measurements makes it difficult to obtain some of the results that we would have liked to provide. We cannot compare the amount of carbon currently found in the agroforestry plots of the Water Funds with the amount of carbon stored in those lands before the interventions were carried out because that data does not exist. However, using this study as a starting point to record the data collected in the forest inventory as a baseline, we will now be able to do so in the coming years.

FUTURE COLLABORATIONS

We would like to explore more deeply how drone images could predict carbon stocks. Our field data provides an excellent starting point that, in the future, could be used to train models that use drone images to predict carbon. We have received funding that allows us to make that type of comparison and model construction.

The Director of Science of the Caribbean Division of TNC has been using drone images to assess carbon reserves, particularly in mangrove ecosystems, and will provide guidance on how to use RGB data to create 3D models of tree clusters to create a canopy height model that could be used to deduce average height and DBH values, allowing for the calculation of Aboveground Biomass (AGB) and subsequently, carbon stock.

Fieldwork on the ground is expensive and requires a lot of labor, and remote sensing (drones and satellites) is very promising, although the satellite images currently available are not yet of sufficient resolution to definitively identify agroforestry areas on the ground. The use of the drone to identify intervention areas is a useful tool when observing in more detail the characteristics of each plot.

Figure 9. Differences between the resolution of a satellite image from Google Earth Pro (A) and the image from the drone (B) model Mavic 3 Multispectral.

Conclusion

One of the most exciting aspects of the results of our study is that the agroforestry promoted by the Water Funds has managed to store around 37,070 tCO_2e since 2015, along with all its other hydrological, socioeconomic, and ecological benefits, without a significant tradeoff for the beneficiaries.

Many activities that avoid or reduce greenhouse gas emissions, such as some forms of climate-smart forestry, increase carbon in the forest but require producing less wood or income. Agricultural techniques such as the use of cover crops may require the purchase of seeds every year and the rental of specialized equipment. However, this does not happen in agroforestry systems.

The soil, as we are beginning to see in our results, adds carbon and becomes more fertile over time. Thus, carbon is removed from the air and stored in crops and shade trees at an impressive rate every year. That is why it is important to continue these types of projects within Water Funds, because the cost per ton of carbon removed from the atmosphere decreases every year as trees and crops grow and reach maturity.

Our preliminary results from the Yaque del Norte basin suggest that each hectare of coffee agroforestry system captures ~11 tCO_2e additional each year, while providing many benefits to the owners of these farms and ecological and water quality benefits to the entire basin.

Also encouraging is the adoption of agroforestry by farmers without connection to the Water Funds. The high density of shade trees in our reference plots was quite surprising. The Dominican Republic has been promoting ecological restoration and sustainable agriculture for many years, and we are seeing that even in randomly selected coffee and cocoa farms, there are a large number of shade trees growing above the main crops.

The Water Funds continue to carry out awareness and community development activities long after planting crops and trees on a piece of land. Finding a way to expand this work even to farmers who are not part of the Water Funds could be a way to ensure that the properties remain in that land use and contribute year after year to the goals of reducing emissions in the Dominican Republic.

Perhaps the most important thing is to dissuade producers who are facing a difficult year or market and may be tempted to completely clear their land for livestock production. Silvopasture, reforestation, and agroforestry are land uses with considerable benefits compared to extensive livestock farming.

Data

The supplementary data can be found in Box, or are available upon request. Also see our interactive map of this study.

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Impact of shade-grown coffee and cocoa agroforestry in watersheds of the Dominican Republic

A STUDY BY THE NATURE CONSERVANCY'S NATURAL CLIMATE SOLUTIONS PROTOTYPING NETWORK

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