PNAT (Project Nature) is a multidisciplinary design company, born as a spin-off of the University of Florence, composed of a team of plant scientists, architects, and engineers, promoting synergistic relationships between the natural and built environment.

Founded in 2014 by Professor Stefano Mancuso along with agronomists and botanists Elisa Azzarello and Camilla Pandolfi and architects Antonio Girardi and Cristiana Favretto, it collaborates with the International Laboratory of Plant Neurobiology (LINV, www.linv.org), one of the most authoritative research centers in the world on plants.

Pnat is dedicated to transferring knowledge about plants into projects at various scales, from domestic to urban, developing and studying innovative technological solutions inspired by plant models. The main area of intervention is the built environment and how to integrate plants into cities, homes, workplaces, and people's lifestyles.

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ConSenso is an important scientific experimentation project launched in Tanzania in the Mbeya region by the Accademia del Caffè Espresso, Cisco, and PNAT.

The purpose of this collaboration is to raise awareness about the coffee supply chain by creating guidelines that can help the coffee community address the challenges posed by global warming, through exploratory investigations and remote analysis of the Utengule plantation, governed by careful agronomic practices. The goal is to enhance its production, highlighting the environmental benefits derived from its CO_2 sequestration capacity, and bringing consumers closer to production by establishing a monitoring network that allows the visualization of images and data in real-time.

This report aims to estimate the current contribution of CO_2 storage from the Itimba plantation, managed by Songwa Estates.

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ConSenso project
// CO_2 Storage of the Itimba Coffee Plantation in Tanzania: estimates and benefits

ACCADEMIA DEL CAFFÈ ESPRESSO

ConSenso project

// CO_2 Storage of the Itimba Coffee Plantation in Tanzania: estimates and benefits

PNAT PROJECT NATURE

ACCADEMIA DEL CAFFÈ ESPRESSO

Accademia del Caffè Espresso is a cultural hub dedicated to the world of Italian espresso coffee, where analyses, research, and dissemination of coffee culture take place. The project stems from the desire of La Marzocco, a Florentine company that produces professional coffee machines, to create a humanistic model that can serve as a reference point for Italian culture worldwide. The Accademia del Caffè Espresso is located a few kilometers from Florence, in the hills of Fiesole, at the original Officine de La Marzocco, transforming from an industrial production site to a center of training, culture, and innovation.

La Marzocco, founded in 1927 by the Bambi brothers, has specialized from the beginning in the artisanal production of espresso coffee machines for bars, with particular attention to quality, cup results, and style. Over its more than 90-year history, the Florentine company has introduced a series of revolutionary technologies and patents, becoming a leader in design and innovation in the field of traditional coffee machines. All models, including the latest ones for the end consumer, are handcrafted and exported to over 100 countries where they can be found in the best coffee shops, restaurants, and homes around the world.

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ConSenso project

// CO_2 Storage of the Itimba Coffee Plantation in Tanzania: estimates and benefits

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INDEX

Preface
by Massimo Battaglia

Introduction

CO_2 storage

The Utengule plantation

Census

Estimation methodology

Results
- Coffee Plants
- Shade Trees
- Itimba Plantation

Shade Trees and CO_2 Storage

Farming techniques and CO_2 storage

Coffee biomass and agronomic system

Conclusions

Preface

by Massimo Battaglia

2023 was the hottest year ever recorded and this can be traced back to human-induced climate change. Rising air and sea temperatures, along with unpredictable weather events and irregular rainfall, have greatly impacted all commodities, especially coffee production. The use of best practices and proper crop management play a key role in addressing these challenges.

If not adequately addressed in the coming years, the climate crisis poses a serious threat to global coffee production and to those who rely on it for their livelihood. Global warming will lead to "continuous systemic shocks," likely reducing both yield and quality. With the growing trend in global coffee consumption, pressure on habitats and forests is intensifying, highlighting the urgent need to adopt more sustainable coffee production methods.

Climate change is expected to negatively affect global coffee production, with forecasted reductions in yield and changes in land suitability. This makes it even more important for the coffee-consuming world to support producers in reducing carbon emissions on coffee plantations and increasing CO_2 storage within their plant ecosystems. With 10 million hectares under cultivation, coffee can play an important role as a global green lung.

With 10 million hectares under cultivation, coffee can play an important role as a global green lung.

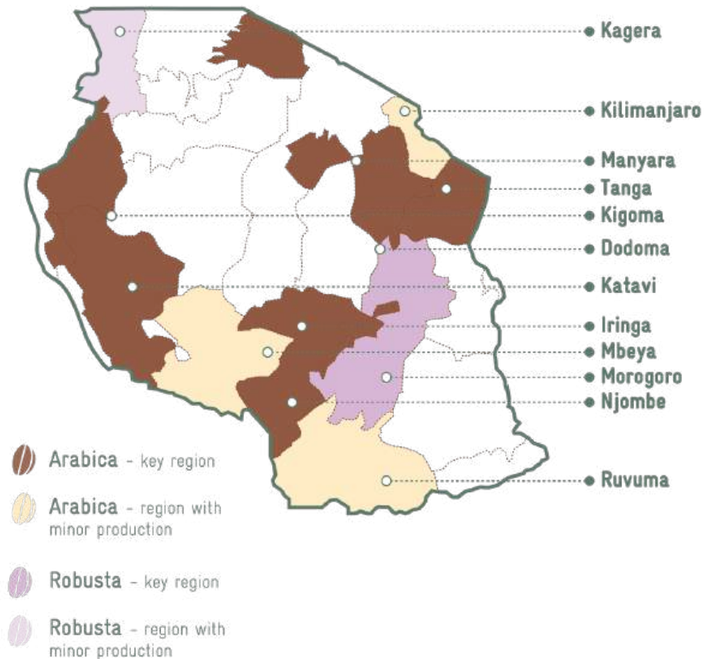
In many coffee producing countries, farmers are already implementing sustainable practices on their farms, transforming plantations into complex agroforestry systems, where coffee plants coexist with shade trees to protect the production cycle. In these agroforestry systems, plantations are transformed into wonderfully "productive forests," achieving extraordinary results. The transition towards regenerative agricultural practices and the need to mitigate and adapt to these challenges are more crucial than ever.

Introduction

by Massimo Battaglia

Coffee production is a significant aspect of the economy of Tanzania, as it is the country's largest export product. Tanzania produces an average of 30,000 to 40,000 tons of coffee per year, of which about 70% is Arabica and 30% is Robusta (90% of the coffee is exported). Coffee production is mostly linked to family-run plantations: 450,000 smallholders produce about 90% of the country's coffee, with farm sizes typically ranging from 0.5 to 2 hectares. Most producers are small-scale operations.

The main coffee export destinations are Japan ($46.1 million), Germany ($34 million), Italy ($19.6 million), the United States ($11.4 million), and Morocco ($10.3 million). The Mbeya Province in Tanzania is a highly agricultural area, densely populated, with optimal climatic and soil conditions, where small farms are predominant.



Coffee remains the most important cash crop, representing about 39% of the land dedicated to permanent crops and cultivated by over 80% of farmers in the Mbeya region. Most farmers primarily grow the Arabica variety. The crop is often intercropped with intensive mixed crops like maize, beans, and bananas, which dominate the system. Some farmers also practice coffee monoculture, especially those with large land holdings.

In addition to a well-orchestrated subsistence agriculture, there are small plots with different crops that ensure the family's supply and provide a small, steady income. This is a somewhat traditional form of agriculture, but very effective: the diversity of plants ensures a balanced diet, and the diversification of cash crops provides a small but reliable and consistent income.

CO_2 storage

Plants provide a vital ecological service by reducing CO_2 emissions, as they are capable of sequestering carbon and using it for their own growth. Through gas exchanges and the process of photosynthesis, carbon is removed from the atmosphere and stored in the plant biomass, where it remains throughout the plant's life cycle.

The amount stored in the biomass depends on many factors, with the growth rate of the species or forest system being the most important.

Since most definitions of "forest" describe a certain coverage of the ground by perennial woody plants over a minimum area, agroforestry systems, such as coffee plantations, may also fall under this categorization.

For example, under the Forest Law of Tuscany, a forest is defined as any area of at least 2,000 m² and more than 20 m wide, covered by spontaneous or artificially grown forest vegetation, at any development stage, with a density of at least five hundred plants per hectare or ground cover of at least 20%, based on canopy projection.

Plants provide a vital ecological service by reducing CO_2 emissions, as they are capable of sequestering carbon and using it for their own growth.

Coffee plantations, consisting of perennial woody shrubs and trees, can be considered as a growing carbon reserve, with the amount sequestered depending on the growth rate of the plantation. The age of the plantation is a particularly important factor: younger plants accumulate CO_2 more quickly than older ones. Additionally, the health of the plants and the maintenance operations that ensure their vitality are crucial for maximizing absorption.

These quantities are significant, especially considering that about half of the dry mass of a plant is carbon (Pearson et al. 2005).

The carbon fraction in dry biomass is calculated following the guidelines of the Intergovernmental Panel on Climate Change (IPCC 2006), a UN body tasked with assessing climate change science.

The carbon balance includes two compartments, which can be termed "in-forest," representing the total biomass of plants present in the surveyed plots, and "out-of-forest," referring to the use of all woody products and waste from pruning, felling, etc.

It is important to emphasize that the carbon fixed in plants remains stored in the woody tissues until the plants are felled and utilized in some way.

The carbon is then re-released into the atmosphere at a rate proportional to how quickly the wood is used. For example, a forest on a thirty-year cycle will sequester carbon throughout the life of the plantation, until the wood products are used and the carbon is released back into the atmosphere. Firewood has a very short cycle, whereas construction wood has a much longer cycle, as the derived product can last many years.

The carbon is then re-released into the atmosphere at a rate proportional to how quickly the wood is used.

The farming system chosen for production, the periodicity, and the management of pruning, which is necessary to ensure production, will be significant.

In the case of a productive coffee plantation, the amount of carbon stored depends on the number and size of the individual coffee plants, and the presence or absence of shade trees on the plots. In particular, the farming system chosen for production, the periodicity, and the management of pruning, which is necessary to ensure production, will be significant.

The Utengule plantation

The Songwa Estates farm is located in the southwest of Tanzania at an altitude of 1,450 meters above sea level. It covers a total area of 144 acres and is connected to the Utengule Estate, which spans 650 acres. 46% of the land is cultivated with coffee, while forests, streams, and hedgerows cover 41% of the property, providing the farm with an excellent ecological balance and rich biodiversity, hosting a wide variety of flora and fauna. The remaining percentage is made up of roads, processing areas, and buildings.

The farm is situated within the monumental Rift Valley in a climate zone typical to the subtropical highlands of the southern hemisphere

The coffee fields are partially shaded with mainly native tree species, including very old and monumental trees such as Faidherbia albida, which host various epiphytes like the leopard orchid. These trees take up a lot of space but play a vital role in preserving the local biodiversity, which is central to the operation of the farm. The location and climate are ideal for growing Arabica coffee. The farm is situated within the monumental Rift Valley in a climate zone typical to the subtropical highlands of the southern hemisphere. The climate, classified as tropical dry, is mild throughout the year, with warm days ranging from 24 to 28°C.

The rainy season lasts from October to early May, bringing around 1,000 mm of rain per year. The dry season, from April to early August, is the harvest season and is characterized by cool temperatures at night. Three years ago, the farm introduced a new policy for its new coffee fields, producing biochar from residual wood, such as that produced by pruning, and adding it to compost made from coffee pulp, coffee husks, and cow manure purchased from local farmers.

This carbonized compost buries significant amounts of carbon in the soil, preserving it for hundreds of years or perhaps indefinitely, making a small but important contribution to the removal of CO_2. Coffee trees grow better and faster in these fields and are more resilient to water stress because biochar can absorb water and nutrients, then release them to the coffee roots at a later stage. Additional techniques to address the challenges of climate change include the selection of more drought-tolerant varieties, excellent soil preparation before planting, higher planting density to achieve better ground cover, light shading from above, ground cover and an improved pruning system.

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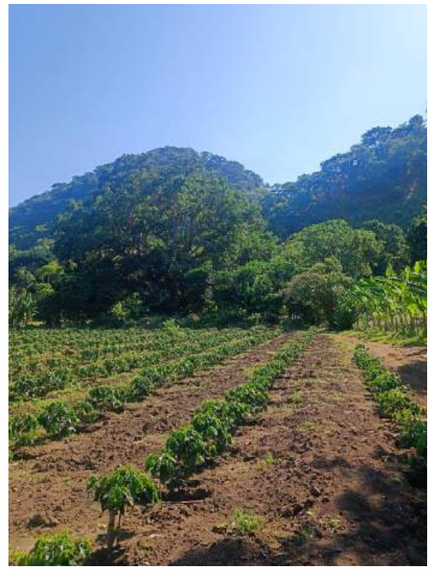
In 2020, a new state-of-the-art, environmentally friendly wet tillage line was commissioned that consumes only 3% of the amount of water of the previous system. In addition, Songwa efficiently irrigates part of its fields from watercourses stemming from the mountains in the farm's vicinity, compensating for a potential shortage of rainfall.

Agricultural practices for coffee cultivation include various activities such as planned irrigation, manual weeding during the rainy season, dosed organic and chemical fertilisation, and disease control of coffee leaves and berries, selective harvesting and processing using specific criteria and methods, coffee resting, regular quality control and sorting, composting of agricultural waste, and plans for nursery and plant propagation, harvesting, coffee processing, quality control and sorting, composting and propagation in the nursery, pruning of shade trees to avoid excessive shading, and pruning of coffee plants to encourage production.

Coffee trees grow better and faster in these fields and are more resilient to water stress because biochar can absorb water and nutrients.

Songwa efficiently irrigates part of its fields from watercourses stemming from the mountains in the farm's vicinity, compensating for a potential shortage of rainfall.

This last operation involves the five-yearly cutting of the primary stems of the coffee plants with the release of the suckers previously developed on the same stump to have a rotation of production on the young stems. The resulting smaller-sized material is used to produce biochar, while the larger diameter stems will serve as support for the young plants in the new plots, as well as being used as firewood and driftwood for handles and poles, being a very strong and durable wood.



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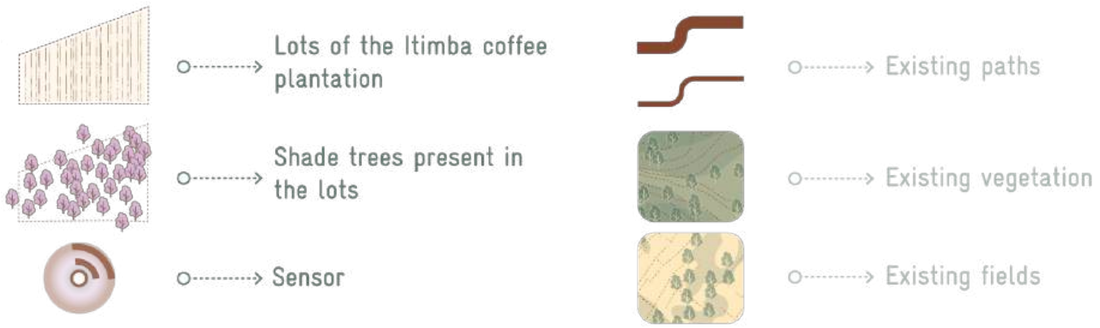

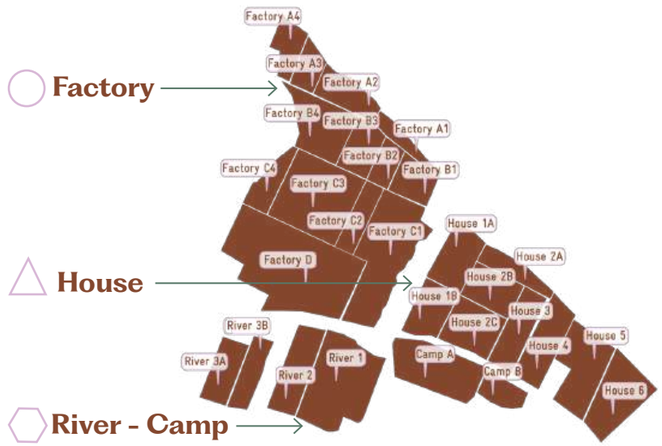

*graphical representation of the **Itimba** plantation divided into plots* ↘

There are four different plantations on the farm, named as follows:

- **Songwa**
- **Tegemeo**
- **Utengule**
- **Itimba**

Given the location and the heterogeneous vegetation, expressed both in terms of the age of the coffee plants and the variety of shade trees, we have taken the Itimba plantation as a reference for the analysis of biomass and consequently of carbon dioxide storage. Itimba is divided into 28 uniquely named plots, as shown on the map.

The first coffee plants were planted in the It. House 3 plot in 1970, while the most recent were planted in 2023 in the It. House 1A plot.

Census

The amount of organic biomass which is the total weight of the vegetation present in the plantation, is correlated with the number of plants and their size (diameter and height), which in turn is closely dependent on their age.

Thanks to the compiled by the managers of the Utengule farm, we know the exact number of coffee shrubs and their age, species, and the number of shade trees that are present on the farm.

As of today (March2024), there are:

- ***160.385 coffee plants*** *(Coffea arabica)*;
- ***883 shade trees*** *of various species, including Grevillea robusta and others less common, such as: Acrocarpus fraxinifolius, Albizia schimperiana, Versicolor, Cordia aliodora, Leucaena leucocephala, Faidherbia albida, Jacaranda mimosifolia, and Persea americana (Avocado).*

We also have diameter data for the coffee plants and shade trees. Specifically, for each plot, measurements were taken from 13 plants (10 coffee shrubs and 3 shade trees), which will be analyzed in the tables on the following pages.

TABLE.1 *number of coffee plants and shade trees divided by plot within the* ***Itimba*** ↘

PLOT	n. Coffee Plants	n. Shade trees
It.House 1A	7.790	15
It.House 1B	5.675	18
It.House 3	3.086	33
It.House 4	8.138	44
It.House 5	5.082	37
It.House 6	5.918	36
It.Camp A	5.143	44
It.Camp B	1.233	28
Itimba Factory A1	1.646	28
Itimba Factory A2	5.550	49
Itimba Factory A3	2.713	32
Itimba Factory A4	2.466	40
Itimba Factory B1	3.699	21
Itimba Factory B2	4.809	5
Itimba Factory B3	4.809	7
Itimba Factory C1	14.950	53
Itimba Factory C2	3.083	20
Itimba Factory C3	11.837	53
Itimba Factory C4	3.083	19
Itimba Factory D	12.753	102
Itimba River 1	16.460	17
Itimba River 2	8.230	30
Itimba River 3A	5.350	22
Itimba River 3B	5.761	18
It.House 2A	2.411	21
It.House 2B	3.289	17
It.House 2C	3.881	31
Itimba Factory B4	1.542	26
TOT	**160.385**	**883**

TABLE.2 *diameter data of coffee plants and shade trees from some example plots of* ***Itimba*** ↘

Factory A4

	n.10 Coffee Plants	n.3 Shade trees
tree 1	50 mm ø	293 mm ø
tree 2	39 mm ø	452 mm ø
tree 3	32 mm ø	597 mm ø
tree 4	41 mm ø	
tree 5	35 mm ø	
tree 6	41 mm ø	
tree 7	43 mm ø	
tree 8	38 mm ø	
tree 9	39 mm ø	
tree 10	42 mm ø	

River 1

	n.10 Coffee Plants	n.3 Shade trees
tree 1	35 mm ø	166 mm ø
tree 2	42 mm ø	383 mm ø
tree 3	40 mm ø	520 mm ø
tree 4	39 mm ø	
tree 5	41 mm ø	
tree 6	40 mm ø	
tree 7	42 mm ø	
tree 8	34 mm ø	
tree 9	45 mm ø	
tree 10	45 mm ø	

House 1B

	n.10 Coffee Plants	n.3 Shade trees
tree 1	39 mm ø	427 mm ø
tree 2	43 mm ø	453 mm ø
tree 3	36 mm ø	356 mm ø
tree 4	42 mm ø	
tree 5	33 mm ø	
tree 6	50 mm ø	
tree 7	39 mm ø	
tree 8	41 mm ø	
tree 9	40 mm ø	
tree 10	32 mm ø	

Factory C

	n.10 Coffee Plants	n.3 Shade trees
tree 1	34 mm ø	478 mm ø
tree 2	37 mm ø	422 mm ø
tree 3	38 mm ø	459 mm ø
tree 4	42 mm ø	
tree 5	43 mm ø	
tree 6	44 mm ø	
tree 7	47 mm ø	
tree 8	52 mm ø	
tree 9	36 mm ø	
tree 10	35 mm ø	

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Estimation methodology

Numerous authors have addressed the issue of calculating biomass in agroforestry in temperate and tropical zones in recent years. Research primarily follows two models:

1. The development of allometric equations derived from the intrinsic physical characteristics of the plants.

2. The analysis of satellite data.

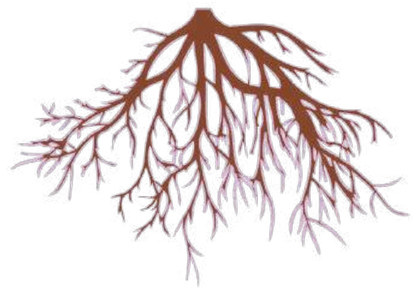
The first model allows for the evaluation of biomass in kilograms using allometric data such as diameter, height, and the number of plants present.

The second model provides an estimate of the biomass quantity through processed satellite images and field surveys.

The method adopted for the study context refers to scientific research published by Hawassa University (Ethiopia)[1] and Universidad del Valle de Guatemala[2], which provide a series of equations that allow for estimating the biomass of each coffee plant and, consequently, the amount of CO_2 stored.

For each plot within the plantation, the average biomass per plant (Coffee trees biomass mean) was calculated. Keeping in mind the known number of total plants per plot, the average biomass allowed us to estimate the following values:

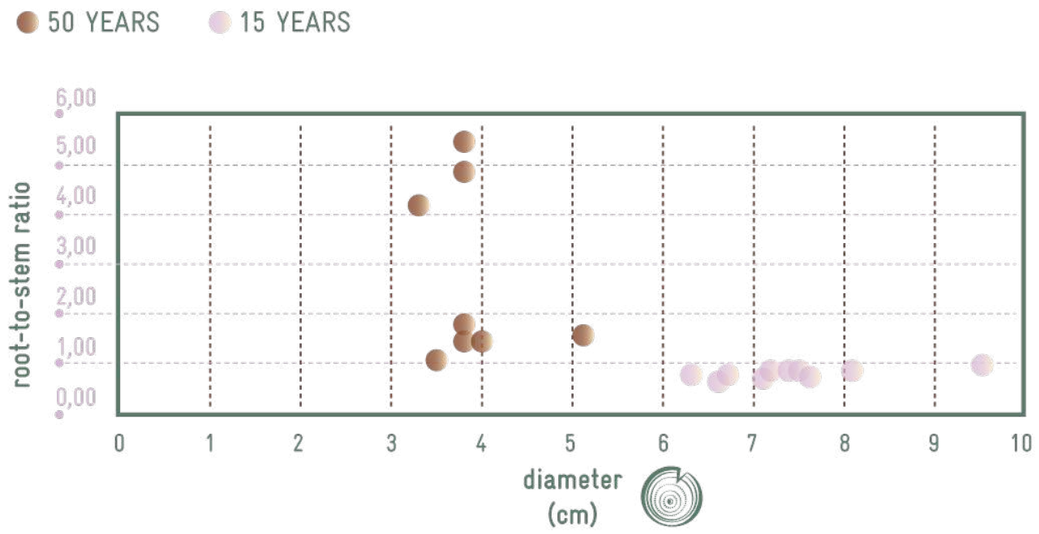
- **Aboveground Biomass** of coffee plants (i.e., stems and branches).



- **Belowground Biomass** (includes the stump and the more substantial roots)

- **TOTAL BIOMASS**, the sum of the two previously calculated values)

1. *Negash, M., Starr, M., Kanninen, M. et al. Allometric equations for estimating aboveground biomass of Coffea arabica L. grown in the Rift Valley escarpment of Ethiopia. Agroforest Syst 87, 953–966 (2013).*



To achieve higher precision in estimating the root biomass compared to the total coffee weight, surveys were conducted on a sample of old plants (50 years or older) and plants with an average age of 15 years.

These plants were uprooted, dried, and weighed. The stump and root system were then separated from the stems and branches. Subsequently, the ratio between the root and stem components was calculated for each sample.

The root/stem ratio is the ratio of underground biomass to aboveground biomass, which is the parameter that most directly reflects the distribution of biomass by the plants.

The average root/stem ratio for the two planting years considered was found to be:

Age of plants	roots / stem
50 years	2,72
15 years	0,82

For younger shrubs (less than 15 years old), the ratio described in the literature by the Universidad del Valle de Guatemala[2] was used.

For shade trees, mainly consisting of Grevillea robusta and species of the genus Inga, the method studied by S. Kuyah et al. at the University of Agriculture and Technology (Kenya)[3] was adopted.

For shade trees, mainly consisting of Grevillea robusta and species of the genus Inga, the method studied by S. Kuyah et al. at the University of Agriculture and Technology (Kenya)[3] was adopted.

After estimating the biomass of the trees with known diameters, the average of the obtained values for each plot (Shade trees biomass mean) and the total biomass was subsequently calculated.

Finally, the fraction of Carbon (C) contained within the plants was calculated following the guidelines of the Intergovernmental Panel on Climate Change (IPCC 2006) , which provide a percentage value of 47% of the biomass. Thanks to this value, it was then possible to obtain the total amount of CO_2 stored by the coffee and shade plants present in the plantation.

2. *Castellanos E, Quilo A, Pons D (2010) Estudio de Linea Base deCarbono en Cafetales. Centro de Estudios Ambientales y de Biodiversidad, Universidad del Valle de Guatemala,Guatemala City.*

3. *Shem Kuyaha,b,*, Johannes Dietzc, Catherine Muthuria,b, Ramni Jamnadassa, Peter Mwangib,Richard Coea, Henry Neufeldta, World Agroforestry Centre (ICRAF), Jomo Kenyatta University of Agriculture and Technology (JKUAT, Kenya,World Agroforestry Centre (ICRAF), P.O. Box 1558, Lima 12, Perù.*

4. *Intergovernmental Panel on Climate Change. 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Volumes 1, 2 and 3. Intergovernmental Panel on Climate Change Secretariat, Geneva, Switzerland.*

Results

The following chapter will analyze and explain the results divided by each plot of the Itimba Plantation concerning the analyses conducted on coffee plants, shade trees, and finally, the data of the entire Itimba plantation will be presented.

- **Coffee Plants**

PLOT	TOTAL BIOMASS		CARBON (Kg)	CO_2 (Kg)
	aboveground biomass (kg)	belowground biomass (kg)		
House 1A	372,17	134,87	238,31	873,80
House 1B	13218,30	28088,88	19414,37	71186,03
House 3	6930,98	14728,33	10179,88	37326,22
House 4	18541,98	14568,70	15562,02	57060,73
House 5	13706,54	10769,43	11503,71	42180,25
House 6	17745,49	13942,88	14893,53	54609,63
Camp A	11304,44	8882,06	9487,65	34788,06
Camp B	2795,80	2196,70	2346,47	8603,73
Factory A1	4108,00	3227,71	3447,79	12641,88
Factory A2	7172,14	2599,17	4592,51	16839,21
Factory A3	6463,77	2342,46	4138,93	15176,07
Factory A4	5766,32	4530,68	4839,59	17745,16
Factory B1	9272,08	3360,18	5937,16	21769,59
Factory B4	15331,04	5555,94	9816,88	35995,22
Factory B3	10037,60	3637,60	6427,35	23566,93
Factory C1	36160,13	76840,28	53110,20	194737,38
Factory C2	7682,66	2784,18	4919,42	18037,86
Factory C3	28659,70	10386,21	18351,58	67289,12
Factory C4	7442,01	2696,97	4765,32	17472,85
Factory D	27028,27	21236,50	22684,44	83176,28
River 1	40497,18	14676,09	25931,44	95081,93
River 2	21650,76	7846,19	13863,57	50833,07
River 3A	3633,85	1316,90	2326,85	8531,78
River 3B	2978,43	1079,38	1907,17	6992,96
House 2A	5114,24	4018,33	4292,31	15738,46
House 2B	6886,25	14633,28	10114,18	37085,32
House 2C	8579,85	18232,19	12601,66	46206,09
Factory B2	3657,16	1325,35	2341,78	8586,52

- **Shade Trees**

PLOT	TOTAL BIOMASS (Kg)	CARBON (Kg)	CO_2 (Kg)
House 1A	5,47	2,57	9,42
House 1B	16361,80	7690,04	28196,83
House 3	25272,19	11877,93	43552,41
House 4	62269,79	29266,80	107311,61
House 5	26014,84	12226,97	44832,24
House 6	22995,03	10807,66	39628,10
Camp A	79406,64	37321,12	136844,11
Camp B	142880,54	67153,86	246230,80
Factory A1	26559,80	12483,11	45771,39
Factory A2	77212,49	36289,87	133062,86
Factory A3	39966,34	18784,18	68875,32
Factory A4	65473,29	30772,45	112832,31
Factory B1	43048,65	20232,86	74187,17
Factory B4	14588,25	6856,48	25140,42
Factory B3	6737,98	3166,85	11611,78
Factory C1	59876,71	28142,05	103187,53
Factory C2	22706,94	10672,26	39131,63
Factory C3	53288,37	25045,54	91833,63
Factory C4	18243,48	8574,44	31439,60
Factory D	177386,74	83371,77	305696,48
River 1	13757,02	6465,80	23707,94
River 2	2456,85	1154,72	4233,97
River 3A	100,01	47,00	172,35
River 3B	62,69	29,46	108,04
House 2A	31780,77	14936,96	54768,86
House 2B	13046,93	6132,06	22484,21
House 2C	37024,31	17401,43	63805,24
Factory B2	12029,89	5654,05	20731,52

CKnowing the amount of CO2 stored by the coffee plants and the shade trees in each plot, it is sufficient to sum the values to obtain the total carbon dioxide content of the entire plantation.

Respectively, therefore:

- CO_2 stored by the coffee plants: **1.100,13 tons**
- CO_2 stored by the shade trees: **1.879,39 tons**

The CO_2 stored by the entire plot corresponds to a total of: **2.979,52 ton**

PLOT	Coffee Plants CO_2 stored (Kg)		Shade Threes CO_2 stored (Kg)	
House 1A	873,80		9,42	
House 1B	71186,03		28196,83	
House 3	37326,22		43552,41	
House 4	57060,73		107311,61	
House 5	42180,25		44832,24	
House 6	54609,63		39628,10	
Camp A	34788,06		136844,11	
Camp B	8603,73		246230,80	
Factory A1	12641,88		45771,39	
Factory A2	16839,21		133062,86	
Factory A3	15176,07		68875,32	
Factory A4	17745,16		112832,31	
Factory B1	21769,59		74187,17	
Factory B2	8586,52		20731,52	
Factory B3	23566,93		11611,78	
Factory C1	194737,38		103187,53	
Factory C2	18037,86		39131,63	
Factory C3	67289,12		91833,63	
Factory C4	17472,85		31439,60	
Factory D	83176,28		305696,48	
River 1	95081,93		23707,94	
River 2	50833,07		4233,97	
River 3A	8531,78		172,35	
IRiver 3B	6992,96		108,04	
House 2A	15738,46		54768,86	
House 2B	37085,32		22484,21	
House 2C	46206,09	TOT CO_2	63805,24	TOT CO_2
Factory B4	35995,22	(tons)	25140,42	(tons)
TOTAL	1.100.132,13	1.100,13	1.879.387,76	1.879,39

Shade Trees and CO_2 storage

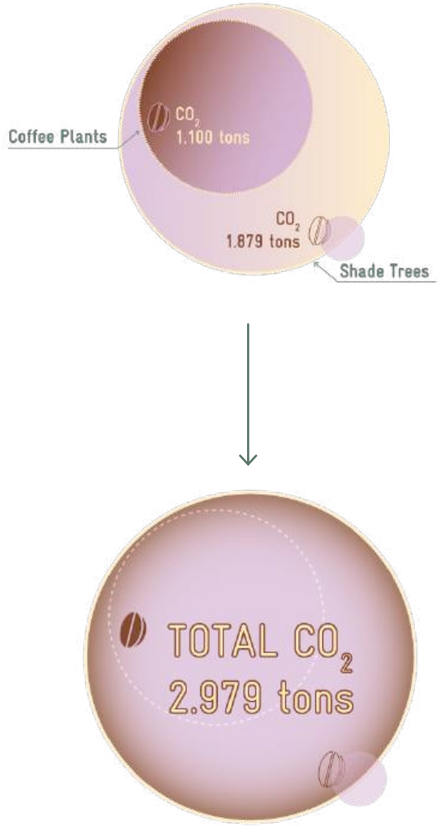
The method adopted has provided us with a suitable tool for calculating the biomass of the Itimba plantation using only data related to diameters and the number of plants. By determining the total biomass expressed in kilograms of dry organic matter, we estimated the CO_2 stored in the aboveground and coarse roots, which amounts to 2,979 tons, divided into 1,100 tons for the coffee plants and 1,879 tons for the shade trees.

As can be easily noted, the influence of trees is decisive; in fact, they are responsible for 63% of the total CO_2 stored in the plantation, while coffee shrubs contribute only 37%.

This data is influenced by the considerable size of the trees compared to the shrubs, which, although there are only 883 compared to 160,385 coffee plants, weigh significantly more. In fact, the average weight of a shade tree is about 1,200 kg, while the average weight of a coffee shrub, including roots and stump, is 4 kg.

As can be easily noted, the influence of trees is decisive; in fact, they are responsible for 63% of the total CO_2 stored in the plantation, while coffee shrubs contribute only 37%.

The importance of trees in an agricultural system is therefore not limited to the agronomic advantages they provide, such as windbreak functions and protection from direct solar radiation with consequences on reducing water consumption, but they also bring significant environmental benefits by removing considerable amounts of carbon dioxide from the atmosphere.



CO_2 stored respectively by coffee plants, shade trees, and the entire Itimba plantation. ↑

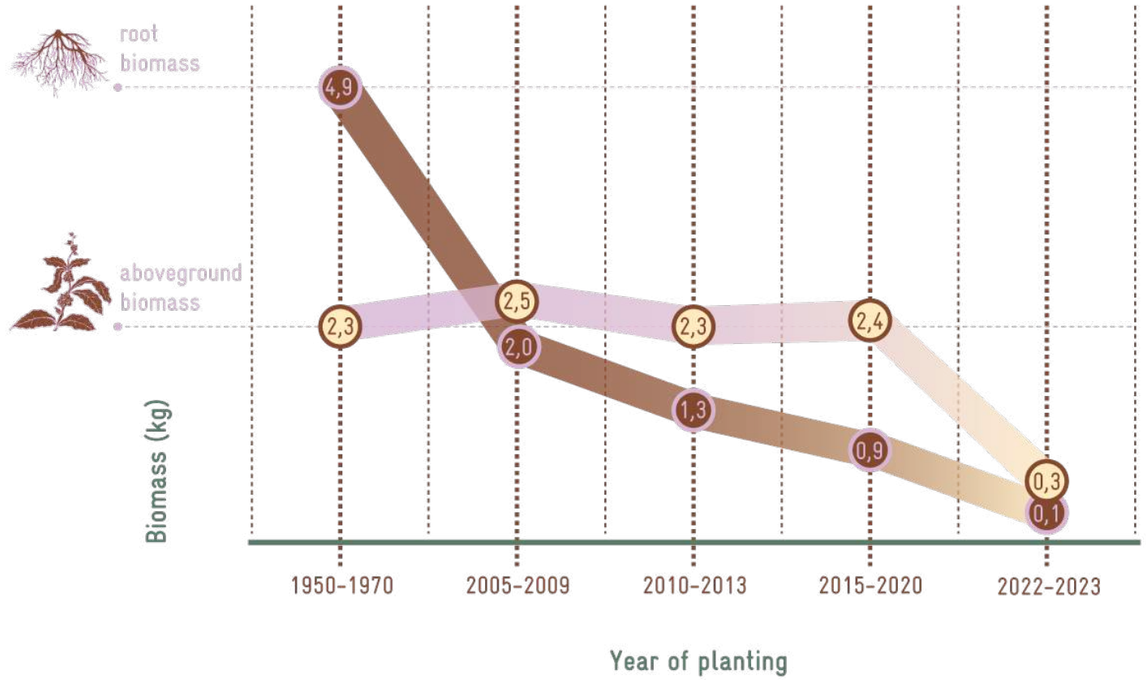
Farming techniques and CO_2 storage

The agronomic system in use involves managing the plants through a pruning cycle that usually occurs every five years, to ensure a renewal of the aerial part of the plant intended for production.

Recently planted trees (2022-2023) have not yet undergone pruning, while those planted in previous years have been pruned a number of times (this is directly proportional to the age of the plant). The older the age of the plant, the greater the number of times it has been pruned.

The vegetative portion of each plant is therefore cyclically reduced through pruning. In this way, the average biomass (i.e., the weight expressed in kg), of the aboveground part of the plant remains practically constant over time once it reaches adulthood. The graph below represents the trend of aboveground biomass (i.e., stump and trunk) and underground in relation to the age of the coffee plants, from the first planting year. The time period analyzed is from 1950 to the last plants planted in 2023. It can be observed that the average biomass of the vegetative portion remains practically constant over time once it reaches maturity.

*Average biomass per single plant within the **Itimba** ↘*



In fact, only the recently planted trees (2022-2023) have values that deviate from the average.

In contrast, the average trend of root biomass over the years is completely different, as there is no correspondence with the average weight of the aboveground part. It can be seen in the graphs that the older plots correspond to a greater amount of average root biomass, while in the more recent ones, the weight of the roots decreases drastically.

This trend reflects the growth of larger roots and the stump portion below the surface.

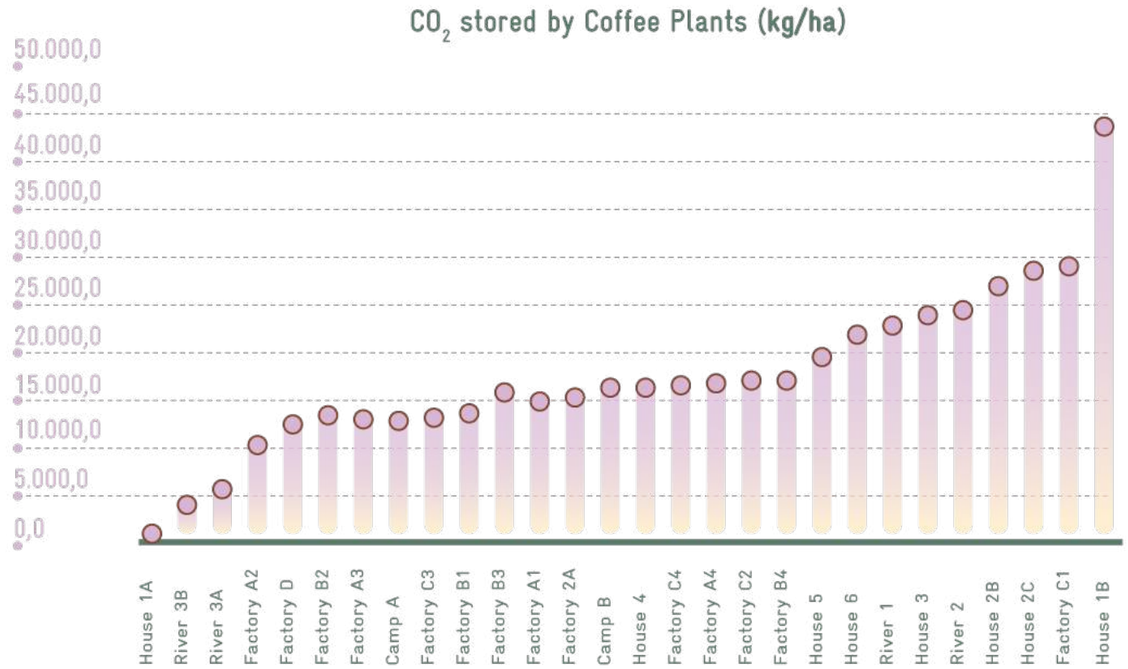
It is interesting to note that in the older plots (1950-1970), the weight of the roots and stump is greater than that of the aboveground portion, while for the plants planted from 2005 onwards, the value of root biomass is always less than that of the aerial part (trunk and branches).

Coffee biomass and agronomic system

The amount of carbon dioxide stored by coffee plants is closely related to their biomass and depends on many factors, such as: the agricultural practices implemented, the training system used, the age of the individual plants, the presence or absence of shade plants, and the planting density.

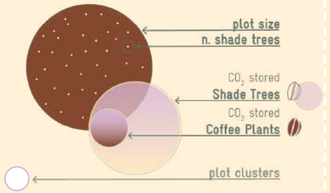
To determine which condition allows for the highest contribution in terms of CO_2 storage, the quantity calculated in each plot was compared to the area unit, namely the hectare. This allows for the assessment of how the factors of planting density and plant age can substantially influence the final result.

Indeed, it can be observed that plot It. House 1B yields the best results in terms of the amount of carbon dioxide stored per hectare of surface area, while plot It. House 1A is the least favorable. The high planting density (3,700 plants/ha), combined with the greater age of the plants (planted in 1970), proves to be the best combination. In fact, it allows for the storage of about 46,000 kg of CO_2 per hectare compared to the 230 kg/ha stored with a density of 2,057 plants per hectare planted in 2023.



LEGEND

Itimba plot // year of planting



Factory **A1** // 2009

Factory **A2** // 2017

Factory **A3** // 2013

Factory **A4** // 2006

Factory **B1** // 2012

Factory **B2** // 2015

Factory **B3** // 2015

Factory **B4** // 2017

Factory **C1** // 1950

Factory

Factory **C2** // 2017

Factory **C3** // 2016

Factory **C4** // 2015

Factory **D** // 2005

The number of shade trees significantly affects the amount of CO_2 stored in each plot.

House

House **1A** // 2023

House **1B** // 1970

House **2A** // 2011

House **2B** // 1970

House 2C // 1970

House **2B** // 1970

House **4** // 2005

House **5** // 2007

House **6** // 2008

River - Camp

River **1** // 2018

River **2** // 2020

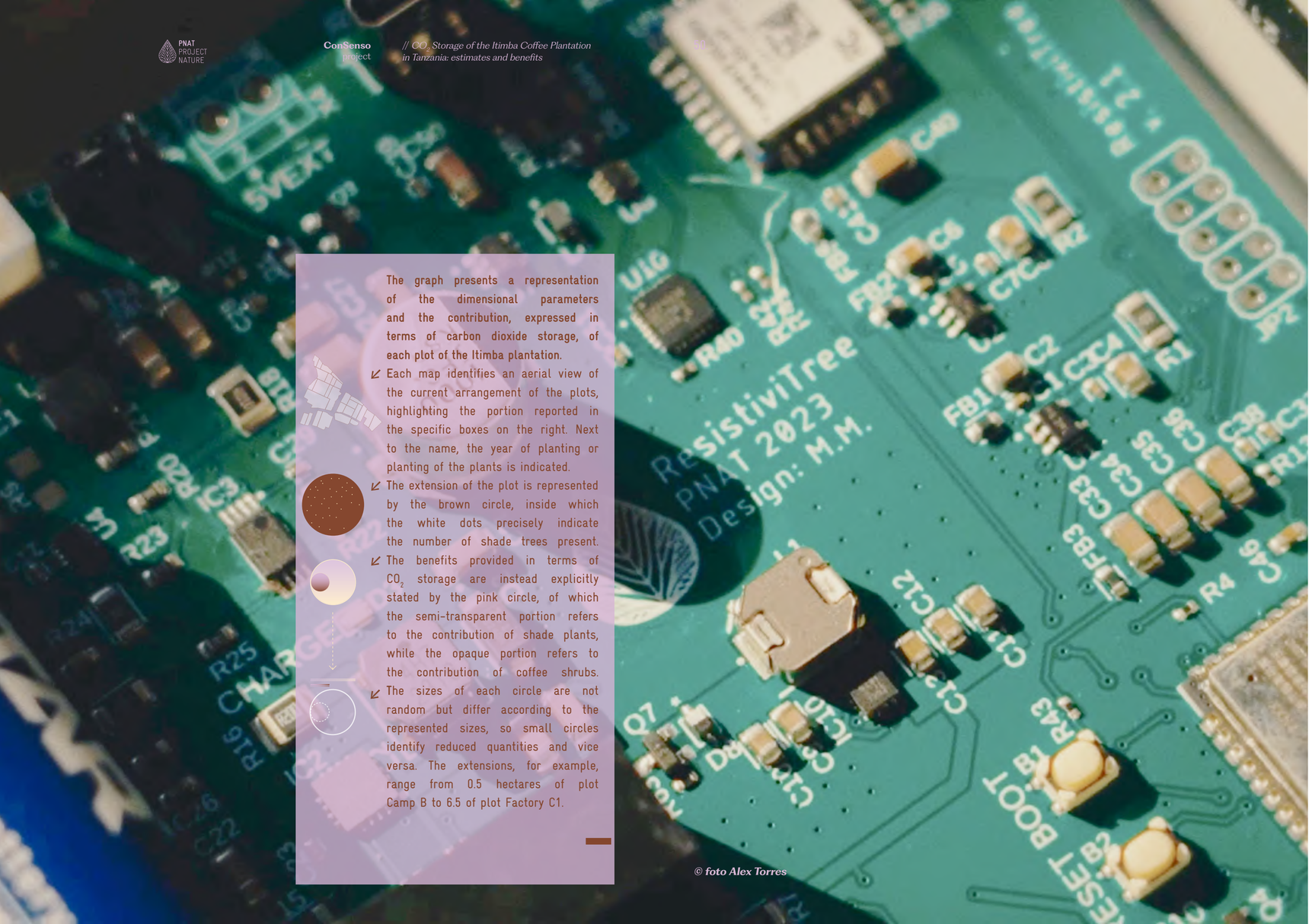
River **3A** // 2022

River **3B** // 2022

Camp **A** // 2007

Camp **B** // 2010

The roots of the older coffee shrubs constitute over 60% of their total biomass.



The graph presents a representation of the dimensional parameters and the contribution, expressed in terms of carbon dioxide storage, of each plot of the Itimba plantation.

- Each map identifies an aerial view of the current arrangement of the plots, highlighting the portion reported in the specific boxes on the right. Next to the name, the year of planting or planting of the plants is indicated.
- The extension of the plot is represented by the brown circle, inside which the white dots precisely indicate the number of shade trees present.
- The benefits provided in terms of CO_2 storage are instead explicitly stated by the pink circle, of which the semi-transparent portion refers to the contribution of shade plants, while the opaque portion refers to the contribution of coffee shrubs.
- The sizes of each circle are not random but differ according to the represented sizes, so small circles identify reduced quantities and vice versa. The extensions, for example, range from 0.5 hectares of plot Camp B to 6.5 of plot Factory C1.

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Conclusions

Climate change represents one of the most serious and urgent challenges of our time.

The continuous rise in global temperatures, the increase in sea levels, and the rise in the frequency and intensity of extreme weather events are just some of the visible consequences of this phenomenon. Greenhouse gas emissions, particularly carbon dioxide (CO_2), are among the main drivers of global warming.

The Mauna Loa Observatory in Hawaii has recorded increasing levels of atmospheric CO_2 in recent decades, highlighting the urgency of taking concrete measures to reduce these emissions. Afforestation is one of the most effective strategies to combat the rise in atmospheric CO_2, but it often clashes with the need to allocate land for agriculture to support a growing global population. Trees absorb carbon dioxide and release oxygen, acting as true carbon reservoirs. However, it is essential to find a balance between forest expansion and the availability of agricultural land. For this reason, it is equally important to promote sustainable agronomic practices, such as agroforestry and the use of innovative technologies to improve crop yields without increasing the ecological footprint. Agroforestry is one of the actions recommended by the Kyoto Protocol to offer an integrated solution that combines agricultural crops and trees, improving biodiversity and soil fertility.

The agroforestry system of Itimba immobilizes a total of 2,979.52 tons of CO_2, of which 1,879.39 tons are represented by shade plants

The in-depth study conducted on the Itimba plantation has highlighted how the adopted agroforestry system, which integrates shade plants with coffee plants, significantly contributes to CO_2 storage.

The Grevilleas, Albizias, Jacarandas, and all the shade species used protect coffee from direct sunlight, reduce the need for irrigation and protect the soil from erosion.

Importantly, as clearly indicated by the reported numbers, these trees also absorb and store a quantity of carbon dioxide that alone represents two-thirds of the total stored. Agroforestry also creates a diversified habitat that supports a wide range of flora and fauna. The shade trees provide shelter and food resources for insects, birds, and small mammals, while their roots improve soil structure and promote the growth of beneficial microorganisms. This complex ecosystem not only improves the yield and quality of coffee but also promotes a natural balance, reducing the need for pesticides and chemical fertilizers, and contributing to the overall health of the environment. Furthermore, the presence of different plant species enhances the resilience of the ecosystem to diseases and climate change, creating a more sustainable and productive agricultural system in the long term.

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Root systems, an important resource for CO_2 storage in older plantations

In order to ensure consistent and quality production, the plantation has implemented a procedure of renewal prunings that consist in the periodic removal of almost 2/3 of the total aboveground biomass, in cycles that repeat approximately every 5 years. As can be easily inferred, these prunings negatively affect the amount of CO_2 stored by individual plants.

Consequently, in order to maximize the contribution of the plantation to CO_2 storage, it is essential to ensure careful management of this periodically removed wood. If this removed word is simply used as firewood, the carbon sequestered would automatically be released into the atmosphere. However, if this removed wood is methodically managed (e.g., if it is composted, buried, or used on the farm) this can guarantee long lasting carbon sequestration over time.

In contrast, the root biomass is not affected by periodic pruning. The underground wood therefore swells until it reaches significant dimensions over time, so much so that it represents 60% of the total biomass in the 50-year-old plants analyzed in this study. Roots, therefore, play a crucial role in carbon sequestration, making older plantations an important reservoir for storing CO_2.

Pnat (Project Nature) is a multidisciplinary team of plant scientists, botanists, architects, engineers, and designers that creates innovative projects related to the plant world. Founded as a spin-off of the University of Florence by Professor Stefano Mancuso along with agronomists and botanists Elisa Azzarello, Camilla Pandolfi, and architects Antonio Girardi and Cristiana Favretto, it can count on the expertise of environmental and electronic engineers and designers to study solutions that amplify the innate ability of plants to produce benefits for the environment in which they live.

Thanks to its collaboration with the International Laboratory of Plant Neurobiology (LINV), one of the most important research centers on plants worldwide directed by Stefano Mancuso, Pnat focuses on transferring knowledge about plants into projects at various scales .

Among the projects developed by Pnat is the Air Factory, an innovative indoor greenhouse equipped with a system designed and created by Pnat that uses plants to absorb and degrade atmospheric pollutants and purify the air efficiently and sustainably. The project is a finalist for the Compasso d'Oro Award. With Jellyfish Barge, a floating greenhouse capable of desalting seawater presented at EXPO 2015, Pnat has received international recognition from institutions such as UNIDO (United Nations Industrial Development Organization) and UNECE (United Nations Economic Commission for Europe). In 2020, Pnat won the MISE Brevetti+ grant for the development of Communitree - a sensor capable of detecting physiological parameters of trees to assess their stability.

Pnat is indeed dedicated to the field of sensors applied to the plant world, developing detection tools and data processing software capable of measuring physiological parameters of plants and correlating them with aspects such as their health, stability, productivity, and systems to accurately quantify the environmental benefits provided by plants to the environment.

The current technological challenge that Pnat is pursuing involves the use of Artificial Intelligence in the form of Machine Learning Systems to build evaluation models that use data collected by sensors to assess the performance of plants in various fields of application.

Pnat also aims to be a scientific partner in the creation of reports and studies to define the environmental benefits provided by plants in specific territorial projects or in the production of plant-based products.