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Original Research

Carbon Sequestration Capacity of Five Agroforestry Systems in Tunisia: A Case Study of the Djebba Living Lab

Azizi-Gannouni Thouraya[1]*, Govit Ajit[2], Mohamed Habib Sellami[3], Ammari Youssef[1], Abassi Mejda[1]

[1]National research institute of rural engineering water and forests, Street Hedy Karray, BP N°10, Ariana 2080, Tunisia
[2]ICARDA, Al Maadi Company, Maadi as Sarayat Al Gharbeyah, Maadi, Cairo Governorate 4212050, Égypte
[3]Higher School of Engineers of Medjez El Bab (ESI Medjez El Bab), University of Jendouba: Route Kef, Km 5 – 9070 Medjez El Bab

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Abstract

Agroforestry is the integration of trees or shrubs with crops and/or livestock on the same plot and/or landscape. The Agroforestry System (AFS) is a promising agroecological approach for climate change adaptation and mitigation through carbon sequestration in both biomass and soil. This work aimed to assess the biomass of fig trees (*Ficus carica*) and their intercrop, their carbon stock (C stock) and CO_2 equivalent (CO_2-eq), as well as the soil organic carbon stock (SOC stock) and soil CO_2 equivalent (CO_2-eq) at a depth of 0-30 cm. The experimental work was conducted in the Djebba region, located in the northwest of Tunisia, during 2023 and 2024. This experimental site was called Djebba Living Lab. In the latter, 5 AFSs were selected based on the variability of intercrop, given that the main tree species was a landrace fig tree, "Bouhouli". The intercrops which were sown under and very close to fig trees in AFS1, AFS3, AFS4, and AFS5 are zucchini, barley, faba bean, and pepper, respectively. AFS2 was a control system composed solely of fig trees in monoculture. In 2024, the highest biomass, C stock, and CO_2 equivalent were recorded in the trees of AFS4, with 78.59 t/ha, 36.94 t/ha, and 135.57 t/ha, respectively. The assessment of soil showed that SOC stock and CO_2 equivalent were 21.41 t/ha and 78.58 t/ha, respectively. AFS5 (mixture of market gardening and pepper landrace) outperformed all others, achieving the highest annual biomass accumulation (2.21 t ha^{-1} yr^{-1}), C stock (1.03 t ha^{-1} yr^{-1}), and CO_2-eq (3.81 t ha^{-1} yr^{-1}). However, the monoculture system (AFS2) registered the lowest values with annual biomass accumulation (0.17 t/ha/year), C stock (0.08 t/ha/year), and CO_2-eq (0.30 t/ha/year). Agroforestry has been acknowledged as a climate change mitigation strategy. Through this agronomic practice, AFSs with various intercropping have the potential to increase the surface area through the use

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*e-mail: najeh.esak@gmail.com
ORCID 0000-0002-3414-9167

of understory crops, improve the biomass, and subsequently increase the carbon sequestration in plants and soil.

Keywords: agroforestry, carbon sequestration, Djebba Living Lab, *Ficus carica,* monoculture

Introduction

Global warming and climate change are results of the enormous emissions of greenhouse gases (GHGs) such as CO_2 and NO_2. The atmospheric concentration of CO_2 has increased from the preindustrial level of about 280 ppm to the current level of approximately 380 ppm and is estimated to be increasing at the rate of 2 ppm annually [1]. Indeed, to decrease the amount of gas emissions, many other solutions have been applied: carbon farming practices based on nitrogen-fixing crops, cover cropping, reduced tillage, agroforestry, the use of organic fertilizer instead of synthetic fertilizers, mulching, etc.

Carbon storage in soils and vegetation contributes both to climate change mitigation and to the adaptation of ecosystems to its effects. Soils and plants capture greenhouse gases from the atmosphere and store them, thus acting as carbon sinks, a process known as carbon sequestration (CS). This process is driven by photosynthesis in plants and by the decomposition of organic matter in soils. It provides a strong argument for both the preservation of natural, agricultural, and forested areas and the promotion of green spaces in urban environments. For these reasons, carbon sequestration represents a key pillar in achieving the carbon neutrality goal by 2050.

Based on the policy perspectives of developed economies, achieving carbon neutrality is challenging because it is nearly impossible to reduce absolute emissions to zero. Therefore, reaching this goal requires compensating for residual emissions through carbon removal and offsetting strategies [2].

Agroforestry (AF), defined as the deliberate integration of trees or shrubs with crops and/or livestock at the plot, farm, or landscape level [2], has become recognized as a carbon sequestration (CS) activity under the Afforestation and Reforestation activities. Agroforestry systems (AFSs) have attracted attention as a CS strategy from both industrialized and developing countries [3-10].

Despite the fact that AFSs serve as a promising strategy for climate change adaptation, they are often not included in carbon sink measurements or mitigation reports, and they are rarely measured in adaptation actions [10-12].

To enhance productivity, profitability, diversity, and ecosystem sustainability, AFSs are considered to have a higher potential for carbon (C) sequestration due to their ability to more efficiently capture and utilize growth resources such as light, nutrients, and water, and to reduce soil disturbance, compared to single-species cropping or pasture systems. The total area in the world under agroforestry was estimated at 1023 million hectares [7, 8]. Worldwide, nearly 630 million hectares of unproductive croplands and grasslands are set to be converted to agroforestry [13].

Across Africa, AFSs are gaining traction as a regenerative practice, with estimates suggesting they could sequester as much as 2,000 megatons of carbon annually [14]. AFSs enhance biodiversity and several ecosystem services; they allow the storage of atmospheric carbon. This storage takes place on the one hand in the wood of the tree, in the shrubs and the herbaceous layer (biomass), but also in the organic matter incorporated into the soil (soil organic carbon, SOC). The soil and the plant cover then constitute a carbon reservoir (carbon sink). Therefore, an understanding of carbon storage in soils under AFSs is particularly important. To quantify and monitor ecosystem services and to estimate the amount of sequestered carbon in the soil and the crops, this study aims to assess various parameters such as above- and below-ground biomass (AGB, BGB), soil organic carbon (SOC), carbon stock in biomass and soil.

In Tunisia, the most current agroforestry practices involve fruit trees and semi-forest trees. Case studies were conducted in the northwest of Tunisia by [15], using olive trees with six cover crop types: wheat, vetch, oat, fenugreek, a vetch-oat mixture, and spontaneous vegetation. Study [16] also investigated an AFS located in the center of the oasis of Degache in southern Tunisia (desert). The latter was a combination of date palm and barley (*Hordeum vulgare*)-alfalfa (*Medicago sativa*) as intercrops. According to studies [15] and [16], carbon sequestration varies depending on climatic conditions. These studies have shown that, compared to arid zones, sub-humid regions (Djebba Living Lab) have a greater potential for biomass accumulation and therefore higher carbon storage capacity in both vegetation and soil.

In this work, we are interested in a specific AFS located in Djebba, a village in the northwest of Tunisia. In this region, each AFS contained three farming levels: fig tree level, other fruit trees or olives level, and market gardening or livestock level.

The main income for farmers in Djebba is derived from fig harvest, particularly from the "Bouhouli" variety. The fig tree (*Ficus carica*) is one of the deciduous trees used in Tunisian agroforestry systems such as Djebba Living Lab. This species is native to the Mediterranean basin and has spread widely across the world owing to its adaptability to various soils and climates, as well as the high economic value of its fruit, which is an excellent source of nutrients and antioxidants [17, 18]. Owing to its salt tolerance and adaptability to the climatic and soil conditions of semi-arid regions, fig trees are a promising alternative crop. Assessing suitable

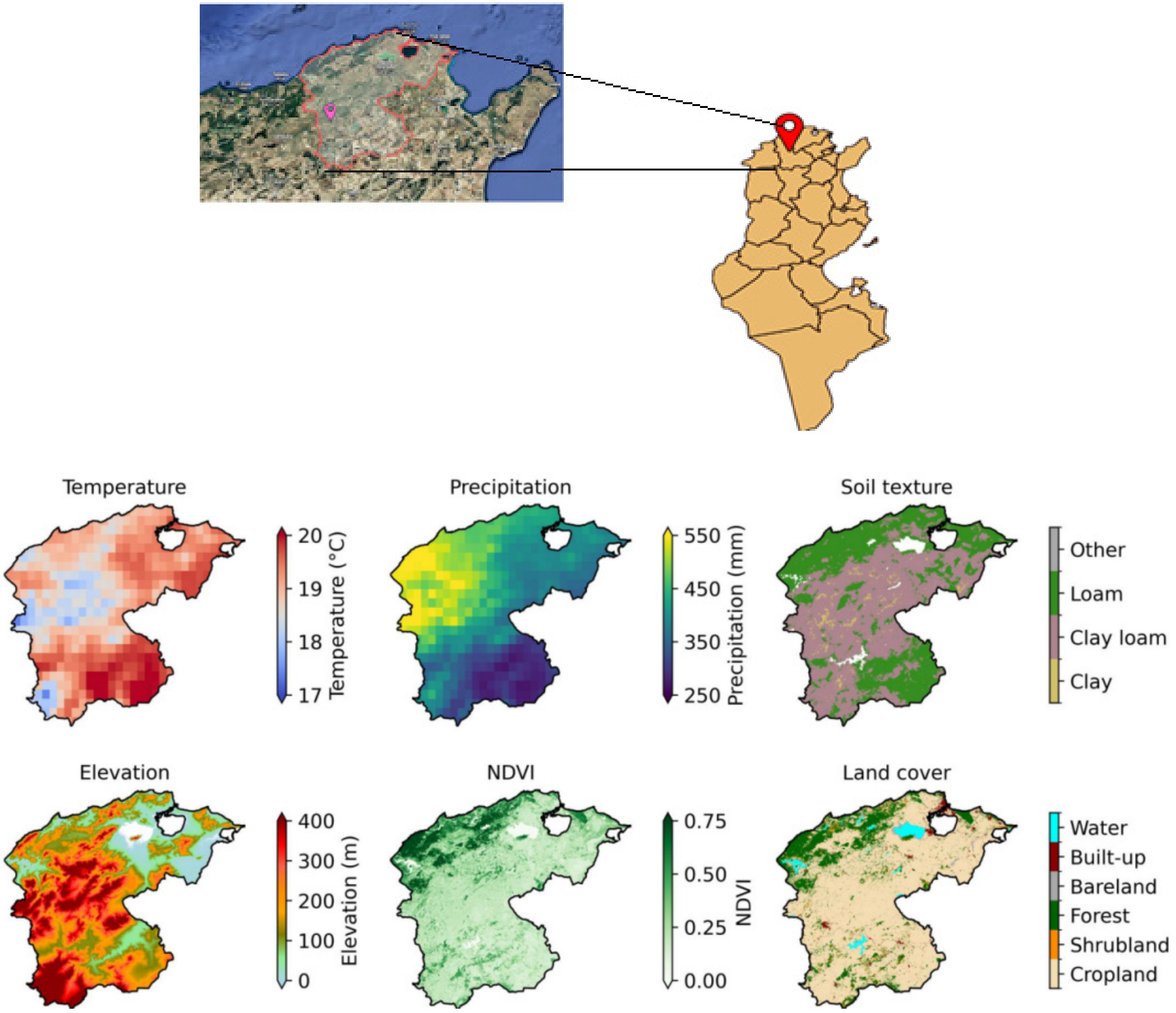

Fig. 1. Map of the study site and spatial distribution of various biophysical variables across the TUMBB landscape.

areas for cultivating crops such as figs is essential for sustainable agricultural planning, conserving natural ecosystems, and ensuring food security [19].

We have adopted the Living Lab (LL) approach. The latter has garnered increased attention as a participatory and user-centered method for the co-design of community services [11, 20, 21]. A Living Lab is a collaboration between multiple stakeholders, including farmers, researchers, and public institutions (e.g., INRGREF Institute), with the main objective of evaluating new techniques, practices, services, and products. Other AF systems as LLs have been exploited in Tunisia and around the world, based on several species and their interaction with the environment.

The objective of this study is the assessment of carbon stock and CO_2-equivalent evolution through agroforestry systems (AFSs) compared to monoculture in Djebba Living Lab using biomass and SOC.

Materials and Methods

Geographic Localization, Climatic, Soil Characteristics, and Canopy General Characteristics of the Five AFSs in Djebba Living Lab

The experiment was carried out in the Djebba region (Djebba Living Lab), located in the northwest of Tunisia (Fig. 1). The assessment of five agroforestry systems in this region took place between 2023 and 2024.

The Djebba region belongs to a sub-humid climate with mild winters and hot summers. In winter, the average temperature is around 8°C, and in summer, the average temperature is around 16°C. This area receives annual rainfall of around 550 mm (Fig. 1). The soil is generally clay to clay loam, sometimes with limestone.

Table 1 presents the geographic coordinates of the five selected AFSs.

Table 1. Geographical coordinates, age, and soil characteristics of the studied AFSs in Djebba LL.

	AFS1	AFS2	AFS3	AFS4	AFS5
Altitude (m)	457	603	579	504	484
Latitude Longitude	36°28'38.7" 9°06'17.3"	36°28'17.1" 9°6'06.6"	36°28"18.3" '9°5'59.1"	36°28’29 ‘’ 9°06’06”	36°28'9° 05'09°.8"
Initial SOC stocks (tC/ha)	3.82±0.05	1.53±0.01	8.3±0.1	3.04±0.03	3.023±0.01
Soil pH	8.03	8.01	7.81	8.12	7.97
Intercrop species	Zucchini (landrace)	-	Barley (landrace)	Legume (landrace faba bean)	Mixture of trees and landrace pepper
Age of trees (years)	25	12	15	35	25

Methodology of Measurement of Tree Biomass

A non-destructive approach based on allometric equations was used to estimate above-ground tree biomass. For this purpose, five trees were selected from each AFS (different diameter classes and different ages). Measurements were carried out at the harvesting stage. The parameters measured were: trunk height, diameters at three positions along the trunk, branch length and diameter, canopy diameter in the perpendicular orientation, and H (canopy height).

Above-ground biomass (AGB) includes all living biomass above the soil, including stem, stump, branches, bark, and foliage, whereas below-ground biomass (BGB) includes all living biomass of live roots. The AGB was calculated using the following Equation [22]:

$$\text{AGB} = \text{Vbiomass} \times \text{dwood} \qquad (1)$$

AGB: Above-ground biomass (gr),

Vbiomass: Volume occupied by plant biomass (cm^3) (π*(CD1*CD2/4)*H,

dwood: Density of plant wood (gr/cm^3),

CD1: the widest crown diameter, and CD2 was its perpendicular diameter in cm [23],

H: height of canopy (cm).

To evaluate the Below Ground Biomass (BGB), Equation (2) [22] was used.

$$\text{BGB} = \text{F(conv-BGB)} \times \text{AGB} \qquad (2)$$

BGB: Below Ground Biomass (gr),

F (conv-BGB): Conversion factor for Below Ground Biomass (about 0.26).

Carbon stock, which refers to the amount of carbon stored in the forest ecosystem, mainly in living biomass and soil, can be determined using the following Equation [24-26]:

$$\text{C (stock-canopy)} = \text{F(conv-carbon stock)} \times \text{AGB} \qquad (3)$$

C (stock-canopy): Carbon stock in the canopy (tonnes),

F(conv-carbon stock): Conversion factor for carbon stock (about 0.47).

Wood density represents the allocation of dry biomass per unit volume of live wood and predicts various mechanical properties of plants. The Wood Biomass Density (WBD) value (0.612 g cm^{-3}) was derived from the Global Wood Density database [27-29].

To estimate the carbon sequestration capacity of a single plant or all canopies, carbon dioxide equivalent (CO_2-eq) was calculated using the following formula [30].

$$\text{C(seques-capacity-canopy)} = 3.67 \times \text{C(stock-canopy)} \qquad (4)$$

C(seques-capacity-canopy): Carbon sequestration capacity of a tree in a canopy or of all canopies (CO_2-eq).

Methodology of Measurement of Intercrop Biomass

Three quadrats of intercrop vegetation (1×1 m each) were established diagonally within each sampling plot [31]. In each quadrat, intercrop vegetation was recorded based on canopy coverage, and all vegetation was harvested. Samples of intercrop vegetation were taken to the laboratory and dried at 65°C to a constant weight for the determination of dry matter and carbon fraction.

The carbon concentrations of all sampled intercrop species were measured using the dry combustion method. Dry weights were converted to carbon stock by a factor of 0.47 and further to carbon dioxide equivalent by a factor of 3.67 [32].

The spacing between tree rows is 7 m, and cereals and legumes are sown at a density of 100 kg/ha. Zucchini and pepper were sown with an interspace of 20 cm between two plants. Tree hoeing is conducted in February-March, and weeding is performed manually. The tree irrigation rate was about 24 L/tree/day from May to September.

The experimental layout consists of tree rows planted at a spacing of 7 m, which allows sufficient light penetration and facilitates intercropping practices.

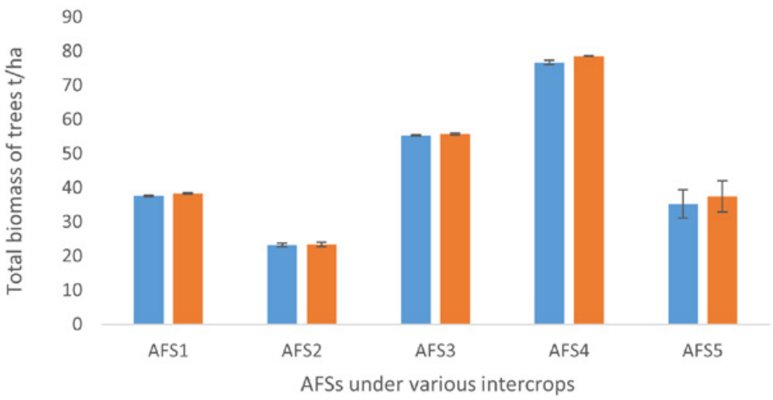

Fig. 2. Total tree biomass recorded for the five AFSs during two agricultural years (2023 and 2024). Error bars are the standard error of the mean.

Between the tree rows, cereals and legumes are established at a seeding density of 100 kg per hectare, ensuring adequate plant coverage. Zucchini and pepper are cultivated with an interplant distance of approximately 20 cm. Tree hoeing operations are carried out during February and March to improve soil aeration. Manual weeding is performed periodically to reduce competition for water and nutrients while minimizing the use of chemical inputs. Irrigation for the trees and subsequently the intercrops is provided from May to September, corresponding to the critical growth and fruiting stages, with an application rate of about 24 liters per tree per day.

Methodology to Evaluate the Carbon Storage Capacity of the Soil for the Five AFSs

Three points at 0-30 cm in each plot were sampled using an auger. Organic litter on the ground surface was cleared at each sampling site before auger insertion and sediment boring. Soil organic carbon (SOC) per hectare per layer (0-30 cm) was determined according to the following formula, as described by [33].

$$[\text{Stock}]\text{SOC} = \text{SOC} \times [\text{BD}]\text{soil} \times D(\text{soil samp depth}) \quad (5)$$

[Stock]SOC: Stock of soil organic carbon in t C ha^{-1},
SOC (%): Soil organic carbon concentration in %,
[BD]soil: Bulk density of the soil (g cm^{-3}),
D(soil samp depth): Soil sampling depth in cm.

Soil's capacity to sequester carbon, or the amount of carbon it can store, is a crucial factor in mitigating climate change. This capacity is influenced by various factors, including soil type, organic matter content, and management practices.

For soils of each AFS in Djebba LL, we evaluated their sequestration capacities as follows [34]:

$$C(\text{seques-capacity-soil}) = 3.67 \times C(\text{stock-soil}) \quad (6)$$

C(seques-capacity-soil): soil capacity sequestration in t CO_2,
C(stock-soil): Carbon soil stock in tonnes.

Statistical Analysis of the Data

Data processing and analysis were carried out using the SPSS software.

Results

Analysis of Carbon Sequestration Capacity for the Five AFSs

Evaluation of the Carbon Sequestration Capacity for the Tree Farming Level

In Fig. 2, we present the total biomass recorded in the five AFSs for the two agricultural years 2023 and 2024.

The results indicated that AFS4, composed of fig trees intercropped with faba bean, consistently produced the highest biomass among all systems. In 2023, the biomass reached approximately 76.62 t/ha, increasing slightly to 78.59 t/ha in 2024. This performance was followed by AFS3, which combined fig trees with barley landrace; its biomass levels were about 53 t/ha in 2023 and rose to 56 t/ha in 2024. In contrast, AFS2, consisting solely of fig trees without intercrops, exhibited the lowest biomass values, with 23.22 t/ha and 23.40 t/ha in 2023 and 2024, respectively. The intermediate systems, AFS1 (fig trees with zucchini landrace) and AFS5 (fig with a mixture of trees and pepper landrace), showed comparable outcomes. Both systems recorded around 40 t/ha of biomass in 2023, which increased modestly to about 42 t/ha in 2024.

The carbon stock amounts for all the AFSs studied are presented in Fig. 3. AFS4 sequestered the highest amount of carbon compared to the other systems, with approximately 36.04 t/ha and 36.94 t/ha in 2023 and 2024, respectively. AFS2 stored about 9 t/ha of carbon

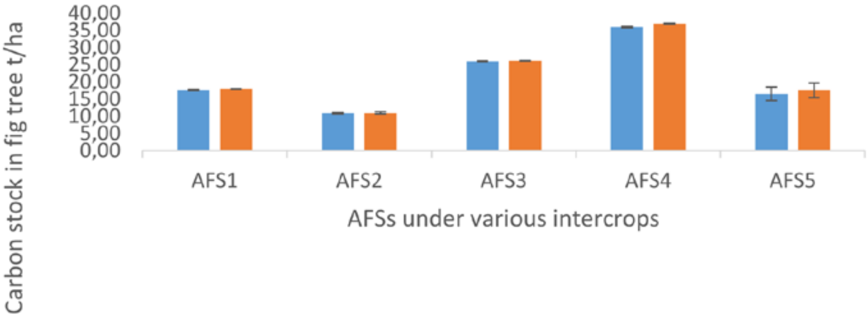

Fig. 3. Total carbon stock in trees recorded for the five AFSs during two agricultural years (2023 and 2024). Error bars are the standard error of the mean.

Table 2. Evolution of tree biomass accumulation, CO_2-eq, and C stock per year under various intercrop species.

	AFS1	AFS2	AFS3	AFS4	AFS5
Biomass (t/ha)/year	0.72533333	0.17866667	0.344	1.92533333	2.2112
CO_2 (t/ha)/year	1.25112747	0.30818213	0.5933656	3.32100747	3.81409888
C stock (t/ha)/year	0.3409067	0.08397333	0.16168	0.90490667	1.039264

in both 2023 and 2024. AFS1 and AFS5 stored similar amounts of carbon, around 18 t/ha in 2023 and 19 t/ha in 2024.

In Table 2, we summarized the tree biomass accumulation, CO_2-eq, and C stock per year for the five studied AFSs.

The comparison of agroforestry systems practiced by farmers in Djebba LL (Table 2) clearly showed that AFS5 outperforms all others, achieving the highest annual biomass accumulation (2.21 t ha^{-1} yr^{-1}), carbon stock (1.03 t ha^{-1} yr^{-1}), and CO_2 sequestration potential (3.81 t ha^{-1} yr^{-1}).

Evaluation of the Carbon Sequestration Capacity for the Under-Farming Level in the Five AFSs

In Fig. 4, a graphical summary is presented to illustrate the variation in biomass observed during the years 2023 and 2024 across the five agroforestry systems (AFSs) for the under-farming store.

The total dry biomass of the same produced intercrops (for each AFS) showed no significant differences between the two cropping seasons of 2021 and 2022; however, there is a significant difference among the four AFSs at $P \leq 0.05$ (Fig. 4).

The evaluation of the five agroforestry systems (AFSs) demonstrated significant differences in biomass production across the different crop combinations. Among them, AFS3, which incorporated fig trees with barley landrace, recorded the highest level of biomass. The harvested barley contributed approximately 16.23 t/ha, highlighting the strong compatibility between fig trees and barley under the given environmental and management conditions. At the opposite end, AFS1, where zucchini landrace was cultivated beneath the fig trees, exhibited the lowest biomass yield, with only 4 t/ha. AFS4, combining fig trees with faba bean landrace, achieved intermediate but promising results. Biomass production reached around 10.04 t/ha in 2023 and increased further to 11.83 t/ha in 2024. Finally, AFS5, consisting of a mixture of market gardening crops with pepper landrace, produced substantial amounts of barley dry biomass. Recorded values were 13.73 t/ha in 2023 and 12.33 t/ha in 2024.

The variation of carbon stock for the under-farming stores in the five AFS for two years (2023 and 2024) is reported in Fig. 5.

C stock in intercrop showed a significant difference among the different AFSs at $P<0.05$. The C stock of intercrops in the studied AFSs (except AFS2) varied from one system to another but remained stable from year to year. The behavior of the agroforestry systems in terms of carbon stock follows the same pattern as that of biomass accumulation. Carbon stock peaked in cereals sown in AFS3 at 7.52 and 7.63 t/ha throughout 2023 and 2024 respectively and was minimal in zucchini sown in AFS1 (1.88 t/ha during 2023 and 2024), with beans sown in AFS4 and peppers in AFS5 displaying moderate values which are 4.88-5.56 t/ha and 6.45-5.79 t/ha during 2023 and 2024 respectively.

The mitigation potential of the five AFSs was worked out by calculating equivalent carbon dioxide (CO_2-eq) (Fig. 6). The highest value of the equivalent carbon dioxide was recorded for the intercrop barley landrace in the AFS3 with 27.59 t/ha in 2023 and 28.00 t/ha in 2024. Faba bean intercropped in AFS4 sequestered approximately 17.5 t/ha and 22 t/ha of CO_2-eq in 2023 and 2024, respectively.

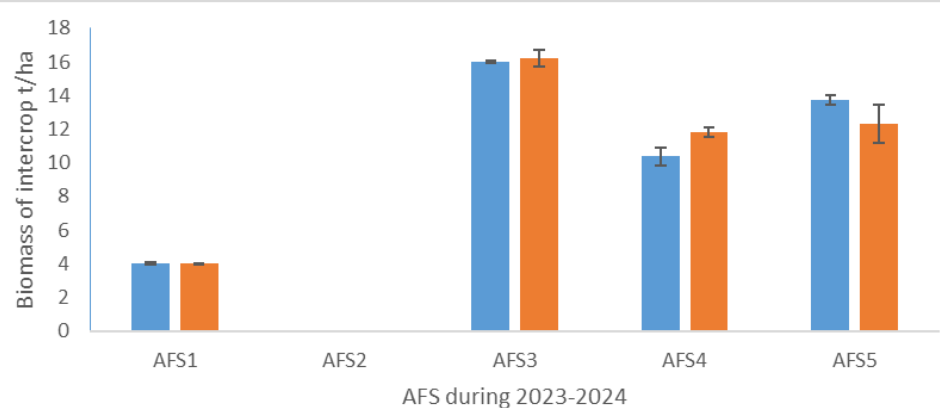

Fig. 4. Biomass variation during the years 2023 and 2024 for the under-farming stores in the five AFSs. Error bars are the standard error of the mean.

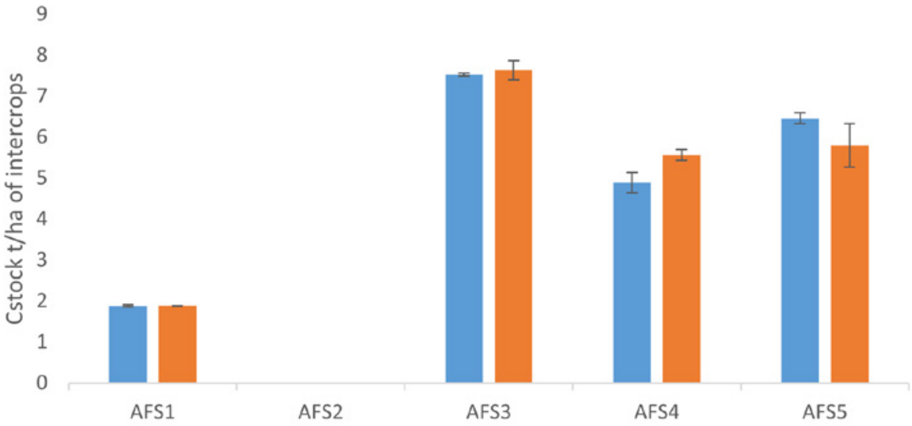

Fig. 5. Carbon stock for the under-farming stores in the five AFSs for two years (2023 and 2024). Error bars are the standard error of the mean.

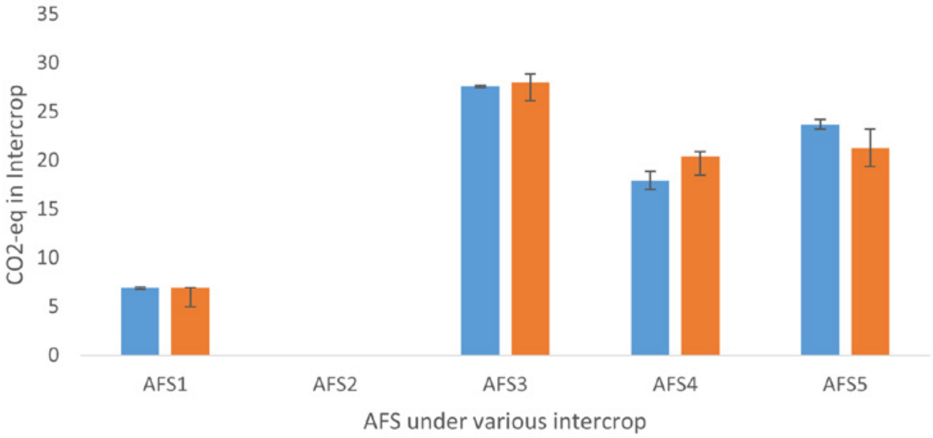

Fig. 6. The equivalent carbon dioxide sequestered by each AFS for the years 2023 and 2024. Error bars are the standard error of the mean.

The two agroforestry systems (AFS1 with zucchini landrace and AFS3 with barley landrace intercrops) did not exhibit any statistically significant differences in biomass at $P \leq 0.05$. However, a slight variation in CO_2-equivalent emissions was observed during 2023, with AFS1 (zucchini intercrop) showing lower values compared to the other systems. Despite this variation, no significant differences were detected in CO_2-eq between the two AFSs across the study period (2023-2024), indicating that both intercrop types performed similarly

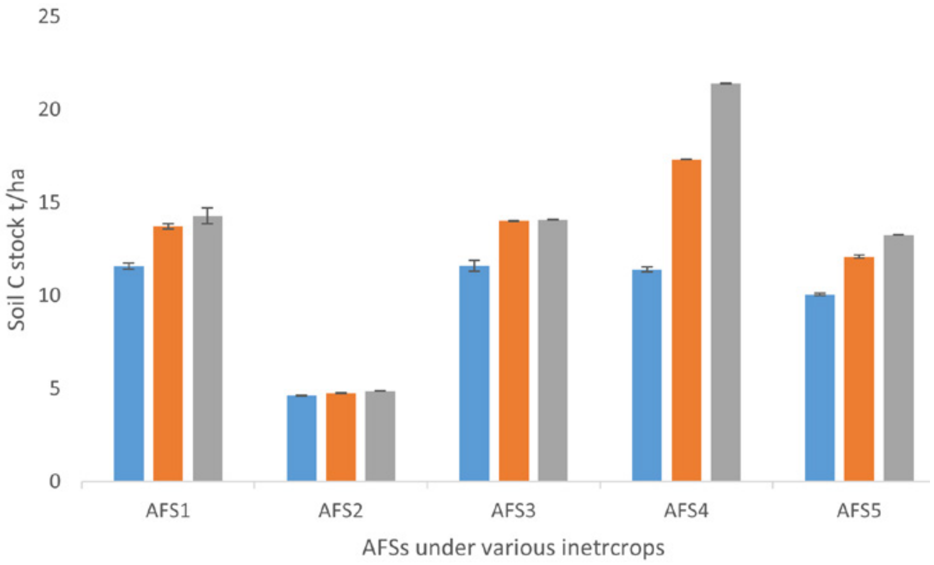

Fig. 7. Soil carbon stock in the five AFSs throughout the years 2022-2024. Error bars are the standard error of the mean.

in terms of carbon balance under the given management and environmental conditions.

Analysis of Soil Carbon Sequestration Capacity for the Five AFSs

The mean difference between the initially sampled and analyzed soil carbon stock in 2022 at a depth of 0-30 cm, as well as the intermediate and final soil organic carbon stock assessed in 2023 and 2024 within the five AFSs, are depicted in Fig. 7.

Soil organic carbon stock (SOC stock) in AFS2 (monoculture) did not exhibit any significant differences (at $P<0.05$) over the three-year study period. In contrast, the four other agroforestry systems, which incorporated various intercrops, showed significant differences in SOC stock, reflecting the influence of intercropping on soil carbon dynamics. Notably, AFS3 (fig trees with barley landrace) was an exception, displaying no significant variation in SOC stock during 2023 and 2024, suggesting that this particular intercrop combination maintained relatively stable soil carbon levels over the two years. These results highlight that the type of intercrop and system management can significantly affect soil carbon accumulation, whereas monoculture systems tend to show limited changes over time.

We observed a clear year-to-year increase in SOC stocks in the agroforestry systems (AFSs) composed of two or three production strata, while the monoculture system (AFS2, with only fig trees) showed little to no improvement. Specifically, in AFS1, SOC stocks rose from 11.59 t/ha in 2022 to 13.73 t/ha in 2023, reaching 14.29 t/ha in 2024. By contrast, AFS2 remained relatively stable, with values ranging from 4.63 t/ha in 2022 to only 4.86 t/ha in 2024.

The highest SOC accumulation was recorded in AFS3 (fig trees intercropped with barley), where values increased from 11.61 t/ha in 2022 to 14.02 t/ha in 2023 and 14.09 t/ha in 2024. In AFS4, SOC stocks rose substantially from 11.40 t/ha in 2022 to 17.32 t/ha in 2023, reaching 21.41 t/ha in 2024. For AFS5, which included mixed intercropping with pepper, the recorded values were 10.06 t/ha in 2022, 12.09 t/ha in 2023, and 13.27 t/ha in 2024. The differences in SOC stocks were statistically significant ($P \leq 0.05$) across the systems. Overall, SOC increased steadily over the three years in all AFSs except AFS2, which remained almost unchanged. Among them, AFS3 achieved the highest SOC values.

The corresponding results for the evolution of carbon dioxide equivalents (CO_2-eq) measured in the 0-30 cm soil depth across the five AFSs are presented in the following figure.

The soil in AFS3 sequestered the highest amount of CO_2-eq, with values of approximately 42.61 t/ha, 51.44 t/ha, and 51.72 t/ha in 2022, 2023, and 2024, respectively. In contrast, the lowest values were recorded in AFS2, at about 17 t/ha for all three years. In AFS1, soil CO_2-

Table 3. Annual average (2022-2024) of SOC stock and CO_2eq recorded for the five AFSs.

	AFS1	AFS2	AFS3	AFS4	AFS5
SOC stock t/ha/year	1.345	0.115	1.24	5.005	1.6
CO_2-eq (t/ha)/year	4.94	0.42	4.55	18.37	5.88

eq values were 42.55 t/ha, 50.37 t/ha, and 52.44 t/ha in 2022, 2023, and 2024, respectively. In AFS4 and AFS5, CO_2-eq values ranged from 36.94 t/ha (AFS5) to 78.58 t/ha (AFS4) in 2022 and 2024, respectively. Differences among the AFSs for CO_2-eq were statistically significant ($P \leq 0.05$).

In Table 3, we have summarized the annual averages of SOC stock and CO_2-eq for each AFS in Djebba LL.

SOC stock per year varied depending on the agronomic management in the five AFSs (Table 3). Fig trees intercropped with beans recorded the highest increase in SOC stock from 2022 to 2024, with 1.34 t/ha/year. However, when the AFS is based on monoculture (AFS2), the amount of carbon stored in the soil is extremely low, in certain instances nearly absent. For CO_2-eq, AFS4 recorded the highest value (18.37 t/ha/year), while the lowest was registered for AFS2, at 0.42 t/ha/year.

Discussion

The agricultural sector is the main source of income and a key contributor to food security in Tunisia, especially in the northwest of the country. Conservation systems such as AFSs (agroforestry systems) with crop diversity have the potential to improve soil health, as well as agro-ecosystem productivity and resilience [35]. Agroforestry systems are defined as a combination of agriculture and forestry to create integrated and sustainable land-use systems. Although agroforestry fruit trees have potential in mitigating climate change, research on their role in Tunisia remains limited, as most studies have focused on forest trees and shrubs. Cover crop biomass and SOC were used as indicators of carbon storage conditions under various AFSs.

When comparing the five agroforestry systems (AFSs) studied at Djebba LL with those analyzed by [36] using the same allometric models, notable similarities can be observed despite differences in system types. For example, the horti-silvi-pasture system reported by [36] recorded a total tree biomass of 55.73 t/ha, which is comparable to that of AFS3 in 2024 at Djebba LL (Fig. 2). Similarly, the agri-silviculture system (boundary plantation) showed a tree biomass of 19.3 t/ha, substantially lower than that observed in AFS1 and AFS5, which ranged from 37.68-38.38 t/ha and 35.27-37.40 t/ha, respectively, in 2023 and 2024. The similarity in tree biomass between AFS1 and AFS5 may be explained by similar tree age and planting density, as well as uniform management practices across all systems. In addition, AFS5 (a mixed system of fig and sweet cherry trees intercropped with pepper) recorded a tree biomass value slightly higher than that reported in the agri-silvi-pasture (homegardens) and horti-silvi-pasture systems, which were around 32.76 t/ha. In contrast, AFS2 (the control system, consisting of fig tree monoculture) recorded the lowest tree biomass values, ranging from 23.22 to 23.40 t/ha. On the other hand, AFS4 (fig trees intercropped with faba bean) registered the highest biomass among all systems, reaching 76.67-78.59 t/ha in 2023 and 2024, respectively, exceeding that of the horti-silvi-pasture and homegarden systems reported by [36].

Overall, all five AFSs studied in Djebba LL exhibited higher total tree biomass than the agri-silviculture system (boundary plantation) reported by [36], which was limited to 19.3 t/ha.

The carbon stock values observed for fig trees in Djebba LL (Fig. 3) are considerably lower than those reported for the above-mentioned species. Similarly, the carbon stocks reported by [37] for coffee-based agroforestry systems in Mexico (55.12 t C ha^{-1}) are also higher than those recorded at the Djebba LL. Likewise, [38] showed that biomass carbon (C) stocks ranged from 45, 65, 76, to 214 t C ha^{-1} for oil palm, cocoa, orange, and rubber, respectively. The low values observed in the Tunisian study were attributed to Tunisian (North-West) climatic conditions that enhance net primary productivity (NPP), as well as differences in tree architecture. However, the carbon stock values observed in AFS3 (fig trees) during 2023 and 2024 are comparable to those reported for citrus (25.95 t C ha^{-1}) and nut trees (27.40 t C ha^{-1}) in the [37] study. Likewise, the AFS3 results are consistent with the findings of [39], who reported carbon stocks of 28 t C ha^{-1} and 29 t C ha^{-1} during 2000 and 2010, respectively, in European agroforestry systems. These authors also estimated carbon stocks in tree cover on agricultural land to range between 9.3 and 9.4 t C ha^{-1}, which aligns with the values observed in our control system (AFS2, monoculture). Finally, the carbon stocks measured in fig trees in AFS1 and AFS5 are similar to those found in olive trees in Catalonia by [39], which ranged from 16.87 to 17.31 t C ha^{-1} despite differences in the studied species.

When comparing the carbon stock in tree biomass across the studied agroforestry systems (AFSs) with different AFSs studied by [36], the control system (AFS2), which consists of a monoculture (fig trees), recorded a value (10.99 t/ha in 2023 and 2024) similar to that of the horti-agriculture agroforestry system, with both reaching approximately 10.66 t/ha. In contrast, the agri-silviculture system (boundary plantation), which relies exclusively on forest tree species, exhibited lower carbon stock values (8.68 t/ha). This difference may be attributed to the nature of the tree species used and their growth characteristics.

Fruit trees such as figs, which were central to all the studied AFSs, tend to be more productive in terms of biomass under the given management and environmental conditions. These findings highlight the potential of fruit-tree-based agroforestry systems not only for food production but also for enhanced carbon sequestration compared to systems based solely on forest species.

The differences in tree carbon stock and biomass observed among the five AFSs and across the two studied years indicated a certain degree of variability. This could be attributed to differences in tree age and subsequently their architecture and dimensions, intercrop species, and overall system composition. This variability may also complement the findings of [40, 41], who reported that carbon stock is influenced by several factors, including tree age, species composition, management practices, and interactions with intercrops. These results support the idea that system design and species selection play a critical role in determining biomass accumulation and carbon sequestration potential in agroforestry systems.

When comparing the average annual carbon sequestration rate from our results (Table 2) with those reported by [38], we found that the annual C sequestration for nut and citrus trees was 2.25 and 3.32 t C ha^{-1} $year^{-1}$, respectively. Similarly, results from [42, 43] for citrus trees ranged from 2.8 to 3.3 t C ha^{-1} $year^{-1}$, which are significantly higher than our findings for fig trees. This discrepancy may be explained by the differences in wood density among species, ranging from 0.45 g/cm^3 for fig wood, 0.66 g/cm^3 for nut trees, and 0.60 g/cm^3 for citrus, to up to 0.95 g/cm^3 for olive trees [28].

The carbon stock estimated in AFS1 (Table 2) is comparable to that reported by [38] for olive trees (0.38 t C ha^{-1} $year^{-1}$ in 50-year-old trees). [44] also found similar values to AFS1 for annual carbon sequestration in permanent living vines in Spain, at approximately 0.3 t C ha^{-1} $year^{-1}$. Our findings align with the results reported by [39], which demonstrate that estimates of biomass carbon stocks are influenced by both the age of the crop and the involved species.

Study [45] showed that intercropping black locust (*Robinia pseudoacacia* L.) with triticale led to an increase in tree stand volume but a reduction in triticale yield. This finding contrasts with our results, particularly in the AFS3 system, where fig trees intercropped with barley (a cereal crop close to triticale) produced relatively high biomass. The high biomass recorded in AFS3 highlights the potential of this system to maintain productivity while supporting tree growth under Mediterranean conditions (Fig. 1). This can be explained by an adequate combination of canopy volume, root development, and their degree of absorption of water and mineral elements.

The faba bean biomass in AFS4 varied depending on the study years, with 10.4 and 11.83 t ha^{-1} in 2023 and 2024, respectively (Fig. 4). These values fall within the range reported by [45], which fluctuated between 13 t/ha (the highest average biomass recorded in 2015) and 9 t/ha (the lowest recorded in 2018). The biomass of barley intercropped in fig orchards was higher than that reported by [15] in the same region under an olive grove. Similarly, our results indicated greater barley biomass compared to that reported by [46] in Morocco. Comparable findings were also observed by [47, 48] in Andalusia and [49] in Portugal, where cereal biomass in olive-based agroforestry systems exceeded that of legumes.

Research by [50] indicates that legume-based agroforestry systems possess exceptionally high carbon sequestration potential. Reported sequestration rates in such systems vary widely, from 0.29 to 15.2 t C ha^{-1} $year^{-1}$, depending on species composition, management, and environmental conditions. In Djebba LL, the AFS4 regenerative practice integrating legumes within fig-tree-based systems demonstrated significantly greater carbon storage capacity (5.95 t C ha^{-1} $year^{-1}$ for SOC and carbon stock in trees) compared to conservation agriculture alone (0.2-0.4 t C ha^{-1} $year^{-1}$).

Incorporating legumes into agroforestry not only enhances carbon capture and storage but also transforms agricultural landscapes into sustainable carbon sinks, improving soil fertility, nitrogen cycling, and overall productivity over time.

Under semi-arid conditions and as monoculture, the biomass of faba bean was lower than our findings and varied between 1.5 and 2 t/ha in the study by [51]. For this purpose, [52-54] have shown that legumes are among the best cover crops sown between the rows of olive groves under Mediterranean conditions.

In Djebba LL, cover crops were planted under the canopy and very close to the trees, sharing the same water sources. To this end, no distance between tree and intercrop was evaluated, as reported by several authors. Studies [55-57] reported that intercrop biomass varied depending on the distance from the trees. Similarly, [58] observed that cereal crop performance was strongly influenced by both the distance from tree lines and the age of the trees. These authors further suggested that higher crop performance observed at certain distances could be attributed to a significant interaction between distance and aspect, likely resulting from slight variations in the intensity and duration of shading caused by boundary tree stands.

Crop biomass is indeed a crucial factor in determining carbon stock and CO_2-equivalent (CO_2-eq). Our results, which showed the highest biomass, carbon stock (C stock), and CO_2-eq values for barley compared to faba beans, pepper, and zucchini, are consistent with previous studies (e.g. [59]), indicating that variations in C stock and CO_2-eq (t/ha) among crop species are often related to differences in biomass production. The variability in intercrop biomass in the different studied AFSs might be attributed to steady and adequate solar radiation in fig tree orchards (small or large trees, depending on their age), resulting from an expanded photosynthetic surface and the absence of resource competition (and vice versa) between trees and cover crops for light and spatial access, among other contributing factors. Study [15] showed that intercrop biomass in olive orchards in the same region as the current study varied according to species, rainfall, soil fertility, and seeding rate.

Through these AFSs in Djebba LL, we seek to establish a more sustainable and efficient system by combining the advantages of fig trees and various intercrops. Considering the results of this study, trees exhibited a higher potential for carbon sequestration compared to annual crops, which is consistent with the

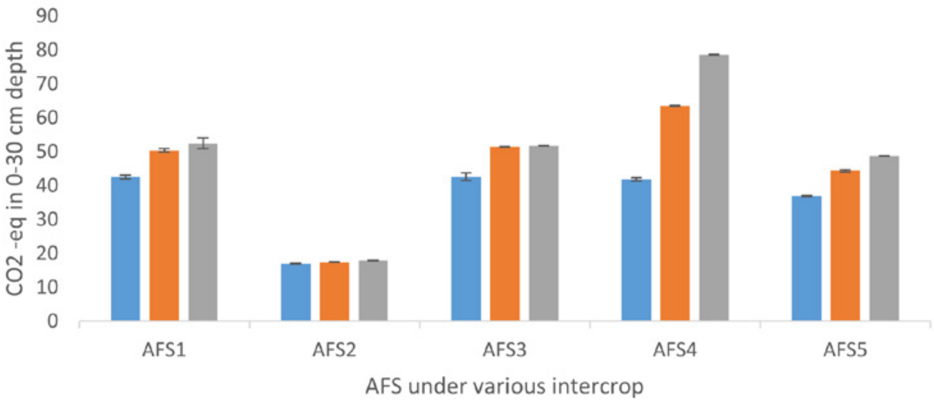

Fig. 8. Soil CO_2-eq in the five AFSs at the 0-30 cm soil depth throughout the years 2022-2024. Error bars are the standard error of the mean.

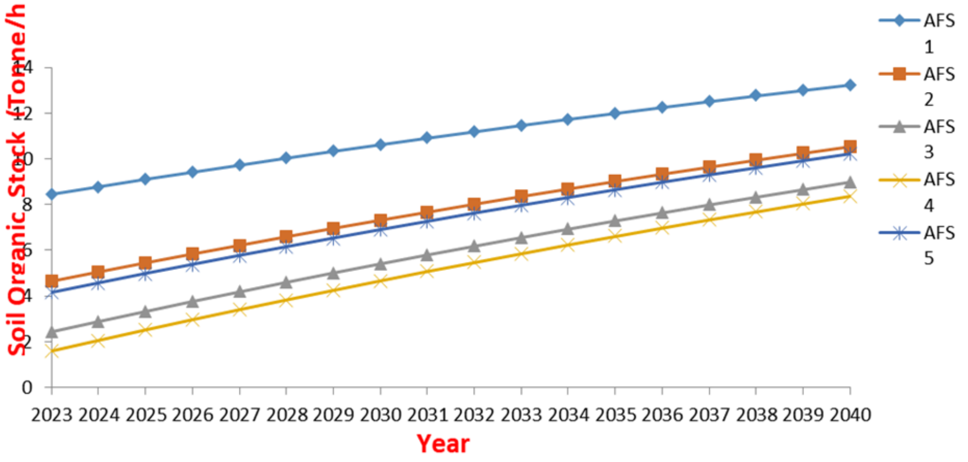

Fig. 9. APSIM model simulation in Djebba LL.

findings of [60] in their assessment of olive groves in southern Spain. Likewise, our results are in line with [61], who reported that tree buffers demonstrated a greater potential for soil carbon sequestration than grass buffers.

For SOC stock in 2024, the analysis showed that when using faba bean as an intercrop, SOC stock increased and registered a significant difference between 2022 (initial stock) and 2023, the first year of legume intercrop sowing. This result indicates that with faba bean, AFS4 appears to be the most powerful system for carbon sequestration (Fig. 8). The SOC stock in AFS1, used as the control agroforestry system, remained stable over the three years, with an SOC stock value of 0.42 t/ha/year. This could be explained by the absence of a cover crop, which would otherwise improve soil fertility, enhance moisture retention, and support higher biomass production and, subsequently, greater carbon storage and CO_2-eq. The mixture of tree species with local pepper in Djebba LL (AFS5) can significantly enhance carbon sequestration capacity, both in biomass (AGB and BGB) and in soil organic carbon (SOC). To optimize this result in AFS5, the choice of tree species should consider canopy structure, root depth, biomass productivity, and compatibility with pepper in terms of shade, nutrient competition, and microclimate regulation.

In AFS5, trees produced substantial woody biomass and subsequently sequestered large quantities of carbon. Indeed, deep roots minimize competition with shallow-rooted pepper, while the implementation of various tree species with pepper enhances leaf litter inputs, increasing soil carbon storage.

It has been shown by [62] that intercropping can act as a sponge to conserve water, prevent flash floods, and increase soil organic matter content, improving soil health and potentially mitigating climate change. Compared to other studies in Tunisia, the SOC stock of Djebba LL under different intercrops was lower than reported by [16] in the Oasis of Dguesh (south of Tunisia), which ranged from 53.5 t/ha to 127 t/ha. These differences can be explained by the differences in climatic conditions and soil texture. Silty clay soil with limestone in Djebba may exhibit low SOC levels. However, this amount can be improved and better retained due to the clay content. In contrast, in southern regions with sandy soils, even when larger amounts of

SOC are present, they are difficult to retain because of the low organic matter holding capacity of sand. The low SOC stock observed in Djebba at the early stage, presented in 2022 (Fig. 7) of the agroforestry system installation, may be attributed to submersion irrigation, as carbon can be leached and transported by water.

APSIM Model Implication

Fig. 9 presents the simulation of soil organic carbon (SOC) stock dynamics from 2023 to 2040 under different agroforestry systems (AFS1-AFS5) using the APSIM (Agricultural Production Systems sIMulator) model. The results show a consistent upward trend in SOC stock across all systems, indicating that agroforestry practices contribute positively to soil carbon sequestration over time.

The APSIM simulation (Fig. 9) demonstrates the potential of agroforestry systems to enhance long-term soil carbon sequestration, particularly under suitable management practices. The results also highlight the variability among AFS types, emphasizing the importance of species composition, management intensity, and climatic suitability in determining carbon storage capacity.

For this purpose, APSIM projections suggest that agroforestry systems can significantly increase SOC stocks over a 17-year period, supporting both climate change mitigation and soil fertility improvement, especially when integrating tree species that promote organic matter accumulation and deep root carbon inputs.

Based on these studies, the implementation of an agroforestry system with various intercrops appears to be a relevant and effective solution for mitigating climate change and enhancing carbon stock on the one hand in trees and grass, and on the other hand, in soil. For this purpose, the agroforestry system is a key factor to assess carbon stock in biomass and soil. Our results are in accordance with those of [63], who showed the effect of agroforestry systems in improving SOC stability and the potential advantage of carbon sequestration.

Conclusions

Agroforestry systems are regenerative practices applied in orchards across Mediterranean regions, such as in the Djebba LL, where they enhance SOC stocks and promote biomass production. These enhancements aim to increase carbon storage by ensuring the survival of trees and crops under climate change effects. The four AFSs in Djebba LL, compared to monoculture (AFS2), have a carbon farming potential to mitigate climate change. They recorded differences in the potential for carbon sequestration.

If we aim to increase the carbon stock and CO_2-eq rate per year, we select AFS5. However, when choosing the agronomic practice with the highest carbon stock and CO_2-eq, we select AFS3 (fig tree with barley intercrop). Therefore, carbon sequestration in stable biomass structures (perennial vegetation) and in soils (carbon sinks) should be incorporated into carbon cycle accounting and life cycle assessments (LCAs) for sustainable crop systems.

Author Contributions

Conceptualization, T.A.G.; methodology, T.A.G., M.H.S., A.G.; validation, T.A.G., M.H.S., A.G.; formal analysis, T.A.G.; writing-original draft preparation, T.A.G., M.H.S.; writing-review and editing, T.A.G., M.H.S., A.G., Y.A., A.M. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no conflicts of interest.

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