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Insights into Beneficial Effects of an Agroforestry System on Soil Properties and Crop Yields: A Case Study from the Experimental Farm at University of Copenhagen, Denmark

Vaibhav Pradip Chaudhary * and Bhim Bahadur Ghaley

Department of Plant and Environmental Sciences, University of Copenhagen, Højbakkegård Alle 30, 2630 Taastrup, Denmark; bbg@plen.ku.dk
* Correspondence: vpc@plen.ku.dk

Abstract: Agroforestry systems are sustainable farming practices with multiple benefits like enhanced biodiversity, soil nutrient cycling, soil physical properties, and carbon sequestration. Investigating these multiple beneficial effects of agroforestry systems compared to monoculture cropping systems under diverse pedo-climatic zones and crop-tree combinations is required to gather robust field evidence for agroforestry performance. Hence, the objective was to investigate the beneficial effects of agroforestry systems on soil properties and crop yields in a combined food and energy production (CFE) agroforestry system compared to the conventional winter wheat (CWW) production system in Denmark. The field methods consisted of soil and crop cut sampling, soil moisture measurement, earthworm abundance count in CFE compared to the CWW fields, and climate data for 2023. The study demonstrated that an agroforestry system viz CFEmean and natural forest (NF) had a lower bulk density viz. 1.48 and 1.01 g cm^{-3}, respectively compared to CWW (1.74 g cm^{-3}) with intensive use of fertilizers and chemicals. CFEmean and NF had higher soil organic matter, total nitrogen %, available potassium (K), potentially mineralizable nitrogen, soil moisture retention, and earthworm count under drought conditions compared to CWW. The study demonstrated that alley cropped winter wheat (CFE WW) recorded similar grain yields and significantly higher straw and aboveground biomass accumulation compared to CWW with intensive use of chemical and fertilizer inputs. The biomass belt (BB) effects on alley crop yield varied with the distance with negative effects on grain, straw, and aboveground biomass yields in CFE WW at the nearest points from the BB, and yields increased gradually in the alley fields further away from the BB with maximum grain yields at 62.83 m away from the BB. The study provided a robust field evidence on the beneficial effects of agroforestry on soil properties and crop and biomass yields compared to CWW for informed decision-making by land managers for the adoption of agroforestry practice.

Keywords: soil properties; alley crop yield; drought; biomass belt; earthworm count; soil moisture

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1. Introduction

Alley cropping is an agroforestry practice whereby crops are grown in alleys between rows of trees or shrubs, which aims to optimize resource use, enhance productivity, and promote agro-ecology. Agroforestry practices mitigate soil degradation [1], loss of biodiversity [2], soil nutrient depletion [3], and acidification of soil [4] and improve soil health to promote sustainable agriculture practice.

The soil health concept is gaining ground to consider soils as vital living systems that provide essential ecosystem services necessary to maintain the ecosystem health. In Europe, soil health is becoming depleted due to various industrial activities, agricultural intensification, urbanization, and climate change [5]. Over longer periods, the use of chemical fertilizers leads to the deterioration of soil health [6,7]. A study conducted in thirty-two member countries by the European Environment agencies [8] emphasized the urgent need for safeguarding soil health and ensuring the long-term viability of agroecosystems. One of the practices that improves soil health is a silvoarable agroforestry system [9]. Silvoarable agroforestry systems can improve soil's physical, biological, and chemical properties, as well as its water regulation [10], and the production of high-value trees can be combined with crops or grass leys, increasing the species diversity and, hence, biodiversity [11]. Soil bulk density plays a major role affecting soil porosity, soil moisture, and water availability [12,13]. In a recent study [14], the soil bulk density in European arable land (1.26 g cm^{-3}) was 1.5 times higher than woodlands (0.84 g cm^{-3}), highlighting the benefits of tree integration in farming landscapes. Agroforestry can add a significant amount of organic matter, which improves soil moisture retention, enhances soil mineralization, increases soil carbon sequestration, and mitigates climate change [15]. Soil moisture content was recorded to be higher in agroforestry systems compared to open field/conventionally cultivated crop fields [16]. Earthworm abundance was measured to be higher in agroforestry systems as compared to a monoculture cropping system [17,18]. Hence, different studies have reported the beneficial effects of agroforestry systems on soil health parameters [19].

In our study, we used NIR spectroscopy to analyze soil samples. Soil analysis using NIR spectroscopy enables a rapid, cost-effective, and non-destructive assessment of soil properties, offering a practical alternative to traditional, time-consuming, and resource-intensive chemical and physical laboratory analyses. NIR spectroscopy provides an alternative to wet laboratory protocol procedures with its robust, user-friendly operation, and no soil is consumed during the analysis process. By leveraging NIR spectroscopy, researchers can predict key soil parameters such as organic matter content, cation exchange capacity, nitrogen levels, and moisture content with high accuracy. These predictions are underpinned by representative statistical models, such as partial least squares regression (PLSR) and principal component analysis (PCA), which extract meaningful correlations between soil spectra and their physical–chemical properties. This innovative approach reduces analytical costs and expedites data collection, making it a powerful tool for large-scale soil monitoring and management. Different soil properties can be analyzed using the spectroscopy technique [20]. Compared to the wet laboratory method, NIR spectroscopy provides numerous analyses of soil samples in a short period of time and at a low cost; hence, sensor-based technology is gaining wider adaptability for accessing soil health [21,22].

Studies on the effects of agroforestry on agronomic productivity have shown that both trees and crops compete for resources, and trees may reduce crops' productivity [23] while the shading effect of trees can reduce the biomass accumulation of alley crops and reduce crop yields [24]. Field studies have reported that crop yields near the tree rows/belts are lower, and crop yields increase as the distance increases away from the tree row/belts [25–27]. Therefore, it is important to assess the effects of the distance from the tree rows/belts on crop productivity. Beneficial effects of agronomic yield parameters have been reported in agroforestry systems as compared to monoculture cultivation practices [28,29]. Hence, there is need to evaluate the beneficial effects of agroforestry systems on soil properties, soil moisture retention, and alley crop yields under different pedo-climatic contexts. Given this knowledge gap, our study objective was to investigate the beneficial effects of agroforestry on soil properties and crop yields in a combined food and energy production (CFE) agroforestry system compared to the conventional winter wheat production system in Denmark.

2. Materials and Methods

2.1. Site Description

At the experimental farm of the University of Copenhagen in Denmark, a combined food and energy (CFE) production system, i.e., alley cropping system, was established in 1995 (55° 40′ N, 12° 18′ E) with the objective to develop a carbon-neutral production system for food, fodder, and energy (biomass belts) production with organic management. The alley cropping system constitutes alleys of 50, 100, 150, and 200 m, where food and fodder crops are grown, bordered by the biomass belts (BBs). Each biomass belt is 10.7 m wide and consists of five double rows of three willow clones (one double row each) of *Salix viminalis* (L.) "Jor", *Salix dasycladus* Wimmer, and *Salix triandra* × *cinerea* (L.), which are bordered by one double row of common hazel *Corylus avellana* (L.) on one side and one double row of alder (*Alnus glutinosa* (L.) Gaertner) on the other side. The BBs are planted at an intra-row spacing of 0.5 m and inter-row distance of 0.7 m. Every four years, the biomass belts are harvested and chipped and sold to a nearby heat and power station, while the food and fodder crops grown in alleys are harvested annually [30]. One biomass belt has not been harvested since the establishment of the system in 1995 and is regarded as a natural forest (NF). The data were collected in the cropping season of the year 2023, and CFE oat, CFE clover, and CFE winter wheat (CFE WW) were sown in 50, 100, and 200 m wide alleys, respectively. The conventional winter wheat (CWW) field is located nearby the CFE field and was treated as the reference control production system. CWW was fertilized with 167.31 kg of nitrogen ha^{-1}, 12.33 kg of phosphorus ha^{-1}, 41.10 kg of potassium ha^{-1}, 28.44 kg of sulfur ha^{-1}, and 3.00 kg of magnesium ha^{-1}: two applications of weedicides and insecticides and three applications of fungicides.

2.2. Crop and Soil Sampling and Weather Data Collection

Soil samples were collected from six different production systems, out of which four production systems were components of the CFE system viz. CFE WW, CFE oat, CFE clover, and BB, and two other production systems were NF (considered at near-natural, undisturbed system) and CWW, as the reference control conventional production system. Soil samples were taken with an augur to a depth of 30 cm in 3 replicates, and each soil sample was a composite sample of 5 augur samplings to obtain a representative sample of the field under each production system (Figure 1). The depth of 30 cm was chosen because it represents the plough depth, and the estimation of soil properties at this depth is of interest in farm management practices. The comparisons of soil properties were performed at two levels: either among the six production systems or the mean comparison between the NF, CWW, and CFE systems (CFEmean) viz. the mean of CFE WW, CFE oat, CFE clover, and BB.

The soils were analyzed with an AGROCARES nutrient scanner (2022), which was purchased from Agrocares (Agrocares is a trademark of Care4Agro B.V., 6709 PA, Wageningen, The Netherlands). Agrocare is a portable handheld tool with a near-infrared (NIR) sensor used to measure soil properties. Agrocares was calibrated as per the guidelines provided by the company. The guideline includes scanning the white side (background) and yellow side (standard sample) of the calibration cap provided by the company at the time of purchase. The equipment is connected to an app through a Bluetooth connection, and the complete calibration and soil scanning steps can be seen in the app and confirmed in the equipment when analyzing. Each soil sample was scanned 3 times. Each sample scan took 30 s, and the scan was carried out on fresh soil samples from the field. Bulk density was determined with a core sampler with a 7.5 cm in height and 7.5 cm diameter (soil core of 331.339 cm^3) in 3 replications per treatment. The fresh weight of the soil core was measured, followed by oven drying at 80° degree temperature for 72 h and reweighing to determine the moisture content. Earthworm counts were taken from a soil volume of 25 cm^3 in three replications per production system. The counting of the earthworms were carried out in five different production systems. Each sampling site was selected in the middle of the production system, avoiding the border effects, with three replications per system. The sampling points were 30 m away from each other and 10 m away from field borders.

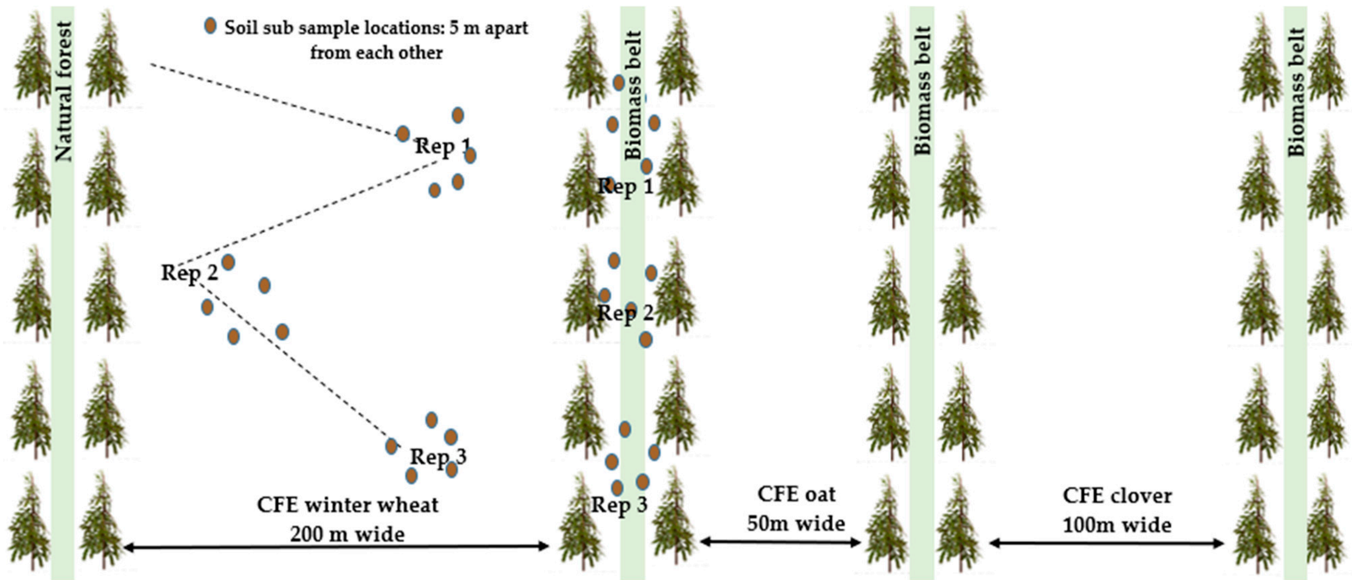

Figure 1. Soil sampling protocol followed in the study. The figure shows soil sampling plan in CFE WW and the BB. Each composite/replicate soil sample consists of 5 sub-samples as shown in the figure.

In order to investigate the BB distance effects on the alley crops, we selected the widest alley of 200 m, cultivated with CFE WW for crop-cut samplings at different distances from the BB. As per findings from an earlier study [27], the height of the BB has effects on the extent of influence on the alley crop. Hence, we used the rationale of the study and identified the crop cut sampling points as the ground distance in the alley from BB (m) at different H values (0.50, 1.00, 1.64, 3.60, 9.52, and 12.00), calculated as below:

$$\text{Ground distance inside alley from BB (m)} = \text{H} \times \text{height of BB (m)}$$

Based on the study by [27], we used H values of 0.50, 1.00, 1.64, 3.60, 9.52, and 12.00 to calculate the different distances in the alley from the BB for crop cut sampling in CFE WW (Figure 2). In our case, the height of the biomass belt was 6.6 m, and the first sampling point in the alley was 3.3 m (6.6 m × 0.5 m) from the BB. In CFE WW, cultivated in the 200 m wide alley, six crop cuts, in three replications, were taken at different distances of 3.3 m, 6.6 m, 10.82 m, 23.76 m, 62.83 m, and 79.2 m (Figure 2) in the alley from the BB, corresponding to the identified H values.

Soil moisture measurements were carried out only in four production systems viz. CFE WW, BB, NF, and CWW, and measurements were recorded with a profile probe PR 2/6 (Frequency Domain Reflectometry, Delta-T Devices Ltd., Cambridge CB25 0EJ, United Kingdom) at six different soil profile depths viz. 10 cm, 20 cm, 30 cm, 40 cm, 60 cm, and 100 cm in four replications in each production system. The sampling points for soil moisture determination were located in four production systems viz. CFE WW, BB, NF, and CWW with four replications each. The soil moisture probes were inserted in each of the systems, and the measurements were performed on the same spot during the experimental period to avoid differences due to different sampling points. These points were located in the middle of all production systems, taking care to avoid the border effects on the point. These points provided the average soil moisture present in each production system. The measurements were carried out on 20 June, 30 June, 7 July, 11 July, 21 July, 27 July, and 4 August in 2023. Further, we collected the precipitation and temperature data for 2023 and compared them with the 5-year mean data (2018–2022) on precipitation and temperature to assess the climate variation in 2023 compared to the last 5 years (Figure 3). Temperature and precipitation data were collected from the weather station at Taastrup campus for the months of March, April, May, June, July, and August for 2023 and for the last 5 years. In comparing the weather data between 2023 and the preceding 5 years, it was clear that there was extremely low rainfall in May and June (5.6 mm and 9.8 mm, respectively) in 2023 compared to the 5-year mean (46.2 mm and 32.2 mm, respectively) followed by more than normal precipitation in July and August in 2023 (95.3 mm and 136.1 mm, respectively) compared to the 5-year mean (40.7 mm and 90.5 mm, respectively). Danish Meteorological Institute (dmi.dk) publishes a drought index on an annual basis based on precipitation, actual evaporation, and seepage to the subsoil as an indicator of the amount of available water for the plants in the topsoil, and the scale ranges from 0 (field capacity) to 10 (wilting point). In 2023, in the months of May and June, the drought index was 7.7 and 9.9, respectively, confirming our observation of drought in the Taastrup site.

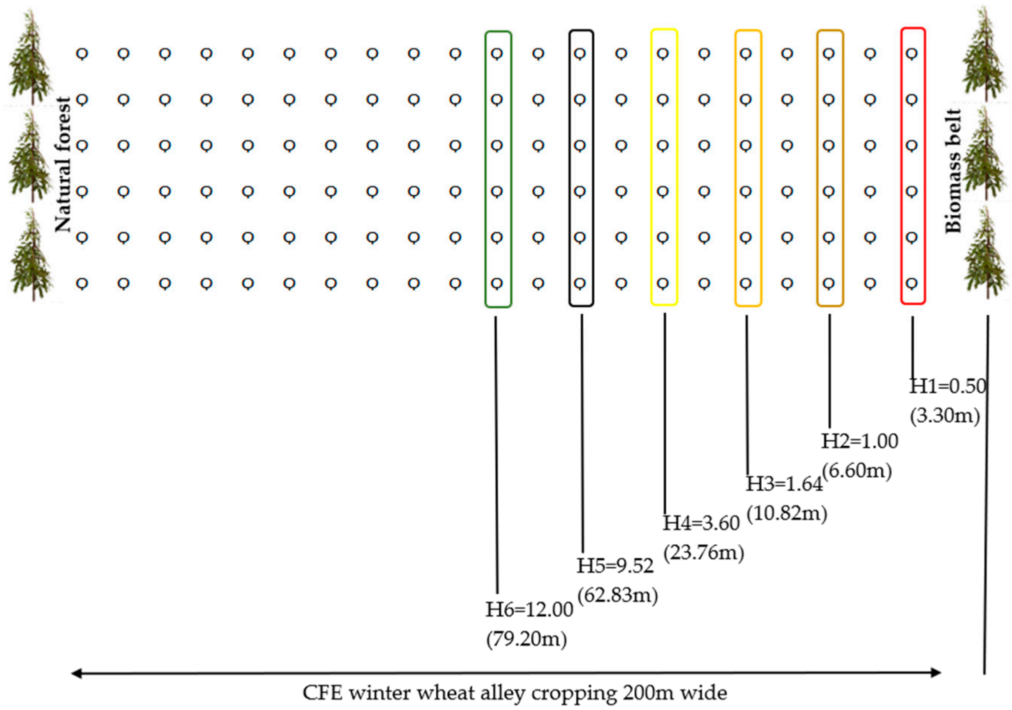

Figure 2. Schematic layout of crop-cut samplings in alley-cropped CFE WW at different H values (0.50, 1.00, 1.64, 3.60, 9.52, and 12.00) from the BB in the CFE system.

2.3. Statistical Analysis

Significant differences were evaluated using one-way analysis of variance (ANOVA) with Tukey HSD test for mean comparisons at $p \leq 0.05$. The comparison was studied for soil parameters between different systems. Mean comparisons were carried out between production systems for soil parameters, earthworm count, soil moisture, grain yield, straw yield, and aboveground dry biomass. Tukey's HSD test was used for mean comparisons at $p \leq 0.05$ between CFEmean, natural forest, and CWW for soil parameters, where CFEmean is the average value of CFE clover, CFE oat, CFEWW, and biomass belt. Soil moisture comparison was performed using the same procedure to compare between the BB, NF, CFEWW, and CWW cropping systems on seven observation dates, and further mean comparisons were performed between CWW and CFEmean, in which CFEmean was the average of the BB, NF, and CFEWW systems. Mean comparisons were carried out between CFEWW and CWW for grain yield, straw yield, and aboveground dry biomass and within CFE WW at six distances away from the base of the biomass belt. The standard error was calculated in a Microsoft Excel spreadsheet, and R programming (version 4.4.2) in RStudio (version 2024.09.1+394) was used for ANOVA and Tukey's HSD analysis for the current study.

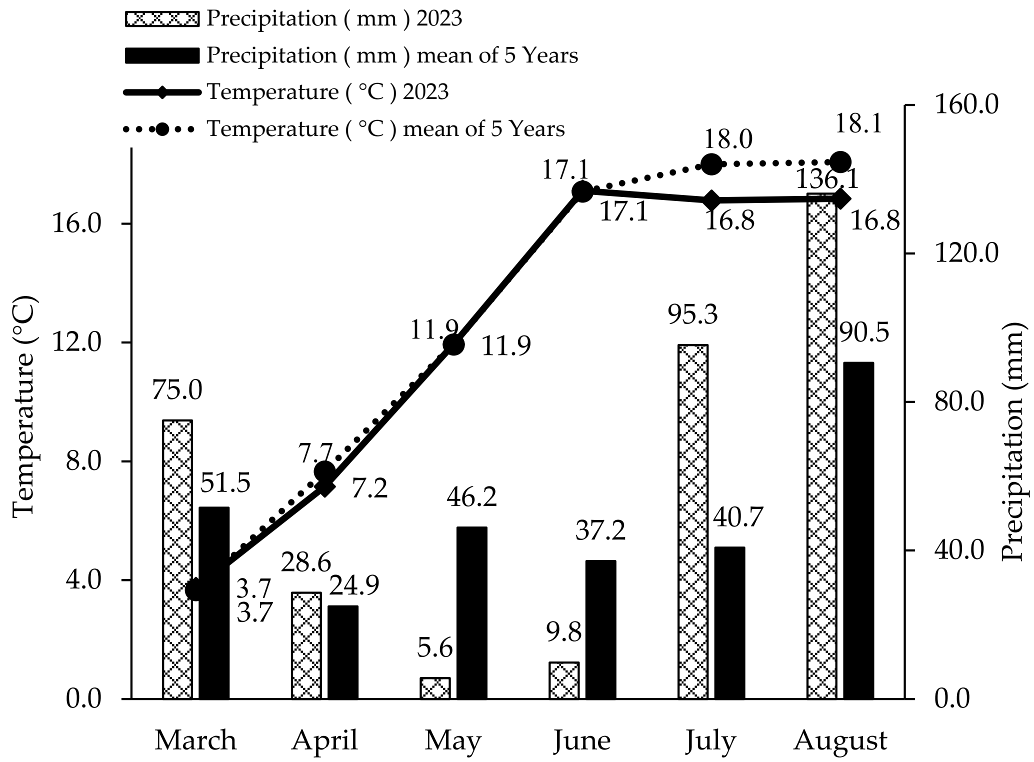

Figure 3. Temperature and precipitation data for 2023 vs. previous five years (2018–2022) at experimental site in Taastrup, Denmark.

3. Results

3.1. Beneficial Effects of Agroforestry System on Soil Properties and Earthworm Abundance

The soil bulk density was significantly ($p \leq 0.01$) different when compared between the CFEmean, NF, and CWW systems (Table 1). The bulk density was the highest in CWW (1.74 g cm^{-3}), followed by CFEmean (1.48 g cm^{-3}), and the lowest in NF (1.01 g cm^{-3}), whereas CFE mean BD was lower than CWW (Table 1). Among the CFE systems, the BB had a significantly higher soil organic matter (% SOM) content at 4.44% compared to the other CFE systems. The SOM content was the highest in NF (6.61% SOM), followed by the BB (4.44% SOM), and the lowest in CWW (2.48% SOM), as shown in Table 1. The total soil nitrogen (TN%) was the highest in NF (4.14%), followed by CFEmean and in CWW (1.47%) (Table 1). The available K content was the highest in NF, followed by CFEmean, and the least in CWW. The potential mineralizable nitrogen (PMN) was significantly different, and the highest content was recorded in NF, followed by CFEmean, and the least in CWW. The cation exchange capacity (CEC) was significantly different, being the highest in NF followed by the BB and the lowest value in CFE WW. Among the observations recorded for earthworm count in three CFE systems, it was observed that the highest population of earthworm was in less disturbed system, i.e., the BB with 240 N m^{-2}, followed by CFE clover (N = 197 N m^{-2}) and CFE WW (N = 85 N m^{-2}) (Figure 4). While comparing the three systems, i.e., CFEmean, NF, and CWW, there was a significant difference between CFEmean, natural forest, and CWW, with the highest earthworm count in CFEmean (N = 174) followed by NF (N = 139) and the lowest in CWW (N = 48), as shown in Figure 4. CFE systems and NF are less disturbed than the CWW system, and the earthworm count was found to be significantly greater in the less or undisturbed systems (agroforestry systems) than the CWW crop production system.

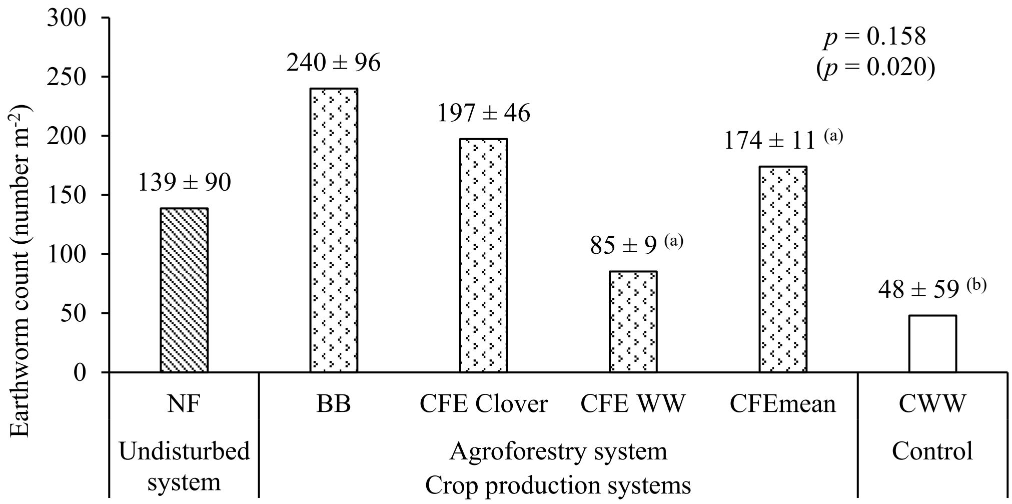

Figure 4. Earthworm count (mean ± SE) in NF, CFEmean (BB, CFE clover, CFE WW), and CWW. BB = biomass belt, NF = natural forest, CFE clover = CFE with clover grass, CFE WW = CFE with winter wheat, CWW = conventional winter wheat crop. The alphabets in parentheses indicates the differences between the production system and if the alphabets are different, there is significant differences between the production systems at the indicated *p* values.

Soil moisture content was significantly different between the BB, NF, CFEWW, and CWW (Table 2). In 2023, we experienced extreme drought, with only 9.80 mm precipitation in June compared to a five-year (2018–2022) average of 37.2 mm, whereas July and August had a record high rainfall of 95.3 mm and 136.1 mm, respectively, compared to the five-year average of 40.75 mm and 90.52 mm, respectively. During the dry spell in June, BBs (22.31% on 20 June and 21.64% on 30 June) maintained significantly higher soil moisture followed by NF (20.18% on 20 June 20.42% on 30 June) compared to ploughed systems viz. CWW (19.76% on 20 June and 19.77% on 30 June) and CFE WW (19.04% on 20 June and 19.33% on 30 June). Consequently, it was observed that the soil moisture content of CFEmean (20.52% on 20 June and 20.46% on 30 June) was significantly higher than the CWW (19.76% on 20 June and 19.77% on 30 June). The data showed that the unploughed systems viz. BB and NF retained higher moisture at the time of the dry spell compared to the ploughed systems viz. CWW.

In contrast, during the wet spell in the month of July and early August, 2023, the soil moisture was significantly higher in CWW (27.37% on 27 July and 28.40% on 4 August) and CFE WW (26.04% on 27 July and 27.27% on 4 August) compared to BB (23.17% on 27 July and 24.09% on 4 August) and NF (22.32%, 22.94%) as shown in Table 2. The CWW recorded a higher soil moisture content of 27.37% and 28.40% on 27 July and 4 August, respectively, compared to CFEmean (23.84% on 27 July and 24.77% on 4 August). This indicated that the excessive rainfall in July and early August led to the saturation of soil in CFEWW and CWW due to low infiltration into the soil caused by soil compaction (high BD), whereas the reverse was true in the BB and NF.

Table 1. Soil parameters (mean ± standard error) in six production systems out of which four production systems are within CFE systems, (CFEmean) and the other two are, natural forest (NF), and conventional winter wheat (CWW).

Soil Properties	CFE Clover	CFE Oat	CFE Winter Wheat (CFE WW)	Biomass Belt (BB)	CFEmean	Natural Forest (NF)	Conventional Winter Wheat (CWW)	*p* Value
BD (g cm^{-3})	1.63 ± 0.04 ^{a}	1.54 ± 0.05 ^{ab}	1.56 ± 0.15 ^{a}	1.18 ± 0.03 ^{bc}	1.48 ± 0.05 $^{(b)}$	1.01 ± 0.06 $^{c(c)}$	1.74 ± 0.09 $^{a(a)}$	*** (**)
SOM (%)	3.06 ± 0.21 ^{c}	2.80 ± 0.02 ^{c}	2.63 ± 0.22 ^{c}	4.44 ± 0.44 ^{b}	3.23 ± 0.1 $^{(b)}$	6.61 ± 0.24 $^{a(a)}$	2.48 ± 0.16 $^{c(c)}$	*** (***)
TN (%)	1.83 ± 0.15 ^{c}	1.71 ± 0.04 ^{c}	1.64 ± 0.16 ^{c}	2.76 ± 0.30 ^{b}	1.99 ± 0.07 $^{(b)}$	4.14 ± 0.18 $^{a(a)}$	1.47 ± 0.08 $^{c(c)}$	*** (***)
K (mg kg^{-1})	269.78 ± 8.48 ^{abc}	246.75 ± 3.39 ^{bc}	146.83 ± 18.92 ^{d}	318.43 ± 28.80 ^{ab}	245.45 ± 2.73 $^{(b)}$	339.72 ± 15.86 $^{a(a)}$	216.34 ± 7.86 $^{cd(c)}$	*** (***)
PMN (mg kg^{-1})	70.97 ± 6.01 ^{bc}	65.65 ± 1.03 ^{c}	65.08 ± 6.75 ^{c}	110.82 ± 12.38 ^{b}	78.13 ± 2.92 $^{(b)}$	175.44 ± 9.41 $^{a(a)}$	55.72 ± 3.39 $^{c(b)}$	*** (***)
CEC (mmol kg^{-1})	142.22 ± 19.63 ^{bc}	129.44 ± 6.22 ^{bc}	85.11 ± 9.99 ^{c}	181.00 ± 27.35 ^{ab}	134.44 ± 9.97 $^{(b)}$	236.67 ± 5.87 $^{a(a)}$	95.44 ± 8.19 $^{c(c)}$	*** (***)

Notes: BD: bulk density (g cm^{-3}); SOM: organic matter (%); TN: total nitrogen (%); K: exchangeable potassium (mg kg^{-1}); PMN: potentially mineralizable nitrogen (mg kg^{-1}); CEC: cation exchange capacity (mmol kg^{-1}). Superscript symbols ** and *** indicate significance levels at $p \leq 0.01$ and $p \leq 0.001$, respectively. Alphabets without parentheses indicate comparisons among six (CFE clover, CFE oat, CFE WW, BB, NF, and CWW) production systems, and alphabets inside parentheses indicate comparison between three (CFEmean, NF, and CWW) production systems.

Table 2. Soil moisture data (mean (% ± SE)) collected at 10–100 cm soil depths in the months of June, July, and August, 2023, in the biomass belt (BB), natural forest (NF), CFE winter wheat (CFE WW), and conventional winter wheat (CWW) in the experimental site in Taastrup, Denmark.

Crop Production Systems	Soil Moisture (%) Content Recorded in June, July, and August 2023						
	20-June	30-June	07-July	11-July	21-July	27-July	04-August
BB	22.31 ± 0.08 ^{a}	21.64 ± 0.09 ^{a}	21.27 ± 0.05 ^{a}	21.84 ± 0.00 ^{a}	22.36 ± 0.02 ^{b}	23.17 ± 0.03 ^{c}	24.09 ± 0.05 ^{c}
NF	20.18 ± 0.23 ^{b}	20.42 ± 0.23 ^{b}	19.72 ± 0.27 ^{b}	21.04 ± 0.18 ^{b}	21.31 ± 0.19 ^{c}	22.32 ± 0.15 ^{d}	22.94 ± 0.18 ^{d}
CFE WW	19.04 ± 0.07 ^{d}	19.33 ± 0.10 ^{d}	19.08 ± 0.08 ^{c}	20.22 ± 0.13 ^{c}	21.51 ± 0.07 ^{c}	26.04 ± 0.10 ^{b}	27.27 ± 0.16 ^{b}
CFEmean	20.52 ± 0.10 $^{(a)}$	20.46 ± 0.13 $^{(a)}$	20.02 ± 0.09 $^{(a)}$	21.03 ± 0.09 $^{(b)}$	21.72 ± 0.09 $^{(b)}$	23.84 ± 0.02 $^{(b)}$	24.77 ± 0.07 $^{(b)}$
CWW	19.76 ± 0.12 $^{c(b)}$	19.77 ± 0.16 $^{c(b)}$	20.20 ± 0.12 $^{b(a)}$	21.68 ± 0.12 $^{a(a)}$	24.90 ± 0.16 $^{a(a)}$	27.37 ± 0.10 $^{a(a)}$	28.40 ± 0.16 $^{a(a)}$
p values	*** (***)	*** (***)	*** (NS)	*** (*)	*** (***)	*** (***)	*** (***)

Note: Symbols *, ***, and NS indicates significance levels at $p \leq 0.05$, $p \leq 0.001$, and non-significant, respectively. The alphabets without parentheses indicate comparisons among four production systems (BB, NF, CFE WW, and CWW), and those alphabets within parentheses indicate comparison between CFEmean (BB, NF, and CFE WW) and CWW.

3.2. Beneficial Effects of Agroforestry System on Crop Yield and Aboveground Dry Biomass Accumulation

The mean yields of grain, straw, and aboveground biomass in CFE WW and CWW are provided in Figure 5. It is interesting to note that similar crop yields were achieved in CFE WW with organic management and CWW with intensive use of fertilizers and chemicals. Further, CFE WW recorded significantly higher straw ($p \leq 0.09$) and aboveground biomass yields ($p \leq 0.1$) compared to CWW (Figure 5). Both production systems faced drought conditions during the critical growing phase, i.e., in May and June, 2023, at the experimental site. However, the drought did not affect the CFE WW yield and produced similar yields and even higher straw and aboveground biomass than CWW, indicating the resilience of alley crops in agroforestry systems to produce a reasonable yield even in times of drought.

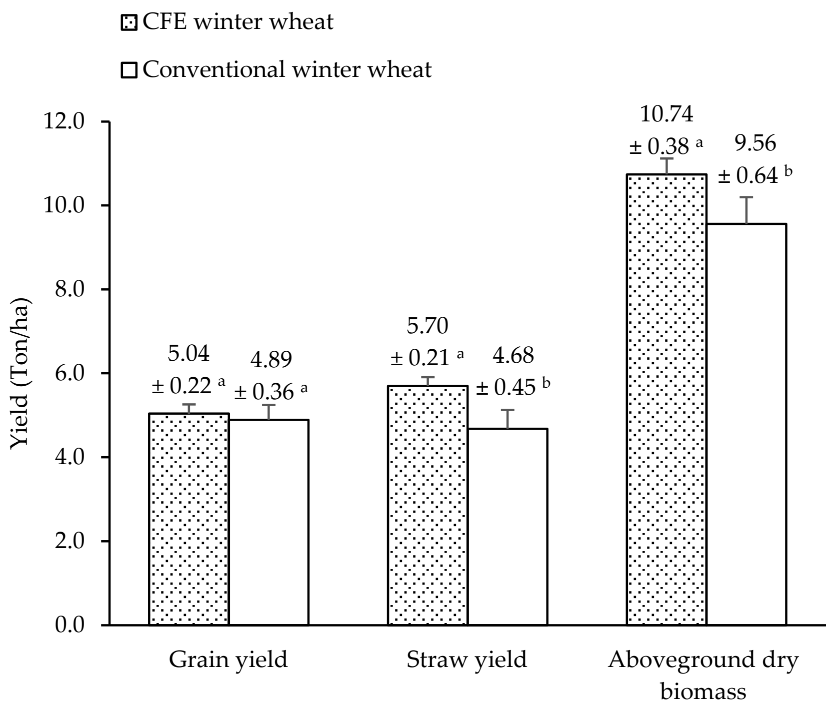

Figure 5. Grain, straw, and aboveground dry biomass yields in CFE winter wheat in the combined food and energy (CFE) production system and conventional winter wheat. Values are mean ± standard error for parameters; superscripts in different alphabets indicate significant differences at $p \leq 0.10$.

The mean yields of grain, straw, and aboveground biomass at H = 0.50, 1.00, 1.64, 3.60, 9.52, and 12.00 in CFE WW and the mean yields of CWW are provided in Table 3. CFE WW grain, straw, and aboveground biomass yields were significantly different between H = 0.50 and H = 9.52, with the lowest at H = 0.50 and the highest at H = 9.52. The negative effects on grain, straw, and aboveground biomass harvest were recorded only at the nearest sampling point to the biomass belt (H = 0.50) in CFE WW with relative grain yields of only 76.5% compared to the CWW (Table 3). The grain, straw, and aboveground biomass yields increased steadily in CFE WW as the distance from the biomass belt increased at H = 1.00, 1.64, 3.60, 9.52 with relative grain yields at 107.15%, 101.63%, 111.24%, and 121.88%, respectively, compared to the CWW. The same trend was recorded for the straw yield and aboveground biomass yield. However, at H = 12.00, the relative grain yield was 99.79% in CFE WW compared to CWW, indicating that the biomass effects were non-existent or negligible at H = 12 (79.20 m). The lowest yield performance was observed at 3.30 m from the base of the BB while the highest yield was observed at 62.83 m from the BB in the crop alley of 200 m in the CFE system.

Table 3. Grain, straw, and aboveground dry biomass yields at H = 0.50, 1.00, 1.64, 3.60, 9.52, and 12.00 in CFE winter wheat in the combined food and energy production (CFE) system in Taastrup 2630, Denmark.

Parameters	H1 = 0.50 (3.30 m)	H2 = 1.00 (6.60 m)	H3 = 1.64 (10.82 m)	H4 = 3.60 (23.76 m)	H5 = 9.52 (62.83 m)	H6 = 12.00 (79.20 m)
GY (ton ha^{-1})	3.74 ± 0.08 [b]	5.24 ± 0.12 [ab]	4.97 ± 0.10 [ab]	5.44 ± 0.25 [ab]	5.96 ± 0.22 [a]	4.88 ± 0.21 [ab]
SY (ton ha^{-1})	4.70 ± 0.07 [b]	5.47 ± 0.19 [ab]	5.54 ± 0.12 [ab]	5.64 ± 0.22 [ab]	6.98 ± 0.10 [a]	5.85 ± 0.20 [ab]
AGDBY (ton ha^{-1})	8.45 ± 0.16 [b]	10.71 ± 0.29 [ab]	10.51 ± 0.23 [ab]	11.09 ± 0.46 [ab]	12.94 ± 0.15 [a]	10.72 ± 0.17 [ab]

GY = grain yield, SY = straw yield, and AGDBY = aboveground dry biomass yield. Values are mean ± standard error, and different superscript alphabets indicate significant differences between six distances for the parameter. H1, H2, H3, H4, H5, and H6 represent sampling points/distances away from biomass belt.

4. Discussion

4.1. Effects of Agroforestry Systems on Soil Properties

The soil bulk density was the highest in the CWW, followed by CFEmean, and the lowest in NF, which was in congruence to another field study conducted earlier in the same site [31]. In the current study, we found a 14.94% higher bulk density in CWW compared to CFEmean. In line with our findings a higher soil bulk density in cocoa monoculture was recorded compared to a cocoa-based agroforestry system, Niether et al. [32]. A higher bulk density was observed in an agriculture site than in an agroforestry site [33]. The TN% was highest in NF, followed by CFEmean and CWW, and the same trend was recorded for exchangeable K, potentially mineralizable nitrogen (PMN mg kg^{-1}), and cation exchange capacity (CEC). These findings of improved soil properties in the agroforestry system are in agreement with other field studies [34,35]. In the current study, CFEmean/agroforestry systems had a significantly higher SOM and TN% content than the CWW, in congruence with other field studies [36–38]. Our results showed that NF (4.14%) had 108.04% more TN% than CFEmean (1.99%), which is in agreement with a previous work [39] that reported that a natural forest system had a higher TN% content than an agroforestry system. Exchangeable K in the soil also exhibited a similar trend to TN%. In our study, significantly higher exchangeable K was present in CFEmean (245.45 mg kg^{-1}), equivalent to 13.45% higher as compared to CWW (216.34 mg kg^{-1}), which is in agreement with other field studies [40], where pecan agroforestry systems recorded higher exchangeable K than the control field (pecan monoculture). Increments in SOC, total N, available phosphorus, exchangeable potassium, and SOC stock levels by 11.9–91.5%, 22.2–125.0%, 31–71%, 32–151.6%, and 15.2–90.9%, respectively, in the soil under the tree canopy compared to outside the canopy were reported [41]. Hence, agroforestry systems have shown multiple benefits, which are mainly due to the addition of significant amounts of SOM, resulting in multiple benefits such as improved soil moisture retention and greater soil nitrogen mineralization, contributing to enhanced productivity with minimum external inputs in agroforestry systems [42].

Earthworm count in the present study was observed to be greater in the CFEmean system than the CWW crop production system, and this is in consonance with other studies [43–45]. In the current study, higher abundance of earthworm was found in CFEmean than the CWW due to the higher SOM, soil moisture, and minimum soil disturbance. Earthworm creates channels in the soil, facilitating water infiltration and aeration, and moving the organic matter into the soil profile, leading to more porosity and, hence, a lower bulk density in CFEmean compared to CWW. The lower earthworm abundance in CWW is also attributed to regular ploughing activity for crop production, removing the earthworm channels, and destroying the habitat for earthworm. The 90% higher abundance in earthworm count was found in agroforestry system supporting the advantages of agroforestry system in favoring the diversity of soil fauna and related ecosystem services [43]. Field investigations on 13 silvoarable systems in France found greater earthworm abundance in tree rows than in crop alley systems in congruence to our findings [46]. The current study recorded beneficial effects of agroforestry on soil properties for improved soil health and increased earthworm count in the agroforestry system (CFEmean) compared to CWW, similar to previous studies [38,45,47–49]. The improved soil health and increased earthworm count can be due to different factors like the high input of leaf litter leading to a high SOM input to support macrobiota and microbiota diversity in the soil. Thus, agroforestry systems improves overall soil health and diversity in the alley cropping system as compared to the conventional crop production system.

4.2. Effects of Agroforestry System on Soil Moisture

The soil moisture in CFEmean was significantly higher than the CWW, demonstrating that the agroforestry system maintained significantly higher soil moisture compared to CWW. This significantly higher soil moisture content in CFEmean during the dry spell (May and June, 2023, in Figure 3) compared to CWW was caused by a high SOM content and a low BD to help conserve soil moisture. A higher SOM content in soil enhances the soil's water retention [50], demonstrating that the agroforestry system helps conserve soil moisture content [51]. Our study demonstrated that agroforestry systems can buffer soil moisture availability to tolerate the drought conditions in agroforestry systems compared to CWW. This can be attributed to the microclimate environment due to several factors like reduced evaporation, increased soil organic matter, and higher plant diversity in the agroforestry system compared to conventional crop production system. In contrast, during the wet spell viz. 27 July and 4 August, 2023 (Figure 3), the soil moisture content was higher by 12.89% and 12.78% on 27 July and 4 August, respectively, in CWW than CFEmean. The greater soil moisture in CWW than CFEmean values indicated that the excessive rainfall in July and early August, 2023, led to the saturation of the soil in CFE WW and CWW due to low infiltration into the soil caused by soil compaction (high BD), whereas the reverse was true in the BB and NF. Agroforestry systems report higher infiltration of water into the soil due to a higher number of macropores, soil aggregate formation, and stability [52–55] in line with our study findings. Ref. [54], which was conducted in Sulawesi (Indonesia), found that increasing soil organic carbon by 1 g km^{-1} of soil (0.1% C-organic improvement) yielded an increase in the available soil water by about 6 mm per m^2 of soil in the agroforestry system in conformity to our results, which show a higher soil moisture content, during dry spells. Better infiltration and increased preferential flow beneath trees potentially reduce runoff generation and erosion risk, promote groundwater recharge, and increase water storage [53].

4.3. Effects of Agroforestry System on Crop Yield and Aboveground Dry Biomass Accumulation

In our study, CFE WW yielded similar grain yields, compared to CWW, and even significantly higher straw and total aboveground biomass yields in CFE WW compared to CWW. This suggested that agroforestry is a beneficial production system for farmers as compared to monoculture farming during extreme weather conditions due to more soil moisture availability, higher SOM, and nutrients in the alley cropping system. This is an interesting finding because CFE WW is managed with no chemical or fertilizer inputs compared to CWW with inputs of fertilizers and chemicals. The CFE WW grain yield was higher by 3.07%, whereas the straw and aboveground biomass yields were significantly higher by 21.79% and 12.34%, respectively, compared to CWW. Our findings on the beneficial effects of agroforestry systems on alley crops are consistent with other field studies [27,56]. In agreement with our study, a yield increase in agroforestry systems was recorded in a tree windbreak system as compared to the open fields of wheat and potato with yield increases of 20–30% and 37%, respectively [57].

In our study, the grain yields in CFE WW at 3.3 m (nearest to the BB) from the BB viz. 3.3 m was lower, which is in agreement with findings reported in other studies [58,59]. This lower yield in winter wheat near the BB in a 200 m wide alley is due to the competition between crops and the BB for light, soil moisture, and available soil nutrients. Beyond point H3 (where H3 = 10.82 m), crop yields increased due to favorable microclimatic conditions. Our study provided evidence of negative and positive effects of biomass belts on annual crops grown in the alleys depending on the H values, and such benefits have been reported in several studies [27,60–62]. Our findings are in agreement with another study [63], which reported the lowest winter cereal yield in the immediate vicinity of the trees (<20 m), and the yield increased beyond the 20 m distance into the alley. Similarly, two winter wheat varieties were found to have lower grain yields at points closer to the tree in two different organically managed agroforestry systems in Feusisberg and Wollerau in Switzerland [64]. This yield loss near the tree row (belt) can be attributed to the reduced germination, lower grain number per ear, poor grain filling [65,66], or shading effects [64,66]. In a two-year-long study [65] in southern France, the lower durum wheat productivity in agroforestry plots was negatively affected because of components like grain weight and the number of grains per spike due to shading effects. Table 4 demonstrates a collection of six different studies from the literature on the shading effects of trees in agroforestry alley crops on grain yield. As shown in Table 4, the study [64] conducted on winter barley in two different agroforestry systems in Central Switzerland found the yield of winter wheat decreased near the tree rows compared to the distances away from the tree rows, In the study conducted at Belgium the yield of the crops under study was reduced due to tree presence with the strongest reduction observed for grain maize and sugar beet near the trees (<10 m) [63]. Hence, the effects of agroforestry can be positive or negative depending on the distance from the tree row and other factors like biomass height, width of the tree row, BB compactness, and age of the tree row including configuration, all of which can affect the microclimate in the alleys and the grain or biomass yield of crops in the alleys.

Table 4. Studies on the shade effect of trees in agroforestry alley crops on grain yield.

Sl. No.	Study Site	Soil Type	Tree Species	Effect on Grain Yield of Alley Crop from Tree Belt	References
1	Dehradun, India	Silty clay loam soil	*Grewia optiva*, *Eucalyptus*, and *Morus alba*	Wheat crop: 40% decrease in crop yield up to 1 m; 33% decrease from 1 to 2 m; 26% decrease from 2 to 3 m; and 16% decrease from 3 to 5 m distance	[58]
2	Ubol Province, Thailand	Aquic Quartzipsamment	*Parinarium anamense*, *Dipterocarpus obtusifolius*, *Dipterocarpus intricatus*, and *Samanea saman*	Lower grain yield, biomass of six different rice varieties was found in the positions closer to the tree base	[59]
3	Padova University, Italy	Not available in the literature	Trees (*Platanus hybrida* Brot.) and shrubs (*Viburnum opulus* L.)	In maize and soybean, losses were only noticeable in the first 4 m of the field from the hedgerow	[61]
4	Tielt-Winge, Belgium	Haplic Luvisol (loess parent material)	Walnut trees (*Juglans regia* L.)	The yield of all crops under study was reduced due to tree presence.	[63]
5	Feusisberg and Wollerau in Switzerland	Sandy, slightly alkaline loam rich in humus	Walnut trees and fruit trees: apple, pear, plum	Grain yield of winter wheat crop was low at points near tree rows	[64]
6	Hérault, France	Silty deep alluvial fluvisol	Walnut trees	The durum wheat cereal crop yield was decreased by shade, by almost 50% for the heaviest shade conditions (31% of light reduction)	[65]

5. Conclusions

This study demonstrated that CFEmean and NF had a lower bulk density compared to CWW, indicating that the CFEmean and NF had a higher soil porosity, less compaction, and increased soil moisture retention. The higher soil nutrients and fertility in CFEmean compared to CWW demonstrated that the agroforestry system had beneficial effects on soil chemical, physical, and biological properties. The BB and NF maintained higher soil moisture during the dry spell due to high SOM, and the converse was true in CFEWW and CWW. This high SOM in CFEmean and NF increases the soil carbon pool, which is of fundamental importance to mitigate the increasing atmospheric carbon balance. The SOM is the storehouse of nutrients for plant growth and soil fertility. Earthworm count was higher in the agroforestry systems compared to CWW, indicating that the agroforestry systems with organic management provided a conducive environment for earthworms to thrive, with multiple benefits on soil properties. The presence of these earthworms in the system helps in litter decomposition, nutrient recycling, water infiltration, and soil aeration, which contributes to conducive environment for plant growth.

This study demonstrated that CFE WW recorded similar grain yields compared to CWW and even higher straw and aboveground biomass accumulation compared to CWW with intensive use of chemical and fertilizer inputs. The BB had negative effects on grain, straw, and aboveground biomass yields in CFE WW at the nearest points from the BB, and the yields increased gradually in the alley fields further away from the BB with maximum grain yields at 62.83 m away from the BB. These findings provided robust field evidence on agroforestry effects on alley crop yields and soil fertility for informed decision-making by farmers. Further, the agroforestry maintained a higher soil moisture content during the dry spell, which can be attributed to the higher SOM in agroforestry systems compared to conventional control. Hence, the agroforestry system contributed to multiple benefits of higher soil fertility and nutrients, soil moisture, and SOM, leading to higher crop yield as well as provision of a suite of ecosystem services like enhanced carbon sequestration and soil moisture, contributing to developing climate-resilient production systems.

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