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Effects of Agro-Ecological Practices on Soil Health and Sorghum Yield as Influenced by Climate Change in the Sudan-Sahelian Zone of Burkina Faso

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Abstract

Drought and low soil fertility remain significant constraints to agricultural production in Burkina Faso. Agro-ecological practices like stone rows (SR), *zaï* (Z), and ridge tillage (RT) have been developed to cope with these challenges. This study aimed to determine the influence of SR, Z, *zaï* combined with stone rows (Z_SR), and RT on soil health and sorghum productivity. The experiment was set up in a randomized Fisher bloc design, with four treatments and five replications. Measurements were carried out on soil parameters and sorghum yield components. The results showed that SR, Z, and Z_SR increased soil moisture content by 5.73%, 23.16%, and 23.55%, respectively, compared to RT. They increased soil carbon, nitrogen, and phosphorus content and pH values. Additionally, they increased grains yield by 130%, 271.36%, and 268.57%, respectively, compared to RT, while straw yields increased by 6.78%, 93.29%, and 66.30%, respectively. The 1000-grain weight increased by 7.08%, 16.23%, and 16.01% for SR, Z, and Z_SR compared to RT. SR improved soil respiration. RT and SR influenced termite development. SR positively influenced the development of earthworms. These results affirm *zaï* and *zaï* combined with stone rows as climate-smart entry point to restoring degraded soil and boosting sustainable production.

Keywords: Agro-ecological practices; Soil fertility; *zaï*; Ridge tillage; Stone rows

Introduction

World cereal production was estimated at 2,756 million tonnes in 2022 [1]. Sorghum currently ranks fifth among cereals. In Africa, sorghum comes fourth after Sudan, with a production of 2.01 million metric tons in 2022-2023 [2]. In Burkina Faso, cereal production was 5,179,000 tons in 2020, with 1,839,570 tons being sorghum, representing 35.52% of national production [3]. Sorghum production, however, faces several constraints such as soil nutrient deficiency [4], inappropriate agricultural practices combined with climate change [5], poor fertilization [3], land degradation and farmers' low income. These factors are keeping sorghum yields below their potential.

To overcome these production challenges, various agroecological practices are developed and disseminated by NGOs, governments, projects and programs, and farmers themselves [6-8]. The practices disseminated include *zaï*, stone rows, cereal-legume cropping associations, Natural assisted regeneration, rainwater collection reservoirs and the use of improved seeds. Agroecology is the integration of research, education, action and change that brings sustainability to all parts of the food system: ecological, economic,

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and social. It's transdisciplinary in that it values all forms of knowledge and experience in food system change [9]. Then agroecological practices are those that enable us to achieve an agroecosystem that is sustainable, equitable, economically profitable and socially and culturally acceptable. Indeed, soil carbon sequestration appears to be one of the alternatives for combating land degradation. Soil C sequestration can be increased by plant species selection, microclimate modification through nutrient and water management, conversion of marginal lands to more productive grasslands and forests, increasing crop and forest productivity through residue management to slow organic matter decomposition, management approaches to reduce carbon loss and the application of technology [10]. Agroecological approach contributes to the sustainable intensification of production and the preservation of soil fertility through the restoration of soil quality, and include integrated landscape management, integrated soil fertility management, integrated pest management. Assessing land management practices that will enhance soil health and crop productivity is crucial for food security and sustainable agriculture. While the scientific community had though that several agricultural practices were successful to fill soil carbon loss [11] there are now proofs that these techniques do not store as much as carbon into soils as it has been claimed [12,13] there are increasing evidence that nutrient supply to soils, either in an organic or inorganic form, is key to revert soil nutrient and soil C depletion [13]. This is where historical practices such as organic inputs such as manure application to soils *zaï,* stone rows, half-moons, grass strips, different types of ploughing, and agroforestry techniques come in.

Several studies have highlighted the positive impacts of the *zaï*, stone rows, soil bund, and ridge tillage techniques on soil chemical and physical properties, as well as on crop yields [14-17]. These techniques positively influenced the physicochemical properties of soils, crop yields, groundwater recharge, and rainfall infiltration [18-20]. For instance, results of [21] indicate that stone rows can increase water infiltration into the soil by 15%, and results from [22] shown that stone bunds improved soil pH, Organic matter (OM), available phosphorous (Av. p), cation exchange capacity (CEC), available potassium (K+), moisture content, and crop yield (*Sorghum bicolor* L. and *Cicer arietinum*) [23] highlight that soil bunds reduced surface runoff and soil loss with 80–92% and 96%. In addition, *zaï* combined with organic manure can double or even triple sorghum yields and improve chemical properties of the soil, such as pH and organic matter content in Burkina Faso [24,25].

However, these agroecological practices' effects on the soil's biological properties and the effects of their combinations on the soil's biological, chemical and physical properties are not sufficiently researched. Therefore, in-depth investigation is needed. Research should thus focus on combining these practices to sustainably improve cereal yields and enhance the soil's biological, chemical and physical properties to mitigate climate change impacts.

This study is based on the hypothesis that *zaï*, and *zaï* combined with stone rows can increase grain and straw production of sorghum. This study aims to determine the influence of *zaï*, stone row and the combination of *zaï* and stone row on the biological, chemical, and physical properties of the soil, as well as on sorghum yield parameters, in the Sudan-Sahelian zone of Burkina Faso.

Material and Methods

Site characteristics

The study was carried out over two cropping seasons from 2021 to 2022 in *Sandogo*, located in the *Kourweogo* province of the Plateau Central region of Burkina Faso. The rainy season primarily spans the months of June to September, with an average rainfall of 729.98 mm for the last ten years (2011-2020), characterized by interannual variability. The total rainfall was 602.8 mm over 43 days in 2021 and 708 mm over 37 days in 2022. The highest rainfall was recorded in August 2021 (231.8 mm) and September 2022 (291.5 mm). The rainfall recorded in both years was below the average of the previous decade. However, the total rainfall in 2022 was higher than in 2021. The main soil types in the study area are indurated leached tropical ferruginous soils and leached tropical ferruginous soils with stains and concretions.

Experimental design

The experimental design was a randomized Fisher bloc with four treatments (Table1) and five replications. The design involves 5 blocks of plots in which all treatments appear once and only once. In each block, which is assumed to be homogeneous, 4 different treatments are randomly allocated. The treatments consisted of Ridge tillage as a control (RT), *Zaï* (Z), Stone Rows (SR), and *Zaï* + Stone Rows (Z_SR). Stone rows are anti-erosion structures consisting of a strategic arrangement of stones along contour lines. One line was built for each treatment. Each stone row consisted of two rows of stones placed in a furrow. The upslope row made up of large stones, was stabilized by the downslope row, composed of smaller stones. Each stone row was about 0.2 to 0.3 meters high. The *zaï* pits were 15 cm deep and had a diameter of about 20 cm.

Table 1: Treatments.

Codification of treatments	Meaning of treatments
RT	Ridge Tillage
Z	Zaï
SR	Stone Rows
Z_SR	Zaï + Stone Rows

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Agronomic management

The *zaï* pits and the stone rows were implemented in June 2021. Organic manure was applied in the first year of the experiment at a dose of 5,000 kg. ha^{-1}. The same *zaï* pits were used in 2022. Sorghum was sown on July 15, 2021, and June 24, 2022, at a spacing of 0.8 m × 0.4 m and thinned to two plants per hill, resulting in 62,500 plants per hectare at a seeding rate of 8 kg. ha^{-1}. The treatments were applied on plots of 20 m × 3.5 m, separated by intervals of 1 m. The fertilizer NPKSB was applied 21 days after sowing (DAS) in microdoses of 2 g per hole. Supplementary urea (1 g per hole) was applied 45 days after planting. Weeding was done manually. Sorghum was harvested at 105 DAS in 2021 and 2022.

Data collection

Weather

The total monthly rainfall data for the 10-years average were obtained from the weather stations closest to the site. All weather stations were within 20 km of the site. During the experiment, a rain gauge was positioned in the village of *Sandogo* to collect rainfall data.

Soil sampling and analysis

Description of pedological pit: A field investigation was conducted, based on both pedological trench description and sampling. For the pedological trenches, soil descriptions and classification were conducted following the guidelines for soil description by the FAO and adapted by BUNASOLS to the agro-climatic conditions of Burkina Faso. Four soil samples were collected in each pedological trench according to the horizon (one composite sample per layer) for laboratory analysis, in order to obtain additional data on the initial soil characterization. For experimental work and the collection of soil samples, we received the oral agreement of the landowner who, in collaboration with his family, supported us in all the operations carried out on the experimental site.

Soil moisture content: Starting from the fortieth day after sowing, surface moisture was measured using a portable moisture meter (IMKO Model HD2 probe moisture meter, Germany). Three moisture measurements were done in each elementary plot in the 0-20 cm soil layer. The measurements were made in five successive times: 40 DAS, 50 DAS, 60 DAS, 70 DAS, and 80 DAS.

Soil macrofauna was sampled 68 DAS in 2021 and 60 DAS in 2022 using the Tropical Soil Biology and Fertility method [26], with modifications. A metal frame measuring 25 cm × 25 cm × 30 cm was driven into the soil. A monolith was removed, broken up, crumbled, and excavated by hand on a tarpaulin in order to collect the macrofauna, which was stored in flasks containing 75% alcohol. Macroinvertebrates were identified and counted under a binocular magnifying glass using reference books and dichotomous keys [27,28]. The number of individuals in each group was recorded, and their weights were measured using precision electronic scale.

Soil respiration measurements were made by using an IRGA respirometer according to the following protocol: Three soil samples were collected in each plot at 0-10 cm depth. These individual samples were mixed to create a composite sample for each plot. The soil samples were then air-dried and sieved to 2 mm. Two grams of soil were placed in glass anticoagulant tubes (three replicates), brought to optimum humidity, and then the tubes were sealed. The samples were incubated in the dark at room temperature. After two hours of incubation, the first measurement of CO_2 release was carried out, and then the tubes were returned to darkness. The second measurement was taken after 24 hours of incubation. The other measurements were carried out every 72 hours (twice) to 96 hours of incubation (twice) for a total of two weeks.

Soil Texture was determined by analyzing the granulometric fractions (three fractions) using the international Robinson pipette method. ***Soil pH*** was measured with a glass electrode using a 1:2.5 soil-to-water ratio, following method [29]. ***Soil organic carbon*** (SOC) was determined by Walkley et al. [30] method. ***Soil total nitrogen*** (N) was determined by the Kjeldahl method, as refined by [31]. ***Soil available phosphorus*** was measured using [32] method. The cation exchange capacity (CEC) was determined using a method based on ***extraction with 0.01 M thiourea silver***. It also determines the exchangeable bases [33].

Plant data collection

Grain and straw yields of a plot were determined from all the plants within the useful plot area (35.2 m^2). The useful plot was obtained by eliminating two crop rows on each side of the elementary plot to avoid border effects. Yields were computed by considering all the sorghum plants in the useful plot at harvest. Aliquots of fresh biomass were taken and transported to the laboratory, where they were weighed, air-dried for a fortnight, and then reweighed to obtain the quantity of dry matter with a constant weight. This value was used as the basis for calculations to obtain the average yields in $t.ha^{-1}$ per treatment. A precision scale was used to determine the weights of one thousand grains.

Statistical analysis

The plants and soil data obtained were subjected to analysis of variance (ANOVA) using R software (version 4.2.1) at 5% threshold. The Student Newman-Keuls test was used to perform for mean comparisons.

Results

Characteristics of the soil

Based on the descriptions of the open soil profile, indurated leached tropical ferruginous soil, and leached

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tropical ferruginous soil with stains and concretions have been identified. These soils belong to the class of soils with iron and/or manganese sesquioxide [34]. The soil profile is 120 cm deep. Texture is silty-sandy at surface (17 cm), silty-sandy-clay from 17-43 cm, silty-clay from 43-84 cm, and clayey beyond 84 cm. The structure is weakly developed with subangular polyhedral aggregates throughout the profile. The consistency ranges variable to very firm. Roots are numerous in surface and few at depth. There are numerous pores at the surface and few at depth. Biological activity is well developed at surface but poorly developed at depth.

The organic matter (OM) content is low (0.32-0.77%) throughout profile. OM is highly mineralized (C/N= 9-11). The cation exchange capacity (CEC) is low (4.86-6.45 $cmol^{+}.kg^{-1}$). The sum of exchangeable bases is also low (2.87-3.77 cmol+.kg-1). The base saturation is average (51-59%). The soil has a low level of nitrogen (0.02-0.04%), and low levels of available phosphorus (1.10-1.79 ppm). The soil is strongly to moderately acidic (pH 4.87-5.8) with an average cumulative carbon dioxide release of 2,676.67 ppm in 2021.

Effects of zaï, stone rows, and ridge tillage on soil moisture content

Soil moisture content significantly varied along the treatments ($p<0.0001$). Moisture levels ranged from 33.67±1.94 to 41.60±1.55 on 60 DAS, from 33.07±1.48 to 38.67±1.18 on 70 DAS, and from 30.60±0.98 to 37.67±0.67 on 80 DAS. The SR, Z, and Z_SR significantly improved the moisture content compared to the RT (Figure 1). These improvements were +5.73% under SR, +22.16% under Z, and 23.55% under Z_SR on 60 DAS, + 0.39% under SR, +16.33% under Z and +16.93% under Z_SR on 70 DAS, and +5.46% under SR, +23.10% under Z and +22.87% under Z_SR on 80 DAS. Z and Z_SR had a greater impact on the variation of soil moisture levels. RT and SR recorded the lowest moisture content. Moisture contents decreased from 60 DAS to 80 DAS, but treatments including *zaï* always remained wetter than those consisting only of SR and RT.

Effects of stone rows and zaï on soil carbon dioxide release variability

The treatments significantly influenced soil CO_2 release. Analysis of variance revealed two homogeneous groups: the SR treatment, which recorded 4,070 ppm, occupied the first group (Table 2). The second group consisted of the RT, Z, and Z_SR treatments, which recorded 2,965.3, 2,978.7, and 2,924 ppm, respectively.

Effects of stone rows and zaï practices on soil macrofauna variability

In 2021, the Shannon diversity index showed that Z had the richest macrofauna community with IS = 2.0059. It was followed by the SR, RT, Z_SR with IS values of 1.9587, 1.7591, and 1.7507, respectively. In 2022, RT had more macrofauna diversity with IS = 2.3706 (Table 3). It was followed by the Z_SR, Z, and SR with values of 2.2489, 2.0802, and 2.0146, respectively. Three species of earthworms belonging to the order Haplotaxida, family Octochaetidae (*Dichogaster affinis*), Acantthodrilidae (*Milsonia inermis*), and Lumbricidae (*Lumbricus terrestris*) were found. In 2021, RT and Z_SR recorded the highest number of termites.

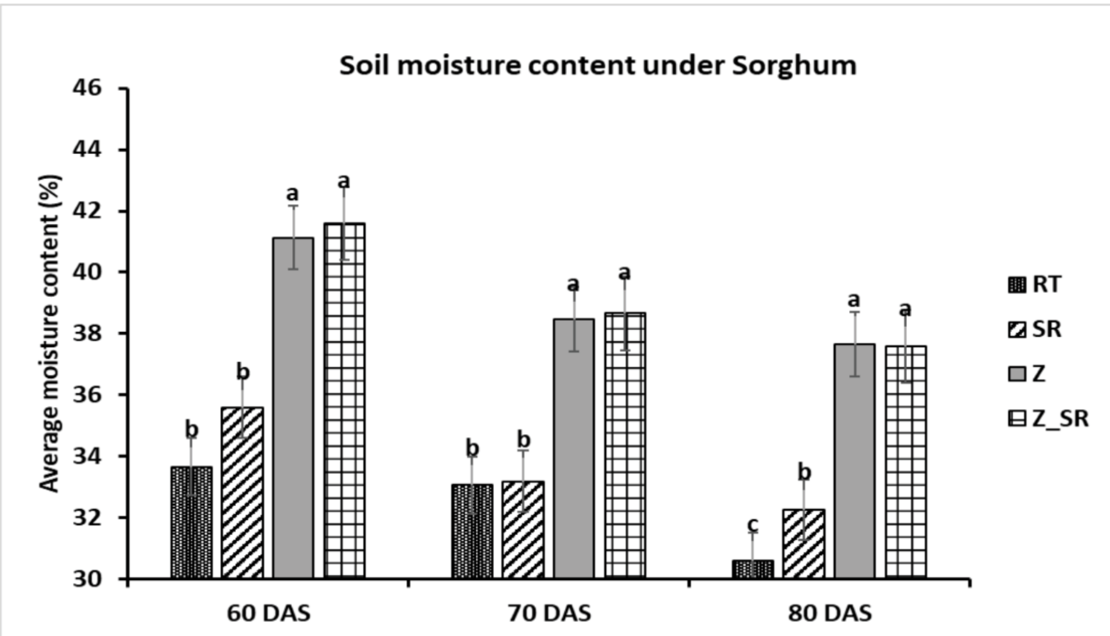

Figure 1: Soil moisture content variation (The histograms correspond to the means; the means with same letter do not differ significantly at the 5% level; **n** = 5; **DAS**= Days after sowing).

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Table 2: Dynamic of soil carbon dioxide release under sorghum

Treatment	CO_2 Release (ppm)	
	2021	2022
RT	2,965.3±83.32**b**	1,819.47±55.94**b**
SR	4,070±61.96**a**	2,235.33±43.94**a**
Z	2,978.7±45.62**b**	1,829.33±25.97**b**
Z_SR	2,924±69.58**b**	1,804.67±17.73**b**
P-value	0.0001	0.0001
Signification	***	***

Microtermes upembae and *Microtermes* sp. are the most encountered species. In 2022, RT and SR had more termites than Z and Z_SR. *Microtermes upembae*, *Macrotermes* sp, and *Microtermes* sp were the most encountered with a total of 227, 99, and 38 respectively. As for ants, eight species were inventoried. In 2021, RT and Z_SR recorded a lot of ants. In 2022, Z and Z_SR recorded more ants than RT and SR. *Camponotus pennsylvanicus*, *Monomorium pharaonis*. *Pogonomyrmex* sp., and *Camponotus* sp had the highest numbers with total values of 109, 99, 64, and 42, respectively. Three earthworm species were inventoried: *Dichogaster affinis*, *Milsonia inermis*, and *Lumbricus terrestris*. In 2021, SR, Z, and Z_SR recorded earthworms with identical numbers. In 2022, SR and Z stimulated the development of many earthworms. *Dichogaster affinis* and *Milsonia inermis* were mostly encountered with total values of 128 and 54, respectively.

Effects of ridge tillage, stone rows, and zaï on soil chemical properties

The results showed three statistically homogeneous groups (Figure 2). Z and Z_SR form the first group. The second group contains the SR treatment, while RT represents the third group. Treatments significantly influenced total carbon ($p<0.0001$), total nitrogen ($p<0.0001$), and available phosphorus ($p<0.0001$) contents, and pH values ($p<0.0001$). The highest carbon, nitrogen and phosphorus contents and pH values were found in the *zaï* (C=0.572%, N=0.053%, P5.860 ppm, pH=5.77) and *zaï* + stone rows (C=0.580%, N=0.053%, P=5.980 ppm, pH=5.80) treatments, followed by the SR (C=0.436%, N=0.045%, P=3.316 ppm, pH=5.51) treatment. The lowest nutrients content and pH values were observed in the RT (C=0.297%, N=0.033%, P=2.016 ppm, pH=5.25) treatment. Z, Z_SR and SR treatments significantly improved Carbon (C), Nitrogen (N), available phosphorus (P) and mean pH values of soils collected at harvest compared to the RT treatment.

Table 3: Shannon Diversity Index and Equitability Index of macrofauna.

Treatment	RT		SR		Z		Z_SR	
	2021	2022	2021	2022	2021	2022	2021	2022
H’	1.7591	2.3706	1.9587	2.0146	2.0059	2.0802	1.7507	2.2489
IE	0.3883	0.3536	0.4769	0.3713	0.4073	0.3703	0.3436	0.2712

H’ = Shannon diversity index, **IE**= Equitability index

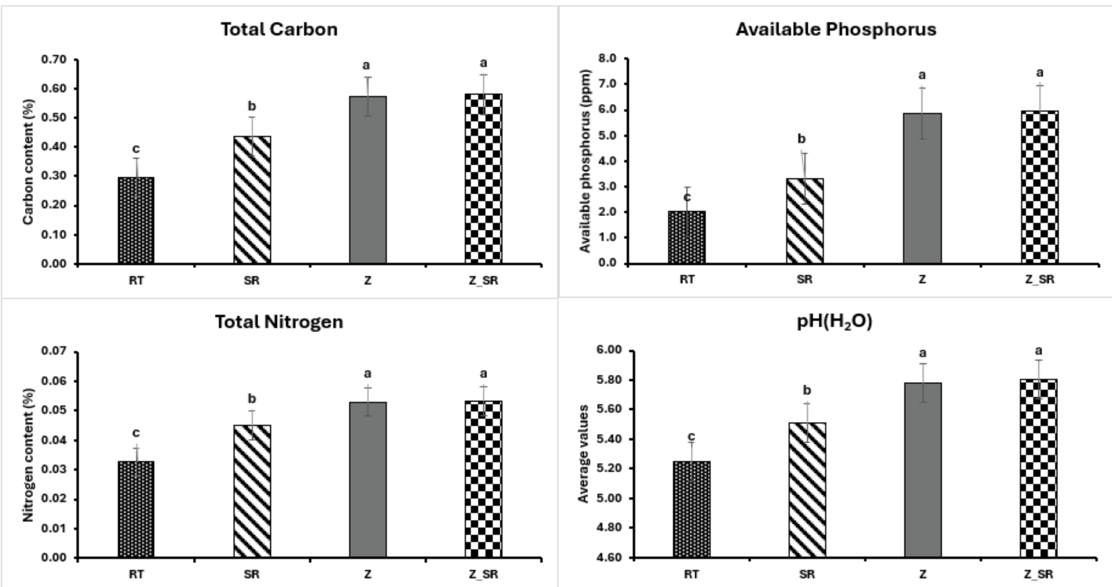

Figure 2: Effects of treatment on C (a), P (b), N (c) content, and pH (d) values. (the means with same letter do not differ significantly at the 5% level; **n** = 5).

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Effects on the grains and haulm yields and 1000 grains weight.

Grain yields significantly increased in 2021 (p<0.0001) and 2022 (p<0.0001) under SR, Z, and Z_SR treatments compared to RT (Table 4). In 2021, this increase was 36.57% for SR, 337.48% for Z, and 332.67% for Z_SR. In 2022, this increase was 130% for SR, 271% for Z, and 268% for Z_SR. In 2021, the increase in 1000-grain weight was 6.39% for SR, 22.02% for Z, and 17.09% for Z_SR. In 2022, the increase was 7% for SR and 16% for Z and Z_SR. A similar trend was observed in straw yields for all three treatments and in both seasons. Specifically, SR stimulated an increase of 10.99%; Z by 139.84%, and Z_SR by 92.74% compared to RT in 2021.

Table 4: Effects of treatments on grains yields, straw yields and 1000-grains weight.

Treatment	Grains Yield ($kg.ha^{-1}$)		Straw Yield ($kg.ha^{-1}$)		1000-GrainsWeight (g)	
	2021	2022	2021	2022	2021	2022
RT	380.38±9.67**c**	467.55±8.22**c**	2,038±719.81**c**	2,920±783.96**b**	19.40±0,97**b**	18.48±1.55**b**
SR	519.47±8.99b	1,075.06±14.32**b**	2,262±688.60**c**	3,118±1012.73**b**	20.64±1.50**b**	19.79±0.81**ab**
Z	1,664.01±23.46**a**	1,736.32±11.53**a**	4,888±507.81**a**	5,644±631.29**a**	23.67±2.14**a**	21.48±1.34**a**
Z_SR	1,645.77±20.86**a**	1,723.28±15.85**a**	3,928±895.08**b**	4,856±907.02**a**	22.74±1.13**a**	2.44±0.81**a**
P-value	0.0001	0.0001	0.0001	0.0002	0.0014	0.0023
Signification	***	***	***	***	**	**

Discussion

Effects on soil carbon, nitrogen, available phosphorus, and pH

The C, N, and P content of soils under Z, Z_SR, and SR are greater than soils under RT. Then Z, Z_SR, and SR treatments increased soil organic carbon, total nitrogen, available phosphorus, and pH values. Bedada et al. [35], Xin et al. [36], Nyawade et l. [37] reported that treatment with cattle manure and a combination of manure and half dose of inorganic fertilizer resulted in an increase in soil organic carbon. Muchai [38] found that *zaï* pits combined with organic fertilizer increased soil organic matter levels. The increase in carbon is likely due to the addition of cattle manure at the time of establishment and to the return of a small portion of the plant through the roots, as they are the main carbon depositors in the soil [39,40]. Moreover, some authors found that the roots of sorghum can accumulate up to 14% of the total carbon captured in the above-ground and below ground biomass [40,41]. According to the study by Cai et al. [42], the application of manure promotes the increase of soil organic carbon contents, pH, and nutrients content. Therefore, we can conclude that *zaï,* when combined with cattle manure and the return of sorghum roots, contribute to increasing soil carbon content. Soil nitrogen levels were also improved under Z, Z_SR, and SR compared to those sampled under RT. This result is logical due to the urea supply and the return of roots coupled with the increase in organic matter in *zaï*. Indeed, organic matter reduces the inflow rate and improves the soil's water retention, thus preventing nitrogen being transported to deep by water [43]. Available phosphorus levels were higher under the Z, Z_SR, and SR treatments compared to the RT treatment. These treatments are therefore beneficial for improving the soil's available phosphorus content. These results corroborate those of [44], who found that *zaï* combined with manure increased the levels of soil available phosphorus content. In our case, this improvement in available phosphorus levels is attributable to the interaction of *zaï*, manure, and NPK mineral fertilizer. Soil amendment through the application of manure improves the physicochemical properties of the soil and the nutrient cycle by reinforcing the enzymatic and microbial activities of the soil. This triggers the process of bioavailability of phosphorus for plant uptake [45] and provides phosphorus in the soil through the content of inorganic orthophosphates in manure. Z, Z_SR, and SR treatments stimulated higher pH values than RT. This dynamic is similar to that of carbon, nitrogen, and available phosphorus. Thus, Z, Z_SR, and SR treatments positively influence the soil pH. The higher pH values under these treatments could be attributed to the manure that increased the organic matter content. Aalkalinity of organic matter as a result of the decarboxylation of organic anions and ammonification of organic nitrogen stimulates the increase of soil pH and neutralizes its acidity [42,46].

Effects on soil moisture content

Our results showed a significant increase in soil moisture content under *zaï* and *zaï* associated with stone rows, confirming the key role of *zaï* pits in improving soil water retention on degraded soils. Blanco-Canqui et al. [47] reported that the application of manure increased the water retention capacity of semi-arid soils. Muchai et al. 2023 concluded that combining organic amendments with Zai pits promotes moisture retention and increases water infiltration. Indeed, the highest moisture levels were recorded in soils under *zaï* and under *zaï* combined with stone rows. This is because

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the *zaï* pits collect water and retain moisture. The addition of organic manure increases soil organic carbon content, which improves porosity and water holding capacity [48] and contributes to conserve soil moisture content. In the SR treatment, even with ridging, moisture levels remain lower in the *zaï* treatments. This suggests that even with the use of organic fertilizer and ridging, which should reduce water transport of fertilizers, *zaï* pits are more efficient in storing and retaining water.

Effects on soil respiration

A significant cumulative release of CO_2 was observed in soil under the SR treatment. SR improves soil respiration conditions. This is attributed to the application of organic fertilizer, which increases the organic matter content and raises the soil pH. Both, pH and organic matter influence the biological activity of the soil. In addition, tillage practices such as flat plowing and ridging contribute to lowering the soil bulk density [49]. This improvement in soil moisture and aeration fosters the development of microorganisms. Consequently, the mineralization of organic matter is accelerated, and the amount of CO_2 released depends on the microbial population, its diversity, and the metabolic enzymes secreted.

Effects on soil macrofauna dynamic and diversity

The RT, SR, and Z_SR treatments recorded more termites than the Z treatment. Doamba et al. [50] have shown that stone rows have a positive effect on soil macrofauna. The presence of mushroom termites can be explained by the addition of manure, as cow dung manure is a lignocellulosic biomass [51]. According to Maldague [52] and Zaremski et al. [53], termites primarily feed on cellulose. Furthermore, the adaptability of termites may be enhanced by the symbiotic relationship they maintain with certain fungi, which facilitates the degradation of their food [54].

As for the ants, species from the genera Camponotus, Monomorium, and Pogonomyrmex were mostly represented, while genera like Messor and Formica were the least encountered. This suggests that the combination of soil management techniques, manure, mineral fertilization, soil type, and crop provides a favorable environment for ant populations.

The application of treatments on sorghum also favored the growth of earthworms. The species recorded included anecitic worms (*Dichogaster affinis* and *Lombricus terrestris*) and endogeic worms (*Millsonia inermis*) worms. The most common species is *Dichogater affinis,* followed by *Milsonia inermis*. *D. affinis* feeds mainly on soil taken from the 0-10 cm horizon and sometimes deeper, while *Milsonia inermis* feeds on organic fractions taken from the soil at a depth of 30 cm, where they live. The presence of this earthworm population can be explained by the incorporation of manure [55].

Our results indicate that the treatments associated with the type of soil and the culture stimulate good development of soil engineers, such as termites, ants, and earthworms. However, the conditions seem to be more favorable for termites and ants than for earthworms. This leads us to hypothesize that the existence of ants may hinder the development of termites or earthworms. Additionally, the number of individuals of these three soil engineers was higher in 2022 than in 2021, which can be explained by the higher soil moisture in 2022 compared to 2021. Indeed, soil moisture stimulates the appetite of invertebrates.

Effects of zaï, stone rows, and ridge tillage on agronomic parameters of sorghum

The results indicated that Z, Z_SR and SR treatments had significant effects on grain yields, straw, and thousand-grain weight compared to RT treatment. Our findings corroborate those of several authors [56,57] and confirms the key role of *zaï*, stone rows and microdosing, as well as their combined effects on the physical, chemical, and biological fertility of the soil, which significantly impact sorghum yields and growth. Indeed, treatments involving *zaï*, stone rows, *zaï* combined with stone rows and manure reduce runoff and evaporation, facilitate infiltration, improve water retention capacity, and concentrate organic matter [58]. These improvements enhance crop growth and development, leading to increased grain yields and better water and nutrient use efficiency.

Furthermore, Z and Z_SR treatments produced significantly higher yields than SR and RT. This is because *zaï* pits and stone rows along contour lines collect water and fine soil, reducing runoff and thus improving soil moisture [59]. However, sorghum yields in 2022 were higher than those in 2021 due to the irregularity of rains observed in 2021. Sorghum yields are considerably influenced by water availability in terms of quantity and time [57,60].

Improved water and chemical properties are the result of organic fertilizer inputs and the breaking of the surface crust, which allowed for better water penetration [61,62]. Additionally, *zaï* favors the increase in carbon and nitrogen content of the soil. Thus, the addition of micro-dose fertilizers combined with good water retention capacity has boosted sorghum yields.

Conclusion

This research showed that the agroecological practices of zai and zai combined with stone rows significantly influence the variability of soil organic matter, nutrients and soil biological activity, as well as sorghum productivity. *Zaï* pits and *zaï* pits combined with stone rows improved soil pH values, as well as carbon, nitrogen and phosphorus contents. The addition of nitrogen (from urea and NPK), potassium (from NPK), phosphorus (from NPK) and manure to the *zaï* pits and stone rows increased the availability of nutrients in

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the soils, thus stimulating sorghum vegetative development and yields. Based on our results, the addition of manure and mineral fertilizers in microdose form to *zaï* pits and *zaï* pits combined with stone rows are more competitive climate-smart combinations for improved sorghum production and soil management. However, further investigations are needed to push the limits of our study. These could include conducting the experiment in the country's two other agro-ecological zones and on other contrasting soil types, and laboratory analysis of their effects on biomass and grain biochemical parameters.

Authors' Contributions

Edmond HIEN and Harouna OUEDRAOGO designed the study, wrote the protocol, performed the statistical analysis. Harouna OUEDRAOGO followed the experimentation and collected field data. Yacouba DIALLO, Poulouma Louis YAMEOGO and Udo NEHREN supervised the work. Harouna OUEDRAOGO wrote the draft of the manuscript. All authors have approved the final manuscript.

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Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled: "*Effects of agro-ecological practices on soil health and sorghum yield as influenced by climate change in the Sudan-Sahelian zone of Burkina Faso*".

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