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Performance of Sorghum (*Sorghum bicolor* (L.) Moench) Under Marula Tree, *Sclerocarya birrea* (A. Rich.) Horchst Subspecies *birrea* in Northwestern Drylands of Tanzania

Abubakari H. Munna[1] | Nyambilila A. Amuri[1] | Dino A. Woiso[2] | Proches Hieronimo[3]

[1]Department of Soil and Geological Sciences, Sokoine University of Agriculture, Chuo Kikuu, Tanzania | [2]Department of Biosciences, Sokoine University of Agriculture, Chuo Kikuu, Tanzania | [3]Department of Agricultural Engineering, Sokoine University of Agriculture, Chuo Kikuu, Tanzania

Correspondence: Abubakari H. Munna (amabmunna81@gmail.com)

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ABSTRACT

Introduction: Unsustainable agricultural practices contribute to biodiversity loss globally, calling for efforts to reconcile agricultural productivity and biodiversity conservation in agroecosystems. However, the potential benefits of *Sclerocarya birrea* in drylands agroforestry are not documented. This study investigated the effects of *S. birrea* subspecies *birrea* on soil chemical properties, sorghum productivity and nutritional quality in Northwestern drylands of Tanzania.

Materials and Methods: Field experiments were conducted in the 2019/20 and 2020/21 farming seasons with three treatments (i) the presence of marula tree, (ii) tree sex nested within tree treatment, and (iii) control (no tree). Thus, the treatments were arranged in a nested block design (NBD) experimental design.

Results: The soil pH, organic carbon (OC), total nitrogen (TN), electrical conductivity (EC), manganese (Mn), calcium (Ca), cation exchange capacity (CEC), and potassium (K) were significantly ($p < 0.05$) higher in soils under the tree canopies than in no tree during the 2019/20 farming season. Similarly, OC, EC, Ca, CEC, Mg, and K were significantly ($p < 0.05$) higher in soils under the tree canopies than in no tree during the 2020/21 farming season. Sorghum plants basal diameter, stem height, chlorophyll concentration, and sorghum grain yields were significantly ($p < 0.05$) higher under trees canopies than in plots with no trees. Sorghum grain yields were 3 359.38 kg/ha and 3 305.21 kg/ha under tree canopies while in no tree plots were 2 146.43 kg/ha and 2 050.00 kg/ha for 2019/20 and 2020/21, respectively. Iron concentration in sorghum grains from sorghum plants grown under tree canopies was higher than those away from the canopies, but no significant differences in proximate composition and other minerals concentration in grains.

Conclusion: Subsp. *birrea* improved soil chemical properties, and sorghum yields. Thus, it is a potential tree for agroforestry in drylands.

1 | Introduction

Investigating the potential for improving crop production through drylands-adapted agroforestry is essential for ensuring food security and biodiversity conservation. This is because food insecurity, extreme poverty, and environmental degradation nexus are the most challenging in drylands (Jama et al. 2008). Drylands cover about 43% of Africa's terrestrial area (Wei et al. 2021), and around 67% of Tanzania's terrestrial area is classified as drylands (Abdillahi et al. 2012). Drylands of Africa provide opportunities for development and attainment of food security, but only if suitable crops are grown (Macauley and

Ramadjita 2015) in an appropriate manner to conserve the otherwise vulnerable drylands ecology. Thus, addressing the food and nutritional insecurity in sub-Saharan Africa requires finding ways to improve crop yields, bio-fortification of staple food (Ofori et al. 2014) and exploring agroforestry practices that use adaptive native tree species.

Sorghum (*Sorghum bicolor* (L.) Moench) is the major dryland crop (Rao 2014). The crop is genetically adapted to the drylands and light soils (Kaminski et al. 2013), and with an increasing global human population and depleting water resources, sorghum will play a significant role in agriculture in the future (Taylor et al. 2006). In Tanzania, sorghum is the third most important cereal, and it is cultivated in an estimated area of 650 000 hectares per annum [International Crops Research Institute for the Semi-Arid Tropics (ICRISAT 2014)]. Smallholder farmers in almost all the semi-arid areas grow the crop for food, feed and beer making (Demissie et al. 2020).

Many fruit trees could be integrated into dryland farming systems in sub-Saharan Africa to support income and nutritional security. Marula tree, *Sclerocarya birrea* (*S. birrea*), (A. Rich.) Horchst is one of the five cross regional important trees (Jama et al. 2008). The *S. birrea* is a drought-tolerant, multipurpose, and economically important fruit tree indigenous to Africa, which is extensively distributed across drylands in sub-Saharan Africa (Hall et al. 2002). As a center of genetic diversity with all three subspecies of *S. birrea* (subspecies *birrea*, subspecies *caffra* and subspecies multifoliata) (Hall et al. 2002), Tanzania can benefit from integration of *S. birrea* in agroforestry.

Sclerocarya birrea and sorghum has common ecological traits adaptive to drylands conditions. *S. birrea* and sorghum are both drought-tolerant species that can strives in poor soils (Hall et al. 2002; Khoddami et al. 2023). Sorghum can survives under seasonal rainfall as low as 250 mm, an altitude of 0 to 2500 m above sea level and optimum temperatures of 20°C–35°C (SNV 2020). Similarly, the subspecies of *S. birrea* can strives under the altitude, rainfall and temperature conditions ranging from 800 to 1800 m, 500–1400 mm and 19°C–29°C, respectively (Hall et al. 2002). Thus, *S. birrea* is among many tropical fruit trees that could be integrated into drylands sorghum growing farming systems in sub-Saharan Africa to support nutrition, health, and income security due to its multiple uses (Jama et al. 2008).

In most agroforestry systems competition for light, moisture, and nutrients exists at the crop-tree interface [Technical Centre for Agricultural and Rural Cooperation (CTA 1996)]. Thus, crops and tree species integration must be optimized. Furthermore, the effect of male and female trees on crops may be different for diecious tree species like *S. birrea*. This is because production of seeds and fruits by female plants requires a significant amount of macro and micronutrients (Krstić et al. 2019). Because soil is the main source of most of the nutrients obtained by plants (Kachi and Hirose 1983), the effects of male and female trees on soil chemical properties, crop growth, yields, and nutritional quality of grains are likely to vary in agroforestry. However, knowledge gap exists regarding potential effects of *S. birrea* subspecies *birrea* on the performance of associated cereal crops, including sorghum. Therefore, this study was conducted to (i) determine the effect of *S. birrea* subspecies *birrea* on soil chemical properties (ii) determine the effect of *S. birrea* subspecies *birrea* on sorghum growth and yields and (iii) determine the effect of *S. birrea* subspecies *birrea* on sorghum grains nutritional quality.

2 | Materials and Methods

2.1 | Description of the Study Area

The study was conducted in Bonchugu village in Serengeti district (Supporting Information SI: Figure S1). The Serengeti district lies between latitude 1° 30′S and 2° 40′S, and 34° 15′E and 35° 30′E, and at an altitude ranging from 1 000 to 2 300 m. The district receives bi-modal rainfall, short rain season is experienced from October to December while long rain season is experienced from March to May. In the southern part of the district, long rains start in February to April. On average, the district's rainfall hovers at around 900 to 1 000 mm per year in greater part of the area. The temperatures in Serengeti district generally range from 15°C in April to 29°C in July. The land cover for Serengeti district can broadly be classified as very open shrubs, closed herbaceous vegetation, scattered natural vegetation, savanna trees and shrubs, and the district harbours *S. birrea* subspecies *birrea*, among other tree species. The major soil types in Serengeti district are Ferralic Cambisols and Eutric Planosols (Western Serengeti), Luvic Phaeozems (Northeastern Serengeti) and Luvic Phaeozems, Mollic Solonetzs and Luvic Chernozems (East Serengeti) (Masuki and Mbogoni 2003). Agro-pastoralism is the main source of livelihood for most people living in the Serengeti district. Major subsistence crops produced in the district are maize (*Zea mays*), millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor* (L.), cassava (*Manihot esculenta*), beans (*Phaseolus vulgaris* L.), sweet potatoes (*Ipomoea batatas*), wheat (*Triticum aestivum*) and finger millet (*Eleusine coracana* (L.) Gaertn.).

2.2 | Data Collection Procedure

2.2.1 | Reconnaissance Survey

Prior establishment of experimental trials, a reconnaissance survey was conducted in December 2019 to document preliminary information about the experimental site and select *S. birrea* subspecies *birrea* trees to be used for the study. Seven trees of subspecies *birrea* were selected for this study, and their sexes were identified by checking the presence or absence of fruits and seeds in each tree under and around the tree canopy, and seeking final confirmation from farm owners (Supporting Information SI: Table S1). Four trees were identified as female and three were male. The coordinates and elevation where trees were located were recorded by using a handheld GPS (Garmin etrex version 3.5). In addition, the canopy size, diameter at breast height (DBH), and the management practices of the farms were documented. The DBH was measured by using a caliper, canopy size was measured by using a tape measure, and farms management practices were documented based on farms management history provided by farm owners.

The composite soil samples were collected at the depth of 0 to 20 cm in each plot under the canopy of each selected tree and away from the canopy (no tree). Composite soil samples were made by mixing five subsamples randomly collected under the tree canopies, and in no tree plots, 40 m away from the tree (control plot). The composite samples were used for determination of baseline soil physical and chemical properties of the experimental site.

2.2.2 | *Field Experimental Design and Set-up*

The field experiment was conducted in two farming seasons, in 2019/20 and 2020/21, during the long rain season. The study adopted a Nested Block Design (NBD) experimental design with one factor, *S. birrea* subspecies *birrea*. The study used *S. birrea* subspecies *birrea* trees in their natural settings in the smallholder farmers' agricultural fields and the tree sex treatment is within the tree treatment, which consequently necessitates the use of NBD design. Under the *S. birrea* subspecies *birrea*, the treatments were (i) *S. birrea* subspecies *birrea* tree with sorghum grown under the canopy at 1-m distance from a tree trunk, Figure 1a, and (ii) control (sole sorghum plots with no subspecies *birrea* tree), Figure 1b.

The experimental unit was a plot of 8 x 8 m in size with a tree trunk with DBH ranging from 1.3 to 2.3 m located in the middle. The control treatment (plots with no tree) was established at 40 m away from treatment plots. The treatments were replicated in three locations with similar characteristics within a study site (Ndlovu et al. 2016).

2.2.3 | *Management of Experimental Trial*

The timing of sorghum planting was based on rainfall seasonality and local farming practices. The experimental site was

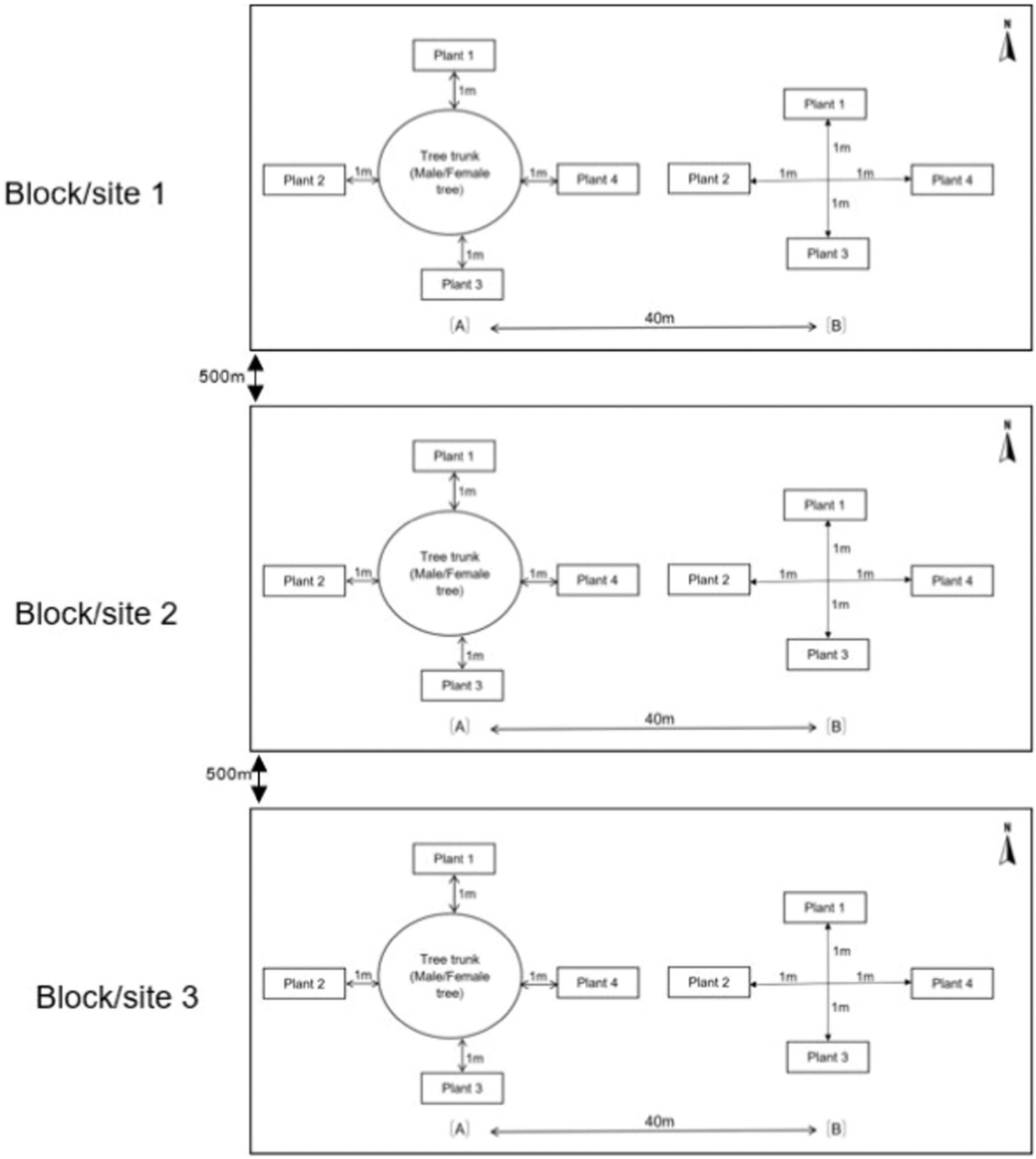

FIGURE 1 | Field experimental trial layout showing (A) treatment plot with a male/female tree trunk in the middle, and (B) control plot with no tree trunk.

prepared on 24th January 2020 and 25th January 2021, and experimental plots were tilled by hand hoe. The study used ICRISAT′s improved sorghum seed, the Macia variety. The seeds were sown at a spacing of 0.75 m intra rows and 0.30 m inter rows and each 64 m^2 experimental plot had a plant density of 260 plants. Sorghum seeds were planted on 25th and 26th of January 2020 and 2021, for season one and season two, respectively. About five to eight sorghum seeds were sown in each hole at a depth of approximately 2 cm. Weeding was done twice in each farming season. The first weeding was done on 3rd and 4th of March 2020 for season one and on 4th and 5th March 2021 for season two, by using a hand hoe, and sorghum seedlings were thinned to two seedlings per hole. The second weeding was done on 1st and 2nd of April 2020 and 2nd and 3rd April 2021. No fertilizer was applied in this study. More details on farm management practices of the experimental sites are in Supporting Information SI: Table S1.

2.2.4 | *Management of Field Experiment*

Measurements of sorghum plants' growth parameters, that is, stem height, basal diameter, and chlorophyll content was done in two phases in each farming season, 77 and 118 days after sowing (DAS). Two sorghum plants were randomly selected in each direction of the subspecies *birrea* tree (North‐South‐East‐West), making a total of eight plants per plot. Sorghum plants were tagged to allow repeated measurements throughout the experiment. Basal diameter, chlorophyll content and stem height readings were measured for each tagged sorghum plant. Chlorophyll content was measured by using atLEAF CHL PLUS meter (FT Green LLC, 1000 N. West St. Suite 1200# 638 Wilmington, DE19801 USA, www.atleaf.com) by taking readings at four positions along the third youngest leaf of each tagged plant and, an average was computed and recorded for each tagged plant. Stem height was measured from the soil surface to the tip of the third youngest flagged leaf by using a tape measure. The basal diameter was measured at three points along the stem by using a string and a tape measure, and the means were computed and recorded.

The sorghum panicles were harvested on 15th June 2020 and 17th June 2021, sun‐dried for 1 day, and de‐husked on 17th of June 2020 and 19th June 2021 for season one and two, respectively. The sorghum panicles were harvested in a 4 m^2 size observation plots in the eastern direction of the marula trees canopies. The weight of sorghum seeds was measured by using a weighing balance and sorghum grain samples of 0.25 kg were taken and stored in well‐labeled paper bags and transported to Sokoine University Agriculture′s Food Science Laboratory and Soil Science Laboratory for proximate composition and minerals concentration analysis, respectively.

2.2.5 | *Soil Sampling and Samples Preparation*

Composite soil samples were collected before planting and after harvesting in each farming season. The soil samples collected during a reconnaissance survey were used as baseline information for the first farming season, and soil samples collected before plots preparation for the second farming season served as baseline information for the second farming season.

The composite soil samples made by mixing five subsamples were collected at 20 cm depth using a soil auger under the canopies of subsp. *birrea* trees selected and in 8 × 8 m no tree plots located at least 40 m away from treatment plot. Composite soil samples were collected at five randomly selected points in each plot following the four compass cardinal directions and, one point at the middle of the plot. In each treatment, soil samples were collected under a tree canopy, not more than 1 m away from the tree trunk, and thoroughly mixed to obtain a composite soil sample for each plot. The soil samples were packed in well‐labeled plastic bags with zip‐lock and transported to the Soil Science Laboratory of Sokoine University of Agriculture for physical and chemical analysis. The soil samples were air‐dried in a screen house and ground to pass through a 2 mm sieve for chemical analysis.

Soil pH was determined by electrode method in 1:2.5 soil: water ratio using a glass electrode pH meter (McLean 1982). Available phosphorus (P) was extracted using Bray I method, followed by blue colour development described by Murphy and Riley (1962) and quantified by UV Spectrophotometer. Total N (TN) was determined by using the Micro Kjeldhal method (Bremner and Mulvaney 1982) and organic carbon (OC) was determined by the Walkley and Black method (Nelson and Sommers 1983). The exchangeable cations potassium (K), calcium (Ca) and magnesium (Mg) were extracted using 1 N ammonium acetate (NH_4OAc) leaching solution, buffered at pH 7 (Thomas 1986) and Ca and Mg was quantified by Atomic Absorption Spectrophotometer (AAS) Thermo Scientific version iCE3300 AAS, and K by Flame photometer Digital Flame Analyzer version 2655‐00 from Cole Palmer Instrument Co. Cation exchange capacity (CEC) was determined by distillation‐titration method using the NH_4OAc extract (Okalebo et al. 2002). Monocalcium phosphate $[Ca(H_2PO_4)_2]$ extracting solution was used to extract sulphur (S) and quantified by $BaCl_2$‐turbidity and UV spectrophotometer as per method described by Combs et al. (1998). Micronutrients, zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn) were extracted using diethylenetriaminepentaacetic acid (DTPA) (Lindsay and Norvell 1978) and quantified by AAS. The texture of soil was determined by hydrometer method after dispersion with sodium (Na) hexametaphosphate as described by Day (1965).

2.2.6 | *Preparation of Sorghum Grains Samples*

The sorghum grain samples were oven‐dried at 70°C to constant weight and ground to a fine powder using a laboratory plant grinder, Gerrano et al. 1093 Cyclotec Sample Mill P/N 10002016. One gram of ground grains sample was taken for proximate analysis in duplicate at the Food Science and Technology Laboratory of Sokoine University of Agriculture. The crude protein, extractable ether, ash content, crude fiber, moisture content, and total carbohydrates were determined by using the standard procedures described by the Association of Official Analytical Chemists (AOAC 2000) methods. The chemical analysis of sorghum grain samples to determine the concentration of Ca, Fe, P, Mg, Mn, Cu, Zn, and Na was done using Atomic Absorption Spectrophotometer (AAS) Thermo Scientific version iCE3300 AAS (UK) following wet digestion by Microwave Digestor (Multiwave Pro) made by Anton Par.

2.2.7 | *Statistical Analysis*

The analysis of variance (ANOVA) nested mixed model was used to determine the effects of the subsp. *birrea* tree on sorghum plants growth and grains nutritional quality. The subsp.

birrea sex was nested within the Marula tree treatment. Significant differences among treatment means were separated by the Least Square Means Difference (LSD) post hoc test ($p < 0.05$) technique. Means separation was done by using Tukey's Honest Significance Difference (HSD) at alpha = 0.05. The statistical analysis was done using SAS software version 9.4.

3 | Results

3.1 | Soil Chemical Properties of the Experimental Site

3.1.1 | *Effect of* S. birrea *Subspecies birrea Tree on Initial Soil Chemical Properties*

The results showed that soils under the canopies and in no trees significantly differ in initial (2019/20) soil pH ($p = 0.0082$, OC ($p = 0.0004$), EC ($p = 0.0194$), total N ($p = 0.0047$), CEC ($p = 0.0001$), Mn ($p = 0.0081$), Mg ($p = 0.0012$), and K ($p = 0.0004$) (Table 5.2). No significant differences in initial available P, Cu, Zn, Fe, S, Ca, and exchangeable Na between the soil under the canopy and in no tree areas in 2019/20 (Supporting Information SI: Table S2). Tree sex resulted in no significant difference in all soil properties except EC ($p = 0.03220$, CEC ($p = 0.0003$), Ca ($p = 0.0013$), and Mg ($p = 0.0156$) (Supporting Information SI: Table S2). Generally, the initial soil characterization showed that the soils in the experimental plots were loamy sand. The soil pH ranged from 6.47 ± 0.06 to 6.17 ± 0.06 (Figure 2) which is categorized as slightly acidic (Horneck et al. 2011), and adequate for most crop growth and yield, according to Amuri et al. (2017). Electrical conductivity (EC) ranged from 48.71 ± 9.37 to 85.15 ± 9.46 μS/cm (Figure 2), indicating no salinity problem. The soil had OC and TN ranged from 0.37 ± 0.06 to 0.83 ± 0.06% and 0.06 ± 0.01 to 0.08 ± 0.01% respectively (Figure 2), which is rated as low (0.60–1.25%) and very low (< 0.10%) respectively (Msanya et al. 2001). The exchangeable K, Ca, Mg were 0.21 ± 0.04 to 0.50 ± 0.03, 2.67 ± 0.11 to 3.01 ± 0.11 and 0.53 ± 0.06 to 0.91 ± 0.06 cmolc/kg respectively (Figure 2), with K and Mg being at sufficient level, while Ca is low (Landon 1991). The concentration of Na ranged from 0.16 ± 0.03 to 0.21 ± 0.02 cmolc/kg (Table 1) which is low according to Msanya et al. (2001). The concentration of S and available P ranged from 9.89 ± 2.40 to 14.12 ± 2.43 mg/kg and 5.92 ± 1.69 to 6.05 ± 1.68 mg/kg respectively (Table 1), which are medium (10–15 mg/kg) and low (< 7.0 mg/kg) respectively (Msanya et al. 2001). These results indicating that P is deficient for adequate growth and yield for most crops (Landon 1991).

Extractable Cu and Fe ranged from 0.30 ± 0.06 to 0.47 ± 0.06 mg/kg and 37.44 ± 11.85 to 47.93 ± 11.73 mg/kg respectively (Table 1), and both are in sufficient ranges for crop production (McKenzie 1992). On the other hand, Zn and Mn in these soils ranged from 0.62 ± 0.16 to 1.05 ± 0.17 mg/kg and 38.11 ± 3.06 to 52.15 ± 3.09 mg/kg respectively (Table 1), and Zn is in deficient (< 1.0) to adequate range, while and Mn is under adequate range (McKenzie 1992). The soil CEC was 5.20 ± 0.10 cmolc/kg (Figure 2), which is regarded as very low according to Msanya et al. (2001). The soil C: N ranged from 9.00 to 21.5 (Table 1), and is generally regarded as ideal for microbial activities, according to Kaminski et al. (2013).

For 2019/20 farming season, soils under tree canopies had significantly ($p < 0.05$) higher pH (6.47 ± 0.06), OC (0.83 ± 0.06%), TN (0.08 ± 0.01%), EC (85.15 ± 9.46 μS/cm), Mn (52.15 ± 3.09 mg/kg), CEC (5.20 ± 0.10 cmol/kg), Mg (0.91 ± 0.06 cmol/kg) and K (0.50 ± 0.03 cmol/kg) than that in no tree plots (Figure 2; 3). Furthermore, the results showed that OC, TN, pH, EC, Mn, CEC, Mg, and K were higher in soils under the canopies than in no tree (Figure 2). The concentration of Cu, Zn, S, Na, and Ca were numerically higher in soils under the canopies than away from the canopies (Table 1), and Fe and P were numerically lower in soils under tree canopies than away from the canopies (Table 1).

Moreover, OC, EC, CEC, Ca, Mg and K concentrations in soils under tree canopies differed significantly ($p < 0.05$) from that in no tree during the 2020/21 farming season (Supporting Information SI: Table S2; Figure 2). The CEC (5.45 ± 0.52 cmol/kg), and concentration of Ca (4.45 ± 0.42 cmol/kg), Mg (0.45 ± 0.04 cmol/kg), and K (0.51 ± 0.07 cmol/kg) were higher under tree canopies than in soils away from trees canopies (CEC = 2.55 ± 0.51 cmol/kg, Ca = 2.02 ± 0.41 cmol/kg, Mg = 0.28 ± 0.04 cmol/kg and K = 0.23 ± 0.07 cmol/kg) (Figure 2). Moreover, OC, EC was similarly higher (OC = 0.84 ± 0.11%, EC = 89.79 ± 8.96 μS/cm) in soils under tree canopies compared to soils in no tree (OC = 0.48 ± 0.11%, EC = 48.91 ± 8.86 μS/cm) (Figure 2). The soil pH, TN, Cu, Fe, Zn, Mn, S, P, and Na did not differ significantly (Supporting Information SI: Table S2; $p < 0.05$). However, soil pH and Cu, Fe, Zn, Mn, and P concentrations were numerically higher in soils under tree canopies than in no tree plots (Table 1), and S was higher in soils away from the canopies than under tree canopies, and Na did not differ (Table 1).

3.1.2 | *Soil Chemical Properties as Influenced by S. birrea Subspecies birrea Tree Sex*

Soil EC, CEC, Ca, and Mg differed significantly ($p < 0.05$) between male and female trees during the 2019/20 farming season (Supporting Information SI: Table S2; Figure 3). No significant difference was observed in pH, TN, OC, P, Cu, Zn, Fe, Mn, S, K, and Na concentration between soils under the canopies of male and female trees (Supporting Information SI: Table S2). Soils under the canopies of male trees had higher CEC, Ca, and Mg (5.73 ± 0.15 cmolc/kg, 3.47 ± 0.16 cmolc/kg, and 1.09 ± 0.09 cmolc/kg, respectively) than under female trees (Figure 3). Similarly, EC was higher (108.37 ± 14.31 μS/cm) in soils under the canopies of male trees compared to female trees (61.95 ± 12.3931 μS/cm) (Figure 3). However, tree sex resulted in no significant differences in all measured soil properties in the 2020/21 farming season (Supporting Information SI: Table S2). However, soils under the canopies of male trees generally have numerically higher nutrient concentrations compared to female trees during the 2019/20 and 2020/21 farming seasons (Figure 3; Table 1).

3.2 | Effect of *S. birrea* Subspecies *birrea* Tree on Sorghum Plants Growth and Yields

The results show that presence of subsp. *birrea* trees in agricultural fields significantly affected sorghum growth parameters measured and yields, except stem height at 118 DAS in the season 2019/20 (Supporting Information SI: Table S3). The sorghum plants basal diameter at 77 DAS ($p = 0.0165$), stem height at 118 DAS ($p = 0.0249$), chlorophyll content at 77 DAS ($p = 0.0003$), and sorghum grain yields ($p = 0.0112$) were significantly affected by subsp. *birrea* during the 2019/20 farming season (Supporting Information SI: Table S4). Sorghum basal

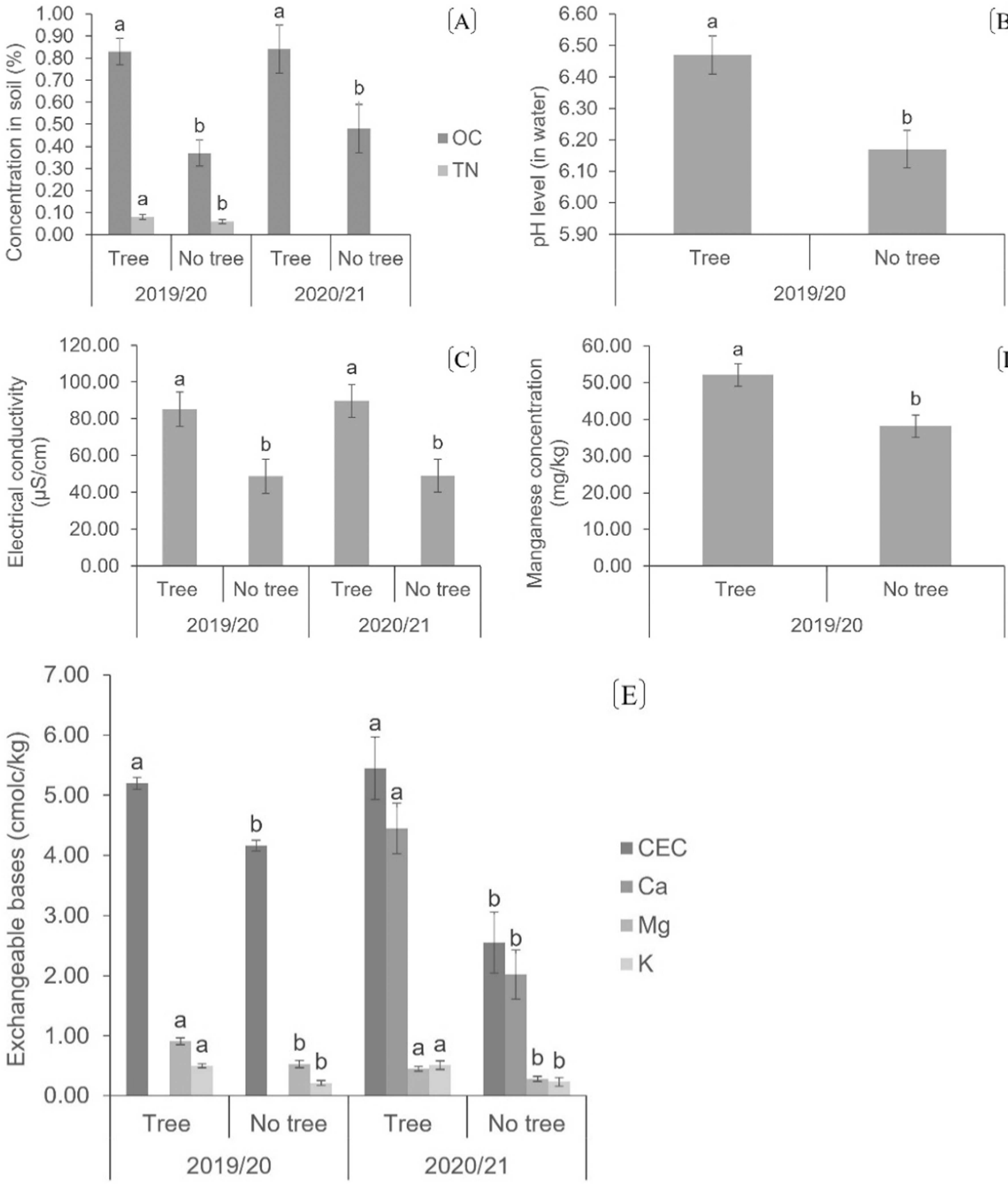

FIGURE 2 | Effect of *S. birrea* subspecies *birrea* tree on soil organic carbon and total nitrogen (A), pH (B), electrical conductivity (C), manganese (D), and exchangeable bases (E) in Bonchugu village, Serengeti district, Tanzania during the 2019/20 and 2020/21 farming seasons. Bars with the same color and different letters within the year are significant different based on Tukey's Honest Significance Difference (HSD) test ($p < 0.05$).

diameter, stem height at 77 DAS and chlorophyll content at 77 DAS (54.79), 118 DAS (57.90), and the grain yields (3 359.38 kg/ha) were higher under tree canopies than in plots with no trees which gave 49.05, 48.47 and 2 146.43 kg/ha for chlorophyll at 77 DAS, 118 DAS and grain yield, respectively, in season one (Figure 4). Furthermore, chlorophyll content at 77 DAS ($p = 0.0365$) and 118 DAS ($p = 0.0024$), and grains yield ($p = 0.0123$) were significantly affected by subsp. *birrea* during the 2020/21 farming season (Supporting Information SI: Table S3). Like 2019/20 farming season, chlorophyll content at 77 DAS and 118 DAS, and grain yields during 2020/21 farming season were higher (48.74, 54.81 and 3 305.21 kg/ha) under the canopies than in plots with no trees (42.07, 42.81 and 2 050.00 kg/ha (Figure 4). The results furthermore revealed that tree sex had no significant effect on sorghum growth parameters and yields in the 2019/20 and 2020/21 farming seasons (Supporting Information SI: Table S3).

3.3 | Effect of *S. birrea* Subspecies *birrea* Tree on Sorghum Grains Nutritional Quality

The carbohydrate, dry matter, ash content, moisture content, extract ether, crude fiber and crude protein content in sorghum

TABLE 1 | Effect of *S. birrea* subspecies birrea tree and tree sex on secondary, micro and macro-nutrients concentration in soil of Bonchugu village, Serengeti district, Tanzania during the 2019/20 and 2020/21 farming seasons.

Farming season	Source of variation	df	Exchangeable bases (cmolc/kg)		Micronutrients and macronutrients (mg/kg)					C: N
			Ca	Na	Cu	Fe	Zn	S	P	
2019/20	Tree	1	3.01 ± 0.11	0.21 ± 0.02	0.47 ± 0.06	37.44 ± 11.85	1.05 ± 0.17	14.12 ± 2.43	5.92 ± 1.69	10.38
	No tree	1	2.67 ± 0.11	0.16 ± 0.03	0.30 ± 0.06	47.93 ± 11.73	0.62 ± 0.16	9.89 ± 2.40	6.05 ± 1.68	
2020/21	Tree	1	4.45 ± 0.42	0.03 ± 0.008	0.50 ± 0.03	24.07 ± 2.27	0.88 ± 0.07	12.56 ± 1.59	10.69 ± 2.56	21.00
	No tree	1	2.02 ± 0.41	0.01 ± 0.008	0.41 ± 0.03	19.57 ± 2.25	0.80 ± 0.07	14.28 ± 1.57	3.86 ± 2.53	
2019/20	Male	1	3.47 ± 0.16	0.18 ± 0.04	0.56 ± 0.10	27.23 ± 17.92	1.20 ± 0.25	12.10 ± 3.67	5.32 ± 2.56	10.44
	Female	1	2.53 ± 0.14	0.24 ± 0.03	0.38 ± 0.08	47.66 ± 15.52	0.90 ± 0.21	16.13 ± 3.18	6.52 ± 2.22	9.00
	No tree		2.67 ± 0.10	0.16 ± 0.02	0.30 ± 0.06	47.93 ± 11.73	0.62 ± 0.16	9.89 ± 2.40	6.05 ± 1.68	
2020/21	Male	1	4.71 ± 0.63	0.03 ± 0.01	0.52 ± 0.05	22.16 ± 3.43	0.90 ± 0.12	13.64 ± 2.40	9.07 ± 3.87	21.50
	Female	1	4.18 ± 0.54	0.03 ± 0.01	0.48 ± 0.04	25.97 ± 2.97	0.87 ± 0.10	11.47 ± 2.08	12.30 ± 3.35	20.75
	No tree		2.02 ± 0.41	0.01 ± 0.01	0.41 ± 0.03	19.57 ± 2.25	0.80 ± 0.07	14.28 ± 1.57	3.86 ± 2.53	

Note: Values are mean ± standard error; df = degree of freedom.

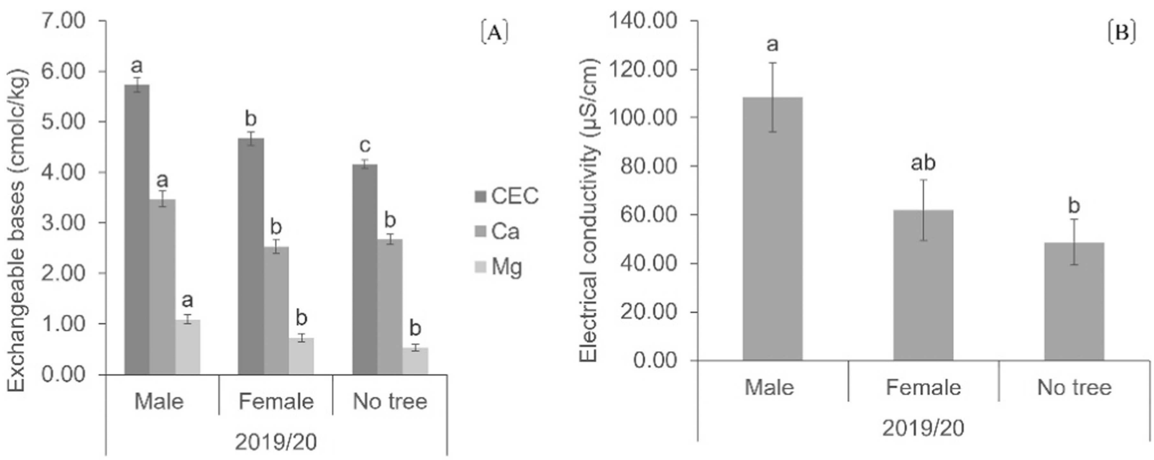

FIGURE 3 | Effect of *S. birrea* subspecies *birrea* tree sex on exchangeable bases (A), and electrical conductivity (B) in Bonchugu village, Serengeti district, Tanzania during the 2019/20 and 2020/21 farming seasons. Bars with the same color and different letters within the year are significant different based on Tukey's Honest Significance Difference (HSD) test ($p < 0.05$).

grains were not significantly affected by subsp. *birrea* in both farming seasons, 2019/20 and 2020/21 (Supporting Information SI: Table S4; $p < 0.05$). The carbohydrate, dry matter, crude protein, ash content, moisture content, extract ether, and crude fiber ranged from 63.70 ± 1.03 to 74.86 ± 2.48%, 88.83 ± 0.24 to 90.92 ± 2.69%, 9.61 ± 0.34 to 11.16 ± 0.51%, 1.75 ± 0.04 to 2.18 ± 0.27%, 9.07 ± 2.69 to 11.16 ± 0.24%, 4.24 ± 0.68 to 8.13 ± 0.89%, and 0.87 ± 0.61 to 4.08 ± 0.30% respectively (Supporting Information SI: Table S5). The ash content, and extract ether were numerically higher in sorghum grains under tree canopies than in no trees during both the 2019/20 and 2020/21 farming seasons (Supporting Information SI: Table S5). However, grains' carbohydrate, dry matter and crude protein were numerically lower in sorghum grown under tree canopies than in plots with no trees in 2019/20, but not in 2020/21 farming season (Supporting Information SI: Table S5).

The concentration of minerals in sorghum grains were not significantly affected by subsp. *birrea* during the 2019/20 farming season (Supporting Information SI: Table S4; $p < 0.05$). However, Fe was significantly higher ($p = 0.01$) during the 2020/21 farming season (Supporting Information SI: Table S4), and numerically higher under tree canopies in both farming seasons than in treeless plots (Table 2). Nevertheless, P (27.96 ± 3.08 to 29.47 ± 3.30 mg/kg), Mg (489.69 ± 56.43 to 612.84 ± 97.02 mg/kg) and K (675.04 ± 29.29 to 1 033.65 ± 46.42 mg/kg) Cu (1.87 ± 1.46 to 16.01 ± 0.34 mg/kg), Zn (5.33 ± 1.17 to 13.83 ± 1.70 mg/kg), Ca (106.31 ± 10.81 to 358.16 ± 21.68 mg/kg) and Na (1 956.47 ± 197.14 to 2 753.03 ± 151.88 mg/kg) concentration were numerically higher in sorghum grains from sorghum plants grown under tree canopies than in no trees during the 2019/20 and 2020/21 farming seasons (Table 2). The Mg (662.01 ± 96.03 mg/kg) was the only mineral nutrient which was numerically higher in grains from sorghum plants grown in no tree plots during the 2020/21 farming season (Table 2). However, minerals concentration in sorghum grains were within the recommended daily human body requirements, according to Pontieri et al. (2022).

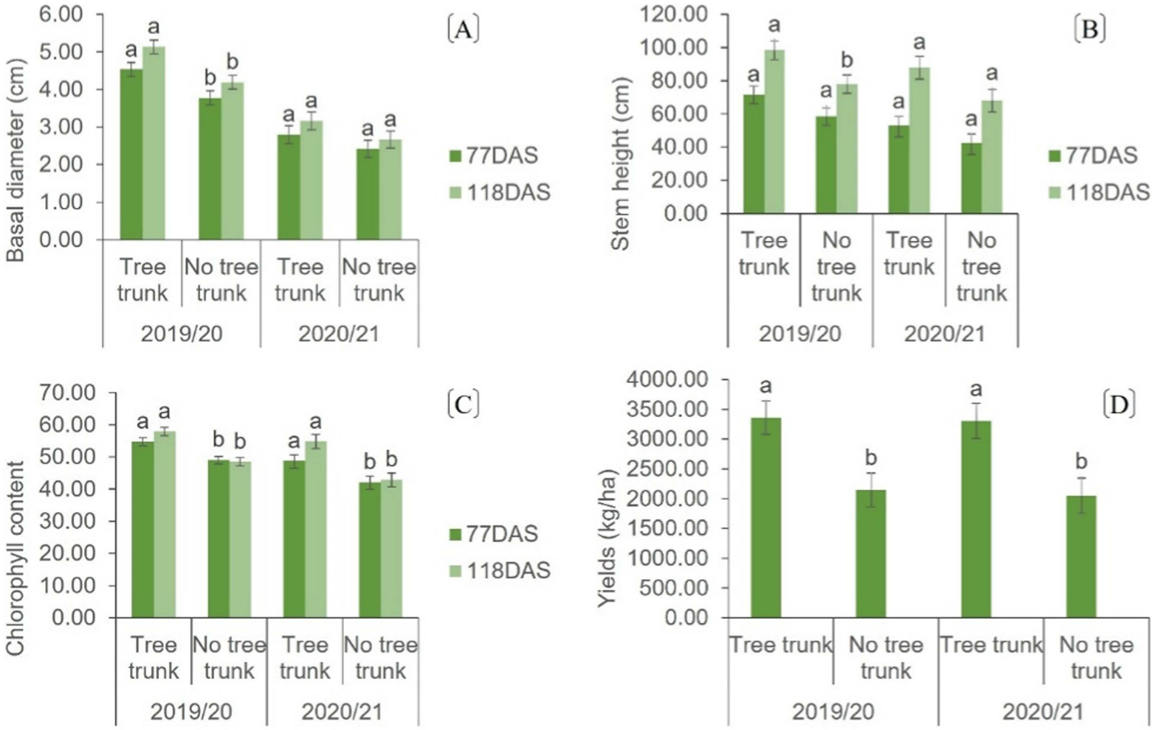

FIGURE 4 | The effect of *S. birrea* subspecies *birrea* tree on sorghum plants basal diameter (A), stem height (B), chlorophyll content (C), and yields (D) in Bonchugu village, Serengeti district, Tanzania during the 2019/20 and 2020/21 farming seasons. Bars with the same color and different letters within the year are significant different based on Tukey's Honest Significance Difference (HSD) test ($p < 0.05$), DAS = days after sowing.

4 | Discussions

4.1 | Initial Soil Chemical Properties of the Experimental Site

The higher soil pH and concentration of most nutrients in soils under the canopies of subsp. *birrea* than in treeless plots indicates that the presence of subsp. *birrea* trees enriched soils with nutrients. Except for S, the study findings agree with Munna et al. (2025). The very low and moderately low concentrations of most nutrients are probably due to sandy and light loamy soils which results into poor nutrients retention (Solberg et al. 1999). However, OC and nutrients concentration are considered sufficient for plant growth, except TN, available P, and exchangeable Ca, which are not sufficient for sorghum growth and in improving yields according to Amuri et al. (2017) and Landon (1991). Higher nutrients concentration under the tree canopies than in no tree plots suggest that in addition to enriching OC and nutrients through its litterfall, the subspecies *birrea* can recycle nutrients by absorbing nutrients deeper in the soil and enriching them on the surface. The findings are in consensus with studies that reported trees to improve soil nutrients status and that, agroforestry in general enriches soil fertility (Dimobe et al. 2025). Therefore, this implies that subsp. *birrea* is a potential tree for agroforestry in drylands. However, the litterfall of subsp. *birrea* can only be used as a supplement to other fertilizers rather than as a stand-alone soil enrichment option. In addition to improving soil fertility, the subsp. *birrea* alters the physical and biological properties of the soil through improving soil OC and soil pH, which consequently improving water and nutrients retention in soil and access by crops (Weil and Brady 2017).

4.2 | Effect of *S. birrea* Subspecies *birrea* Tree Sex on Soil Fertility During the 2019/20 and 2020/21 Farming Seasons

Soils under the canopies of male trees of subsp. *birrea* were more enriched with OC and nutrients compared to soils under the canopies of female trees and plots with no trees. Higher EC, CEC, Ca, and Mg in soils under the canopies of male than female trees in season one is because of nutrients addition through litterfall. Lack of significant differences in nutrient concentrations in soil in season two is probably due to nutrients uptake by sorghum plants relative to low nutrient release due to litterfall decomposition and removal of crop residues and litterfall. Thus, further long-term study to better inform on the effect of the subspecies on soil fertility and the performance of sorghum coupled by crop residue and litterfall management in drylands is recommended.

Moreover, lower nutrients in soils under the canopies of female trees is probably due to high nutrients demand and uptake by female trees for the development and growth of reproductive parts such as fruits and seeds (Johnson and Mirza 2020). Except for S, the study findings agree with Munna et al. (2025) that leaf and fruit litterfall of *S. birrea* subspecies elevates OC and nutrients concentrations in soils under tree canopies. However, nutrients addition in soils through subspecies *birrea* litterfall is relatively lower than the nutrients demand by crops (Munna et al. 2025), which may necessitate either supplementing it with fertilizers or long-term fallow to allow accumulation of sufficient nutrients from litterfall. Similarly, low soil CEC in soils under subspecies *birrea* canopies further implies that soils are at risk of losing nutrients through leaching. Generally, low nutrient levels in the soils studied is probably due to the low

TABLE 2 | Effect of *S. birrea* subspecies *birrea* tree on sorghum grains minerals concentration in Bonchugu village, Serengeti district, Tanzania during the 2019/20 and 2020/21 farming seasons.

Farming season	Source of variation	Df	Minerals concentration (mg/kg)							
			Cu	Zn	Fe	P	Ca	Mg	K	Na
2019/20	Tree	1	1.87 ± 1.46	13.83 ± 1.70	20.05 ± 1.73	29.47 ± 3.30	106.31 ± 10.81	489.69 ± 56.43	1033.65 ± 46.42	1956.47 ± 197.14
	No tree	1	5.48 ± 1.44	16.17 ± 1.68	19.32 ± 1.72	25.42 ± 3.27	129.69 ± 10.70	369.56 ± 55.85	1004.50 ± 45.94	2160.89 ± 195.11
2020/21	Tree	1	16.01 ± 0.34	5.33 ± 1.17	16.91 ± 0.47a	27.96 ± 3.08	358.16 ± 21.68	612.84 ± 97.02	675.04 ± 29.29	2753.03 ± 151.88
	No tree	1	15.98 ± 0.34	4.19 ± 1.16	14.77 ± 0.47b	26.49 ± 3.05	347.93 ± 21.46	662.01 ± 96.03	633.87 ± 28.99	2335.43 ± 150.33
2019/20	Male	1	0.96 ± 2.20	13.27 ± 2.57	19.93 ± 2.62	34.17 ± 4.99	109.22 ± 16.35	559.01 ± 85.32	1073.22 ± 70.18	1754.52 ± 298.04
	Female	1	2.79 ± 1.91	14.38 ± 2.23	20.16 ± 2.27	24.78 ± 4.32	103.40 ± 14.16	420.37 ± 73.89	994.08 ± 60.77	2158.42 ± 258.11
	No tree		5.48 ± 1.44	16.17 ± 1.68	19.32 ± 1.72	25.42 ± 3.27	129.69 ± 10.70	369.56 ± 55.85	1004.50 ± 45.94	2160.89 ± 95.11
2020/21	Male	1	16.25 ± 0.52	5.45 ± 1.77	17.38 ± 0.72a	30.11 ± 4.66	402.99 ± 32.78	631.25 ± 146.69	708.65 ± 44.28	3083.82 ± 229.63a
	Female	1	15.77 ± 0.45	5.21 ± 1.53	16.45 ± 0.62ab	25.82 ± 4.04	313.33 ± 28.39	594.43 ± 127.04	641.42 ± 38.35	2422.23 ± 198.86ab
	No tree		15.98 ± 0.34	4.19 ± 1.16	14.77 ± 0.47b	26.49 ± 3.05	347.93 ± 21.46	662.01 ± 96.03	633.87 ± 28.99	2335.43 ± 150.33b

Note: Values are mean ± standard error. Significant effects are indicated by different letters.

quality (high C:N ratio) of leaf and fruit litterfall of subsp. *birrea* (Munna et al. 2025), and litterfall removal through livestock grazing in agricultural fields after harvesting crops.

4.3 | Effects of *S. birrea* Subspecies *birrea* Tree on Sorghum Growth and Yields During the 2019/20 and 2020/21 Farming Seasons

Presence of subsp. *birrea* in agricultural fields positively affected the basal diameter and stem height of sorghum plants. Effects of trees on basal diameter and stem height of cereal crops grown under tree canopies were similarly reported by Ahmed et al. (2018), and Oliveira et al. (2020) respectively. Chlorophyll is a significant component of plant leaves, which can be used as an indicator of a plant′s general health status (Jin et al. 2021). Chlorophyll is the primary pigment involved in photosynthesis and growth; thus, its concentration has implications on crop stress (Jin et al. 2021). Higher chlorophyll content in the leaves of sorghum plants grown under the canopies of subsp. *birrea* suggests that sorghum plants under the canopies were healthier as they had access to sufficient nutrients compared to those away from the canopies.

Moreover, sorghum grain yields under the canopies of subsp. *birrea* were higher than in plots in open space. The grain yields obtained in this study are generally similar to those reported in the drylands of central Tanzania by Msongaleli et al. (2017), and by Ahmed et al. (2018). Thus, *S. birrea* subspecies *birrea* improves sorghum yields in drylands agroecosystems. Higher sorghum grain yields under the canopies of subsp. *birrea* suggests that this tree enhances soil fertility, despite being non-nitrogen fixing tree species due to high C:N ratio in its leaf and fruit litterfall (Munna et al. 2025). Moreover, our findings are in line with Kuyah et al. (2019) who reported crop yields were relatively higher in both nitrogen-fixing and non-nitrogen-fixing tree species compared to control plots. Larger basal diameter, higher stem height, high chlorophyll content, and grain yields in sorghum plants under the canopies of subsp. *birrea* suggests that soils under the canopies were more enriched with OC and nutrients due to litterfall accumulation and mineralization (Munna et al. 2025).

4.4 | Effect of *S. birrea* Subspecies *birrea* Tree on Sorghum Proximate Composition and Minerals Concentration During the 2019/20 and 2020/21 Farming Seasons

The higher Fe concentration in soils under the tree canopies than in no tree can be attributed to addition of nutrients through litterfall and improved soil properties that enhance Fe availability. Lack of significant differences in proximate composition and other nutrients concentration in sorghum grains may be attributed to sub optimal nutrients addition or removal of litterfall and/or nutrients losses. According to Pérez et al. (2021), during litterfall decomposition process, there are concurrent processes such as microbial immobilization, deep percolation into groundwater, and volatilization that may make nutrients from decomposing litterfall to be partially available for uptake by crops.

Although TN was higher in soils under the tree canopies, soils TN, available P and exchangeable Ca were deficient, hence insufficient to cause significant differences in proximate composition. The leaf and fruit litterfall of subspecies *birrea* have the mean C: N ratios of 34.58 and 52.73 respectively (Munna et al. (2025), while in general, the ideal litter C:N ratio for microbial activity is 20-30, and litterfall mineralization occurs when the litterfall C:N ratio is less than 20:1 (Liu and Sun 2013). This suggests that, in addition to nutrients been immobilized in microbial biomass due to very low N content in the soil, the litterfall of subsp. *birrea* is partially decomposed due to low microbial activity and it is possible that, nutrients are not in the form that can be easily assimilated by sorghum plants. However, the numerically higher proximate composition and nutrients concentration in sorghum grains from sorghum plants grown under the canopies of subsp. *birrea* indicates positive effect of susp. *birrea*. Moreover, the similar trend was observed between male, female and treeless plots. Moisture content in sorghum grains in the study ranged from 8.28% to 11.25% which is generally within the range reported by Mohammed et al. (2019). The carbohydrate ranged from 63.56 ± 1.35 to $76.15 \pm 3.25\%$ which is within the range reported by Saidu et al. (2021). With exception of crude fiber, the study findings on moisture content, ash content, crude protein and carbohydrate in the second farming season did not deviate much from that reported by Saidu et al. (2021) and Saidu et al. (2019, and were within recommended human nutrients requirements (Saidu et al. 2021). The study finding on extractable ether was higher than that reported by Bazié et al. (2023). Moreover, except for Fe and Na, the presence of subsp. *birrea* in agricultural fields did not significantly affect Cu, Zn, P, Ca, Mg, and K minerals concentration in sorghum grains. Furthermore, the study findings on K concentration do not deviate much from the findings by Gerrano et al. (2016), Zn and Mg by Ayuba et al. (2020), and Fe from that reported by Gerrano et al. (2016). Moreover, Na was higher than that reported by Gerrano et al. (2016) and Pontieri et al. (2022).

5 | Conclusions

The presence of subsp. *birrea*, both male and female trees in agricultural fields improved soil fertility in the drylands agroecosystems of northwestern Tanzania. Soils under the canopies of male trees were more enriched with nutrients than those under the canopies of female trees and where there were no trees. Moreover, subsp. *birrea* improved sorghum plants growth, yields and grains nutritional quality by enriching more Fe compared to those grown away from the canopies. Thus, the *S. birrea* subspecies *birrea* trees can be naturally retained in agricultural fields to improve soil fertility and carbon storage in drylands and improve agricultural productivity while conserving drylands biodiversity. The scalability of *S. birrea* subsp. *birrea* in agroforestry may be limited in suitable areas of occurance for the tree, unless there are efforts to propagate the tree. Therefore, the subspecies *birrea* has the potential to be adopted and integrated into dryland agroforestry systems to improve agricultural productivity and food security while also enhancing its conservation in global drylands. The effect of subspecies *birrea* on sorghum was erratic, and besides subspecies *birrea*, *S. birrea* has two more subspecies namely subspecies *caffra* and *multifoliata*. Thus, further long-term study involving the other two subspecies of *S. birrea*, as well as other dryland cereal crops other than sorghum is recommended.

Author Contributions

Abubakari H. Munna: conceived the study, methodology, data curation and analysis, interpretation of results, writing the first draft, reviewing and editing of the manuscript, and project administration; **Nyambilila A. Amuri:** supervised the study, methodology, software, data curation and analysis, validation, and interpretation of results; reviewing and editing of the manuscript; **Proches Hieronimo:** supervised the study, reviewing and editing of the manuscript and **Dino A. Woiso:** supervised the study, reviewing and editing of the manuscript. All authors endorsed the publication of the manuscript.

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Ethics Statement

The authors confirm that they have adhered to the ethical policies of the journal.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
Figure_1_SuppInfo. Supporting Information SI: Table S1: Baseline information of *S. birrea* subspecies *birrea* trees and farm management practices of the experimental sites. Supporting Information SI: Table S2: ANOVA results on the effect of *S. birrea* subspecies *birrea* tree on initial soil chemical properties of the experimental site. Supporting Information SI: Table S3: ANOVA results on effect of *S. birrea* subspecies *birrea* tree on sorghum plants growth and yields. Supporting Information SI: Table S4: ANOVA results on effect of *S. birrea* subspecies *birrea* tree on sorghum grains proximate composition and minerals concentration. Supporting Information SI: Table S5: Effect of *S. birrea* subspecies *birrea* tree on sorghum grains proximate composition.