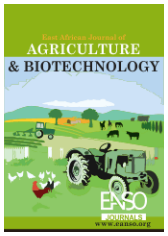

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Original Article

Effect of Legume-Finger Millet Intercropping on Finger Millet Productivity and Soil Organic Carbon Stocks

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Finger Millet, Intercropping, Land Equivalent Ratio, Legumes, Soil Organic Carbon.

ABSTRACT

The soils in the semi-arid areas of eastern Uganda are mainly ferralsols and plinthosols, characterised by low soil organic carbon (SOC) and soil fertility. On-farm experiments were therefore conducted in Kumi and Amuria districts in the parishes of Olupe and Kuju, respectively, in eastern Uganda. To assess the effect of finger millet legume integration options on finger millet productivity and soil organic carbon stocks. One farmer household with fields having ferralsols and plinthosols was purposively selected from each parish to host the experiment. The study adopted a factorial experiment, where two finger millet varieties (Seremi II, and NARO MIL 3) were the main plot, three legumes (groundnuts, green gram, and cowpeas) constituted the subplot, and one planting pattern (one row of legume and two rows of finger millet) made the sub-sub plot treatment, totaling eleven treatments. The experiment was laid down in a randomised complete block design (RCBD) with three replicates. Three experimental seasons (2021 B, 2022 A, and 2022B) were conducted. Soil and crop data were collected and analysed using GenStat and Minitab 14th editions. Results revealed that intercropping finger millet (NARO MIL 3 and SEREMI II) with cowpea recorded the highest yield returns (2617 and 2387) kg ha-1, respectively, land equivalent ratio of 1.8 and 1.2, respectively, and SOC of 0.310 t ha-1 yr-1. It was therefore concluded that intercropping finger millet with cowpea at a 1x2 planting arrangement improves finger millet yield and SOC stocks in ferralsols and plinthosols.

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INTRODUCTION

The Teso sub-region is predominantly characterised by a crop-livestock-based farming system and is located in eastern Uganda, dominated by semi-arid weather conditions, manifesting in the form of prolonged dry spells Uganda National Meteorological Authority (UNMA, 2022). In addition, the predominant soil types in the region are ferralsols and plinthosols, which are characterised by high levels of sand and thus high water infiltration rate, low soil fertility and high deficiency in nutrients, especially nitrogen, phosphorus, and potassium (NPK) and low soil organic carbon (SOC) (Ebanyat et al., 2021; Tenywa et al., 1999). The low soil fertility and prolonged dry spell have continued to adversely affect food production in the region, with maize, sorghum, and finger millet being the most affected crops (Andiku et al., 2021; Ekwangu, Tenywa, et al., 2020; Owere et al., 2014a). Declining soil fertility has been reported to adversely affect sorghum and finger millet (Ekwangu, Balaba, Ateenyi, Tenywa, Opie, et al., 2023), largely because they are traditional, low-value crops typically grown with minimum external inputs due to their non-commercial production in Uganda. Despite the decrease in finger millet yield by 22% over the past decade (Ekwangu, Balaba, Ateenyi, Tenywa, Opie, et al., 2023), it has attracted limited research and management. In spite of these challenges, finger millet is emerging as a climate-smart crop in semi-arid regions because of its ability to withstand prolonged dry conditions, low soil fertility, and pests and diseases (Gupta et al., 2018; 2017). Majorly grown by smallholder farmers in eastern Uganda, finger millet has proven to be a main source of food and nutrition security, owing to the high amount of iron, calcium, amino acids, and vitamins in the grain (Gupta et al., 2017). The crop has also been reported to be a remedy for diseases like diabetes, cancer, and pressure because of its anti-oxidation abilities due to the high fibre and phenolic compounds found in the grain (Devi et al., 2014; K & Morya, 2022; Maharajan et al., 2021). Finger millet, therefore, is a crop of importance not only in Uganda but also in Asia and the entire African continent.

Studies on soil fertility management in finger millet cropping systems in the semi-arid regions have recommended legume integration (Derebe et al., 2021). Legume integration is one of the major components of integrated soil fertility management in sub–Saharan Africa (Masvaya et al., 2017). When crops are complementary in terms of growth pattern, aboveground canopy, rooting system, and their water and nutrient demand, intercropping effectively enables a more efficient utilization of available resources (sunlight, moisture, and soil nutrients), and can result in relatively higher yields than when the crops are grown as pure stands (Willey & Osiru, 1972). Different legumes fix nitrogen at varying rates and also generate varying biomass. This biomass contributes to SOC stocks and enhances soil fertility and grain yield (Myaka et al., 2006). In addition, farmers commonly intercrop to secure food production by averting risk and maximising the utilisation of land and labour (Derebe et al., 2021; Bitew et al., 2019). Current

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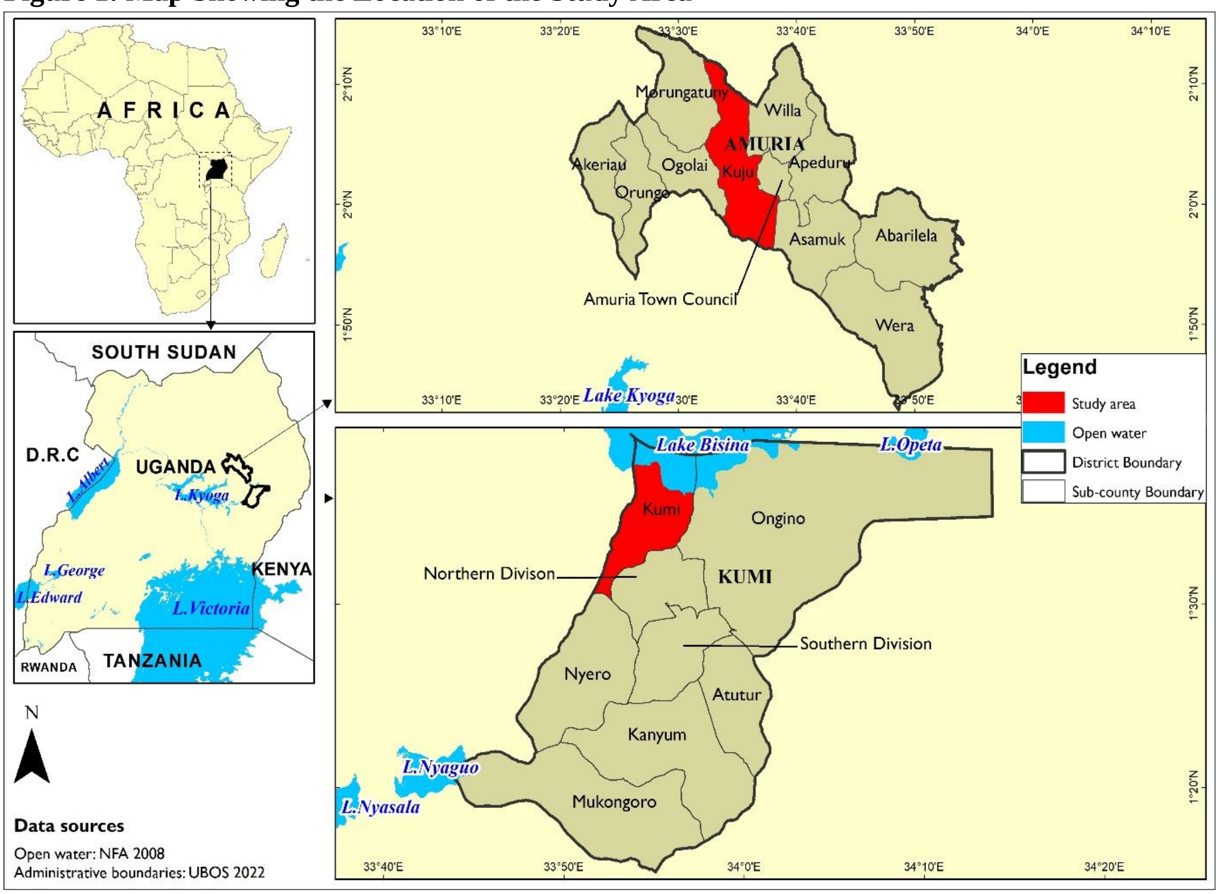
studies on the effect of legume finger millet intercropping reported cowpea to be well adapted to finger millet intercrop and recorded finger millet yield improvement (Bitew et al., 2019; Derebe et al., 2021). However, the effect of intercropping legumes with finger millet on soil organic carbon stocks and finger millet growth and grain yield in ferallsols or plinthosols soils remains limited. Thus, the purpose of this study was to assess the effect of legume finger millet intercropping on soil carbon sequestration and finger millet productivity in ferallsols or plinthosols soils in the crop-livestock farming system of eastern Uganda.

METHODOLOGY

Study Site

Field experiments were conducted in Olupe Village in Kumi District and Morubaya Village in Amuria District. These two districts are major finger millet-producing areas in the Teso sub-region, and the experimental locations were chosen because of being the most degraded areas in the two selected districts (Ekwangu et al., 2023). The area receives 800-1500mm of rainfall per year, distributed biannually, with the first season running from March to June (short rains) and August to November (long rains). The average annual temperature ranges from 31^0c-35^0c, with ferralsols and plinthosols being the dominant soil types (FAO classification) and are characterised by low nutrients, especially N and P (Ebanyat et al., 2021). The vegetation is mainly savannah grassland with pockets of woody savannah, and the area is generally flat (Egeru, 2012; UNMA, 2022; UNDP, 2014). The areas also experience high incidences of unreliable rainfall and low soil fertility, a major production challenge (Ekwangu et al., 2020).

Figure 1: Map Showing the Location of the Study Area



Study Design

One farmer household was purposively selected from Olupe and Morubaya villages, and randomly selected from Kumi and Amuria districts, respectively, to host the experiment. The two districts were purposively selected based on finger millet production data which showed the two districts as the leading finger millet producers in Teso sub-region (Owere et al., 2014b), and the two farmers were purposively selected to enable the researcher to select fields with ferralsol and plinthosol soils for the establishment of the experiment. The selected farmers freely consented to host the experiment after explaining to them the nature of the study and their role in the experimentation process. A field experiment was set out for three seasons, starting with the second rains of 2021 (2021 B) and the first and second rains of 2022 (2022A and 2022B), and the study adopted a factorial experiment laid down as a Randomised Complete Block Design (RCBD). Two finger millet varieties, Serere millet II and National Agricultural Research Organization (NARO) Mille 3 (Seremi II and NARO MIL 3) respectively, constituted the main plot, and three legume crops (groundnuts, green gram, and cowpeas) were the subplot treatment, and one planting arrangement was the sub-subplot treatment, all together totalling eleven treatments.

The treatments, therefore, included: 1= intercrop of Seremi II with cowpea; 2= intercrop of Seremi II with groundnuts; 3= intercrop of Seremi II with green gram; 4=intercrop of NARO MIL 3 with cowpea; 5= intercrop of NARO MIL 3 with groundnuts; 6= intercrop of NARO MIL 3 with green gram; 7= sole crop of Green gram; 8= sole crop of cowpea; 9= sole crop of groundnuts; 10= sole crop of NARO MIL 3; and 11= Sole Seremi 2. Finger millet was intercropped with legumes in a 1 by 2 arrangement (one row of legume followed by two rows of finger millet). The treatments were replicated three times, making a total of 33 plots. The plot size was 3.3 m x 3.3 m, weeding was done 20 days after sowing for all the treatments, and pest and disease management was uniformly done across treatments.

Data Collection and Processing

Prior to experimentation, soil samples were taken from three spots, purposively selected along the fertility gradient in the experimental site (35 m by 50 m), and samples were taken at a depth of 0-30 cm. A composite sample was obtained by quarter sampling and was packed in a polythene bag, clearly labelled, and taken for air drying at Makerere University College of Agriculture and Environment Sciences (CAES) Department of Soil Science and Land Use Management for the determination of soil bulk density and SOC levels as described below.

Soil bulk density was determined by removing 2 cm of surface soil from the area where the soil sample was to be taken. A 5 cm diameter thin sheet metal tube of known weight (W1) and volume (V) was inserted into the soil surface, the soil from around the tube was excavated, and the soil beneath the tube was cut. The excess soil from the tube ends was removed using a knife. The process was repeated at three randomly selected points in each plot. The soil obtained at each sampling point was dried at 105 ^{0}C for 2 days, and the weight (W2) was taken. The average weight from the three points sampled from each plot was determined (W1a+W1b+W1C) =W1abc; W2a+W2b+W2C=W2abc, where a, b, and c are sampling points. The soil bulk density (g cm^{-3}) was determined using the equation: Soil bulk density (g cm^{-3}) = (W2abc) g – (W1abc) g)/V cm^{3}.

Soil Organic carbon (SOC) was determined by using dichromate oxidation (Walkley & Black, 1934) as described by Okalebo et al. (2002). The annual quantity of SOC added in each treatment (SOC t ha^{-1}) was determined as the difference between the contents of SOC in the final and initial seasons (Kong et al., 2005). Positive and negative changes in SOC values were interpreted as gains and losses of SOC, respectively, in each treatment. The SOC annual rate of accumulation was also

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determined using equation 1, stated as SOC = [(SOC_{final} x SBD_{final}) - ($SOC_{initial}$ x $SBD_{initial}$) x d/n]. Where 'final' and 'initial' are the contents in the final and initial seasons for each experiment, respectively; n is the duration of the experiment in years; SBD (g cm^{-3}) is the soil bulk density measured at the initial and final years of the experiment; and d is the depth of the soil horizon.

After harvesting finger millet and legume crops in the last (third) season of the experimentation, three soil sub-samples were collected from each plot, and by quarter sampling, a composite soil sample was obtained per plot. The soil samples were packed in polythene bags, clearly labelled, and taken for air drying at the Makerere Soil Analytical Laboratory (MSAL). Air-dried composite samples were ground and sieved through a 2 mm sieve and later subjected to physio-chemical analysis at the soil analytical laboratory at the College of Agriculture and Environmental Sciences (CAES) of Makerere University using spectral and standard wet chemistry analysis procedures (Walkley & Black, 1934).

The growth and yield data from experimental crops were also collected (plant height, days to 50% flowering, number of fingers per head, finger millet head size, number of pods per plant, number of seeds per pod, finger millet grain yield, legume grain yield, and land equivalent ratio). Days to 50% flowering were determined at the initiation of the flowering stage. One-meter by one-meter (1m x 1m) quadrant was randomly placed at each plot of the experiment, and the number of plants that carried at least one flower was counted. If the plants were less than 50%, the process was repeated each coming day until the 50% plants with at least one flower were obtained, and that date were recorded. Days to 50% flowering were recorded for further analysis.

Plant height for finger millet was measured at harvesting (75 days after sowing). Ten plants were randomly selected from the four middle rows out of the ten rows per plot. Plant height was measured from the stem base to the finger millet head by use of a meter rule. The average plant height per treatment was then recorded for further analysis. The number of pods per plant was determined by randomly selecting ten plants from the four middle rows of each plot/treatment, leaving out three border rows from each side. The pod number per plant was then determined. The average pod number and number of seeds per pod per treatment were determined by counting and recording at the pod-filling stage and physiological maturity, respectively.

Pod length was measured using a meter rule and recorded at physiological maturity when the pods hardened and became firm. Ten plants were randomly selected from the four middle rows of each plot, leaving out three border rows from each side. Pod length was taken from the point of attachment of the pod from the stem base to the tip of the pod. The average pod length per treatment was computed and recorded. The number of fingers per plant was determined by randomly selecting 10 plants from the four middle rows of each plot, leaving out three border rows from each side. Fingers from each sampled plant were counted, and the average finger number per plant in each treatment was determined.

Days to maturity were also determined at the initiation of physiological maturity. One-meter by one-meter (1 m x 1 m) quadrant was randomly placed at each plot of the experiment, and the number of plants with yellow pods and brown firm grain was counted. If the plants were less than 90%, the process was repeated every three days until 90% of the plants with yellowing pods or brow firm grain were obtained, and that date was recorded for further analysis. The land equivalent ratio, which is the ratio of the area under intercropping needed to give an equal amount of yield under sole cropping at the same management level, was determined using the equation as stated by Willey & Osiru (1972).

Land Equivalent Ratio (LER) = $\frac{y_{12} \dagger y_{21}}{y_{11}+y_{22}}$

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Where y_{12} is the yield of crop 1 intercropped with crop 2. Y_{21} is the yield of crop 2 intercropped with crop 2. Y_{11} is the yield of sole crop 1, and y_{22} is the yield of sole crop 2.

Data Analysis

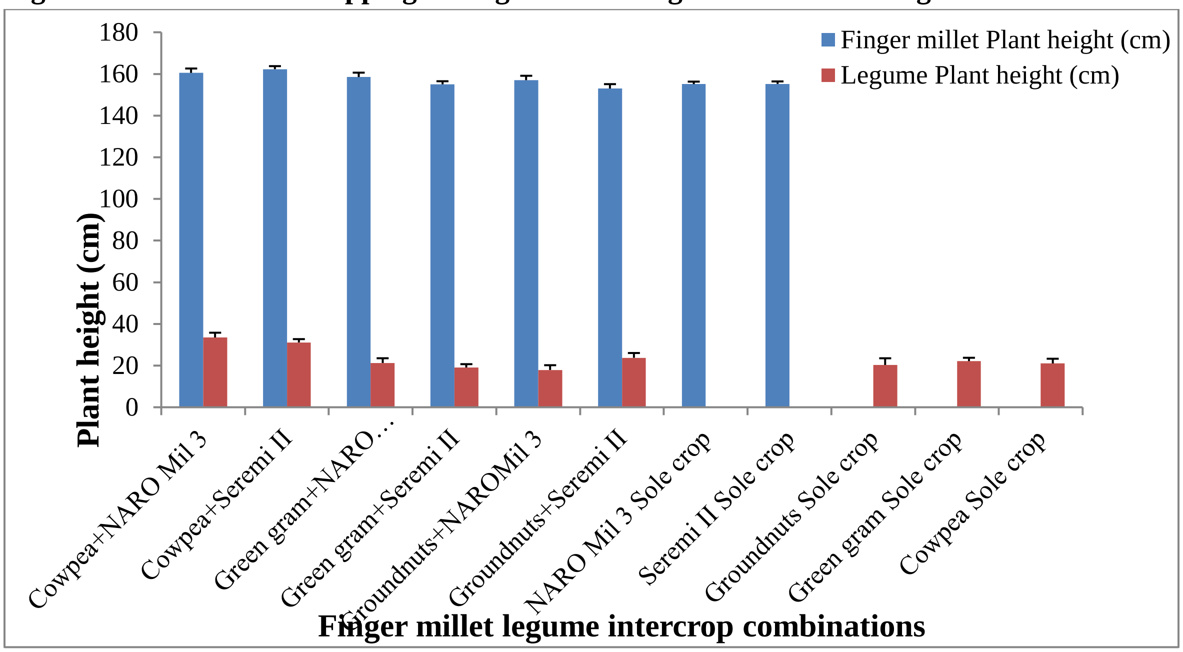
Soil data on SOC, finger millet and legume growth, and yield data that were obtained from each plot/treatment were entered into Excel, and analysis of variance (ANOVA) was conducted on SOC, plant height for finger millet and legume, days to 50% flowering for finger millet and legume, finger millet head diameter, number of pods per plant, number of seeds per pod, number of fingers and grain yield for finger millet and legume using Mini Tab 17th Edition statistical software. The means were separated by Tukey's test at a 95% confidence interval.

RESULTS

Effect of Finger Millet Legume Intercropping on Finger Millet and Legume Plant Height

There was a significant ($p<0.001$) increase in finger millet plant height under legume intercrop (Figure 1). The highest finger millet height (162 ± 1.49 cm) was recorded with an intercrop of cowpea and finger millet (Seremi II). This was followed by the intercrop of cowpea and NARO MIL 3 (160 ± 2.1 cm), and thirdly, the intercrop of green gram with NARO MIL 3 (158 ± 2.1 cm). Also, intercropping finger millet (NARO Mil 3 and Seremi II) led to a significant ($p<0.001$) increase in cowpea height (33 ± 2.28 cm and 31 ± 1.6 cm) respectively. However, no effect was recorded in the intercrop of groundnuts with both varieties of finger millet.

Figure 1: Effect of Intercropping on Legume and Finger Millet Plant Height



Note: Analysis of variance was conducted, and error bars were generated from the Standard Error (SE)

Influence of Intercropping on Legume and Finger Millet Days to Flowering

Intercropping finger millet with legumes significantly ($p<0.001$) reduced the days to 50% flowering of finger millet (Figure 2). The intercrop of finger millet (NARO MIL 3) with cowpea, groundnuts, and green gram contributed to the reduction in finger millet days to 50% flowering from about 60 ± 0.57 to 54 ± 0.57, 55 ± 0.27, and 56 ± 0.33 days, respectively, and 58 ± 0.51, 60 ± 0.73, and 54 ± 0.52 days for the intercrop of groundnuts with Seremi II. Green gram or groundnut

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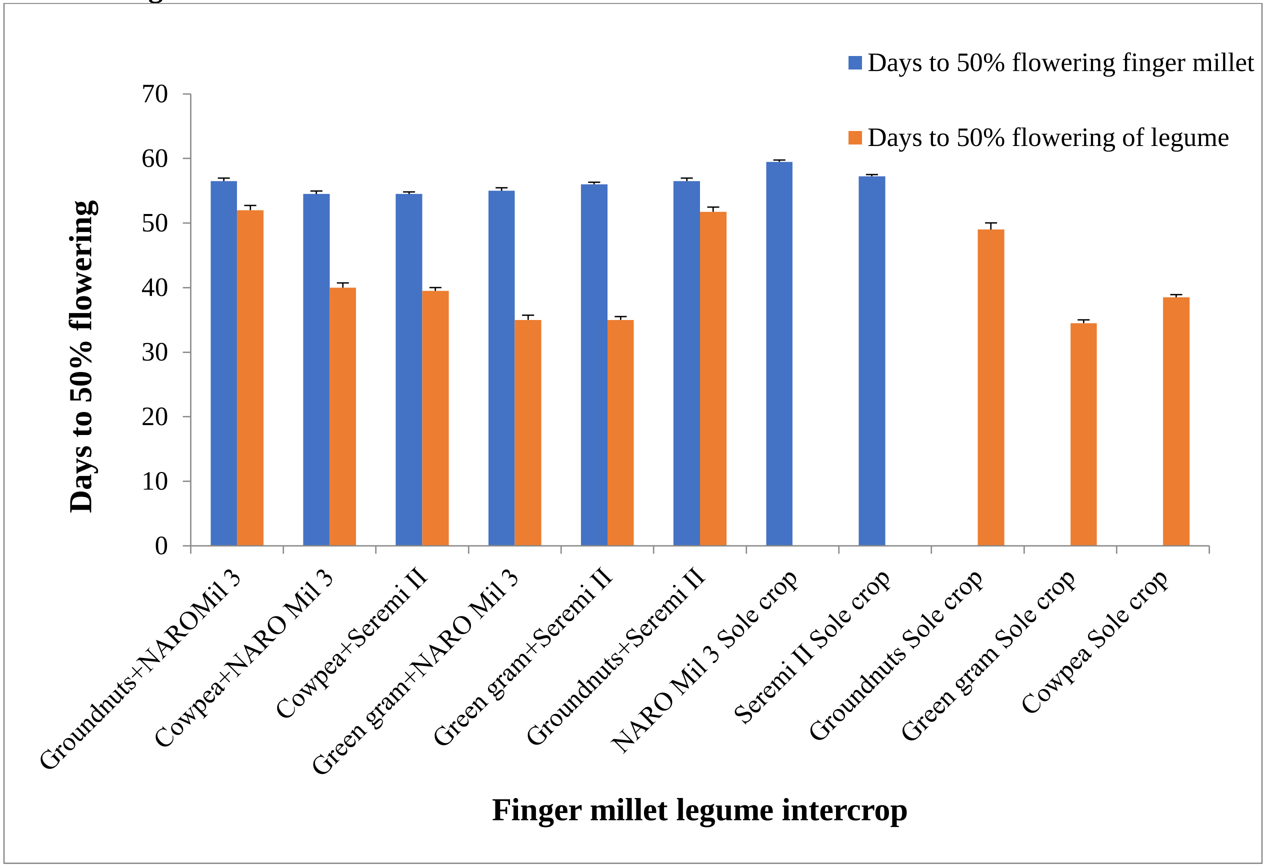
intercropping with finger millet did not affect the days to 50% flowering of Seremi II finger millet variety.

There was a significant (p<0.001) effect of intercropping finger millet with legumes on legume days to 50 % flowering. There was an increase in days to 50 % flowering observed across all the legumes except for green gram, which was not significantly (p<0.001) affected under the two intercrops of NARO MIL 3 or Seremi II finger millet varieties.

Figure 2: Influence of Intercropping Finger Millet with Legume on Finger Millet and Legume Days to Flowering



Note: Analysis of variance was conducted, and error bars were generated from SE

Finger Millet Maturity Time Under Different Legume Intercrops

Intercropping finger millet with legumes significantly (p<0.05) reduced finger millet maturity time (Figure 3). Intercropping NARO MIL 3 with all the legumes reduced NARO MIL 3's days to maturity. Cowpea reduced NARO MIL 3 days to maturity by about 12 ± 0.2 days, and intercropping Seremi II with any of the legumes did not significantly (p<0.05) affect Seremi II days to maturity.

However, intercropping of either Seremi II or NARO MIL 3 with groundnuts increased groundnuts' days to maturity by about five days, with no significant change in the maturity time of green gram and cowpea under NARO MIL 3 or Seremi II intercrop.

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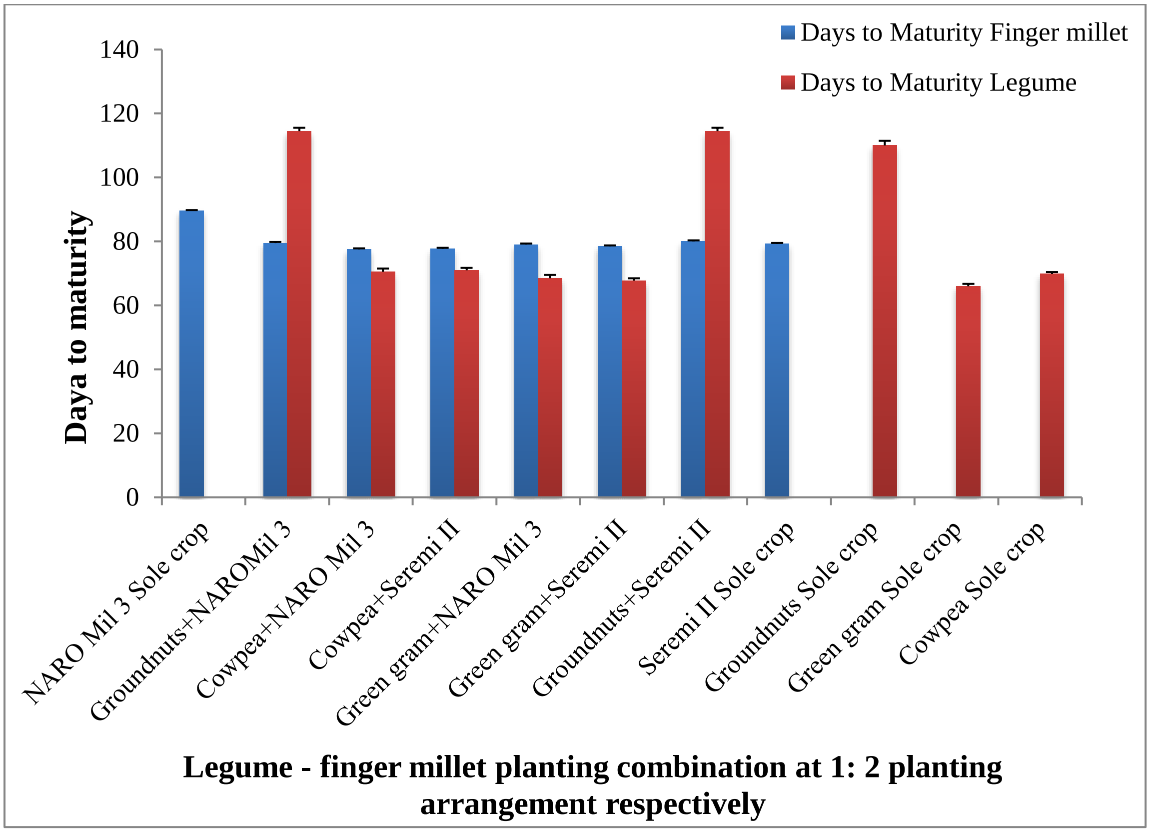
Figure 3: Finger Millet and Legume Days to Maturity Under Intercropping



Note: Analysis of variance was conducted, and error bars were generated from SE.

Effect of Finger Millet Legume Intercrop on Finger Millet and Legume Yield Parameters

There was a significant ($p<0.001$) effect of intercropping finger millet with legumes on crop yield parameters and soil organic carbon stocks, with the intercrop of cowpea with finger millet (NARO MIL 3 and SEREMI 2) performing more than other intercrop treatments (Table 1). The highest figure recorded on head diameter was 11.38 ± 0.340 cm under intercrop of cowpea with SEREMI 2 and was followed by intercrop of cowpea with NARO MIL 3 (11.30 ± 0.470 cm), however, they were not significantly different ($p>0.05$). The least was recorded with an intercrop of groundnuts with NARO MIL 3 (6.20 ±). On the other hand, the highest finger length (9.50 ± 0.350 cm) was recorded with an intercrop of cowpea and SEREMI 2, and the least was recorded with a sole crop of NARO MIL 3 (6.52 ± 0.270 cm). While the highest number of fingers (8.00 ± 0.540) was recorded with an intercrop of green gram and SEREMI 2 finger millet, the lowest was with intercrop groundnuts with NARO MIL 3 (4.00 ±0.540).

Furthermore, the highest SOC stocks were recorded with an intercrop of cowpea with NARO MIL 3 (0.310 ± 0.011 t ha^{-1} yr^{-1}), and the least was recorded with a sole crop of groundnuts (0.045 ± 0.006 t ha^{-1} yr^{-1}) (Table 1).

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Table 1: Effect of Finger Millet Legume Intercropping on Finger Millet Yield Parameters and Soil Organic Carbon Stocks (Values are means ± SE)

Treatment	Finger millet Head diameter (cm)	No. of pods per plant	No. of fingers per head	Finger Length (cm)	Soil organic carbon stocks added (t ha^{-1} yr^{-1})
Cowpea NARO Mil 3 Intercrop	11.30 ± 0.470[ab]	15.50 ± 0.970[abc]	8.00 ± 0.540[ab]	8.75 ± 0.500[ab]	0.310 ± 0.011[a]
Cowpea SEREMI 2 intercrops	11.38 ± 0.340[a]	15.60 ± 0.680[abc]	7.13 ± 0.380[ab]	9.50 ± 0.350[a]	0.282 ± 0.007[a]
Green gram NARO Mil 3 intercrop	8.75 ± 0.470[abcd]	7.65 ± 0.970[abc]	8.50 ± 0.540[a]	8.00 ± 0.500[ab]	0.255 ± 0.011[a]
Green-gram SEREMI 2 intercrops	9.25 ± 0.340[abc]	7.63 ± 0.680[a]	7.00 ± 0.380[ab]	8.25 ± 0.350[ab]	0.187 ± 0.007[ab]
Groundnuts NARO Mil 3 intercrop	7.65 ± 0.470[cd]	1.90 ± 0.970[abc]	4.00 ± 0.540[c]	7.50 ± 0.500[ab]	0.065 ± 0.011[d]
Groundnuts SEREMI 2 intercrops	8.25 ± 0.470[bcd]	2.00 ± 0.970[abc]	6.00 ± 0.540[abc]	7.00 ± 0.500[abc]	0.053 ± 0.011[d]
Sole cowpea	N/A	13.42 ± 0.560[a]	N/A	N/A	0.278 ± 0.006[a]
Sole Green-gram	N/A	8.10 ± 0.680[abc]	N/A	N/A	0.138 ± 0.006[bc]
Sole Groundnuts	N/A	2.00 ± 1.370[ab]	N/A	N/A	0.056 ± 0.006[d]
Sole NARO Mil 3	6.52 ± 0.270[d]	N/A	5.33 ±0.310[bc]	6.50 ± 0.290[bc]	0.277 ± 0.011[a]
Sole SEREMI 2	7.65 ± 0.470[cd]	N/A	6.00 ± 0.540[bc]	7.00 ± 9.500[ab]	0.245 ± 0.011[a]

Note: N/A= Not Applicable, SE = Standard Error of the mean and similar superscript letters not significantly different at 95% confidence interval

Finger Millet and Legume Grain Yield Recorded Under Intercropping

There was a significant (p<0.001) difference in grain yield performance of the two varieties (SEREMI 2 and NARO MIL 3) of finger millet (Figure 4). Intercrop of cowpea and NARO MIL 3 recorded the highest grain yield of about 2617 kg ha^{-1}. This was followed by an intercrop of cowpea with Seremi II (2387 kg ha^{-1}). The lowest finger millet grain yield (688 kg ha^{-1}) was recorded with an intercrop of finger millet with NARO Mil 3.

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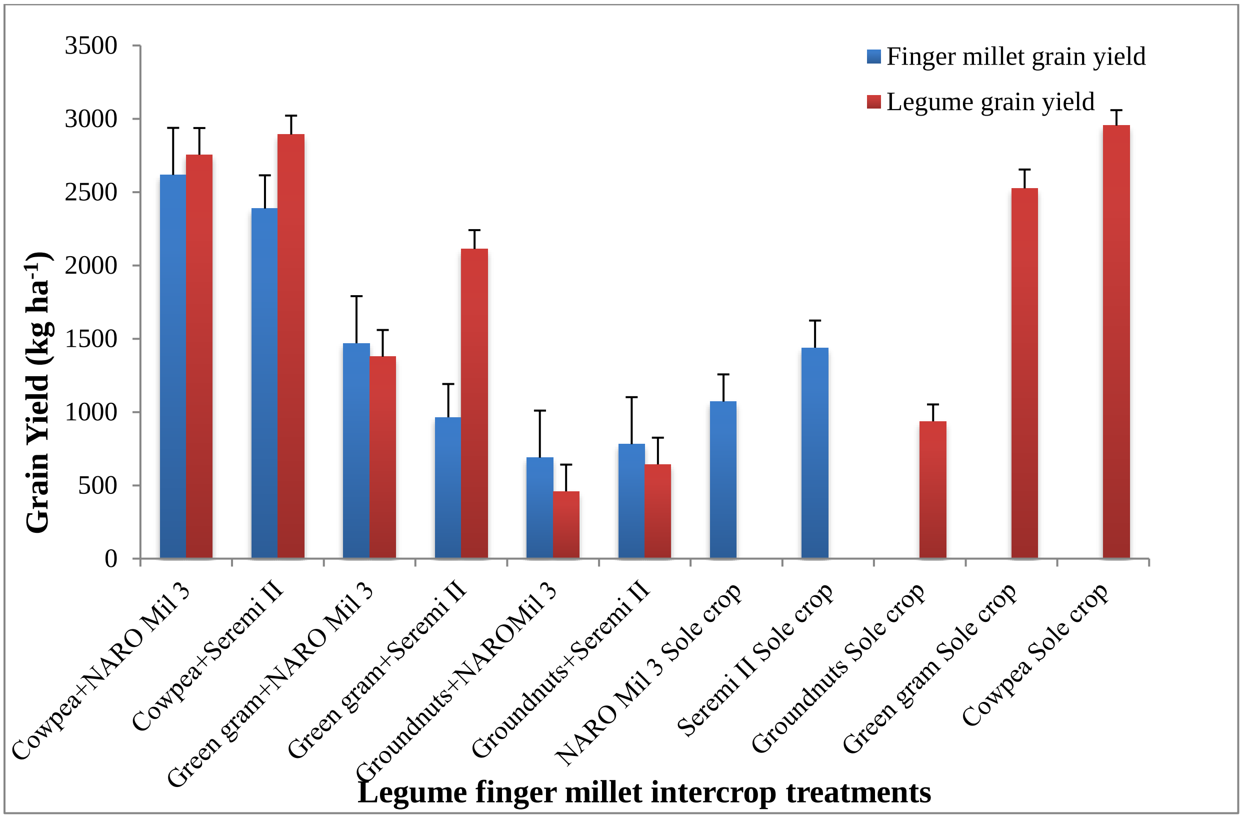
Figure 4: Finger Millet Yield Response to Legume Intercropping



Note: Analysis of variance was conducted, and error bars were generated from SE

Land Equivalent Ratios for Finger Millet Legume Intercropping

The land equivalent ratios were significantly different ($p<0.001$) under different finger millet legume intercrops (Figure 5). Intercrop of cowpea with NARO MIL 3 recorded the highest land equivalent ratio (1.78 ± 0.187), this was followed by intercrop of cowpea with Seremi II (1.208 ± 0.13), and the lowest land equivalent ratio was recorded from intercrop of NARO MIL 3 with groundnuts (0.37 ± 0.187). A land equivalent ratio above 1 means intercropping has an advantage over sole cropping (pure stand), and a land equivalent ratio below 1 means pure stand performs better than intercropping. This means green gram and groundnuts don't give any yield advantage when intercropped with millet and should not be recommended.

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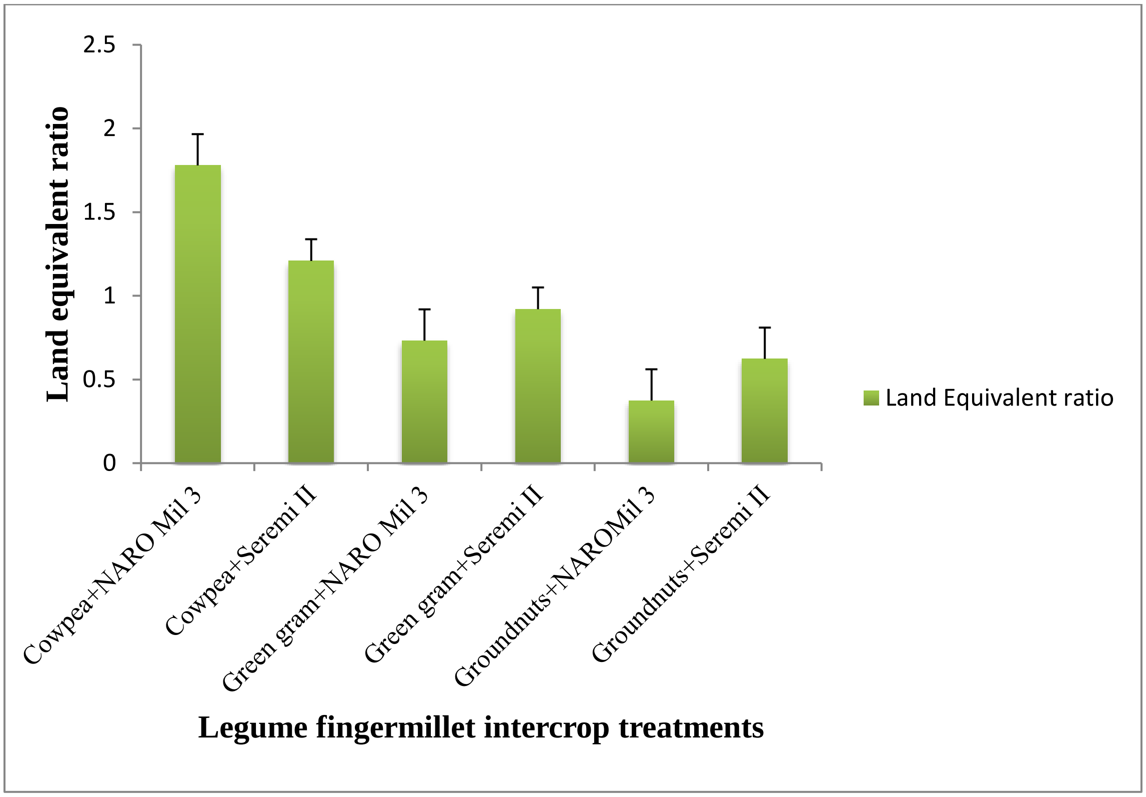
Figure 5: Land Equivalent Ratios of Treatments with Mean Values ± SE



DISCUSSION

Effect of Intercropping on Finger Millet and Legume Growth Parameters

Finger millet is one of the cereals compatible with intercropping and has been ranked 5th among the top 10 crops adapted to the practice (Derebe et al., 2021). In this study, finger millet height increased under cowpea intercropping treatments, which could have been caused by intra-specific competition between finger millet and cowpea for light under the dense vegetative nature of the cowpea. The superior effect of cowpea in enhancing the plant height of the two varieties of finger millet could also be attributed to its ability to develop a dense root network, increasing the surface area for nutrient absorption and colonisation by free-living nitrogen-fixing bacteria (Derebe et al., 2021). In addition, the promiscuous nature of cowpea, where a wide range of rhizobia species can infect and colonise its roots, as opposed to the limited species for both groundnuts and green gram (Favero et al., 2021), gives it an advantage over the two legume crops (Groundnuts and green gram). Given the short life cycle of bacteria, the large quantities that colonise the cowpea provide easily decomposable biomass when they die. The decomposition process generates nitrogen and phosphorus necessary for plant growth and therefore supports stem elongation and growth of both cowpea and finger millet. Thus, contributing to the superior performance of cowpeas over other legumes. The superior performance of cowpea over green gram was also reported by Kebede and Bekeko (2020) in their study assessing the performance of finger millet under legume intercropping in Ethiopia.

The decrease in finger millet days to flowering across all three legume intercrops, except for groundnuts and green gram intercrop with SEREMI 2, suggests that legumes may provide favourable conditions for the effective growth of finger millet. Also, a shorter maturity period for intercropped cereals is normally related to improved nutrition, and lower competition among plants for resources

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such as sunlight, soil moisture, and nutrients, since they are accessing resources at different soil depths (Gupta et al., 2017). The dense vegetative cover from cowpeas and groundnuts contributes to the improvement of the soil micro-climate, leading to the retention of moisture for longer periods of time (Gupta et al., 2017). The legumes also help to fix nitrogen in the soil, enhancing mediation and biochemical processes in the plants, including respiration and photosynthesis, which are essential for plant growth, as reported earlier by Gupta et al. (2017) and Li et al. (2019).

The findings of this study also showed that there was no difference in days to 50% flowering between sole cropping of finger millet and intercropping of finger millet (SEREMI 2) with groundnuts or green grams. This could be attributed to slow vegetative growth in groundnuts and green gram and early maturing characteristics of SEREMI 2. Also, these two legumes have limited root biomass and, therefore, are not able to aggressively fix nitrogen compared to cowpeas with both lateral dense roots and tap roots. This root architecture facilitates maximum nutrient uptake and colonisation by free-living beneficial rhizobia. Moreover, at the early stages of root colonisation by rhizobia, the micro-organisms require nutrients, especially nitrogen, for cell growth before they start to fix their own nitrogen for their growth, and these nutrients are provided by the host plant (Hayat et al., 2010). Where the host plant is unable to provide nutrients to the rhizobia at the initial stages of colonisation, there will be reduced or no effective colonisation by the rhizobia. This, therefore, could explain the low and no difference in performance in green gram and groundnut intercrops with the sole crop of finger millet. Similar studies assessing the effect of finger millet legume intercropping and rotations on finger millet yield reported poor performance of green gram and groundnuts in enhancing finger millet growth and yield parameters (Bitew et al., 2019; Kumar & Ray, 2020). Also, the aggressiveness in nutrient mobilisation observed in cowpeas, which was translated into dense vegetative growth, could have contributed to the improvement of the plants' micro-climate. Thus, contributing to sustained moisture conservation, which is critical for plant nutrition and growth, given that the area where the experiment was conducted is semi-arid. The slow-growing and less vegetative crops like green gram and groundnuts performed poorly due to their growth habits. The ability to grow and accumulate biomass are key attributes of good legumes for intercropping (Ojiem et al., 2006; Sennhenn et al., 2017; Xing et al., 2017). However, the mechanisms through which cowpea is able to improve finger millet yield, especially the plant microorganism interactions in the rhizosphere need to be investigated.

The influence of cowpea in reducing finger millet days to maturity confirms the observations made by Derebe et al. (2021). In this study, intercropping of cowpea with either NARO MIL 3 or SEREMI 2 finger millet varieties contributed to a decrease in finger millet days to flowering by five days. The decrease in finger millet days to flowering across the two legume intercrops with the two finger millet varieties, except for groundnuts intercrop with all the two finger millet varieties, suggests that legumes may provide favourable conditions for effective growth of finger millet. The dense vegetative cover from cowpea contributes to improvement in the soil micro-climate, leading to retention of moisture for longer periods of time (Gupta et al., 2017; Li et al., 2019). The legumes also help in fixing nitrogen to the soil, benefiting both the legume and the component crop. Nitrogen mediates bio-chemical processes in plants, including respiration and photosynthesis, which are essential for plant growth, as reported earlier by Gupta et al. (2017) and Li et al. (2019). When the crop receives enough assimilates from photosynthesis, its growth is promoted, thus supporting the observations made in this study, where there was superior performance of cowpea against green gram and groundnuts.

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Effect of Intercropping on Finger Millet Grain and Yield Parameters

There was a significant effect of intercropping legumes with finger millet on finger millet yield parameters and grain yield, underscoring the role of legumes in nutrient recycling and soil fertility improvement (Olupot et al., 2021; Vanlauwe et al., 2010).

The observed similarity between legume sole crop and legume intercrop grain yield and yield parameters in the results of this study indicates that both finger millet and the legumes are adapted to intercropping, as reported by Derebe et al. (2021) in their study assessing the effect of intercropping finger millet with legumes, reported 27% finger millet grain yield gain under finger millet cowpea intercrop. These findings contrast with those of Kumar & Pankaj (2020), who reported finger millet growth parameters to be superior in sole crop than in intercropping practices. It should, however, be noted that the benefits of intercropping range from sustainable soil fertility improvement to diversified food and ecosystem services (Sululu et al., 2022). The ecosystem services provided by this cropping system range from increased micro and macro diversity due to diversified food systems, increased moisture levels, improved soil aeration, and water infiltration. As earlier noted, microbes contribute to nutrient turnover, hence improving soil fertility and SOC stocks (Mason et al., 2023). Therefore, even where finger millet intercrop yields are lower, the other benefits of intercropping should be considered.

The superior performance of cowpea in influencing finger millet yield parameters and translating that performance to grain yield and to Land Equivalent Ration (LER), where intercropping of cowpea with NARO MIL 3 recorded the highest land equivalent ratio of 1.77, followed by rotation of cowpea with Seremi II that recorded a LER of 1.2. This, therefore, suggests that intercropping cowpea with either NARO MIL 3 or Seremi II in ferralsols and plinthosols is more sustainable than sole cropping of either cowpea or finger millet. Intercropping finger millet with legumes has been reported to have a complementary contribution to the growth of each component crop. However, for a long time, information on which legume provides complementary benefits to finger millet grown in ferralsols and plinthosols in the semi-arid regions of eastern Uganda has been limited. With these findings, farmers will have hope of increasing the productivity of finger millet, especially in the adaptation to climate variability and reducing the land area per household in the region. Derebe et al. (2021) reported up to a 27% yield advantage on intercropping finger millet with cowpea, and it was highly preferred by farmers because of its ability to conserve soil moisture. It was also reported that cowpea-finger millet intercropping improved soil fertility due to its high biomass and ability to fix a considerable amount of nitrogen to the soil (Bitew et al., 2019).

CONCLUSIONS

The study findings demonstrated that finger millet cowpea intercropping increases finger millet grain yield and soil organic carbon stock in plinthosols and ferralsols soils. Cowpeas contributed to a grain yield advantage of 116% (2200 kg ha^{-1}) in plinthosols and ferralsols in the tropical region of eastern Uganda.

Cowpea intercropping with NARO Mil 3 finger millet substantially increases SOC levels by 66.7% (0.248 t ha^{-1}) per year in plinthosols and ferralsols in the tropical region of eastern Uganda. The study therefore recommends farmers to intercrop finger millet with cowpea for increased finger millet grain yield and soil organic carbon stocks in ferralsols and plinthosols.

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