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Intercropping millet with low-density cowpea improves millet productivity for low and medium N input in semi-arid central Senegal

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ABSTRACT

Cereal-legume intercropping has been traditionally practiced across West Africa by farmers and provides resilience of agriculture to climate variability. Intensification of these extensive intercropping systems in order to meet future food demand is critical. This study aims at evaluating the agronomic performance of the intensification of millet-cowpea intercropping with low cowpea density, and its variation with climate variability, using an on-station experiment in Bambey, Senegal. Two trials (irrigated vs rainfed) were set up to compare millet sole- and inter-cropping with a grain and a fodder variety of cowpea, in 2018 and 2019. Two levels of fertilization were tested: 0 kg(N) ha^{-1} and 69 kg(N) ha^{-1}. The two cropping years were contrasting and water stress around flowering and/or during grain filling (indicated by the Fraction of Transpirable Soil Water) was higher in 2019 than in 2018 in the rainfed experiment. In both experiment and for all treatments, land equivalent ratio (LER) in the intercropping was 1.6 and 1.4 for grain and biomass respectively. Millet aboveground biomass was significantly higher in intercropping than in sole cropping in the irrigated experiment but not in the rainfed experiment. In the rainfed experiment, the interaction between cropping system and year was significant, so that millet aboveground biomass was greater in intercropping than in sole cropping in 2018 (year of lower water stress) but not in 2019 (year of higher water stress). The effect of fertilization on millet aboveground biomass did not significantly interact with cropping system (sole vs intercrop). For grain yield, fertilization interacted significantly with the cropping system in the irrigated trial: the benefits of intercropping on millet grain yield were greater with 69 kg(N) ha^{-1} than with 0 kg(N) ha^{-1}. This

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significant interaction could not be observed in the rainfed trial, potentially due to water stress. These results show that the level of water stress (related here to the year and to the rainfed or irrigated experiment) and that of fertilization modulate the performance of millet-cowpea intercropping in the semi-arid context of Senegal. Overall, fertilization had a stronger effect on millet grain yield than intercropping. The two strategies (intercropping and mineral fertilization) can be complementary to achieve sustainable intensification of cropping system in semi-arid areas of West Africa.

1. Introduction

Sub-Saharan Africa (SSA) faces food insecurity with cereal crop yield lower than in other regions of the world [1,2], mostly because of nutrient limitations [3]. Increase in droughts and the corresponding more frequent water and heat stresses is expected to further constrain crop production [4,5]. Arable land being limited, ecological intensification is a promising pathway to improve food security and farm income while minimizing negative impact of agriculture on the environment by harnessing the biological processes regulating primary production [6–8]. Diversification of cropping systems helps maintaining regulatory services and coping with risks resulting from the inter-annual variability of climate [e.g. Ref. [9]]. Diversification of cropping systems can be achieved with intercropping. In the tropical world, particularly in SSA, intercropping is a widespread practice [10]. Intercropping favors complementarity and facilitation between intercropped species for the use of environmental resources and contributes to improve systems productivity [11]. Intercropping a cereal with a legume is the most common strategy, as it can provide grain for human consumption and fodder for livestock [12,13]. Under semi-arid climate, farmers and researchers see it as a promising option to cope with climate variability [14]. However, the benefits of intercropping originating from facilitation between the component species may not always be fully realized, depending on the climate of a specific year. For example, in their modelling study [15] suggested that sorghum and cowpea competed for water in drier years, while nitrogen stress prevailed in the wetter years. More experimental work is thus needed to unravel the impact of climate variability and water stress on intercropping performance. The interplay between the fertilization of the cereal and the performance of the cereal-legume intercropping is also a controversial topic: while some studies show that the benefit of intercropping decreases with fertilizer N inputs [11], others show that these benefits are maintained, even at greater fertilizer N inputs [16]. More experimental work on the impact of the intensification of cereal-legume intercropping is therefore required to unravel the impact of soil, climate, and crop management.

Pearl millet (*Pennisetum glaucum (L.) R. Br.*) is one of the main cereal crops in Senegal: 80,744 tons were produced in 2019 reprensenting 29% of national cereal production [17]. The millet variety Souna is generally grown by farmers under rainfed conditions with little or no inputs, resulting in low yields of about 0.5–0.6 t/ha, well below the potential yield of circa 3 t/ha with that same variety. This potential could be further increased if varieties with higher potential harvest index were made available to farmers [18]. Population growth in Senegal is 3% per year, which means a doubling of population in two decades. Given the limited scope for expanding the area under cultivation, this will pose huge challenges to food security in the near future. The “old groundnut basin” is the country’s grain basket. In the most arid northern half of this region, the typical cropping system is a biennal millet –groundnut rotation with millet as the staple crop, frequently intercropped with cowpea (*Vigna unguiculate*), sown at very low density. Cowpea is chosen by farmer because it is a good quality fodder for livestock, and it also provides a protein-rich staple for human consumption [19].

This study aims at exploring the scope for intensified millet-cowpea intercropping. We evaluate the agronomic performance of millet-cowpea intercropping with and without N fertilizer inputs and with and without water stress. In doing so, we explore the hypotheses that i) intercropped millet produces more grain and biomass than sole millet, and ii) the benefits of intercropping is maintained with water stress and at greater N fertilizer input, and hence it is a crucial component of sustainable intensification of cropping systems in the region.

2. Material and methods

2.1. Experimental site

The study was conducted in Senegal at the experimental station of the National Center for Agronomic Research of Bambey (14°42′48″ N, 16°28′ 47″W) during two growing seasons, in 2018 and 2019. The climate in this area is predominantly Sahelo-Sudanian with annual rainfall ranging from 400 to 900 mm. During these two years of experimentation, the rainy season began at the end of June. The cumulative rainfall was 448 mm in 2018 and 488 mm in 2019. Average temperatures ranged from 21 °C to 42.5 °C (Fig. S1). The soil in the experimental plot is tropical ferruginous with sandy-silt texture. Average total N content in the topsoil was 0.03%, and average C was 0.34%. Assuming a bulk density of 1400 kg/m3 in the 0–20 cm topsoil, 13 kg ha^{-1} of mineral N would be provided by the decomposition of soil organic matter [considering that 1.5% of the N in soil organic matter is mineralized throughout the season [20]].

2.2. Experimental design and crop management

The impact of two factors was investigated: cropping system and fertilization. The experimental design included fertilization as a blocking factor with three replicates (Fig. S2): the replicates were nested in the blocks represented by fertilization. The fertilized and the non-fertilized blockswere adjacent and distant only a few meters. We assumed that these two fertilization blocks were fully comparable and there were no potential differences in soil characteristics that would be confounded with the potential effect of fertilizer. Fertilization had two levels: 0 kgN ha^{-1} (f0) and 68.5 kgN ha^{-1} (f1). The cropping system factor had three levels for millet: sole, intercropped with cowpea grain variety "Baye Ngagne", or intercropped with cowpea fodder variety "58-74f". For cowpea (regardless of variety), this treatment had two levels: sole, or intercropped with millet.

Each year, this design was implemented in two separate fields, corresponding to two separate experiments, one under rainfed conditions, and the other with a total supplemental irrigation of 117 mm and 154 mm in 2018 and 2019, respectively (Fig. S2). Irrigation was done on the third dry day after the last rainfall event, in order to reduce the occurrence of water stress as much as technically possible. In each trial (rainfed and irrigated), each elemental plot had an area of $81/m^2$ (9 m × 9 m). The experiments (irrigated and non-irrigated) were conducted in the exact same fields in 2018 and 2019, and the fertilizer block were in the same fields and in the same locations in the two years. However, within each replicate block (see Fig. S2), all treatments were re-allocated each year in order to have the cereal and the legume rotated on the same plot and thus harmonize potential legacy effects.

The millet variety Souna 3 and the cowpea varieties "Baye Ngagne" and "58-74f", both known to be adapted to local conditions, were used. Baye Ngagne is a local grain variety and 58-74f is a variety with high fodder production potential. Their average cycle length is of 65 days and 70 days respectively. The millet variety "Souna 3″ is the most widely grown variety in the area with a crop cycle of 85–95 days and a potential grain yield of 3.5 t/ha [21]. Sowing was done manually on July 27, 2018 and August 18, 2019 with 4 kg ha^{-1} of millet seeds. Millet was sown with 90 cm in both directions between planting stations for sole and intercropping treatments corresponding to a density of 12346 plants/ha. Cowpea was sown on the same day with a seeding rate of 16 kg ha^{-1}, with 45 cm between planting holes in both directions (49383 plants/ha) in sole cropping. In intercropping, cowpea was sown at a reduced density (12.5% of sole cropping density) on each millet row with a density of 6173 plants/ha (see planting pattern in Fig. S3). This corresponds to a low density compared with other studies, e.g. in the study of [22], intercropped cowpea density was two third of sole cowpea density. Millet was thinned at 2 plants per planting holes 22 days after planting in 2018 and 16 days after planting in 2019. 150 kg ha^{-1} of basal NPK (15-15-15) fertilizer was applied in the fertilized blocks, 50 kg ha^{-1} of urea (46-0-0) was top-dressed during plant-thining and another 50 kg ha^{-1} at 46 days after sowing in 2018 and 35 in 2019 on millet only, i.e. representing a total of 68.5 kg ha^{-1} (N), 22.5 kg ha^{-1} (P) and 22.5 kg ha^{-1} (K) applied. This N input is only relatively high: millet aboveground biomass can reach a potential of 12 t/ha. Considering a 1.6% N content, this would equate to a N uptake of 192 kgN/ha; greater N input than the 68.5 kgN/ha applied in this study would be required to sustain millet potential yield. Cowpea was not fertilized. Plots were weeded with hand hoe to control weeds during the crop development cycle. Pest management consisted mainly of control of *Forficula auricularia,* with application of Deltamethrin when necessary. Harvesting was done manually after millet and cowpea physiological maturity.

2.3. Field measurements

2.3.1. Leaf area index (LAI)

Leaf area index (LAI) was measured once a week in each treatment. Measurements were made using a Licor-LAI2000. Small subplots of 6.48 m^2 were delimited within the final harvesting plot (12.96 m^2) in order to always repeat the measurements on the same piece of land until harvest. In intercropping, we measured the overall LAI of the intercrop, i.e. that of the canopy formed by the two crops jointly.

2.3.2. Fraction of transpirable soil water (FSTW)

Soil moisture of each treatment was monitored in one of the three replicates using a Diviner 2000 probe (https://sentektechnologies.com/products/soil-data-probes/diviner-2000/) once a week for the entire soil profile accessible to roots. Access tubes for the probe, allowing measurements down to a depth of 160 cm, were installed in the center of harvesting plots (12.96 m^2) used to measure yield and yield components. Measurements were taken every 10 cm. The total water stock at 1.60 m depth was used to compute the fraction of total soil transpirable water (FTSW) [23], as per equation (1):

$$\mathrm{FTSWi} = \frac{\mathrm{ASWi}}{\mathrm{TTSW}} \times 100 \tag{1}$$

where ASWi (mm) is available soil water on day i and TTSW (mm) is the total transpirable soil water. ASWi (mm) and TTSW were calculated for the entire soil profile (0–160 cm). Available soil water ASWi was the difference between soil water content on day i and soil water content at wilting point. Total transpirable soil water TTSW was the difference between soil water contents at field capacity and at wilting point. Soil water content at wilting point was set as soil water content at the end of the dry season before the first rain of the next rainy season and soil water content at field capacity was set as the highest observed soil water content during crop cycle.

A threshold of 0.5 for FTSW, meaning that the soil water content is only half of total transpirable soil water, was considered to indicate potential water stress for millet growth.

2.3.3. Grain yield and aboveground biomass

An area of 12.96 m^2 was delimited in each plot, containing four rows and 16 millet plants in sole- and inter-cropping. 49 cowpea plants (seven rows) were harvested for sole cropping treatments and 8 for intercropping treatments. Fresh weight of panicles, pods and stover were determined in the field. The samples were sun-dried for two weeks. Stover and grains were oven-dried at 60 °C for 72 h. Grain yield and aboveground biomass (grain + stover) were then determined.

2.4. Land equivalent ratio (LER) calculations

LER was defined by Ref. [24] as the area of sole crops required to obtain the same yield as a hectare of intercropping. LER was calculated as follows (equation (2)):

$$LER = pLER_{millet} + pLER_{cowpea} = Y_{IMillet} / Y_{SMillet} + Y_{ICowpea} / Y_{SCowpea} \tag{2}$$

where $pLER_{millet}$ and $pLER_{cowpea}$ are partial LER of millet and cowpea. $Y_{IMillet}$ and $Y_{ICowpea}$ are yield (grain or aboveground biomass) of millet and cowpea with intercropping, respectively, and $Y_{SMillet}$ and $Y_{SCowpea}$ that of sole millet and sole cowpea, respectively.

2.5. Statistical analysis

In order to analyze the effect of experimental treatments on LAI, aboveground biomass, grain yield of millet and cowpea, one linear model and two linear mixed models [25,26] were elaborated. In the linear mixed models, the experimental factors were fixed effects. In the first mixed model, an identifier combining the replicate number and the fertilization block (Fig. S2) was used as a random effect. In the second mixed model, an identifier combining the replicate number, the fertilization block, and the year of the experiment was used as a random effect. The three models were specified as follows (equations (3)–(5)):

$$(\text{Model 1})\ Y_{ijkl} = inter + aF_i + bCS_j + cA_k + dFCS_{ij} + eACS_{kj} + fAF_{ki} + gAFCS_{kij} + R_{ijkl} \tag{3}$$

$$(\text{Model 2})\ Y_{ijkl} = inter + aF_i + bCS_j + cA_k + dFCS_{ij} + eACS_{kj} + fAF_{ki} + gAFCS_{kij} + iRepF_{il} + R_{ijkl} \tag{4}$$

$$(\text{Model 3})\ Y_{ijkl} = inter + aF_i + bCS_j + cA_k + dFCS_{ij} + eACS_{kj} + fAF_{ki} + gAFCS_{kij} + iRepFA_{ikl} + R_{ijkl} \tag{5}$$

where Y_{ijkl} is the variable to be explained (LAImax, aboveground biomass or grain yield), inter is the intercept, F_i is the level i of fertilization, CS_j is the level j of cropping system, A_k is level k of year, FCS_{ij}, ACS_{kj} and AF_{ki}, are the interactions between F_i and CS_j, A_k and CS_j, and A_k and F_i, respectively, $AFCS_{kij}$ is the interaction between the three factors, $RepF_{il}$ is an identifier combining the replicate number and the fertilization block (Fig. S2), and $RepFA_{ikl}$ is an identifier combining the replicate number, the fertilization block, and the year of the experiment, R_{ijkl} is the residual, and aF_i, bCS_j, cA_k, $dFCS_{ij}$, $eACS_{kj}$, fAF_{ki}, $gAFCS_{kij}$ are fixed effects coefficients and $iRepF_{il}$ and $iRepFA_{ikl}$ are the random effect coefficients. Model 1 was built with the *lm()* function of R. Models 2 and 3 were built with the *lmer()* function of R, using Restricted Maximum Likelihood Estimation (Reml = True option of the lmer() function). Model 2 and 3 (with random effects) were compared to model 1 (without random effects) by calculating the Akaike information criterion (AIC) of the two respective models using the *AIC()* function of R. The AIC is an indicator that decreases when model quality increases, i.e. when its capacity to explain the variations of Y_{ijkl} increases. AIC is further penalized by the number of parameters in the model. Hence, it allows selecting the most parsimonious model with the best fit. The model with the lowest AIC was selected for the final analysis of the effects of experimental factors (cropping system, fertilization and year). For the final full model we tested the additional information provided by a given factor by performing F-tests with R *anova()* function using sum of squares of type II for mixed models containing RepF or RepFA, and with R *Anova()* function for linear models not containing RepF and RepFA. Fig. S4 provides an example of the R code used to perform the statistical analysis.

This statistical analysis was used separately for the irrigated experiment and the rainfed experiment so that irrigation was not part of the experimental factors in the statistical models. Pairwise adjusted means comparison was done using the *multcomp()* and *cld()* functions of the *lsmeans* and *means* package of R, with an alpha threshold of 5%.

Millet and cowpea yield was averaged across the replicates and LER was computed with the average yields to study the impact of year, fertilization and cowpea variety. The following model was used (equation (6)):

$$(\text{Model 4})\ LER_{ijkl} = aF_i + bVar_j + cA_k + R_{ijkl} \tag{6}$$

where LER_{ijkl} is the variable to be explained (LER in grain and aboveground biomass), F_i is the level of fertilization i, Var_j is the level j of cowpea variety, A_k is level k of the year, R_{ijkl} is the residual, and aF_i, $bVar_j$, cA_k are coefficients of fixed effects. Significant effects were analyzed using ANOVA. The comparison of means was done using the LSD (least significant difference) test at the 5% threshold in case of significance.

3. Results

3.1. Fraction of transpirable soil water (FTSW)

FTSW was below the 0.5 threshold from planting to about 30 days after planting in 2018, and from planting to 5 days after planting in 2019, in the irrigated trial and in the rainfed trial, regardless of the levels of cropping system and fertilization. Only in 2019 in the irrigated trial with fertilization, FTSW was above 0.5 for millet intercropped with cowpea fodder variety during the five days after planting whereas it was below the threshold during the same period for sole millet and millet intercropped with cowpea grain variety (Fig. 1). In the irrigated trial, FTSW then remained above 0.5 throughout the reproductive phase (from flowering to maturity). In the rainfed trial, FTSW was below 0.5 during most of the reproductive phase in 2018, indicating possible water stress. In the rainfed trial, the stress endured by the crop, as indicated by FTSW, expanded over a longer period and reached more severe levels in the year 2019 compared to 2018 during the reproductive phase. Overall, water stress as experienced by the crop was, from lowest to highest: 2019 in the irrigated trial, 2018 in the irrigated trial, 2018 in the rainfed trial, 2019 in rainfed trial.

3.2. LAI, aboveground biomass and millet yield with sole- and inter-cropping

Millet average maximum LAI did not differ significantly between cropping systems (Table S1). In the irrigated experiment, it was significantly impacted by the year, and in the rainfed experiment by fertilization and year (Table S1).

Millet aboveground biomass was significantly affected by cropping system in the irrigated trial, and by cropping system*year interaction, in both rainfed and irrigated experiments (Table S1, Fig. 2C & D). Millet aboveground biomass with intercropping was higher than with sole cropping, with no significant difference between the two intercropped cowpea varieties. With irrigation, millet aboveground biomass (averaged across fertilizer treatments and years) was 8200 kg ha-^{1} with sole cropping, and 10059 kg ha^{-1} when intercropped with cowpea (Fig. 2A), i.e. corresponding to a 23% increase in aboveground biomass. In addition, millet aboveground biomass in the irrigated experiment was also significantly impacted by fertilization: millet aboveground biomass (averaged across cropping system treatments and years) was 8167 kg ha-^{1} with f0 and 10712 kg ha-^{1} with f1, corresponding to a 31% increase in aboveground biomass. In the rainfed trial, millet aboveground biomass was not significantly affected by cropping system alone (Fig. 2B), but the gains with intercropping were higher in 2018 than in 2019, regardless of the cowpea variety intercroppped (Fig. 2D). Cropping system * fertilization interaction was not significant: gains in millet aboveground biomass with intercropping were observed independently of fertilization, in both irrigated and rainfed conditions, when averaged across the two experimental years (Fig. 2E & F).

In the irrigated experiment, grain yield of millet was significantly affected ($p < 0.05$) by cropping system, by the interaction between cropping system and fertilization, and by the interaction between year and fertilizer (Fig. S5): millet grain yield (averaged across cropping systems) was 60% greater with fertilizer input in 2019, and 5% smaller with fertilizer in 2018. Millet grain yield was also significantly impacted by the interaction between cropping system and fertilization (Table S1, Fig. 3E), but not by the interaction between cropping system and year (Table S1, Fig. 3C). Millet intercropped with grain cowpea produced significantly more grain (2275 kg ha^{-1} on average across fertilizer treatments and year) than millet intercropped with fodder cowpea (1992 kg ha^{-1}) and sole millet (1572 kg ha^{-1}) (Fig. 3A). The gain in millet grain productivity with intercropping was greater with fertilization than without fertilization, regardless of the cowpea variety used (Fig. 3E). In the rainfed experiment, cropping system did not significantly impact millet yield, nor did the interaction between cropping system and year and fertilization (Figure B & D & F). Grain yield was significantly affected by fertilization. Millet grain yield was 748 kg ha^{-1} with f0 (averaged across cropping systems and year) and 1423 kg ha^{-1} with f1 (averaged across cropping systems and year), corresponding to a 90% increase in yield.

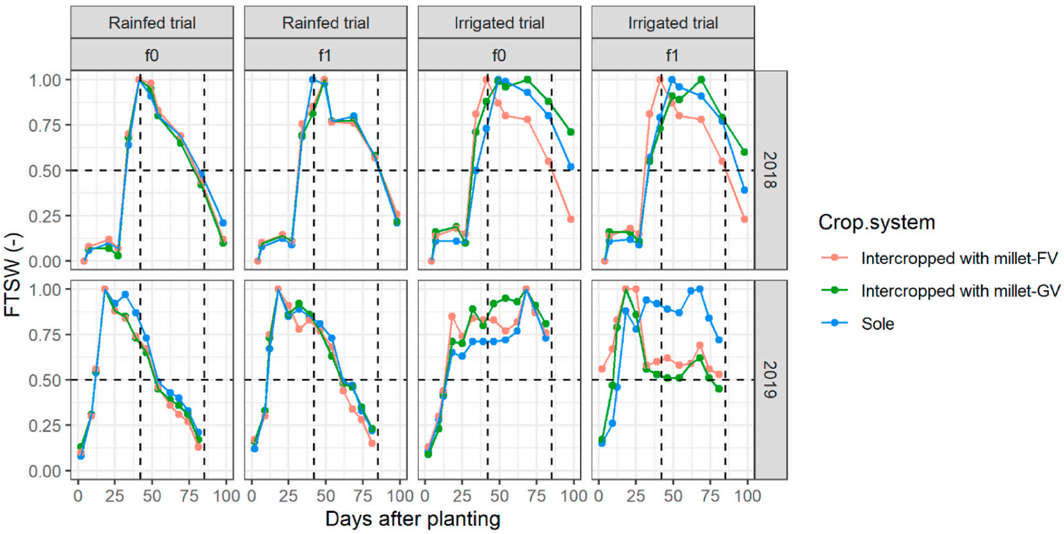

Fig. 1. Fraction of transpirable water (FTSW) in 2018 and 2019 in irrigated and rainfed experiment of sole and intercropped experimental plot. GV = cowpea grain variety, FV = cowpea fodder variety. f0 = without fertilization, f1 = fertilization. Vertical lines show from left to right, flowering (assume to occur 42 days after planting) and physiological maturity (assumed to occur 85 days after planting). The horizontal line is the 0.5 threshold for FTSW indicating potential water stress for millet.

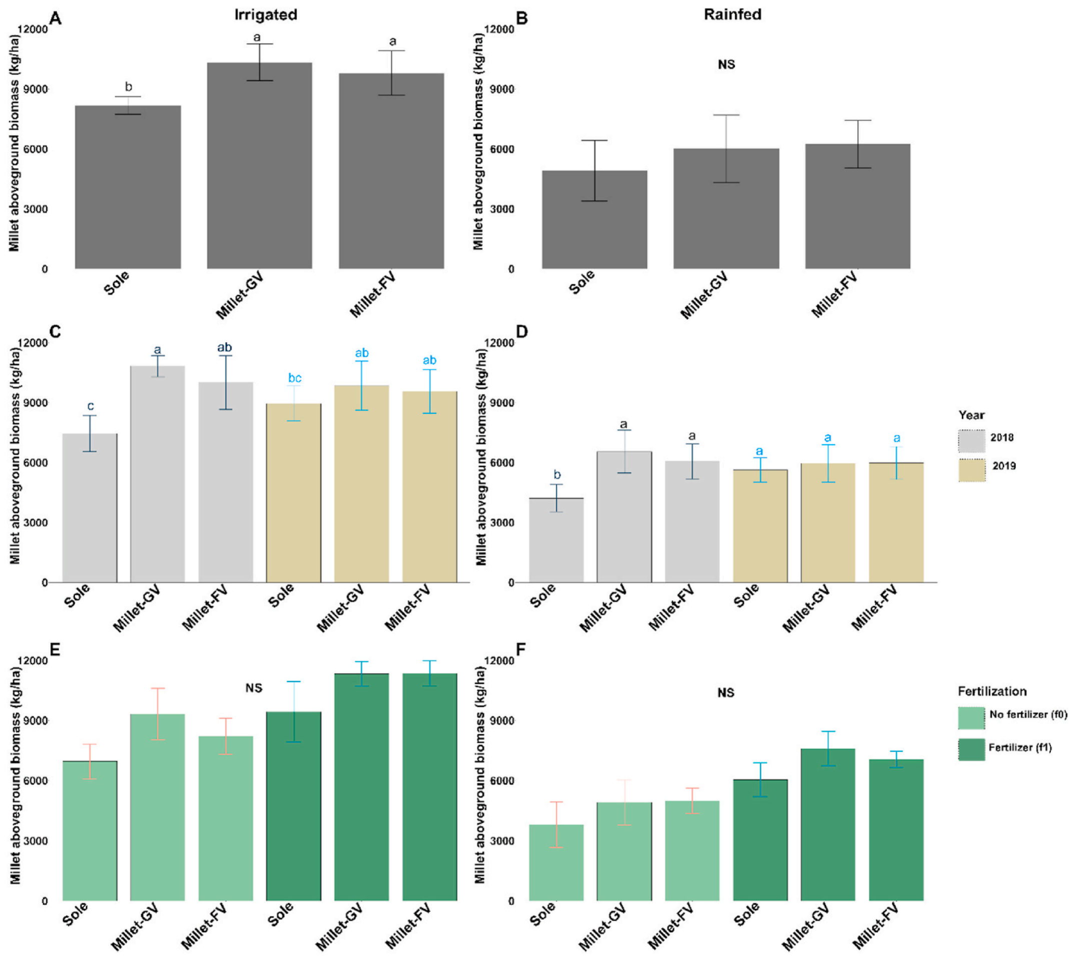

Fig. 2. Millet aboveground biomass at harvest per cropping system (averaged across years and fertilizer treatment, A, B), for cropping system × year interaction (averaged across fertilizer treatments, C, D) and for cropping systems × fertilizer interaction (averaged across years, E, F) in irrigated (A, C & D) and rainfed (B, D & E) fields. GV = cowpea grain variety, FV = cowpea fodder variety, NS: non-significant. Error bars are standard deviations. Averages and standard deviations were computed from the raw data. Treatments with different letters were significantly different ($P < 0.05$).

3.3. LAI, biomass and cowpea yield

Regardless of cowpea variety, the year and the cropping system significantly impacted the maximum LAI of cowpea in the irrigated trial (Table S2): maximum LAI (averaged across cropping systems) was 3.5 in 2018 and 2.8 in 2019, and 4.4 in sole cropping and 2.5 in intercropping (averaged across years).

Cropping system significantly ($P < 0.05$) impacted cowpea aboveground biomass (Fig. 4A and B) and grain yield (Fig. 5A and B) in irrigated and rainfed experiments (Table S2). Intercropping with millet strongly decreased cowpea yields compared to sole cropping. For example, in the irrigated experiment, fodder cowpea (FV) aboveground biomass was 5282 kg ha^{-1} with sole cropping and 624 kg ha^{-1} with intercropping (averaged across years), corresponding to a 90% decrease in aboveground biomass. For grain cowpea (GV), it was 3404 kg ha^{-1} with sole cropping and 322 kg ha^{-1} when intercropped with millet (averaged across years), also corresponding to a 90% decrease in aboveground biomass. The interaction between cropping system and year was also significant (Table S1 and Fig. 4C & D), probably because cowpea sole aboveground biomass was smaller in 2019 than in 2018.

With irrigation, sole cowpea aboveground biomass was significantly lower for the grain variety than for the fodder variety (Fig. 4A). In contrast, sole cowpea grain yield was significantly higher for the grain variety than for the forage variety (Fig. 5A). In the rainfed experiment, cowpea variety did not have a significant impact on total aboveground biomass and grain yield of sole cowpea (Figs. 4B and 5B).

The interaction between cropping system and year significantly affected cowpea aboveground biomass and grain yield in the irrigated and rainfed experiments (Table S2): the decrease in cowpea grain yield (grain variety) with intercropping was greater in 2019 than in 2018 (Fig. 5C and D). In the rainfed experiment, sole cowpea grain yield in 2019 was very low, and equivalent to cowpea grain yield in the intercropping (Fig. 5D). For grain yield of cowpea, no significant effect of variety was observed in the rainfed and the

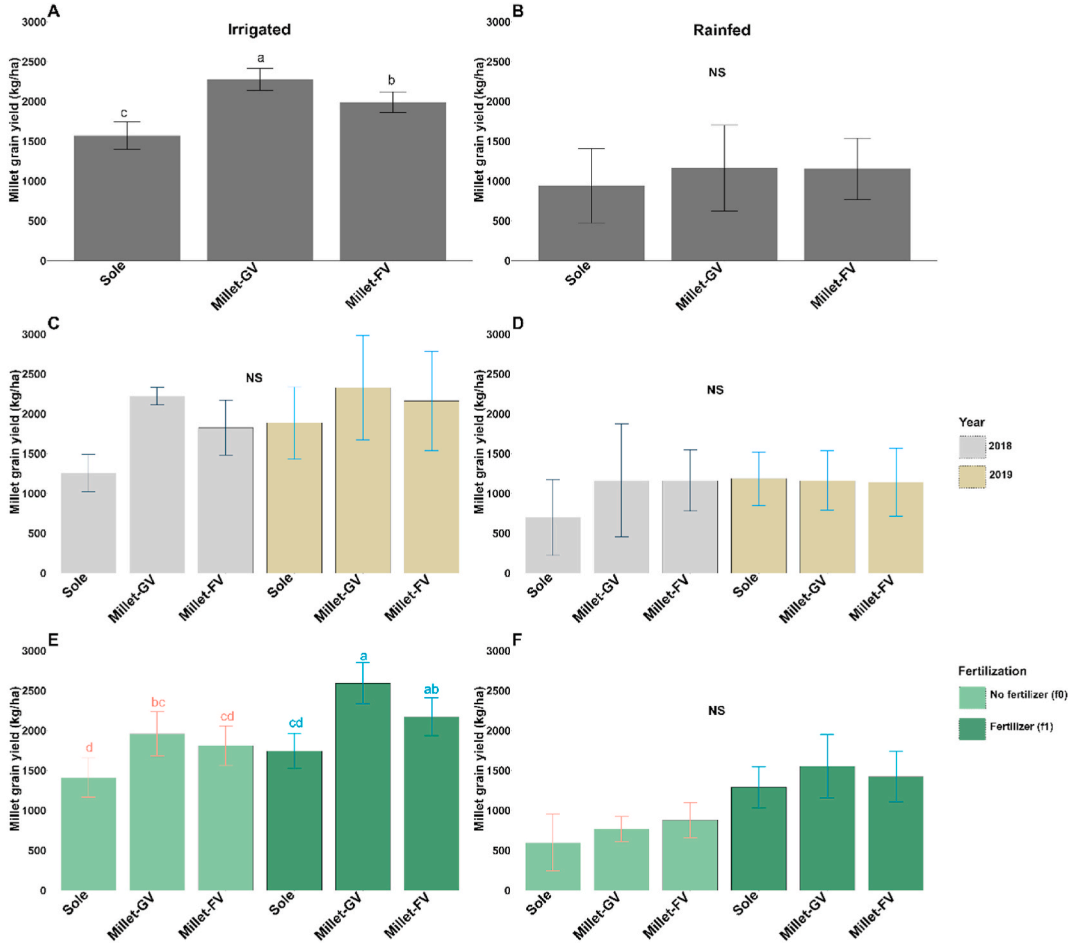

Fig. 3. Millet grain yield at harvest per cropping system (averaged across fertilizer treatments and year, A, B), for cropping system × year interaction (averaged across fertilizer treatments, C, D) and for cropping system × fertilizer interaction (averaged across years, E, F) in irrigated (A, C & D) and rainfed (B, D & E) fields. GV = cowpea grain variety, FV = cowpea fodder variety, NS: non-significant. Error bars are standard deviations. Averages and standard deviations were computed from the raw data. Treatments with different letter were significantly different ($P < 0.05$).

irrigated experiment.

3.4. Land equivalent ratio

LER for grain yield and aboveground biomass was always above one, regardless of the type of experiment (irrigated vs rainfed), and regardless of the experimental factor, i.e. year, fertilization and cowpea variety (Fig. 6).

Millet pLERs for grain yield (from 0.91 to as high as 3.23) and aboveground biomass (1.03–1.77) were close to- or greater than one, while cowpea pLERs ranged from 0.02 to 0.71 for grain yield and 0.05 to 0.30 for aboveground biomass, and was often below the relative density of cowpea in the intercropping compared with sole cropping (12.5%). Year significantly impacted LER for grain and aboveground biomass ($p < 0.05$): LER was overall greater in 2018 (Fig. 6). Other factors, cropping system and fertilization, did not significantly impact LER for grain yield and aboveground biomass.

4. Discussion

4.1. Millet yield increased with intercropping

Across treatments, millet aboveground biomass and grain yield were greater when intercropped with cowpea than with sole cropping in the irrigated experiment but not in the rainfed experiment. This does not support our initial hypothesis that the benefit of intercropping would be maintained in the case of water stress. In their review of the literature [27], found that intercropping with cowpea decreased millet yield for more than 75% of the 198 observations. Our study stands as an outlier with regard to the literature, though the review did not look into details at relative densities between the sole and intercrop cereal (i.e. the decrease in millet yield

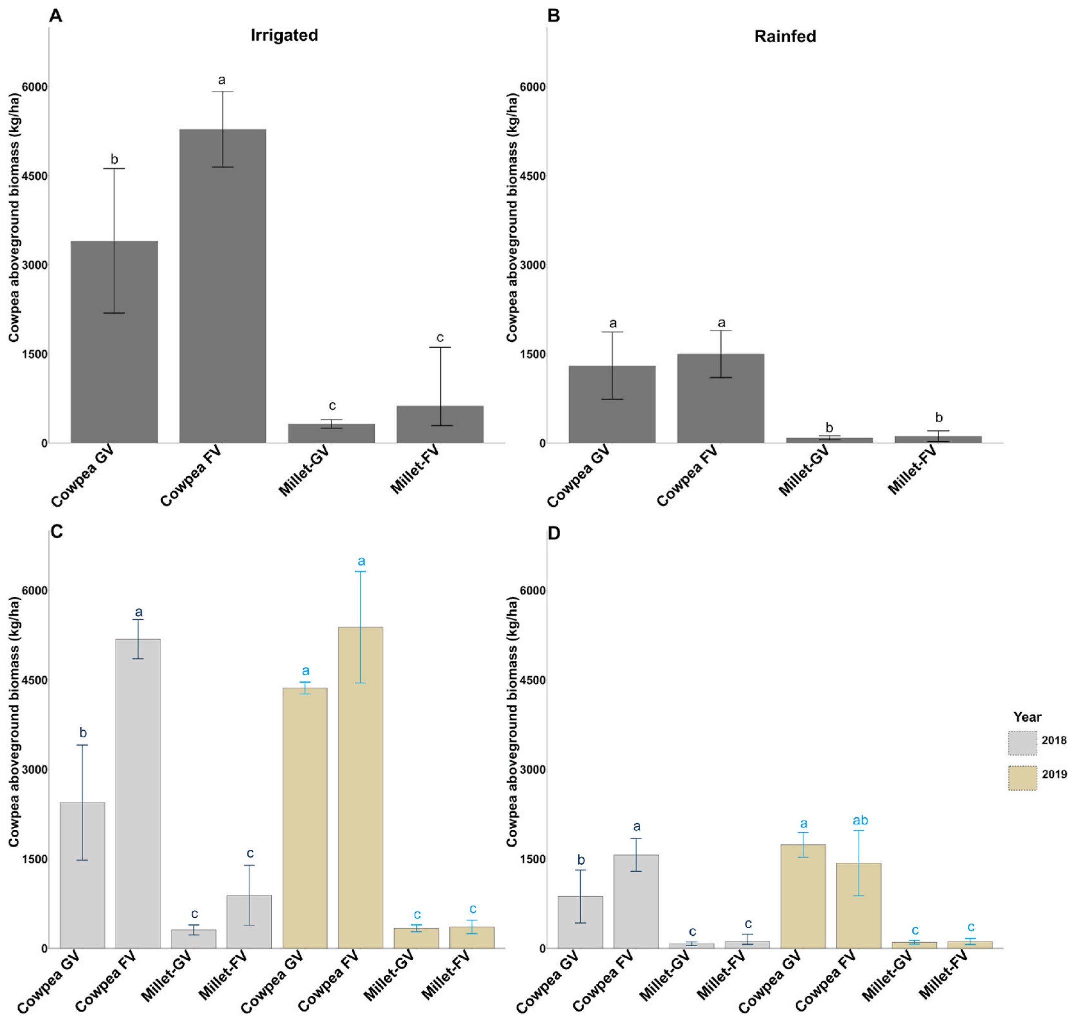

Fig. 4. Cowpea aboveground biomass at harvest per cropping system (averaged across fertilizer treatments and years, A, B) and for cropping system × year interaction (averaged across fertilizer treatments, C, D) in irrigated (A&C) and rainfed (B&D) fields. GV=Cowpea grain variety, FV= Cowpea fodder variety. Error bars are standard deviations. Averages and standard deviations were computed from the raw data. Treatments with the same letter were not significantly different ($P < 0.05$).

with intercropping could be primarily due to a decrease in cereal density and/or due to a higher cowpea density than in our study). Contrastingly, and similarly to our study, [28] found that millet yield increased by 17% when intercropped with cowpea, compared with sole millet at the same planting density, in a two-year experiment in Bambey, Senegal. In Niger [29], also found that millet yield increased by 4% when intercropped with cowpea, on average across three years of experiment. Because millet density was kept similar with sole and intercropping [in our experiment and in the study of Trail et al. (2016) and Reddy et al. (1992)], yield gains with intercropping indicated a facilitation for access of the cereal to either light and/or water and/or nutrients in the intercropping. There is little chance that the understory cowpea modified the light interception of the intercropped millet, because cowpea was smaller than millet allthrough the experiment (data not shown). Possibly, the groundcover brought by cowpea helped increase water infiltration and decrease soil evaporation, leading to better water availability for the crop. Such advantage is often claimed by promotors of intercroping as key to the agroecological intensification in SSA. However, the soil moisture monitoring data of this study do not support such claim. Another hypothesis could be the increased availability of nitrogen for the intercropped millet. This could arise from two processes: i) a direct transfer of belowground N from cowpea to millet [30,31] and ii) the modification of the rhizosphere microbial composition and diversity favoring soil organic matter mineralization and nitrogen availability [32], and nitrogen assimilation for the intercropped cereal [16,33,34]. [30] measured a direct transfer of around 2 kg (N) ha^{-1} in millet/cowpea intercropping. This small amount is unlikely to be responsible alone for the observed increase in millet aboveground biomass with intercropping in this study (that was 1.54 t/ha on average across treatments, i.e. an additional 25 kg (N)/ha accumulated by the intercropped millet, assuming a 1.6% N concentration in millet biomass) [33]. measured an increase in Proso millet N uptake of 5–6 kg (N)/ha when intercropped with mungbean (two rows of millet and two rows of mungbean), indicating a possible greater contribution of the modification of rhizosphere microbial composition to the increase in yield of the intercropped cereal. Overall, it is not impossible that

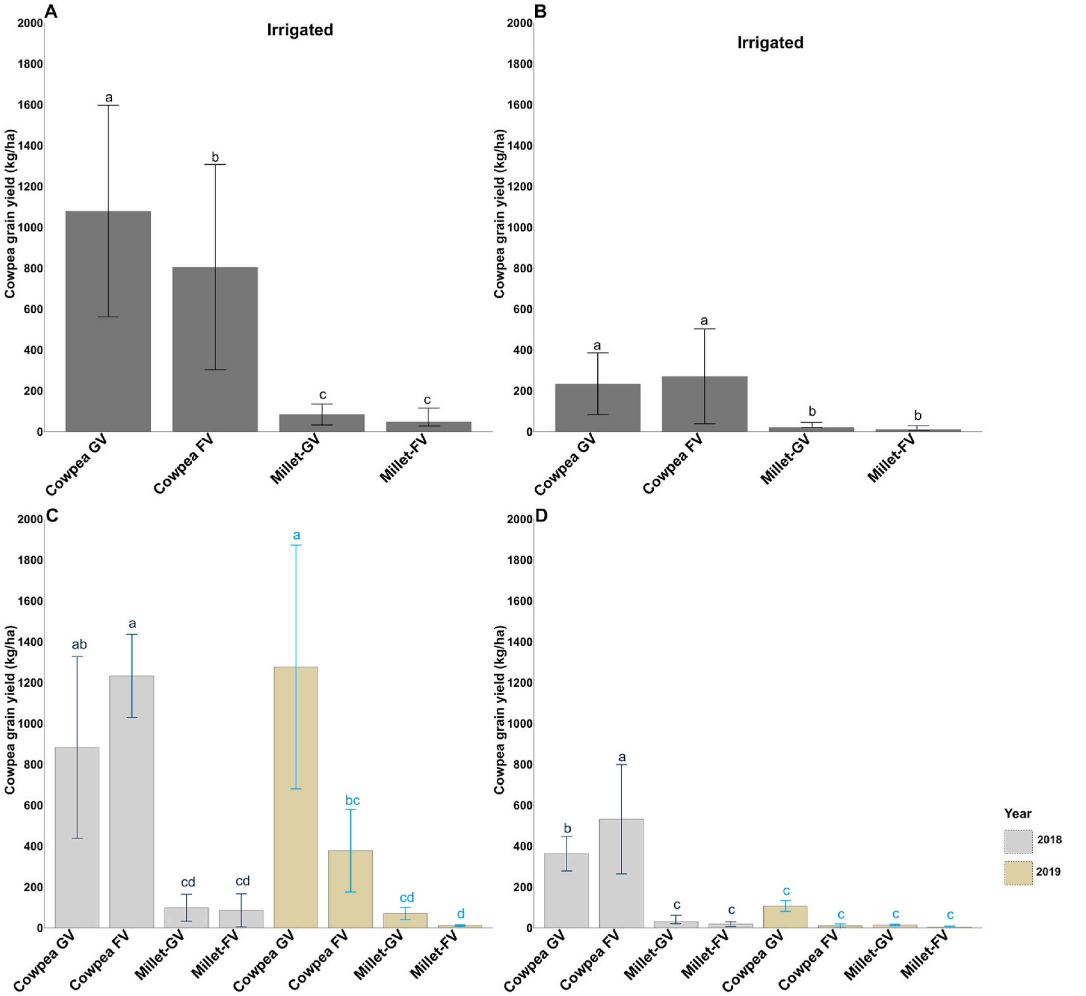

Fig. 5. Cowpea grain yield at harvest per cropping system (averaged across fertilizer treatments and years, A, B) and cropping system × year interaction (averaged across fertilizer treatments, C, D) in irrigated (A&C) and rainfed (B&D) fields. GV=Cowpea grain variety, FV= Cowpea fodder variety. Error bars are standard deviations. Averages and standard deviations were computed from the raw data. Treatments with the same letter were not significantly different (P < 0.05.

these two processes were responsible for the increase in millet yield with intercropping.

4.2. Cowpea yield decreased with intercropping but LER remained above one

Cowpea was sown at a much lower density in the intercropping compared to the sole crop, and cowpea yield always strongly decreased in the intercropping, consistently to what was found in 90% of milet/cowpea intercropping experiments across sub-Saharan Africa [27]. Partial LER of cowpea (0.09 on average across treatments and year for aboveground biomass, 0.11 for grain), was below the 12.5% relative density of cowpea in the intercropping compared with sole cropping. This indicated that cowpea did not benefit from the intercropping, and had its productivity decreased further than by the sole effect of reduction in density. This suggests that cowpea growth suffered from competition with millet for access to resources. Possibly, the shading of the taller millet plant reduced light available to the understorey cowpea.

Despite this strong reduction in cowpea yield with intercropping, and thanks to the increase in millet yield, LER for biomass and grain yield was always above one across year and experimental treatments, i.e. 1.4 for aboveground biomass and 1.6 for grain on average. This latter value is in the upper range of the values computed by Ref. [27] in their review of millet-cowpea intercropping experiments across sub-Saharan: average LER was 1.3 with standard deviation of 0.32.

4.3. Rainfall variability, fertiliser input and intercropping performance

In the rainfed experiment, gains in millet aboveground biomass thanks to intercropping were greater in 2018 than in 2019, and this

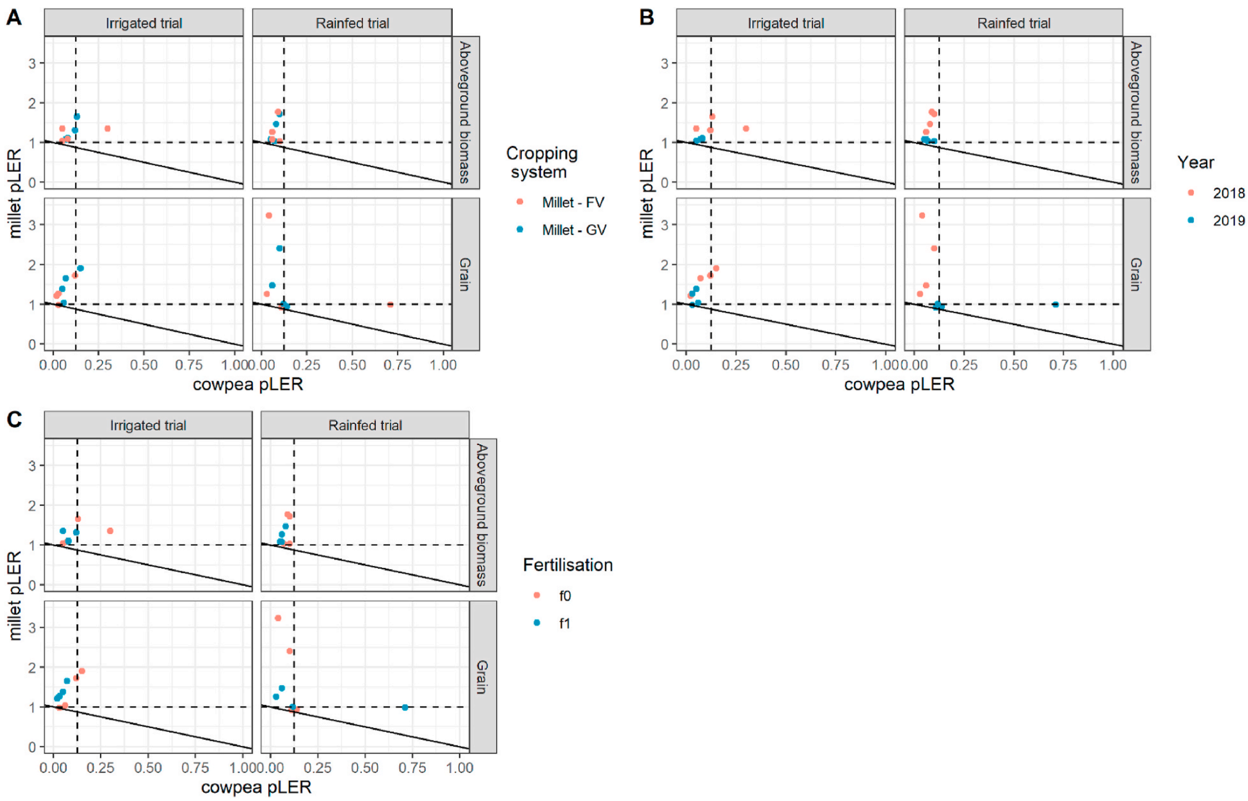

Fig. 6. Millet and cowpea partial LER for aboveground biomass and grain yield according to cropping system (A), year (B), and fertilization (C) in the irrigated and rainfed trial. f0 = no fertilization, f1 = fertilization, GV = cowpea grain variety, FV = cowpea fodder variety. The horizontal dotted line is millet relative density (100%) in the intercropping compared with sole cropping. The vertical dotted line is cowpea relative density in the intercropping compared to sole cropping (12.5%).

may be related to the higher intensity and duration of water stress during the crop cycle in 2019 compared to 2018. This would align well with our hypothesis that higher N availability for millet drove the gains in millet aboveground biomass in the intercropping: millet would have benefited less of this additional nitrogen when low water availability limited photosynthesis during flowering and grain filling. However, aboveground biomass of sole millet was smaller in 2018 than in 2019 in the rainfed experiment, which is not consistent with this hypothesised impact of water stress.

Fertilizer input, though significantly increasing millet aboveground biomass in both experiments, did not interact significantly with the cropping system: the benefit of intercropping on millet aboveground biomass and grain yield was similar across treatments with inputs of 0 kgN ha^{-1} and 69 kgN ha^{-1}. This finding is in line with the study of Baldé et al. (2020) that showed no significant effect on maize aboveground biomass of the interaction between intercropping and fertilizer input. In our experiment, the mineral fertilizer input of 69 kg N ha^{-1} was possibly not sufficient to fully alleviate crop nitrogen stress, so that the possible effect of cowpea on N availability still benefited millet growth. With regard to grain yield, the effect of fertilization interacted significantly with the cropping system in the irrigated experiment: the benefits of intercropping on millet grain yield were greater with 69 kg(N) ha^{-1} than with 0 kg (N) ha^{-1} (Fig. 3E). These results of positive impact of intercropping even at greater N input levels confirm the second hypothesis of the introduction section, and are consistent with the study from Gong et al. (2021): the authors measured a greater response of the cereal to increasing amounts of N with intercropping than with sole cropping, with no more positive effect of intercropping when N input was greater than 180 kg N/ha. Contrastingly, [35] suggested that the increase in fertilizer input favored the growth of the cereal at the expense of the understory legume and the overall positive interaction between intercropping and fertilization, leading to lower LER when fertilization increased.

Intercropping had no significant impact on millet yield under rainfed conditions in our study, whereas fertilisation had a strong impact close to 100% increase. Under irrigated conditions the positive impact of intercropping on millet yield was close to 33% whereas no significant effect of fertilisation was observed. This suggests complex interactions between water stress, N availabilituy and light reaching the understorey crop, and these processes were not completely captured in our experimental design. Furthermore, the effect of fertilizer identified in this study should be interpreted with care as there might also be some other difference between the fertilized and non-fertilized blocks that could be confounded with the effect of fertilizer on crop growth. In pedo-climatic conditions similar to that of this study, studies abound with evidence of a strong positive effect of N input on millet (or other cereal), and such effect could be as high as 500% depending on water stress and inherent soil N availability without N inputs [see e.g Refs. [36,37]]. In constrat, reports of the positive impact on cereal yield of intercropped legume rarely exceeded 50% [27].

4.4. Avenues to understand better the contribution of intercropping to sustainable intensification

Cereal-legume intercropping had, on average, a LER value above one, indicating that this management strategy can contribute to increasing crop productivity on current cropland, thus helping to avoid further cropland expansion at the expanse of natural areas. This "land sparing" strategy is vital to preserve the uncultivated savanna areas that are so essential for carbon sequestration [38] and biodiversity conservation [39]. However, climate inter-annual variability challenges the ability of intercropping to be a meaningful strategy for sustainable intensification; LER for aboveground biomass was greater with less water stress (as in 2018) than in the more water constraining conditions of 2019, where LER was close to one, meaning limited advantage of intercropping over sole cropping. Field experiments are crucial to measure and understand the interplay between rainfall variability and intercropping performance. However, they only provide a meagre sample of possible growing seasons, and are very costly to implement if designed to unravel the interactions between water stress, N availability for plants in relation to soil microbionte and N fixation by the legume. Long-term experiments on intercropping are currently rare [40] and challenging to maintain over time. Recent advance in crop model development and calibration for cereal-legume intercropping [15,41] offers the prospect to investigate in details the impact of historical (and possibly future) climate variability on intercropping performance. Our current work is focused on using the experimental data of this study to calibrate a soil/crop model to explore the impact of climate inter-annual variability on intercropping performance.

5. Conclusion

This two-year experiment in central Senegal confirms a widely published and acknowledged behavior of cereal-legume intercropping in the savannahs of sub-Saharan Africa: LER was above one across experiments (irrigated vs rainfed), treatments (fertilizer input and cowpea variety), and growing seasons. Interestingly, this advantage was obtained mainly through an increase in millet yield with intercropping, a feature that was seldom reported, but can be backed-up by recent evidence that the presence of a legume can increase nitrogen availability for the cereal.

Inter-annual variability of rainfall did play a role: the intercrop performed better in less water constraining conditions of 2018, suggesting not to take as granted the claim that intercropping could be a relevant entry point for adaptation to climate variability and change. The equally good performance of intercropping with low and (relatively) high N input indicate that this strategy is also compatible with integrated soil fertility management and sustainable intensification strategies. Climate variability goes beyond the two years of this experimental work. Before long-term experiments are available, investigating the impact of climate inter-annual variability with the use of crop models can help further detail our understanding of the performance of intercropping in the face of climate change. Such analysis is critical for the careful desing of tailored cropping systems that will help smallholder farmers of central Senegal (and those who share a similar environment across SSA) improve their livelihoods in the face of climate variability and change.

Author contribution statement

Yolande Senghor: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Alpha B. Balde; Cesar Bassene: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Anicet G.B Manga: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

François Affholder: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Philippe Letourmy; Antoine Couedel; Louise Leroux; Gatien N. Falconnier: Analyzed and interpreted the data; Wrote the paper.

Ghislain Kanfany; Malick Ndiaye: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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