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Testing pearl millet and cowpea intercropping systems under high temperatures

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ABSTRACT

With the potential threat of more frequent climate extremes putting semi-arid crop production in jeopardy, there is a need to establish more climate resilient cropping practices. Intercropping is often practiced by farmers in semi-arid regions and is perceived as a risk reducing practice. However, there is little knowledge of how and to what extent it can be a viable option under future conditions. As testing a complex adaptation strategy in controlled environments is difficult, conducting field experiments in the dry season offers opportunities to test cropping systems under extreme but real-world conditions. Consequently, a field trial was run in semi-arid India over a two-year period (2015 and 2016) in the dry and hot (*summer*) season. These trials were set up as a split-split-plot experiment with four replicates to assess the performance of simultaneously sown sole versus intercropped stands of pearl millet and cowpea, with two densities (30 cm and 60 cm spacing between rows - both with 10 cm spacing within rows), and three water treatments (severe stress, partial stress, and well-watered) applied with drip irrigation.

Results showed that intercropping pearl millet led to a significantly lower total grain yield in comparison to the sole equivalent. Pearl millet's highest yields were 1350 kg ha^{-1} when intercropped and 2970 kg ha^{-1} when grown as a sole crop; for cowpea, 990 kg ha^{-1} when intercropped, and 1150 kg ha^{-1} as a sole crop. Interestingly, even when maximum daily temperatures reached up to 42.2 °C (on Julian day 112 in 2016), well-watered, pearl millet produced reasonable yields. Cowpea yields were often lower than 1000 kg ha^{-1}. Only under the highest irrigation treatment (well-watered) sole cropped, low density were yields of 1150 and 1110 kg ha^{-1} achieved in 2015 and 2016, respectively. We conclude that successful intercropping systems must be highly specific to conditions and demands. More research would be needed to identify suitable cowpea genotypes and planting densities that could allow for higher intercropped pearl millet yields.

1. Introduction

Intercropping is an important crop production strategy for smallholder farmers, as it can lead to productivity improvements per unit of land when compared with those of sole cropping systems (Vandermeer, 1989). For instance, Rusinamhodzi et al. (2012) presented an example of this where intercropping maize with pigeonpea led to more than a threefold increase in financial return compared with sole maize on smallholder farms in Mozambique. Explanations for the benefits of intercrop systems are typically related to at least one of the following three factors (Brooker et al., 2015): First, complementary use of resource niches, especially in terms of the different rooting behaviour of crops. As an example, intercropping has been found to enhance root-length density in subsoil (Schröder and Köpke, 2012). Secondly, the combination of different crops can result in better system protection against pests and diseases. A classic example is the widely promoted 'push-pull' system in eastern Africa (Cook et al., 2007). Thirdly, intercropping leads to the development of a more complex canopy structure that can help to generate a more favourable micro-climate, which could potentially reduce soil moisture evaporation (Harris et al., 1987; Tsubo et al., 2004). Harris et al. (1987) presented an interesting example for this third factor based on sorghum/groundnut intercropping experiments conducted on the ICRISAT Research Station, Patancheru, India. Increases in groundnut pod weight per plant were found in intercropped stands, especially under drought conditions, which were to some extent due to shading and cooling effects of sorghum on groundnut.

Recent studies have highlighted areas of India that have become

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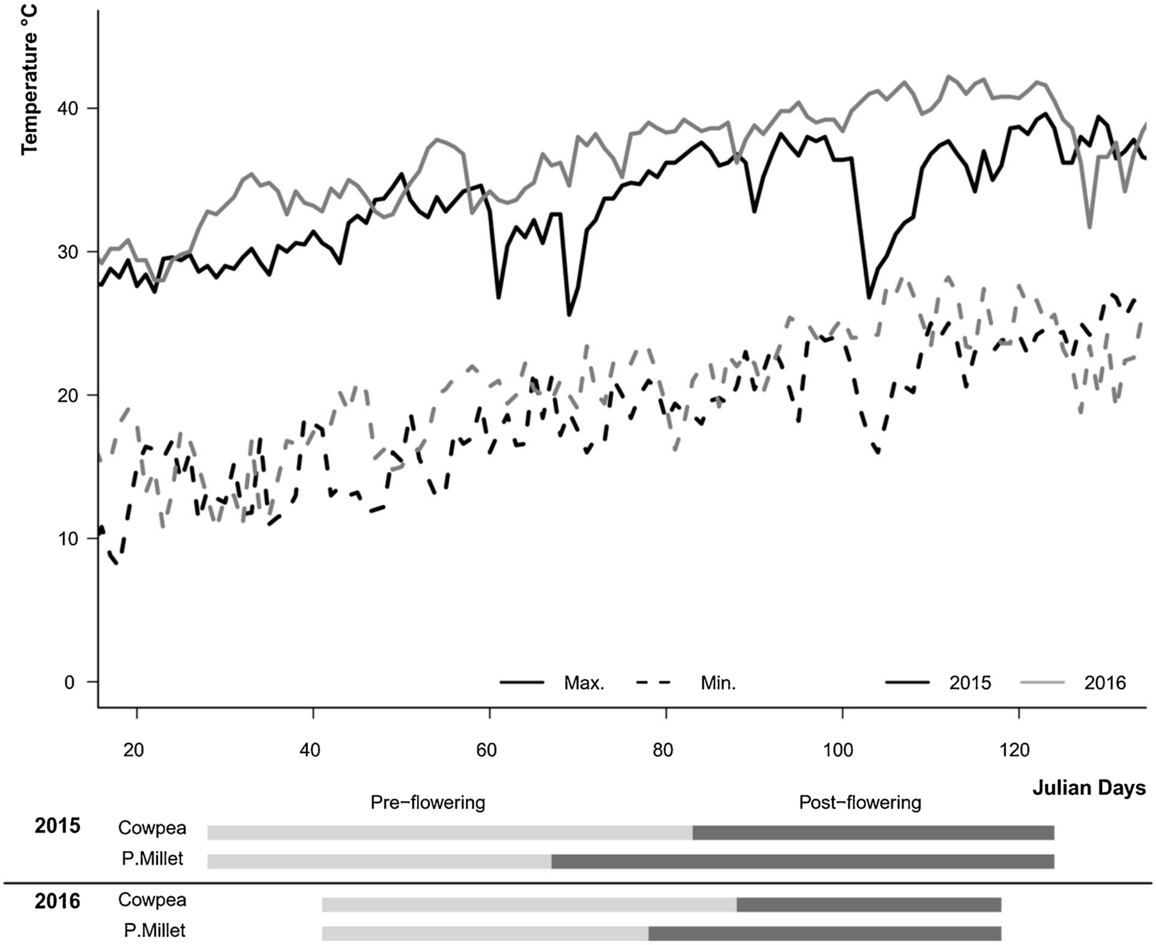

Fig. 1. Daily maximum and minimum temperature and physiology timeline 2015 and 2016. Solid lines represent the daily maximum temperatures and dashed lines the minimum. Development phases of both cowpea and pearl millet are presented for both years separately. Horizontal bars filled in light grey (below the plot) represent the time from germination to the completion of flowering of both crops. The following grain/pod filling to final harvest stage is shown through the dark grey bars.

increasingly drought-prone, leading to a decline in cereal production (Nath et al., 2017). Intercropping could therefore be an interesting option for farming in dryland areas with large variability in precipitation, resulting in potentially high climate-induced risk. Observations show and climate models project a higher frequency of extreme weather events, such as heat waves, droughts, or heavy rains, causing reductions in crop yields and putting food security under further strain (Coumou and Rahmstorf, 2012; Rummukainen, 2012).

Climate models project that large areas of the sub-tropics, including the Indian subcontinent in particular, will experience drying through precipitation decline (Chadwick, 2016; He and Soden, 2016), highlighting the need for robust, climate smart crop production strategies.

Experimentation under controlled conditions, such as in climate chambers and greenhouses, could offer valuable insights into stress physiology and plant reactions in relation to a variety of high temperature and limited water supply scenarios. However, it is arguably difficult to properly test more complex strategies like intercropping under controlled conditions. With this in mind, a pearl millet/cowpea intercropping trial was conducted within the dry (Rabi) season, which typically runs from October to March. The trial ran from January to May over two years in Telangana, India. Little to no precipitation during the growth period and high temperatures of up to 42.2 °C - compared with observed maximum temperatures of 36.5 °C during the main (Kharif) cropping season (taken from a period of July to October, 1980–2010) - mimic harsher climate conditions. Intercrop performance is, to a large extent, determined by resource competition between plants and therefore cropping density. Relatively low densities are often used in low rainfall regions (Dadson et al., 2005) due to better performance and lower risk, for example through the requirement of less seed in comparison to higher density stands. We doubled the locally used density (60 cm between row spacing, known as low density in this experiment) to have a comparable high density treatment. Finally, we controlled water supply to quantify the amount needed to achieve reasonable yields independent of cropping system (sole vs intercrop) and density. A fundamental aim of the experiment was to identify cropping system adaptation strategies for harsher climate conditions than those of the current key cropping seasons.

2. Materials and methods

2.1. Study site

The trial was conducted at the ICRISAT Research Station, Patancheru, India (17.25 ° N, 78.05 ° E, Altitude: 545 m). The climate of the region is semi-arid tropical with annual rainfall averaging 910 mm (taken from a period of 1980–2010). The year is divided into five climatic seasons: a dry season (January to March, 37 mm), a pre-rainy season (April to May, 56 mm), a rainy season (June and September, 681 mm), a post-rainy season (October to November, 127 mm), and a post-rainy dry season (December, 5 mm) (Virmani et al., 1982; ICRISAT-India, Patancheru Weather Station Records 1980–2010). Our field trials were conducted across two seasons. Planting took place in late January/early February, and harvesting in early May. Both experiments were conducted on the same piece of land, of which the

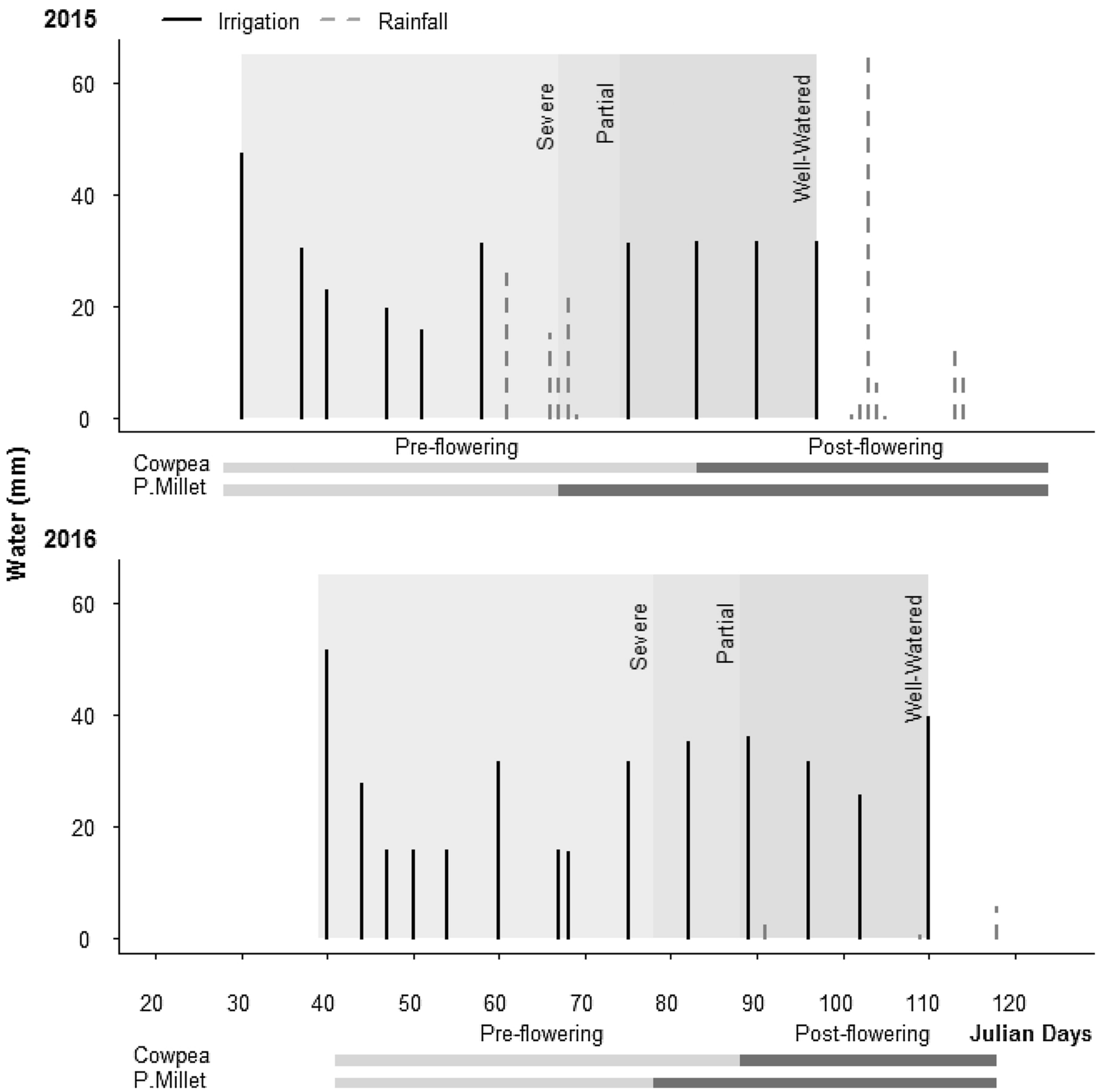

Fig. 2. Water supply and physiology timeline 2015 and 2016. Vertical bars represent the amount and type of water supplied to each treatment. Solid bars represent irrigation water applied, and dashed lines in light grey represent precipitation. The large blocks of grey (in three different shades) represent the days, from and to, in which the irrigation treatments were applied. The treatments were, Severe stress, Partial stress, and Well-watered. Horizontal bars filled in light grey (below each plot) represent the time from germination to the completion of flowering of both crops. The following grain/pod filling to final harvest stage is shown through the dark grey bars.

characteristics, according to Bhattacharyya et al. (2016), were as follows: 79.3% sand, 6.4% silt, and 14.3% clay, with organic carbon in the top soil at 0.55 and the pH 6–7.

2.2. Climatic conditions during the trial periods

The daily mean temperature over the trial period in 2015 was 26.1 °C, with 39.6 °C (Julian day 123) and 11 °C (Julian day 35) the maximum and minimum daily temperatures, respectively. In 2016, the daily mean temperature was 29.7 °C over the trial period, with 42.2 °C (Julian day 112) and 14.8 °C (Julian day 49) the maximum and minimum daily temperatures, respectively. Information on daily temperatures (max. and min.), rainfall and irrigation, and solar radiation is shown in Figs. 1, 2 and A3 (appendix), respectively.

2.3. Experimental design

The experiment was set-up as a split-split plot design. Three cropping systems were grown within each density: sole pearl millet, sole cowpea, and intercropped pearl millet and cowpea (Fig. 3). Each plot type (three irrigation treatments, two densities, two systems, and two crops) had four replicates, which led to a total of 72 plots. Two low density pearl millet border rows (1.8 m across) were planted between each irrigation treatment to minimise border effects.

All plots were irrigated using drip irrigation on a weekly basis. The mean weekly irrigation application was 28 mm in both years. Three irrigation treatments were applied once every Monday morning, according to the following: severe stress (317 mm in 2015 and 267 mm in 2016 total water supply; this treatment stopped water supply as pearl millet flowered), partial stress (348 mm in 2015 and 334 mm in 2016 total water supply; this treatment stopped water supply as cowpea flowered), and well-watered (442 mm in 2015 and 399 mm in 2016 total water supply). Irrigation supply was conducted taking rainfall events into account. If it rained the day before the planned irrigation, the following morning's irrigation supply was reduced by the amount of rain the experimental site received to ensure comparability between the two years.

Consequentially, within each irrigation treatment two densities

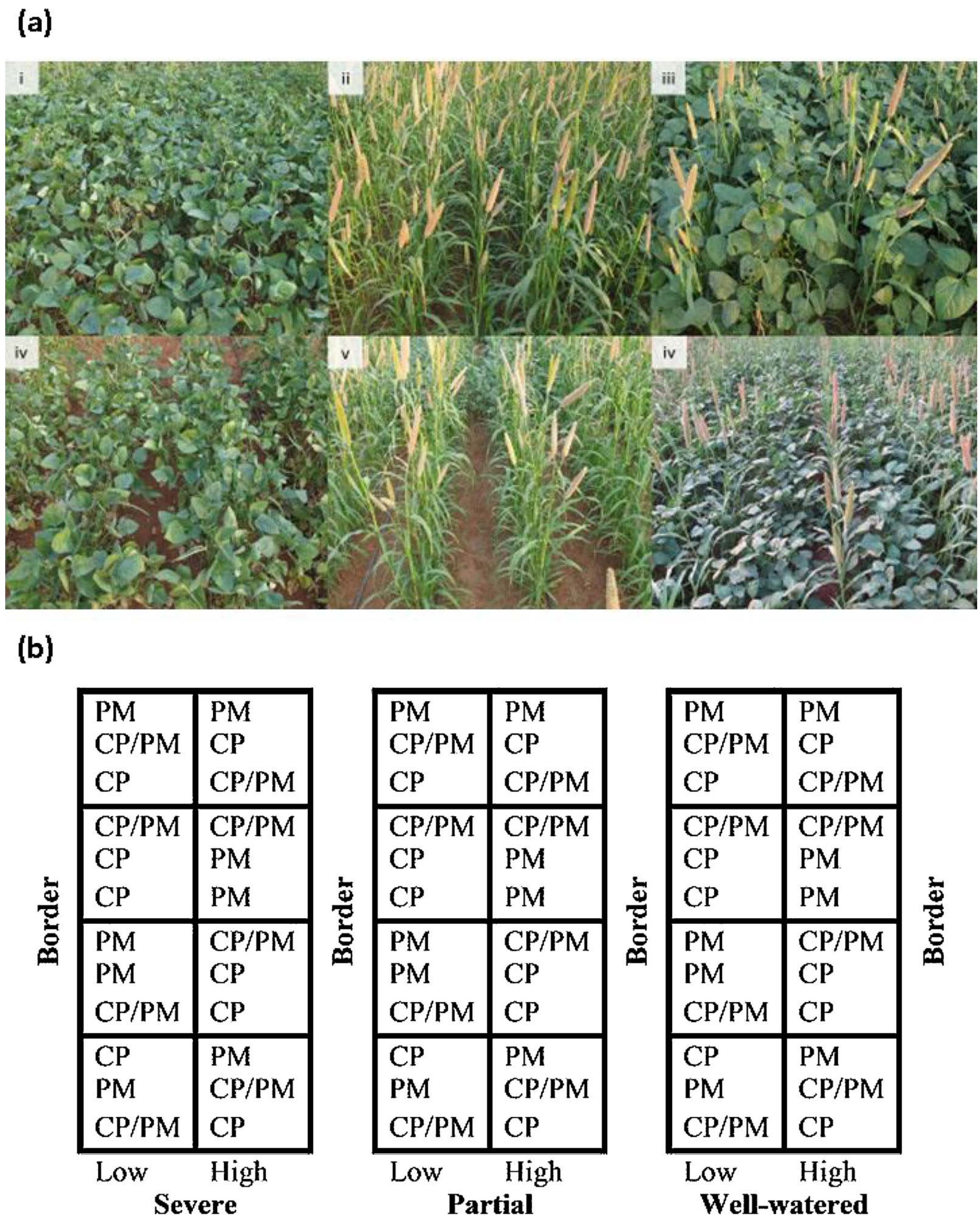

Fig. 3. Plot type (a) and experimental design (b). (i) High density sole cowpea, (ii) High density sole pearl millet, (iii) High density pearl millet and cowpea intercropping, (iv) Low density sole cowpea, (v) High density sole pearl millet, and (vi) Low density pearl millet and cowpea intercropping. Part two (b) of the figure illustrates how the experiments were set-up, highlighting treatment (Severe stress, Partial stress, Well-watered), densities (Low, High), plot type (PM = pearl millet sole, CP = cowpea sole, and CP/PM = cowpea and pearl millet intercropping). Substantial borders were used so that irrigation applications did not mix.

were sown of all cropping systems (as described above): low density at 17 plants/m^2 (60 cm between row spacing), and high density at 33 plants/m^2 (30 cm between row spacing) - within row spacing was 10 cm throughout.

Sowing was conducted by hand on 30/01/2015 and 02/02/2016. An erect forage cowpea cultivar (Russian Giant), and short pearl millet hybrid cultivar (H77/833-2, ICRISAT breeding programme) were used. These two cultivars were chosen as they are commonly used in the region as a cover crop (cowpea) and a popular hybrid grain crop (pearl millet). Soil was fertilised with 100 kg ha^{-1} of Di-Ammonium Phosphate (DAP = 18% N + 46% P2O4) before sowing, as well as 100 kg ha^{-1} of urea nitrogen to pearl millet as a top dressing once plots were well established.

2.4. Plant and soil sampling

Sequential and final biomass harvests were conducted by hand at pearl millet flowering, cowpea flowering as well as two weeks after the cowpea flowering harvest (Figs. A1 and A2 appendix). With 50 cm borders at each end (length ways within the row), harvests consisted of 50 cm of biomass of every plot row, except one border row on either side of the plot. These harvests involved scanning the leaves of four individual plants per plot to obtain the leaf area (data not presented here), as well as dried biomass weights of plant parts separated into leaf, stem, flower, and pod (cowpea) or tiller (pearl millet).

The only difference between the 2015 and 2016 seasons was that plots, and therefore sample size, were larger in 2016. In 2015, each plot was 5 m long and 2.4 m wide. In 2016, each plot was 5 m long and 3 m wide. One metre in length for all rows, excluding the two outer most rows (border rows), was used for the final harvest sample.

Pearl millet plants were threshed and cowpea pods opened to obtain the true yield of each plot before being weighed. The remaining biomass was dried in ovens at 60 °C for 48 h and weighed.

Leaf Area Index (LAI - Figs. A3 and A4 appendix) was calculated using an AccuPAR LP-80 to measure potential (above canopy) and actual (below canopy/on the soil surface) light interception for each plot.

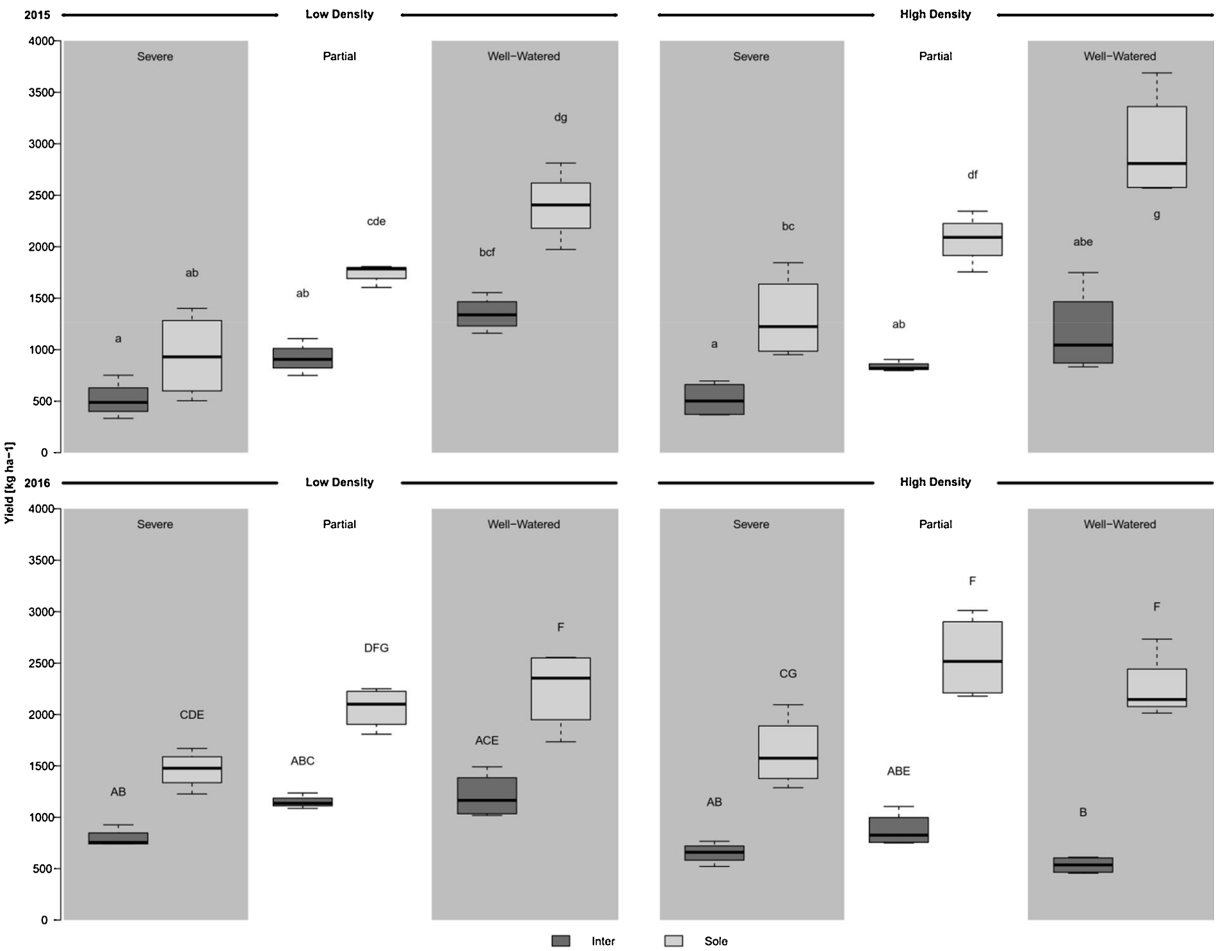

Fig. 4. Pearl Millet Yield 2015 and 2016. The top half of the figure illustrates yield data from 2015, and bottom half that of 2016. This is the same for density, with low density results on the left-hand side of the figure and high density on the right. Treatments are shown in order of the amount of water applied, with severe receiving the least water to the left, followed by partial, and well-watered to the right of each plot respectively. Dark grey boxes represent the yields of intercropped plots and light grey boxes those of sole cropped plots. The three horizontal lines indicate the 75% percentile (up), median (solid line across boxes) and 25% percentile yield (bottom); the upper and bottom bars outside the boxes show the maximum and minimum values respectively. Significant differences are shown through lower and upper case letters for 2015 and 2016, respectively.

LAI was measured on a weekly basis and three repetitions were made in three different sections of each plot. Soil samples were taken one day before sowing and one day after the final harvest by hand so water use could be assessed. These were weighed directly in the field, dried in ovens at 105 °C for 48 h and weighed. Sampling was detailed so it can be effectively used to calibrate crop simulation models.

2.5. Data analysis

Yield and biomass data was subjected to a split-split block analysis of variance (ANOVA). Main plots were defined by irrigation (severe stress, partial stress, well-watered) and split according to density (low and high). Within the densities, plots were split further by system type: sole pearl millet, sole cowpea, and intercropped pearl millet and cowpea. The response variables used for the statistical analysis were yield and harvest index; the explanatory variables that were tested for interactions were system, treatment, density, and year (Tables A1 and A2 appendix). Homogeneity of variance was tested visually and transformed when necessary in order to conform to the requirements of ANOVA. For significant differences ($p > 0.05$), the post-hoc Tukey test was used. The analysis was run for each year (2015 and 2016) separately. The open source software R was used to conduct the analysis and create the figures for this study.

A method for assessing the efficiency of intercropping over sole cropping is to use a ratio, such as the land equivalent ratio (LER) (Willey, 1979). This is the area under sole cropping compared with the area under intercropping required to yield equal amounts at the same level of management. The LER is a common approach to assess the land use advantage of intercropping (Willey and Rao, 1980):

$$LER = LERa + LERb = Ia/Sa + Ib/Sb$$

Ia and Ib are the yields for each crop in the intercrop system, and Sa and Sb are the yields for each of the sole crops. LERa and LERb are the partial LER values for each species. An LER value higher than 1.0 indicates that there is a land use advantage for intercropping.

Partial land equivalent ratio (pLER) refers to the separate parts of the LER equation. Intercropping with two crops such as pearl millet and cowpea is comprised of two pLER values (pearl millet and cowpea), which are added to give the total LER value. Partial land equivalent ratio values are used to assess the contribution of each crop towards total LER and are more detailed in terms of land use assessment.

3. Results

3.1. Grain yield and sequential biomass accumulation

We found certain patterns, which, however, fundamentally differed by year. In 2015, irrespective of plant density, yields increased with irrigation: at low density sole pearl millet yields increased from below 1000 kg ha^{-1} with low irrigation (severe stress treatment) to above 2000 kg ha^{-1} with high irrigation (well-watered treatment), and at high density from above 1000 kg ha^{-1} to more than 2500 kg ha^{-1} with

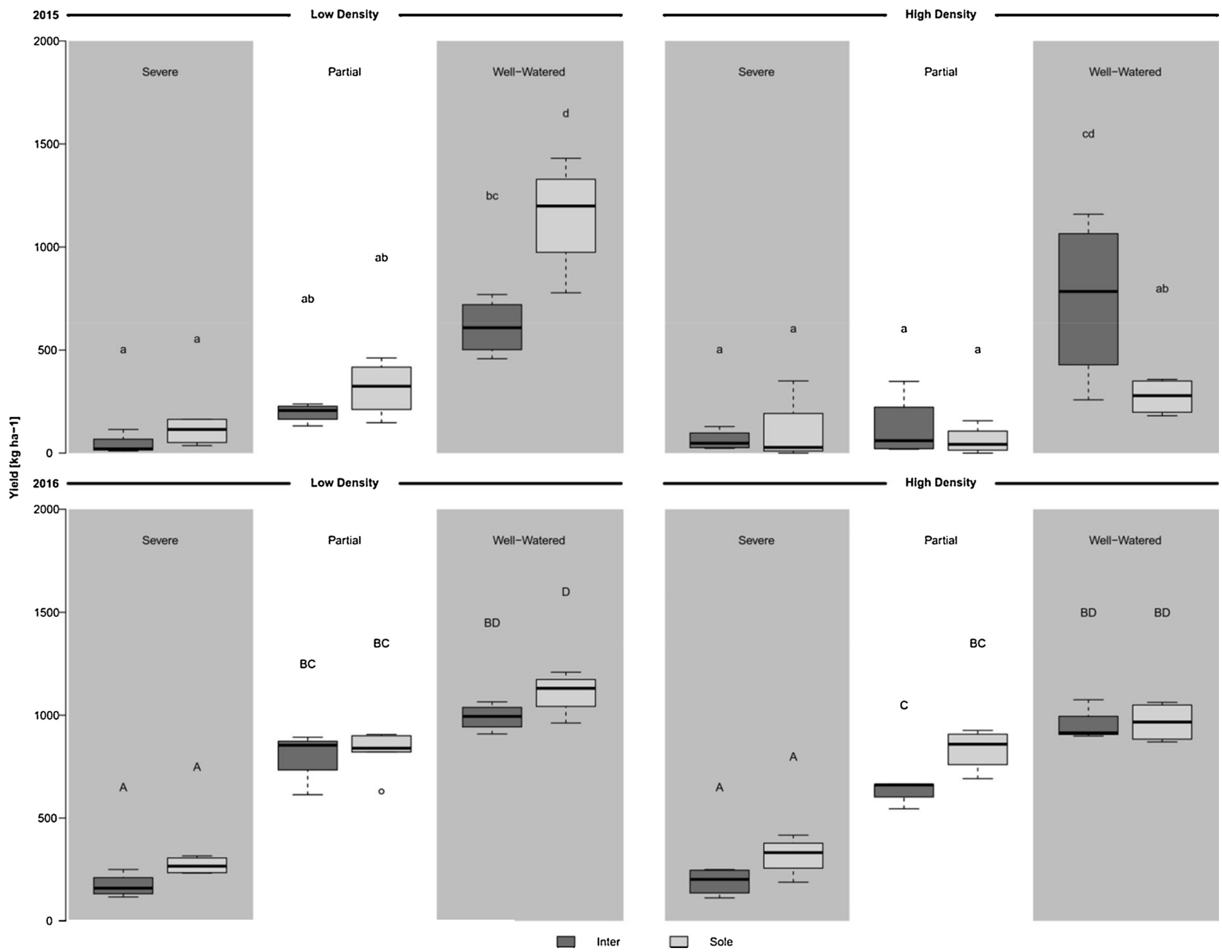

Fig. 5. Cowpea Yield 2015 and 2016. The top half of the figure illustrates yield data from 2015, and bottom half that of 2016. This is the same for density, with low density results on the left-hand side of the figure and high density on the right. Treatments are shown in order of the amount of water applied, with severe receiving the least water to the left, followed by partial, and well-watered to the right of each plot respectively. Dark grey boxes represent the yields of intercropped plots and light grey boxes those of sole cropped plots. The three horizontal lines indicate the 75% percentile (up), median (solid line across boxes) and 25% percentile yield (bottom); the upper and bottom bars outside the boxes show the maximum and minimum values respectively. Significant differences are shown through lower and upper case letters for 2015 and 2016, respectively.

high irrigation (Fig. 4). Interestingly, the pattern could only be seen slightly in the case of intercropped pearl millet at low density, where yields remained below 1500 kg ha^{-1}. The only case in which an increase in water supply significantly improved pearl millet intercrop yield was between partial and well-watered, low density stands in 2015, with average yields of 920 kg ha^{-1} and 1350 kg ha^{-1} respectively (Fig. 4). Intercropping pearl millet with cowpea simultaneously, i.e. with the same sowing date, reduced pearl millet yield significantly in all cases except for severe, low density stands in 2015.

Cowpea yields, however, presented a different pattern, whereby yields were not affected by system (intercrop and sole) except for under the well-watered treatments in both densities in 2015 (Fig. 5).

In the 2016 season, more significant differences could be found between severe and partial treatment stands, in comparison to those found between partial and well-watered (Fig. 5). The highest cowpea yields in 2015 were found in sole, well-watered, low density stands with an average yield of 1150 kg ha^{-1} (Fig. 5). This was the only instance in which sole cowpea out yielded its intercrop counterpart, which yielded an average of 600 kg ha^{-1} (Fig. 5). In terms of system performance, pearl millet yielded significantly more as a sole crop in every case across both years, except for one instance in 2015 at low density under the severe treatment (Fig. 4). Differences in system performance between the years occurred for cowpea. In 2016 the partial treatment yielded almost as well as under the well-watered treatment, at both low and high density, which was not the case in 2015 (Fig. 5). In the 2016 season, more significant differences could be found for cowpea between severe and partial treatment stands (Fig. 5).

In 2015, pearl millet HI ratios increased significantly between severe and well-watered treatments across densities and systems, but not in 2016, where HI remained equal within densities (Fig. 6). In all but one instance (2016, sole pearl millet, partial treatment) high density stands had significantly lower HI ratios in 2016 (Fig. 6). Pearl millet yields across densities in 2016 were equal in all instances but one (well-watered intercrop stands, Fig. 4). Lower HI for pearl millet at high density in 2016 reflected the increased biomass in comparison to yield at this density (Fig. 6). While pearl millet yield was dramatically reduced when intercropped, there were no significant differences in HI between systems in both years (Fig. 6). The presence of cowpea reduced the total production of the entire pearl millet plant, and not just the plant's ability to produce grain.

Significantly higher cowpea HI ratios were found under well-watered as opposed to severe treatments in both years and densities, except under high density in 2015 (Fig. 7). These findings emulated yield results (Fig. 5) and showed biomass and grain production were affected

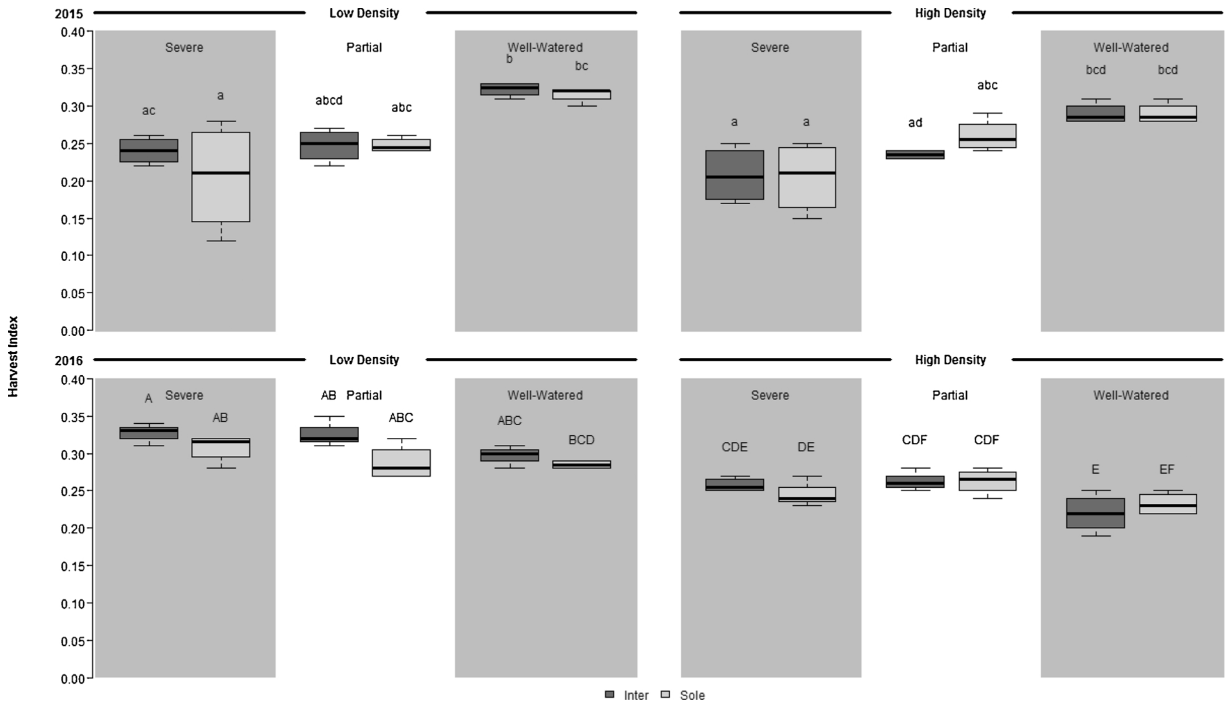

Fig. 6. Harvest Index for Pearl Millet. The top half of the figure illustrates HI data from 2015, and bottom half that of 2016. This is the same for density, with low density results on the left-hand side of the figure and high density on the right. Treatments are shown in order of the amount of water applied, with severe receiving the least water to the left, followed by partial, and well-watered to the right of each plot respectively. Dark grey boxes represent the HI values of intercropped plots and light grey boxes those of sole cropped plots. The three horizontal lines indicate the 75% percentile (up), median (solid line across boxes) and 25% percentile yield (bottom); the upper and bottom bars outside the boxes show the maximum and minimum values respectively. Significant differences are shown through lower and upper case letters for 2015 and 2016, respectively.

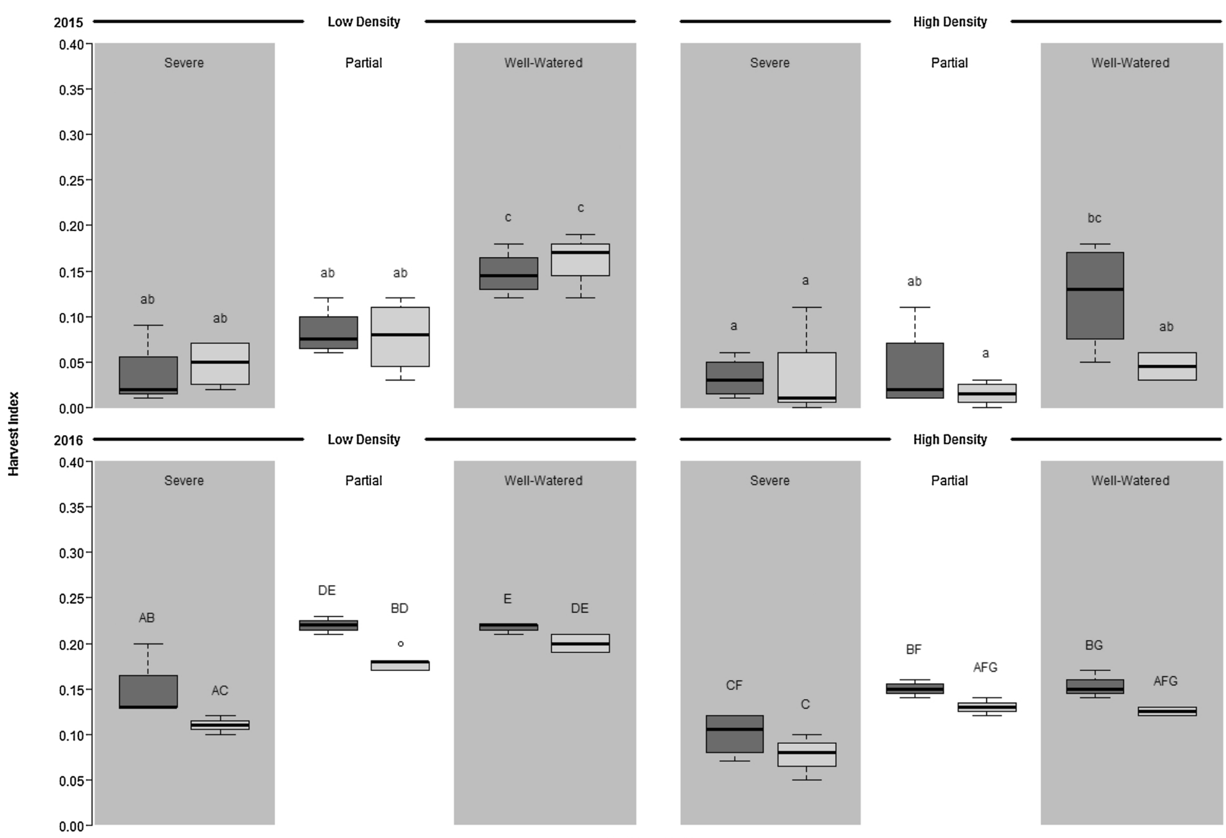

Fig. 7. Harvest Index for Cowpea. The top half of the figure illustrates HI data from 2015, and bottom half that of 2016. This is the same for density, with low density results on the left-hand side of the figure and high density on the right. Treatments are shown in order of the amount of water applied, with severe receiving the least water to the left, followed by partial, and well-watered to the right of each plot respectively. Dark grey boxes represent the HI values of intercropped plots and light grey boxes those of sole cropped plots. The three horizontal lines indicate the 75% percentile (up), median (solid line across boxes) and 25% percentile yield (bottom); the upper and bottom bars outside the boxes show the maximum and minimum values respectively. Significant differences are shown through lower and upper case letters for 2015 and 2016, respectively.

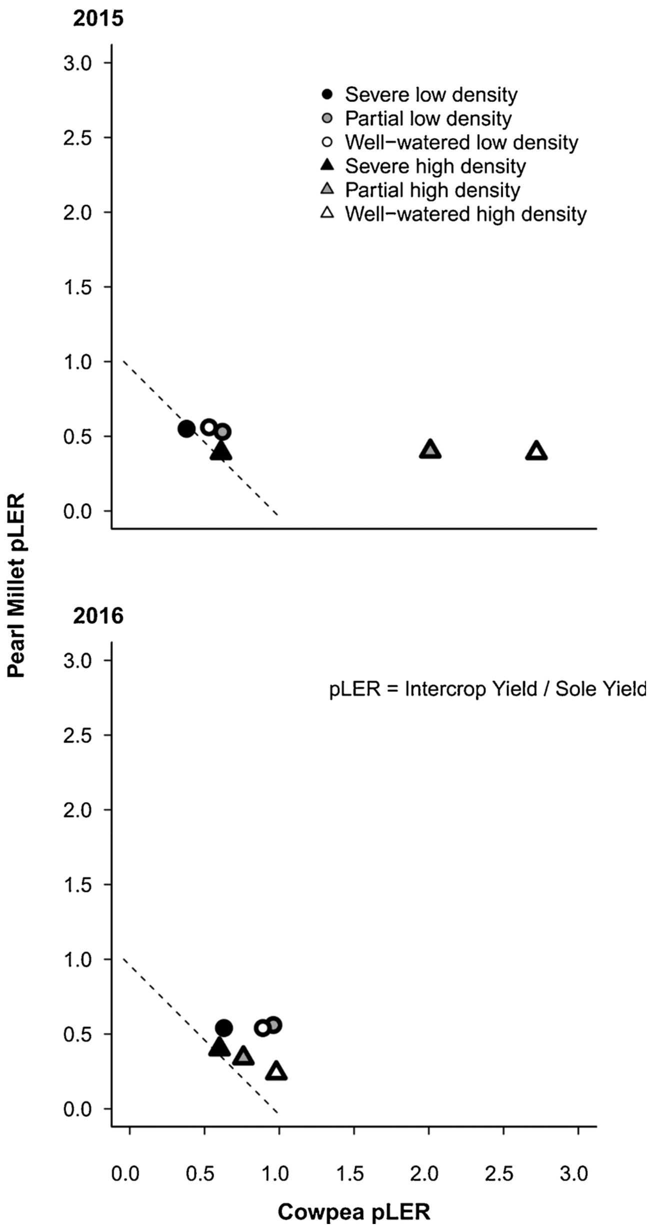

Fig. 8. Partial land equivalent ratio (pLER) of cowpea fodder and pearl millet grain for intercropping patterns at high and low density and under three different irrigation treatments (severe stress, partial stress, and well-watered) over two years of experimentation, 2015 and 2016. Each symbol represents an average pLER value from four replicates of the different density and water regimes. The black line indicates a total LER value of one.

in the same way. In general, HI ratios for both pearl millet and cowpea were significantly reduced by density in 2016 (Figs. 6 and 7). Yield results showed no significant differences between crops in terms of density (Figs. 4 and 5).

In terms of vegetative biomass, pearl millet produced more than cowpea. The 2015 data set (Fig. A1 appendix) clearly shows high density sole pearl millet stands produced more biomass compared with those at low density - this was the case for all treatments in 2015: 3520 kg ha^{-1} and 4990 kg ha^{-1} (severe low and high density); 5260 kg ha^{-1} and 5890 kg ha^{-1} (partial low and high density); and 5280 kg ha^{-1} and 7110 kg ha^{-1} (well-watered low and high density). The same pattern was also found with sole cowpea, but to a lesser extent when compared with sole pearl millet: 2260 kg ha^{-1} and 2820 kg ha^{-1} (severe low and high density); 3860 kg ha^{-1} and 4250 kg ha^{-1} (partial low and high density); and 5860 kg ha^{-1} and 6200 kg ha^{-1} (well-watered low and high density).

3.2. LER of yield

Partial land equivalent ratio values varied between years (Fig. 8), largely due to the 2015 high density sole cowpea yields cultivated under partial and well-watered treatments, for which the yields were 56.5, 157.2, 28.5, and 0 (partial), and 181.2, 357.7, 215.5, and 342.2 kg ha^{-1} (well-watered, Figs. 4 and 5).

Partial land equivalent ratios showed that intercropping did not necessarily perform better under stress. High density stands under the severe stress treatment had two of the lowest values, with 0.9 and 1.0 in 2015 (severe low density), and 1.2 and 1.0 in 2016 (severe high density, Fig. 8). As a comparison, well-watered low and high density stands achieved ratios of 1.1 and 3.1 (2015), and 1.4 and 1.2 (2016, Fig. 8).

Fig. 8 illustrates the necessity to assess partial LER values and not just LER totals. Values from 2016 showed well-watered high density stands to have a total LER of 1.2 (Fig. 8). From this value, 0.2 is from pearl millet, and 1.0 from cowpea - pearl millet was sacrificed for increased cowpea yield (Fig. 8). Mean yields for this example were 966.6 and 950.5 for cowpea, and 2260 and 535 kg ha^{-1} for pearl millet, for sole and intercropped stands (Fig. 8).

3.3. Soil moisture at full maturity and light interception

Soil moisture within both of the top two layers (0–15 cm and 15–30 cm) in 2015 under the severe treatment showed high density plots retained more water than low density plots across all systems (Fig. 9). Complementary to this were the higher LAI values of high density plots across all systems under the severe treatment by Julian day 78, which captured the full flowering periods of both pearl millet and cowpea crops (Fig. A3 appendix). Interestingly, there were larger differences in LAI, i.e. ground cover, between low and high density sole cowpea and intercrop stands, but not between those of sole pearl millet (Figs. A3 and A4 appendix). Higher LAI values in both years (Figs. A3 and A4) linked well with higher soil moisture values in 2015 (Fig. A5 appendix), particularly under the severe irrigation treatment (Figs. 9 and 10).

4. Discussion

4.1. Cropping system performance

Under extreme temperature conditions, as found in the off-season (from January to May 2015 and 2016) at the semi-arid site in Telangana, India, under field conditions, intercropping did not prove to be a suitable adaptation strategy. Pearl millet grown as a sole crop produced significantly higher yields with almost 1650 kg ha^{-1} with high irrigation over both years and densities compared with stands where it was intercropped with cowpea (Fig. 4). Cowpea yields were not consistently affected by the system. Our findings were in-line with those of previous studies that showed the simultaneous sowing of pearl millet and cowpea intercropped stands lead to pearl millet yield reductions (Mohammed et al., 2008; Ntare, 1989; Ntare, 1990; Terao et al., 1997). As described by Zegada-Lizarazu et al. (2006), water-use in this specific system was heavily influenced by the system in the form of competition from cowpea. Root studies confirmed that competition between these two crops in particular was greatest when planted simultaneously, as they shared the same root zone (Terao et al., 1997). Singh et al. (1997) explained how pearl millet yield was reduced, as simultaneous planting with cowpea reduced its ability to develop deep roots. If cowpea is sown two weeks after pearl millet, it could be dominated by the already developed pearl millet root system and therefore suffer yield reductions. A suggested solution is to plant two rows alternately, for example with four rows of cowpea and two rows of

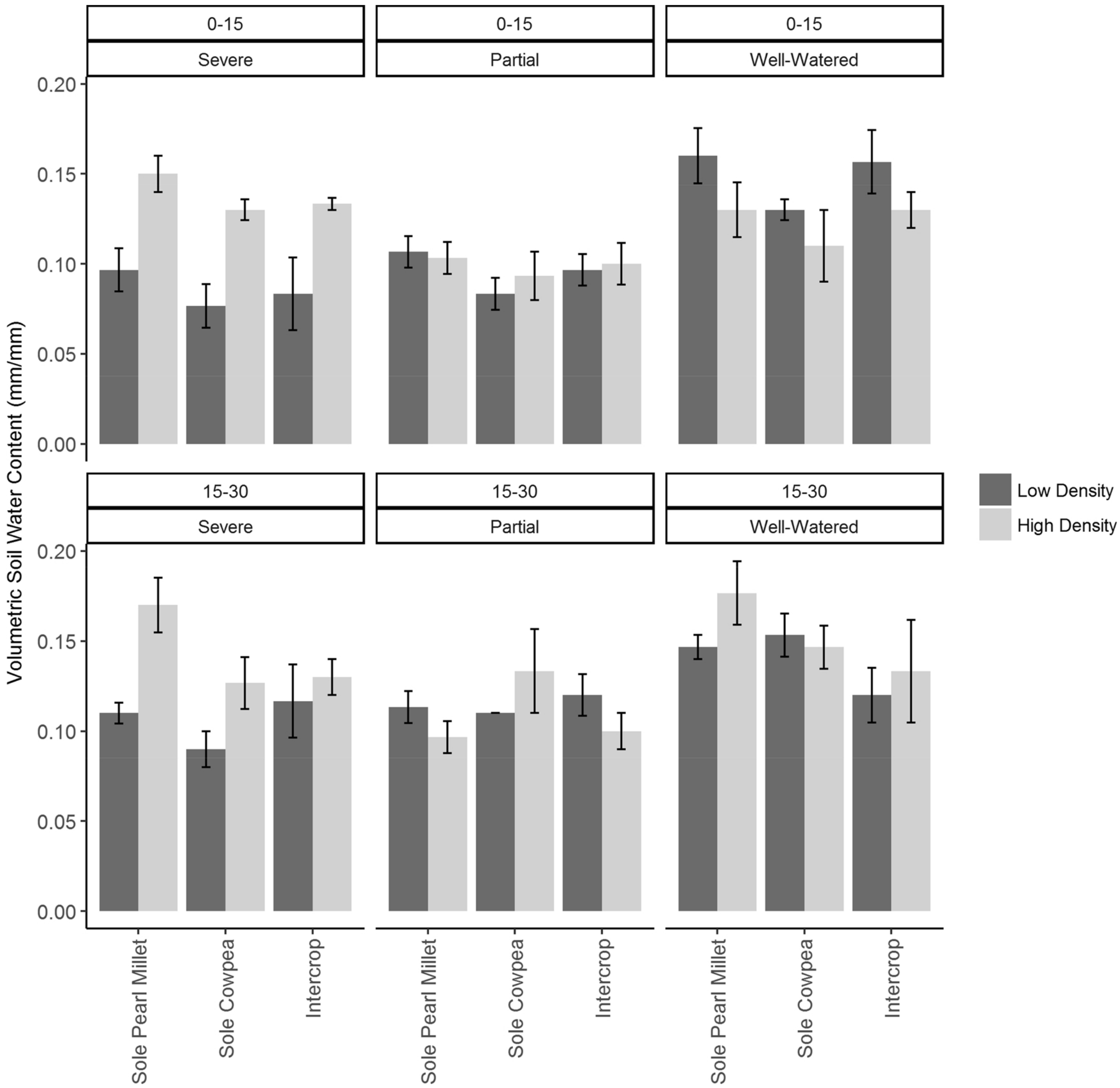

Fig. 9. Full maturity volumetric soil water content (mm/mm), layers 0–15 cm and 15–30 cm, 2015. The effect of cropping system and density on soil moisture directly after the final harvest in 2015. The bars represent the mean soil moisture, along with standard deviation whiskers.

pearl millet. This aims to allow the cereal to penetrate zones under rows of other cereal plants, reducing competition with cowpea roots, which could help compensate for the fact that pearl millet roots do not grow directly beneath their own plant (Terao et al., 1997). Reddy et al. (1992) found no pearl millet yield reduction when cowpea was sown one week after pearl millet, which supports the above-mentioned strategy if pearl millet is of considerable importance to the farmer.

Mohammed et al. (2008) found cowpea yield to decrease by 47% when intercropped with pearl millet, the difference in trial set-up being that cowpea was sown two weeks after pearl millet. The same study suggested that competitive light interception, i.e. shade from taller crops with more biomass, can heavily impact yield. This builds on the previous work of Blade et al. (1997), who showed consistent, gradual decreases in cowpea yield the later it is planted after pearl millet.

It is important to note that the pearl millet used in this trial was a short variety (in terms of height), which, especially at high density, had a large percentage of its leaves over-shadowed by intercropped cowpea, illustrated in Fig. 31c, which shows that almost only the pearl millet panicles grew taller than the intercropped cowpea. The reduction in pearl millet yield in response to intercropping with cowpea was therefore related to light (above-ground biomass), and water (below-ground biomass), which enforces the work of Terao et al. (1997), who stressed the importance of system architecture. The timing of shade development has also been found to be of great importance (Walker, 2015). Leaf area index was captured at plot level in this study. However, in order to understand the canopy architecture of intercrop plots and the impact of shade, more detailed LAI data collection could help with the understanding of such systems in their entirety. This could include recording the light intercepted by the taller of the intercropped species alone, which in some instances casts shade over the lower canopy of the shorter intercropped species.

Land equivalent ratio inconsistencies (Fig. 5) highlight the complexity of analysing and understanding crop production systems, which forces us to assess the relevance of such ratios. When assessing intercropping systems, it was difficult to find trends through ratios, and it was necessary to look into the details. For instance, 2015 LER total

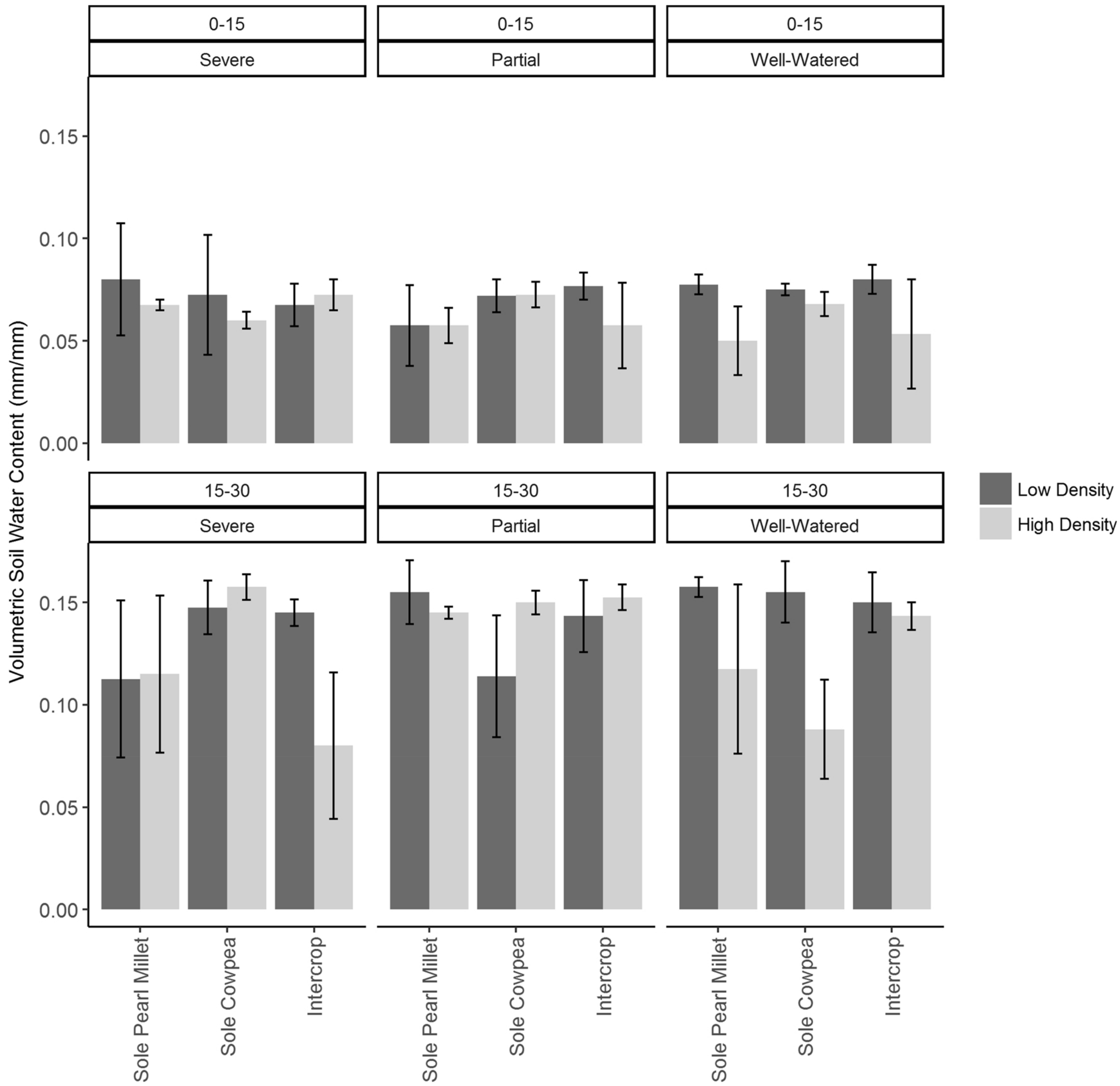

Fig. 10. Full maturity volumetric soil water content (mm/mm), layers 0–15 cm and 15–30 cm, 2016. The effect of cropping system and density on soil moisture directly after the final harvest in 2016. The bars represent the mean soil moisture, along with standard deviation whiskers.

values of 2.4 (high density partial) and 3.1 (high density well-watered) suggest intercropping was far more efficient than sole cropping (Fig. 8) - comparable values in 2016 vary. Further investigation into partial LER and actual yield values showed a very different result (Reddy et al., 1992).

Clearly, when looking at LER, it is vital to take into consideration which crops are more preferable for the farmer. For example, pearl millet proved to be a stable crop that produced reliable yields. The same cannot be said for cowpea however due to its sensitivity to climate variation. The use of LER for data interpretation must therefore be done with caution, as high LER values (above 1.0), indicating the intercrop system in question is more productive than sole equivalents, is clearly not a good measure of yield productivity, nor is it supposed to be. As Prins and Wit (2005) argued, LER is too simple and may not be useful when analysing intercropping systems, in particular when crops show high elasticity and variance. The variability in LER across various systems was clearly a sign that a more developed understanding of the factors responsible is needed (Yu et al., 2015). The literature, as well as the results in this study, so far showed LER to be inconsistent. It is therefore important that the specificity of the farming situation, i.e. the usefulness of each component within the relevant cultural and social setting, is emphasised when interpreting LER as part of field trial analysis.

4.2. Cropping system responses to water treatment

Water supply was a key factor in the determination of yields, but not the most limiting one in all cases. Sole pearl millet responded to increased water supply to an extent, but not consistently past the partial irrigation treatment. Of particular interest is that there were no differences between intercropped pearl millet at treatment and density levels within each year, except for in 2015 at low density between partial and well-watered treatments (Fig. 4). This indicated that intercropped pearl millet suffered from competition with cowpea more than from water stress. Studies have argued that the water sources of pearl millet can be changed by the presence of a cowpea intercrop able to ‘out compete’ the cereal for water. This reaction is said to be due to the presence of cowpea forcing pearl millet to rely on more recently supplied water − be that precipitation or irrigation (Zegada-Lizarazu et al., 2006). However, if this were the case, well-watered intercropped pearl millet should have performed better as water supply increased, which it did not. With this in mind, it seems cowpea outcompeted pearl millet for root space more than anything else. The cereal's reduction in performance when intercropped was not found when cowpea planting was delayed by two weeks. The response was similar when pearl millet is intercropped with other legumes (Zegada-Lizarazu et al., 2005). The strongest change in terms of water supply for both pearl millet and cowpea inter and sole crop stands was observed between severe to partial treatments. Here, it seems the irrigation water supply of 350 mm in 2015 and 330 mm in 2016 (partial water stress) was sufficient. Any additional supply of water led to a diminishing return.

4.3. Plant density

Spatial arrangement of course also influences competition dynamics and yield stability can vary under different types of intercropping systems, be they made up of singular or multiple rows (Dapaah et al., 2003; Mohammed et al., 2008). This highlights the importance of defining the aims of a system prior to assessing its performance. Mohammed et al. (2008) found that pearl millet-cowpea intercropping systems could be enhanced by cultivating two pearl millet rows next to four cowpea rows. In our study, under intercropping, while the presence of simultaneously sown cowpea reduced pearl millet yield, a system effect, density did not play an important role in terms of yield production. However, yield is of course not the only arable cultivation product. Vegetative biomass can be used as animal feed, vegetables for human consumption, and straw input for soil organic matter build-up. There is therefore strong competition for biomass, especially in low-resource systems, as found in many semi-arid regions. With this is mind, density clearly played an important role in terms of vegetative biomass production (Figs. A1 and A2 appendix), where high density pearl millet in particular produced higher yields compared with when sown at low density. Craufurd (2000) found a strong density response with intercrop yields, whereby cowpea yield decreased as pearl millet density increased. Craufurd (2000) went on to explain that intercrop yields were dominated by cereals, which was not the case in our study, and was probably due to the relay aspect of the experiments reported on in which cowpea was sown seven days or more after pearl millet, giving the cereal an advantage. Another possible interpretation is that of a cowpea genotype effect on the pearl millet line used in intercropping. The cowpea line that was used is routinely used as a fallow crop, rather than for grain, indicated by poor harvest index ratios. Being a genotype with inherently high foliage could have been part of the reason for depressed intercropped pearl millet yields. The fact that we used a short pearl millet variety clearly played an important role in cowpea's ability to shade the intercropped pearl millet, especially when sown at high density, as well as the above-described competition for soil resources. Mao et al. (2014) found higher plant densities led to crops with excessive vegetative growth, which supports our findings for pearl millet and cowpea in 2016, as the HI is reduced with increased density (Figs. 6 and 7).

Significantly equal HI ratios for pearl millet are in-line with the findings of Muchow (1989), who observed that although more water supply increased sole pearl millet HI values, the effect was not significant. The decline in pearl millet HI at high density (Fig. 6) in combination with significantly equal yields over density (Fig. 4) highlights the higher level of grain-yield efficiency that comes from low density cultivation. As density was the only influential factor in terms of pearl millet HI, it is clear that the provision of sufficient space is important to achieve pearl millet's yield potential. Of course, only one pearl millet genotype was tested and more work would be needed to test the possibility of genotype-by-density interactions. This also showed that when pearl millet was under stress, the entire plant was affected i.e. biomass and yield production. The fact that water deficits have little influence on pearl millet HI further emphasised the stability and reliability of the crop as suitable for farmers in semi-arid regions, particularly with climate variation and instability in mind. Cowpea on the other hand showed a great deal more variation. Higher HI values were found at low density, and as water supply increased. The overriding output of HI values from both crops in intercropped and sole stands was that low density planting was more preferable (60 cm between row spacing), be it as an inter- or sole crop system.

5. Conclusion

The off-season experiment showed that the cultivation of both pearl millet and cowpea under extreme heat was possible. Intercropping, at least when simultaneously planted, did not improve yield productivity, despite LER values above one, and reduced the performance of pearl millet. The provision of supplemental water through drip irrigation increased yields of both crops, but more so for cowpea of which yields were low across treatments and years as well as being sensitive to water supply and seasonal climate variation. Pearl millet on the other hand, proved to be well-adapted to high temperatures and limited water supply. The locally practiced low density (60 cm between row spacing) was the most efficient in terms of seed supply and yield output, whereas biomass production was higher when sown at high density. The most effective drip irrigation water supply in terms of grain yield was made up of around 340 mm (partial stress water application mean over the two years) divided over and applied once a week up until 48 DAS (mean length of partial stress irrigation in 2015 and 2016). As we have shown, the off-season can be used effectively to test strategies under climatic conditions that may shift into key cropping seasons. Our observations suggest that there may be opportunities to develop intercropping options for farmers, even under harsher conditions. Two key aspects that require further research include: (i) broader testing of genetic material of both pearl millet and cowpea as part of intercropping systems, and (ii) investigation of whether delayed planting of cowpea would reduce the negative effect on pearl millet grain yield when intercropped.

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Appendix A

Sequential biomass harvests

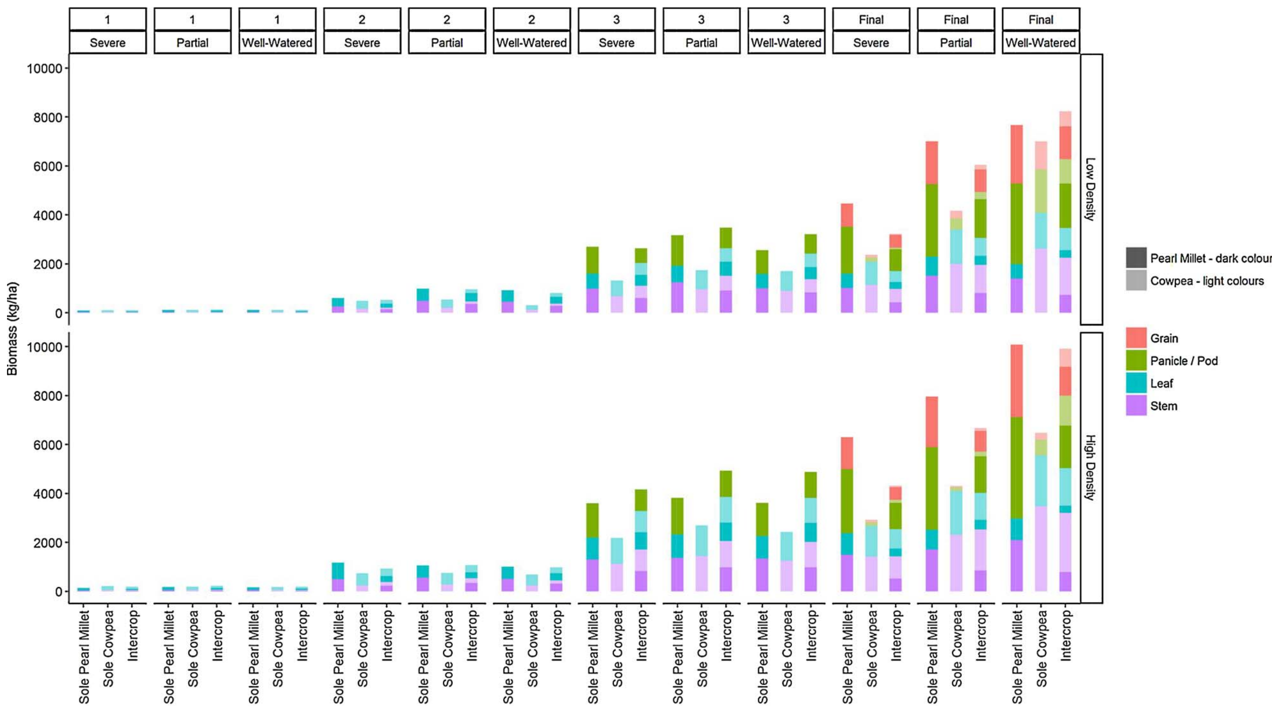

Fig. A1. Biomass accumulation over time - four separate harvests in 2015, split into Julian day. The biomass of each plant part is given a different colour, as indicated in the legend. Pearl millet plant parts are represented by the darker shades of the colours in the legend, and cowpea by those that are lighter. Biomass growth of low density plots is shown in the upper most time series, that of high density below.

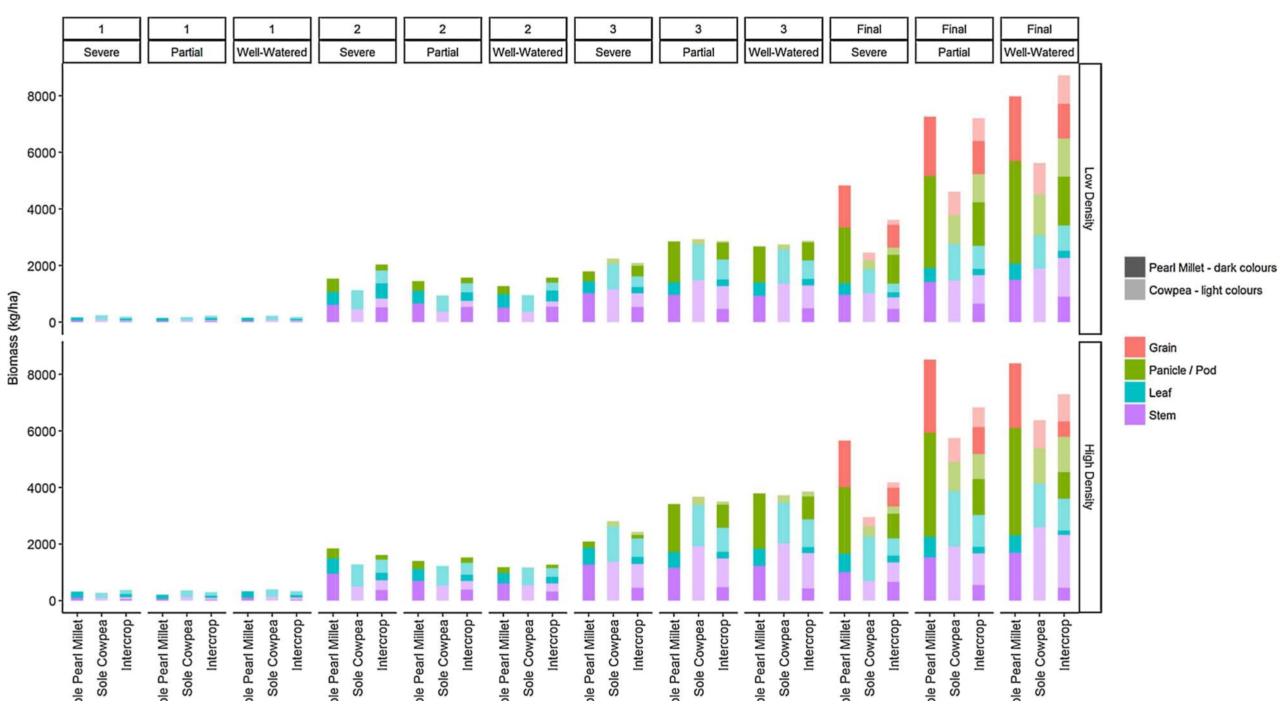

Fig. A2. Biomass accumulation over time - four separate harvests in 2016, split into Julian day. The biomass of each plant part is given a different colour, as indicated in the legend. Pearl millet plant parts are represented by the darker shades of the colours in the legend, and cowpea by those that are lighter. Biomass growth of low density plots is shown in the upper most time series, that of high density below.

Leaf Area Index – light interception

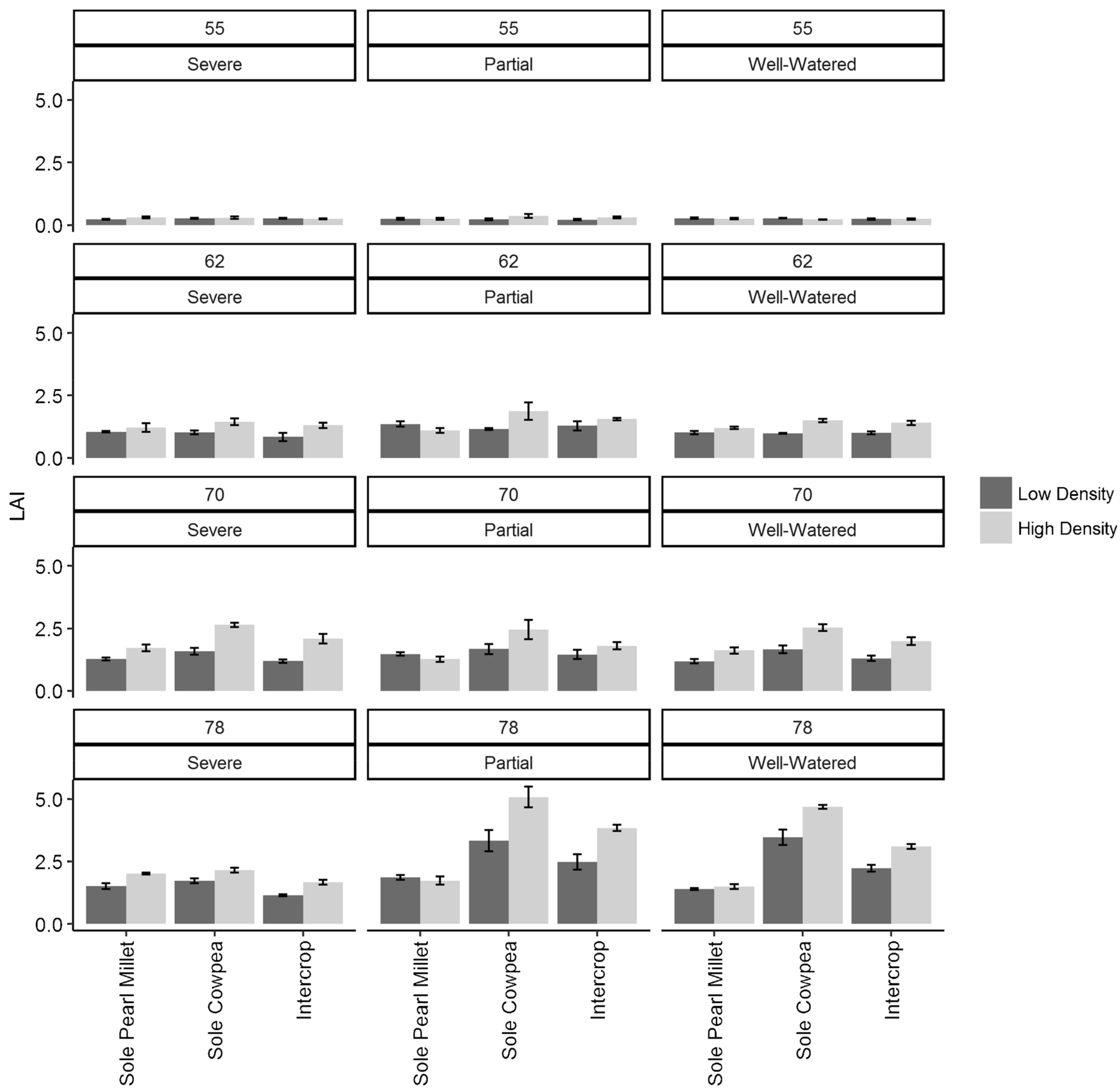

Fig. A3. Leaf Area Index over four dates (Julian day) in 2015, with standard error bars across treatments. Densities are indicated via the shade of grey used, low density (dark grey), and high density (light grey). The measurements shown capture the end of flowering for both crops.

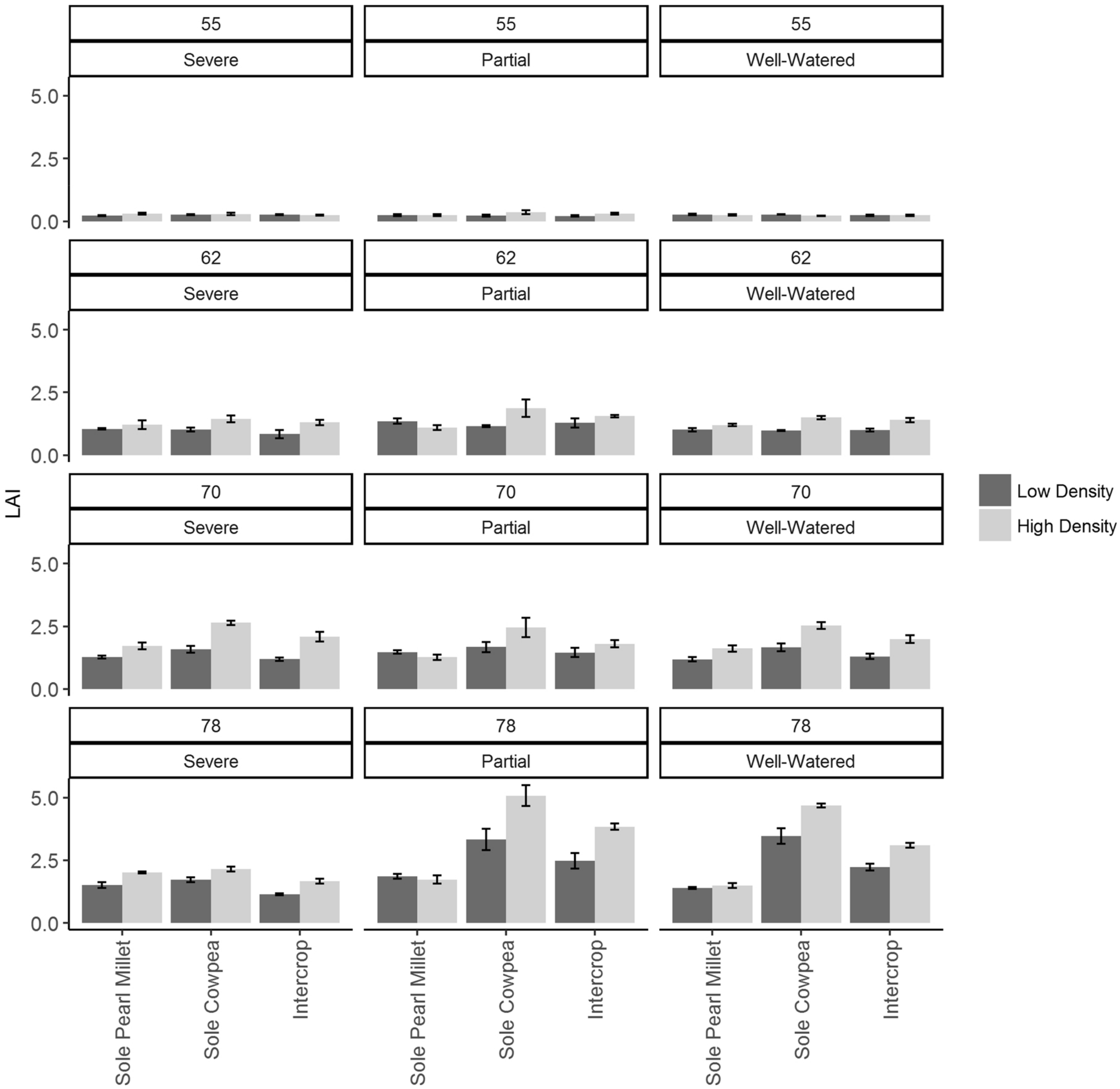

Fig. A4. *Leaf Area Index over four dates (Julian day) in 2016*, with standard error bars across treatments. Densities are indicated via the shade of grey used, low density (dark grey), and high density (light grey). The measurements shown capture the end of flowering for both crops.

Solar radiation

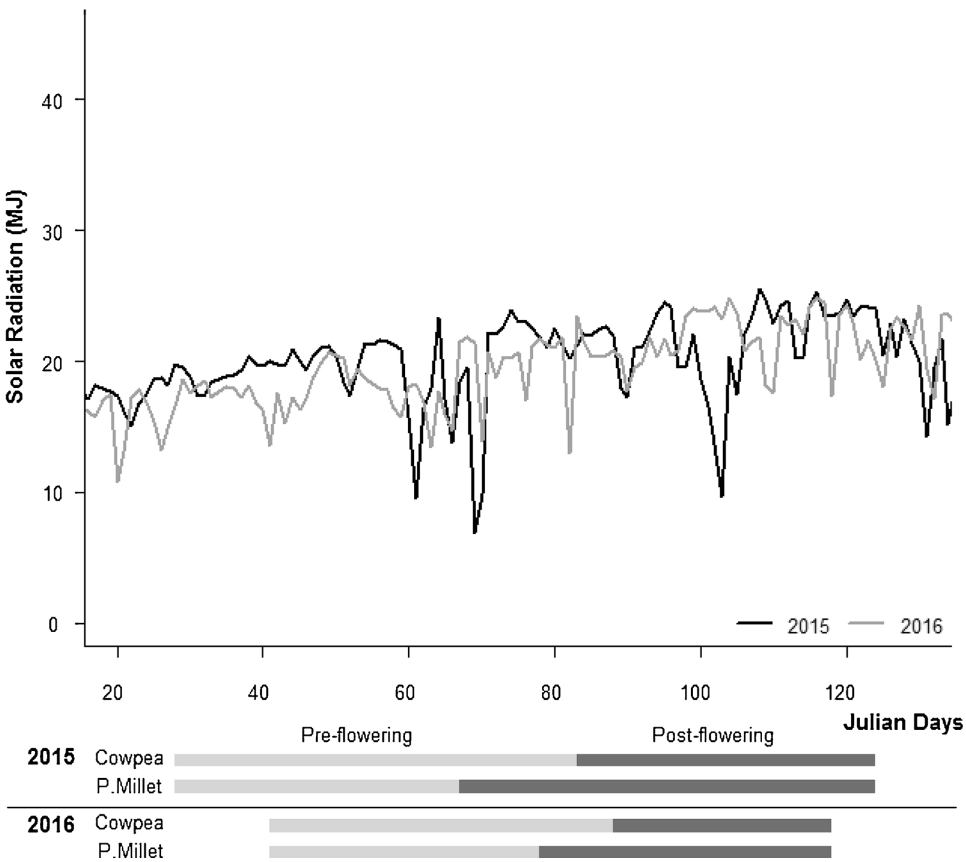

Fig. A5. Solar Radiation and physiology timeline 2015 and 2016. Solid lines represent the daily solar radiation, black 2015, and grey 2016 (MJ). Development phases of both cowpea and pearl millet are presented for both years separately. Horizontal bars filled in light grey (below the plot) represent the time from germination to the completion of flowering of both crops. The following grain/pod filling to final harvest stage is shown through the dark grey bars.

ANOVA results

Table A1
Results of ANOVA on the effects of System, Treatment, Density, and Year and their interactions on cowpea and pearl millet yield.

Cowpea	Df	Sum Sq	Mean Sq	F value	Pr(> F)	
System	1	159226	159226	8.6194	0.0044621	**
Treatment	2	7690426	3845213	208.155	< 2.2e-16	***
Density	1	280267	280267	15.1718	0.0002175	***
Year	1	2994224	2994224	162.0879	< 2.2e-16	***
System:Treatment	2	6056	3028	0.1639	0.8491271	
System:Density	1	231849	231849	12.5508	0.0006996	***
Treatment:Density	2	252561	126281	6.836	0.0019132	**
System:Year	1	28812	28812	1.5597	0.215759	
Treatment:Year	2	743289	371645	20.1184	1.15E-07	***
Density:Year	1	118583	118583	6.4193	0.0134659	*
System:Treatment:Density	2	405760	202880	10.9826	6.87E-05	***
System:Treatment:Year	2	3581	1790	0.0969	0.9077529	
System:Density:Year	1	284511	284511	15.4016	0.0001967	***
Treatment:Density:Year	2	69409	34704	1.8787	0.160206	
System:Treatment:Density:Year	2	189724	94862	5.1352	0.008226	**
Residuals	72	1330044	18473			
Pearl Millet						
System	1	28793523	28793523	376.4765	< 2.2e-16	***
Treatment	2	10422097	5211048	68.1347	< 2.2e-16	***
Density	1	66016	66016	0.8632	0.356	
Year	1	73470	73470	0.9606	0.33036	
System:Treatment	2	1955820	977910	12.7862	1.81E-05	***
System:Density	1	1764901	1764901	23.0762	8.40E-06	***
Treatment:Density	2	172106	86053	1.1251	0.33032	
System:Year	1	136020	136020	1.7785	0.1866	
Treatment:Year	2	2601677	1300838	17.0085	9.23E-07	***

(*continued on next page*)

Table A1 (*continued*)

Cowpea	Df	Sum Sq	Mean Sq	F value	Pr(> F)	
Density:Year	1	338778	338778	4.4295	0.03886	*
System:Treatment:Density	2	147092	73546	0.9616	0.3872	
System:Treatment:Year	2	106978	53489	0.6994	0.50029	
System:Density:Year	1	10044	10044	0.1313	0.71813	
Treatment:Density:Year	2	277264	138632	1.8126	0.1707	
System:treatment:Density:Year	2	57063	28531	0.373	0.68997	
Residuals	71	5430193	76482			
Signif. codes: 0 ‘***’ 0.001	‘*	*’ 0.01	‘*’ 0.05	‘.’ 0.1	‘ ’ 1	

Table A2
Results of ANOVA on the effects of System, Treatment, Density, and Year and their interactions on cowpea and pearl millet harvest index.

Cowpea	Df	Sum Sq	Mean Sq	F value	Pr(> F)	
System	1	159226	159226	8.619	0.004462	**
Treatment	2	7690426	3845213	208.155	< 2e-16	***
Density	1	280267	280267	15.172	0.000217	***
Year	1	2994224	2994224	162.088	< 2e-16	***
System:Treatment	2	6056	3028	0.164	0.849127	
System:Density	1	231849	231849	12.551	0.0007	***
Treatment:Density	2	252561	126281	6.836	0.001913	**
System:Year	1	28812	28812	1.56	0.215759	
Treatment:Year	2	743289	371645	20.118	1.15E-07	***
Density:Year	1	118583	118583	6.419	0.013466	*
System:Treatment:Density	2	405760	202880	10.983	6.87E-05	***
System:Treatment:Year	2	3581	1790	0.097	0.907753	
System:Density:Year	1	284511	284511	15.402	0.000197	***
Treatment:Density:Year	2	69409	34704	1.879	0.160206	
System:Treatment:Density:Year	2	189724	94862	5.135	0.008226	**
Residuals	72	1330044	18473			
Pearl Millet						
System	1	159226	159226	8.619	0.004462	**
Treatment	2	7690426	3845213	208.155	< 2e-16	***
Density	1	280267	280267	15.172	0.000217	***
Year	1	2994224	2994224	162.088	< 2e-16	***
System:Treatment	2	6056	3028	0.164	0.849127	
System:Density	1	231849	231849	12.551	0.0007	***
Treatment:Density	2	252561	126281	6.836	0.001913	**
System:Year	1	28812	28812	1.56	0.215759	
Treatment:Year	2	743289	371645	20.118	1.15E-07	***
Density:Year	1	118583	118583	6.419	0.013466	*
System:Treatment:Density	2	405760	202880	10.983	6.87E-05	***
System:Treatment:Year	2	3581	1790	0.097	0.907753	
System:Density:Year	1	284511	284511	15.402	0.000197	***
Treatment:Density:Year	2	69409	34704	1.879	0.160206	
System:Treatment:Density:Year	2	189724	94862	5.135	0.008226	**
Residuals	72	1330044	18473			
Signif. codes: 0 ‘***’ 0.001	‘*	*’ 0.01	‘*’ 0.05	‘.’ 0.1	‘ ’ 1	

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