Received: 16 April 2021 | Revised: 11 August 2021 | Accepted: 12 August 2021

DOI: 10.1111/jac.12552

DROUGHT STRESS

Journal of Agronomy and Crop Science WILEY

Can intercropping be an adaptation to drought? A model-based analysis for pearl millet–cowpea

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Funding information

Bundesministerium für Bildung und Forschung, Grant/Award Number: 01LL1802A and 031A351A

Abstract

Cereal–legume intercropping is promoted within semi-arid regions as an adaptation strategy to water scarcity and drought for low-input systems. Our objectives were firstly to evaluate the crop model APSIM for pearl millet (*Pennisetum glaucum* (L.))—cowpea (*Vigna unguiculata* (L.) Walp) intercropping—and secondly to investigate the hypothesis that intercropping provides complimentary yield under drought conditions. The APSIM model was evaluated against data from a two year on station field experiment during the dry season of a semi-arid environment in Patancheru, India, with severe, partial and no water deficit stress (well-watered); densities of 17 and 33 plants per m^{-2}, and intercrop and sole crop production of pearl millet and cowpea. Overall, APSIM captured the dynamics of grain yields, indicated by the Willmott Index of Agreement (IA: 1 optimal, 0 the worst) 0.91 from 36 data points (n), total biomass (IA: 0.90, $n = 144$), leaf area index (LAI, IA = 0.77, $n = 66$), plant height (IA 0.96, $n = 104$ pearl millet) and cowpea (IA 0.81, $n = 102$), as well as soil water (IA 0.73, $n = 126$). Model accuracy was reasonable in absolute terms (RMSE pearl millet 469 kg/ha and cowpea 322 kg/ha). However, due to low observed values (observed mean yield pearl millet 1,280 kg/ha and cowpea 555 kg/ha), the relative error was high, a known aspect for simulation accuracy in low-yielding environments. The simulation experiment compared the effect of intercropping pearl millet and cowpea versus sole cropping under different plant densities and water supplies. A key finding was that intercropping pearl millet and cowpea resulted in similar total yields to the sole pearl millet. Both sole and intercrop systems responded strongly to increasing water supply, except sole cropped cowpea, which performed relatively better under low water supply. High plant density had a consistent effect, leading to lower yields under low water supply. Higher yields were achieved under high density, but only when water supply was high: absolute highest total intercrop yields were 4,000 (high density) and 3,500 kg/ha (low density). This confirms the suitability of the common practice among farmers who use the low planting density under water scarce conditions. Overall, this study confirms that intercropping is no silver bullet, i.e. not per se a way to achieve high yield production or reduce risk under drought. It does, however, provide an opportunity to diversify food production by additionally integrating protein rich crops, such as cowpea.

KEYWORDS

adaptation, drought stress, intercropping, *Pennisetum glaucum* (L.), *Vigna unguiculata* (L.) Walp

1 | INTRODUCTION

Intercropping is promoted as a promising climate risk reducing option in particular for low input smallholder systems (Brooker et al., 2015; Rusinamhodzi et al., 2012). Traditionally, intercropping is used because of low plant population, where farmers hope to capitalise on niches, i.e. the space left between the initial plantings. A common system sees alternate rows of, for example, a sole crop cereal stand, replaced by companion crop rows (usually a legume), known as replacement intercropping, as seen in Nelson et al. (2018). It is argued that by using two different species important resources such as water and nutrients can be used complementarily (Brooker et al., 2015). Indeed, Rapholo et al. (2019) found intercropping maize-lablab (relay intercropping, i.e. lablab was planted 28 days after maize) to produce higher grain yields (2,865 kg/ha) than sole maize (2,623 kg/ha) despite no difference in soil water use. Differing root architecture of the two intercrop components, maize and lablab, could contribute to this water use complementarity. However, it is clear that using intercropping as a silver bullet across regions and scenarios does not work, as system performance depends on management, germplasm, site-specific environmental and socio-economic conditions (Li et al., 2006; Nelson et al., 2018; Rapholo et al., 2019). A more site-specific approach to planting practices is therefore required that can respond to evolving farmer needs (Haussmann et al., 2012). However, optimisation of cultivar choices and management practices is difficult due to the numerous possible interactions with environmental factors.

The challenges stated above suggest that field-based experimentation alone may be too time-consuming and costly to address the many potential climate- and management-based scenarios associated with such systems, as well as providing too little information on the mechanisms of intercrop growth dynamics and resource use. Process-based modelling has evolved as an option to conduct and evaluate virtual experiments within days as opposed to field-based experimentation that requires years. This kind of modelling has limitations however, such as when assessing yield limiting factors, potentially beneficial in intercropping (Rötter et al., 2018). Conducting simulation experiments that systematically vary plant input, such as water supply, can provide valuable information for farmers, as well as highlight potential areas of model improvement and guide field experimentation (Akinseye et al., 2017; Casadebaig et al., 2016; He et al., 2017). We present an interesting case study that exemplifies the field experimentation-crop modelling cycle, where each research method compliments one another.

So far, crop models have rarely been used to evaluate different intercropping practices (Gaudio et al., 2019)—intercrop research has in general been largely descriptive (Brisson & Bussiere, 2004; Tsubo et al., 2005). The Agricultural Production Systems sIMulator (APSIM; Holzworth et al., 2014) contains a module for intercropping (Carberry et al., 1996), which has been evaluated for sorghum-cowpea intercropping (Chimonyo et al., 2016).

With the potential use of crop modelling for management improvements in mind, this study had two objectives: (a) the crop model APSIM was evaluated for pearl millet-cowpea intercropping against a detailed field trial data set; (b) the model was used to explore interactions between pearl millet (*Pennisetum glaucum* (L.) and cowpea (*Vigna unguiculata* (L.)Walp) under intercrop and sole crop production, different densities and water supplies. Pearl millet-cowpea intercropping was chosen as a common system for dryland smallholder farmers. Pearl millet is a key staple food for dryland regions (Hadebe et al., 2017) and cowpea an important protein source with leaves used as vegetables or fodder (Sennhenn et al., 2017).

2 | MATERIALS AND METHODS

2.1 | Study region and conditions

This study took place at the ICRISAT Research Station, Patancheru, India (17.25°N, 78.05°E, Elevation: 545 m) in the dry season (experimental details in Section 2.2.2 Field data). The climate of the region is semi-arid tropical with annual rainfall averaging 910 mm (taken from a period of 1980–2010). The year consists of a dry season (January to March, 37 mm), a pre-rainy season (Zaid: April to May, 56 mm), a rainy season (Kharif: June and September, 681 mm), a post-rainy season (Rabi: 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). The systems investigated are typical Kharif crops, grown with the onset of the monsoons. Irrigation is required for agricultural production outside of the Kharif season. Temperatures around planting for the field experiments were similar to those at the beginning of a typical Kharif season. While Kharif season temperatures would typically decrease through the season, they increased over the experimental period. Daily mean temperature over the experimental period in 2015 was 26.1°C, with 39.6°C and 11°C the maximum and minimum daily temperatures. In 2016, the daily mean temperature was 29.7°C over the experimental period, with 42.2°C and 14.8°C the maximum and minimum daily temperatures. Further details can be found in Nelson et al. (2018). All plots were heavily irrigated prior to sowing. Throughout the experiment, irrigation applications took rainfall into account. If it rained the day before irrigation was due, the following morning's application was reduced by the amount of rain the experimental site received to ensure comparability between the two years. The topsoil was a sandy loam with 79.3% sand, 6.4% silt, and 14.3% clay, with organic carbon in the topsoil at 0.55% and the pH 6–7 (Bhattacharyya et al., 2016). Diammonium phosphate (DAP=18% N + 46% P_2O_4) was applied at 100 kg/ha before sowing to all plots, and urea-N was top-dress applied to pearl millet at 100 kg/ha once plants were well-established. This was done to eliminate N limitations. Weeds, pests and diseases were controlled throughout the experiment.

2.2 | Model testing

2.2.1 | APSIM

The process-based model APSIM (version 7.9) used in this study, with a focus on dryland agriculture (Akinseye et al., 2017; Hoffmann, Odhiambo, et al., 2018; Whitbread et al., 2017), was described by Holzworth et al. (2014) and has been widely used (Gaydon et al., 2017; Hoffmann, Isselstein, et al., 2018; Whitbread et al., 2010). The pearl millet model in APSIM (van Oosterom et al., 2001a, 2001b) simulates the growth of the main stem and five tillers per plant separately. Applications are reported in Akponikpè et al. (2011), and O'Leary et al. (2008). The APSIM cowpea model (Robertson et al., 2002) follows the generic APSIM plant description (Wang et al., 2002) and simulates biological nitrogen (N) fixation to meet crop N needs (Chen et al., 2016). Of particular importance is that due to cowpea's ability to fix N from the air, APSIM assumes, in the case of a lack of mineral N for plant growth, that any deficit is supplied via fixation. Limitations of N-fixation, such as low phosphorous supply or acidic soils, are ignored (Chen et al., 2016).

Intercropping was simulated using the APSIM Canopy module, whose routines for light interception and competition for water and N were described by Carberry et al. (1996) and introduces different aboveground layers based on the simulated height of the plant. This enables the modelling of light interception by layer from the tallest stand, with remaining light entering the layer below, determining light competition between intercrop components. Competition for water and N with intercropping is calculated by daily alternations of the crop that has first access to available resources. This alternation continues until final harvest. It is important to note that the resources available to a crop may differ due to the characteristics of that crop, such as rooting depth, soil water extraction capacity, crop lower limit, and N fixation. Competing intercrops therefore have an indirect impact on one another through the simulated influence of resource availability (Carberry et al., 1996).

2.2.2 | Field data

The field data used were derived from a trial conducted at the ICRISAT experimental station in the dry seasons of 2015 and 2016, as described in Nelson et al. (2018). The trials were purposefully conducted during the off-season to ensure complete control of the water supply. The treatments tested were sole crop versus intercrop, 33 versus 17 plants per m^{-2} (reported as high and low plant density, respectively), and irrigation for severe stress, partial stress, and well-watered treatments. Intercrop components, pearl millet and cowpea, were sown simultaneously. Cultivars used were Russian Giant for a forage cowpea crop, and a short pearl millet hybrid H77/833-2 (known as HHB 67 in India). The experiment was set-up as a split-split plot design. Biomass harvests consisted of 150 mm (length of crop row sampled) for every row in all plots except for the two outermost rows that were left as borders. Harvests were conducted by hand at pearl millet flowering, cowpea flowering, two weeks after cowpea flowering, and at full maturity with the addition of grain yield. Leaf area index (estimated using an AccuPAR LP-80) on a plot basis, and stem height (crop-specific for intercrop stands) were measured weekly. Soil samples were taken one day before sowing and one day after each biomass harvest using a hand probe; thus water use could be assessed from 0 to 600 mm in 150 mm increments. These were weighed directly in the field, dried in ovens at 60°C for 24 hr, followed by 105°C for a further 24 hr and weighed. More details can be found in Nelson et al. (2018).

2.2.3 | Model calibration

APSIM simulations require daily weather data, soil properties, management practices, and cultivar information to be run for specific field trials. Solar radiation, maximum and minimum temperature and precipitation were measured at the experimental station. Information on planting, fertiliser and irrigation practices was collected during the trial. Soil and cultivar data were used to calibrate the model, as explained in detail below. Cowpea and pearl millet sole crop well-watered high plant density treatments of 2015 were used to derive cultivar specific parameters—these treatments were then excluded from the statistical validation of the model (Figures 1 and 2). Missing soil parameters were based on standard values found in the literature. The same model parameterisation was used to simulate the remaining treatments.

Soil parameterisation is especially important for the determination of plant available water holding capacity, defined as the difference between crop lower limit (CLL) and drained upper limit (DUL; Whitbread et al., 2017). The CLL and DUL were determined according to Dalgliesh et al. (2016). The CLL was assessed by positioning rainout shelters over pearl millet and cowpea monoculture stands at flowering and using the volumetric soil water at harvest for crop-specific lower limits (Table 1). Drained upper limit was assessed by drip irrigation wetting of the soil profile (Table 1). Bulk density values were assessed prior to this study. The maximum rates of total water extraction by the crop (KL) were estimated similarly to Dalgliesh et al. (2016) (Table 1).

The APSIM SoilWat parameters were set at 73 for the runoff curve number, 88 for the diffusivity constant of water percolation, 35

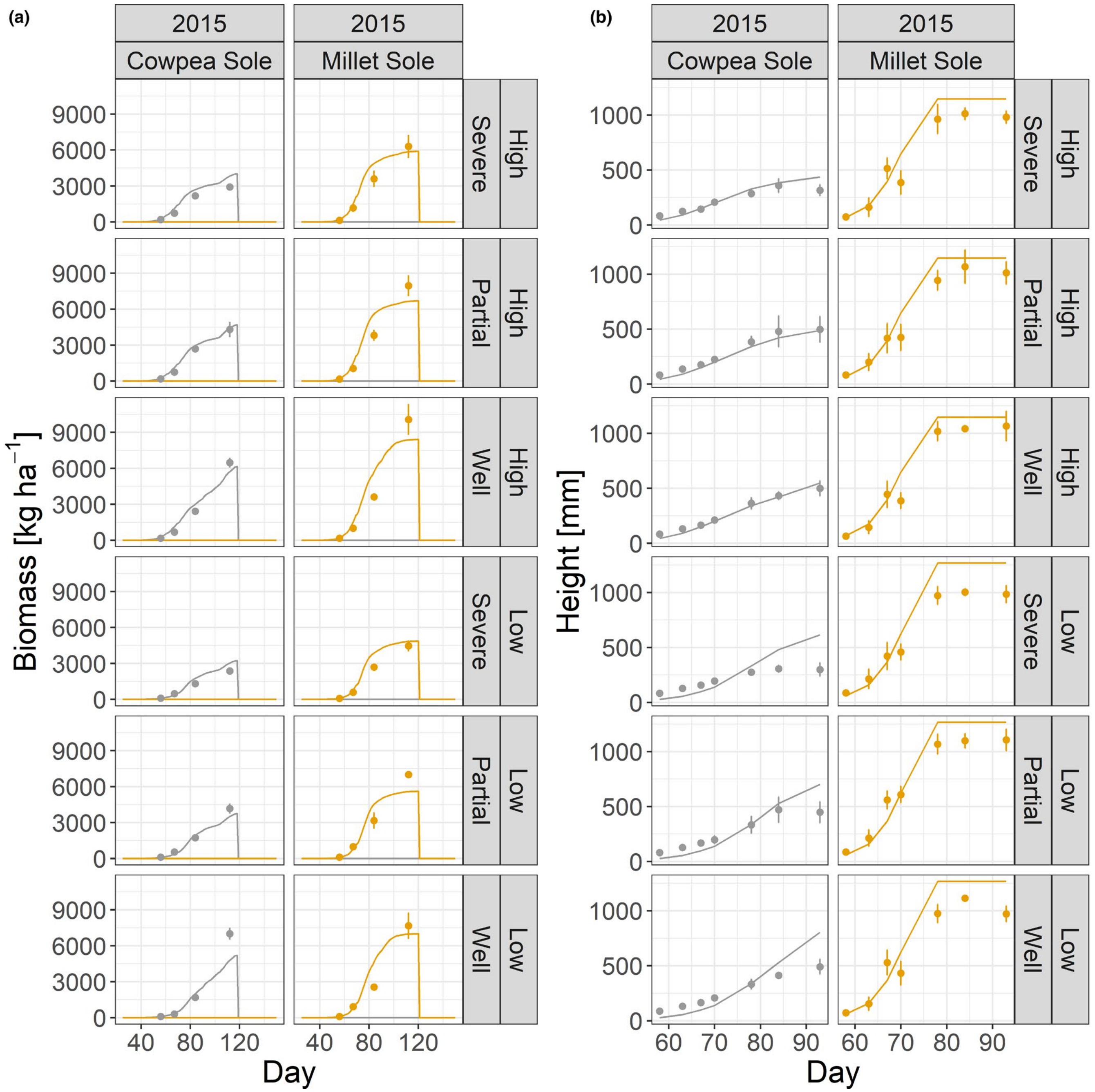

FIGURE 1 APSIM calibration runs for aboveground biomass (a) and plant height (b) compared simulated lines and observed points throughout the 2015 season for pearl millet and cowpea sole crops in Patancheru. The right-hand-side y-axis identifies the following: high, 33, and low, 17 plants per m^{-2} planting densities; weekly irrigation treatments: severe, until pearl millet flowering; partial, until cowpea flowering; and well-watered, until after cowpea flowering

for the diffusivity slope under unsaturated conditions, and 0.5 for the SWCON for saturated conditions (Hoffmann et al., 2017; Whitbread et al., 2017). Soil evaporation is assumed to take place in two stages, constant and falling rates based on the Priestly-Taylor approach. These are described within APSIM as cona and U, set at 4 and 2, respectively. Initial soil water conditions were measured for both years.

The APSIM model's phenological stages are simulated through calculating thermal time (tt, degree days) using base (10°C and 10°C), optimal (33°C and 23°C), and maximum temperatures (47°C and 44°C) for pearl millet and cowpea, respectively, based on empirical data (pearl millet: van Oosterom et al., 2001a, 2001b; and cowpea: Robertson et al., 2002). Pearl millet cultivar HHB 67 was already characterised in APSIM, and the characterisation of cowpea cultivar Banjo was used for Russian Giant. Using the trial data, the cultivars were re-parameterised for phenology and canopy development (Table 2). The determination of the parameters was done

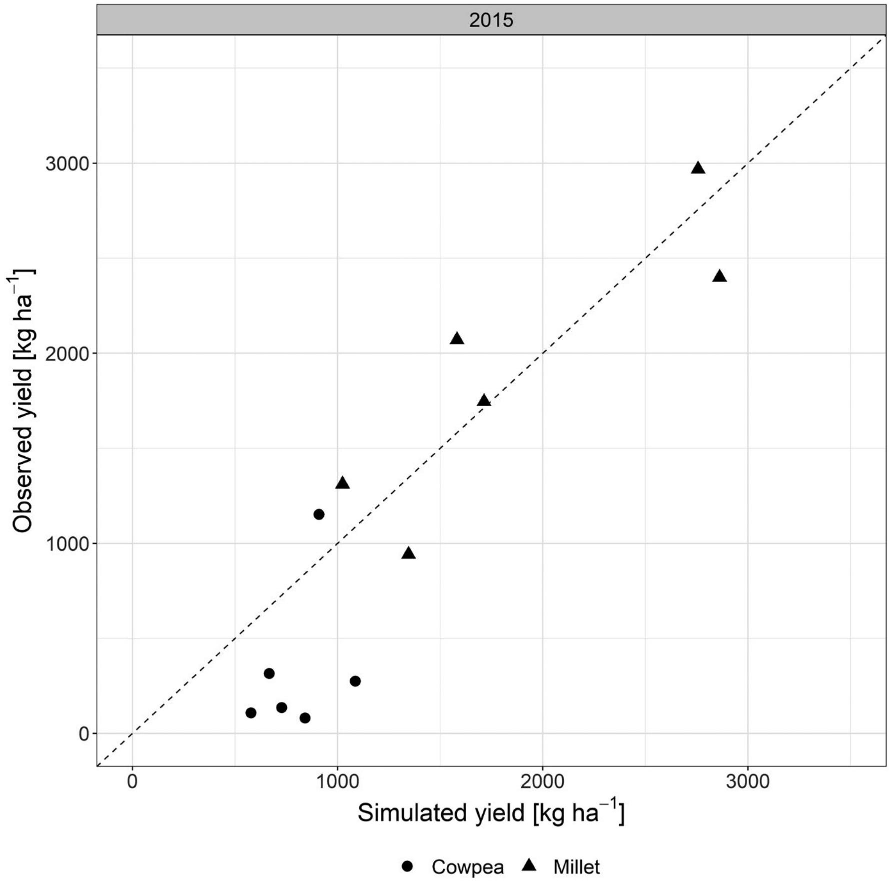

FIGURE 2 Calibration runs for simulated (*x*-axis) versus observed (*y*-axis) grain yield throughout the 2015 season for pearl millet (triangles) and cowpea (circles) sole crops in Patancheru

TABLE 1 Soil physical properties for the estimated rooting depth, including bulk density (BD), low limit of available soil water for each crop (LL), drained upper limit/field capacity (DUL), and saturation (SAT)

Depth (cm)	BD (g/cc)	Air dry	Millet LL (mm/mm)	Cowpea LL (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	Millet KL (/day)	Millet XF (0–1)	Cowpea KL (/day)	Cowpea XF (0–1)
0–15	1.350	0.074	0.102	0.082	0.172	0.441	0.08	1.0	0.08	1.0
15–30	1.350	0.155	0.178	0.172	0.188	0.441	0.08	1.0	0.08	1.0
30–45	1.420	0.170	0.181	0.170	0.292	0.414	0.08	1.0	0.08	1.0
45–60	1.420	0.154	0.165	0.154	0.290	0.414	0.08	1.0	0.08	1.0
60–75	1.420	0.151	0.161	0.151	0.273	0.414	0.06	1.0	0.06	1.0
75–90	1.420	0.128	0.128	0.128	0.279	0.414	0.04	1.0	0.04	1.0
90–105	1.420	0.128	0.128	0.128	0.211	0.414	0.03	1.0	0.03	1.0
105–120	1.420	0.128	0.128	0.128	0.257	0.414	0.02	1.0	0.02	1.0
120–135	1.420	0.128	0.128	0.128	0.216	0.414	0.02	1.0	0.01	0.0
135–150	1.420	0.128	0.128	0.128	0.198	0.414	0.01	1.0	0.01	0.0

Note: Fraction of plant available water able to be extracted/day (KL) for each crop and layer (Dalgliesh et al., 2016), and an exploration factor (XF) with 1 for no root growth impediment and 0 if roots cannot penetrate a layer.

by visually matching model output against observed results of grain yield, biomass, LAI, and plant height (Figures 1–3). A key cultivar parameter adapted for pearl millet addressed the height of the plants. In APSIM, actual plant height is a function of the parameters maximum plant height and stem weight. Overall, parameters were set within reasonable ranges found in the literature in order to avoid overfitting the model (see Section 2.2.1).

2.2.4 | Statistical validation

All treatments other than those used for calibration were used to validate model performance independently using root mean square error (RMSE), and its normalisation (nRMSE 0–1, the closer to zero is better), model efficiency (EF 0–1, the closer to one the better), and Willmott Index of Agreement (IA 0–1, the closer to one the

TABLE 2 Cowpea and pearl millet cultivar parameters used for APSIM, highlighting the adaptations made to default APSIM parameters; tt represents the unit thermal time

APSIM parameter	Description	Unit	Default	Adapted
Cowpea			Banjo	Russian Giant
y_hi_incr	Rate of HI increase	0.0164/days	0.014	0.010
y_hi_max_pot	Max. HI	0–1	0.4	0.25
tt_emergence	tt emergence to end juvenile	°C days	552	680
y_tt_flowering	tt flowering to start grain fill	°C days	100	120
y_tt_start_grain_fill	tt to start of grain fill period	°C days	280	390
x_stem_wt	Stem weight	g/plant	0–15	0–15
y_height	Plant height	mm	0–1000	0–1000
y_node_app_rate	Node appearance rate	°C days	50 50 50 50	40 40 40 40
Pearl millet			HHB 67	HHB 67
Millet main stem				
leaf_app_rate1	tt required to fully emerge	°C days	62	75
leaf_app_rate2	tt required to fully emerge	°C days	36.4	40.4
head_grain_no_max	Potential grains per head	Grains/head	2,600	5,200
tt_emerg_to_endjuv	tt emerg. to end of juvenile	°C days	199.4	119.4
tt_flower_to_maturity	tt flower to maturity	°C days	457	610
tt_maturity_to_ripe	tt maturity to harvest	°C days	1	50
y0_const	Largest leaf area intercept *y*-axis regression of the area of the largest leaf on total leaf number		7,280	4,280
Millet tiller 1				
leaf_app_rate1	tt required to fully emerge	°C days	62	95
leaf_app_rate2	tt required to fully emerge	°C days	36.4	80.4
tt_flower_to_maturity	tt flower to maturity	°C days	457	610
tt_maturity_to_ripe	tt maturity to harvest	°C days	1	50
y0_const	Largest leaf area intercept *y*-axis regression of the area of the largest leaf on total leaf number		3,480	1,480
Millet tillers 2, 3, 4 & 5				
leaf_app_rate1	tt required to fully emerge	°C days	62	75
tt_flower_to_maturity	tt flower to maturity	°C days	457	610
tt_maturity_to_ripe	tt maturity to harvest	°C days	1	50
y0_const	Largest leaf area intercept *y*-axis regression of the area of the largest leaf on total leaf number		3,480	1,570

better; Hoffmann, Isselstein, et al., 2018). Further details of the various statistical performance indicators used for model evaluation are documented and discussed in Palosuo et al. (2011) and Wallach et al. (2016). All analyses were done using R software and the package 'ZeBook' (Wallach et al., 2018) for statistical validation and ggplot2 for visualisation (Wickham, 2016).

2.3 | Simulation experiment

The APSIM model was setup for a simulation experiment to explore the effect of water supply under different management strategies for pearl millet-cowpea intercropping on grain yield performance. The soil used was the same as the one used for model validation. The simulation experiment was repeated for 31 years from 1980 to 2010 based on observed weather station data. Although the growing period used is typically very dry, certain years received rainfall. The sowing date was the 28th of January. The water supply amounts per season and duration after sowing were 280 mm during six weeks for severely stressed; 340 mm over seven weeks for partially stressed; and 500 mm over ten weeks for well-watered. A plant density of 33 plants per m^{-2} with 300 mm between row spacing was compared with 17 plants per m^{-2} with 600 mm between row spacing. Within row plant spacing was 100 mm.

Soil water was set at each sowing event to field capacity and the above-described irrigation treatments were applied in addition, as water declined from field capacity. Taking management (three systems, two plant densities, three levels of irrigation) and 31 years into account, there were 558 simulations.

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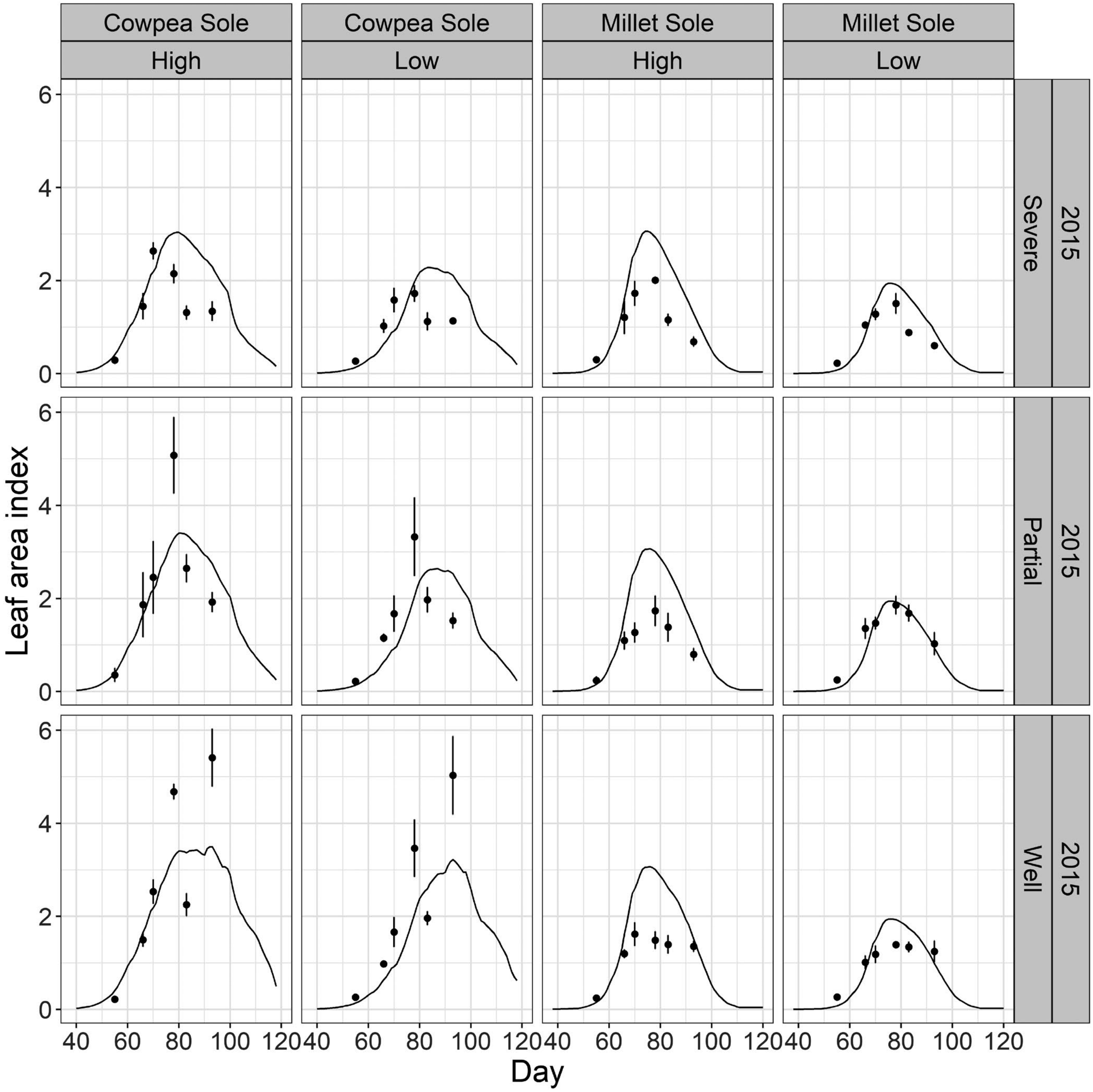

FIGURE 3 Calibration runs for simulated lines and observed points of LAI throughout the 2015 season for pearl millet and cowpea sole crops in Patancheru. The right-hand-side *y*-axis identifies the following: 2015, season; and weekly irrigation treatments: severe, until pearl millet flowering; partial, until cowpea flowering; and well-watered, until two weeks after cowpea flowering. The upper column identifies the following: cowpea and pearl millet sole crop systems; and high, 33, and low, 17 plants per m^{-2} planting densities

3 | RESULTS

3.1 | Model validation

Willmott Index (IA) values for yield of 0.87 and 0.83 for both cowpea and pearl millet, respectively, show that the model performed well in terms of capturing growth dynamics and distinguishing treatment effects. Model efficiency was satisfactory for both crops combined at 0.60, with cowpea yield at 0.22 and pearl millet yield at 0.46 (Table 3). Model accuracy was variable and highly crop specific, as indicated by nRMSE values of 0.44 for both cowpea and pearl millet combined, but with 0.58 and 0.37 for cowpea and pearl millet individually (Table 3). While higher pearl millet yields were captured by the model overall, it seemed to have difficulties reproducing large yields for high plant density sole crop conditions (Figure 4). Importantly, cowpea yields were still simulated with a RMSE of 322 kg/ha, but against a low observed average of 555 kg/ha.

While model accuracy was not high for biomass (high relative nRMSE values of around 0.55), the IA emphasised the effectiveness of the model, with 0.91, 0.91, and 0.88 for both crops, pearl millet, and cowpea, respectively (Table 3), which captured the dynamics of plant growth. Model efficiency values of 0.68, 0.69, and 0.68 confirmed solid model performance (Table 3).

Cowpea biomass yield predictions were particularly accurate under the severe stress treatments at both high and low plant densities but worsened over time as water supply increased. This trend can also be seen for pearl millet sole crop in 2016 with both plant densities. The model clearly simulated the impact of intercropping and the resource competition that occurs, as pearl millet biomass was low when intercropped compared to when grown as a sole crop (Figure 5).

The dynamics of LAI were simulated well by the model, with an IA value for intercrop stands of 0.75 (Table 3). Simulated LAI was low for cowpea and more accurate for pearl millet (Figure 6). Simulations for sole crop cowpea 2016 for the severe stress, high plant density treatment captured the effect senescence had on LAI, as values peaked around Julian day 80 and declined as the crop neared maturity. This trend was also seen for the same treatment at the low plant density, although the values and peaks were not as high. For all sole crop cowpea 2016 treatments, LAI peaks were accurately captured in terms of the stage of the season. There was little difference between observed and simulated partial and well-watered LAI values for all 2016 densities and systems. Simulated intercrop LAI matched observed values especially well for severe stress in 2016 (Figure 6).

The model simulated pearl millet stem height accurately with a nRMSE value of 0.31, EF of 0.72 and a IA value of 0.94 (Table 3). Figure 7 highlights the solid model simulations for both cowpea and pearl millet sole crops. Although in general all treatments were simulated well in this instance, sole crop cowpea 2016 simulations were better at low plant density towards the end of the season compared to those for high plant density treatments. For the intercrop treatments in general, the competition from pearl millet was simulated as having a greater impact on cowpea height than observed (Figure 7).

With a nRMSE of 0.28 (Table 3), soil water content trends were clearly well simulated (Figure 8).

3.2 | Simulation experiment: sole versus intercropping under different water supplies and plant densities

The simulation experiment examined the effects of water supply on sole and intercrop pearl millet and cowpea yields at two densities. Pearl millet yield was strongly affected by treatments, with sole crop yields ranging from 600 to 3,100 kg/ha (low density) and 50 to 3,800 kg/ha (high density)—pearl millet struggled under low water supply. Cowpea yield was less affected by treatments than pearl millet and varied as a sole crop from 500 to 1,700 kg/ha (low density) and 500 to 1900 kg/ha (high density). Crucial for high pearl millet yield, was sufficient water supply (Figure 9).

Mean sole pearl millet and total intercrop yield differences under low water supply were minimal (low plant density: 800 versus 1,000 kg/ha; high plant density: 2,500 and 2,400 kg/ha; Figure 9). However, the three absolute lowest sole pearl millet yields were 50, 125, and 150 kg/ha (low water supply, high plant density). The lowest total intercrop yields were higher, with 260, 270, and 300 kg/ha (low water supply; high, low, and high plant density). Both high plant density treatments only produced cowpea grain yield; pearl millet failed when intercropped with cowpea under stress (low water supply and high plant density). In fact, eight out of the lowest ten intercrop yields did not include any pearl millet yield (low water supply and high plant density).

The mean of the ten lowest intercrop yields at low plant density and low water supply was around 500 kg/ha (pearl millet 200 kg/ha; cowpea 300 kg/ha; Figure 9). Total intercrop yields increased

TABLE 3 Model validation: mean observed value, mean simulated value, root mean square error (RMSE), RMSE normalised to the observed mean (nRMSE), Model Efficiency (EF) and the Willmott Index of Agreement (IA)

Variable	Value	*N*	Mean obs.	Mean sim.	RMSE	nRMSE	EF	IA
Biomass (both crops)	kg/ha	144	1836	1872	1,020	0.55	0.68	0.91
Cowpea biomass	kg/ha	72	1695	1,215	924	0.54	0.68	0.88
Pearl millet biomass	kg/ha	72	1977	2,528	1,100	0.56	0.69	0.91
Yield (both crops)	kg/ha	36	918	808	402	0.44	0.60	0.87
Cowpea yield	kg/ha	18	555	479	322	0.58	0.22	0.64
Pearl millet yield	kg/ha	18	1,280	1,137	469	0.37	0.46	0.83
LAI intercrop stands	–	66	1.72	2.37	1.10	0.64	0.06	0.75
LAI cowpea sole crop	–	30	2.59	1.61	1.32	0.51	0.28	0.75
LAI pearl millet sole crop	–	30	1.03	1.36	0.53	0.51	−1.19	0.66
Pearl millet height	mm	102	567	653	176	0.31	0.72	0.94
Cowpea height	mm	102	287	164	154	0.54	0.07	0.75
Soil water[a]	mm/mm	126	0.15	0.18	0.04	0.28	0.22	0.73

[a]Contains measurements from layers 0–150, 150–300, 300–450, and 450–600 mm (see Figure 8).

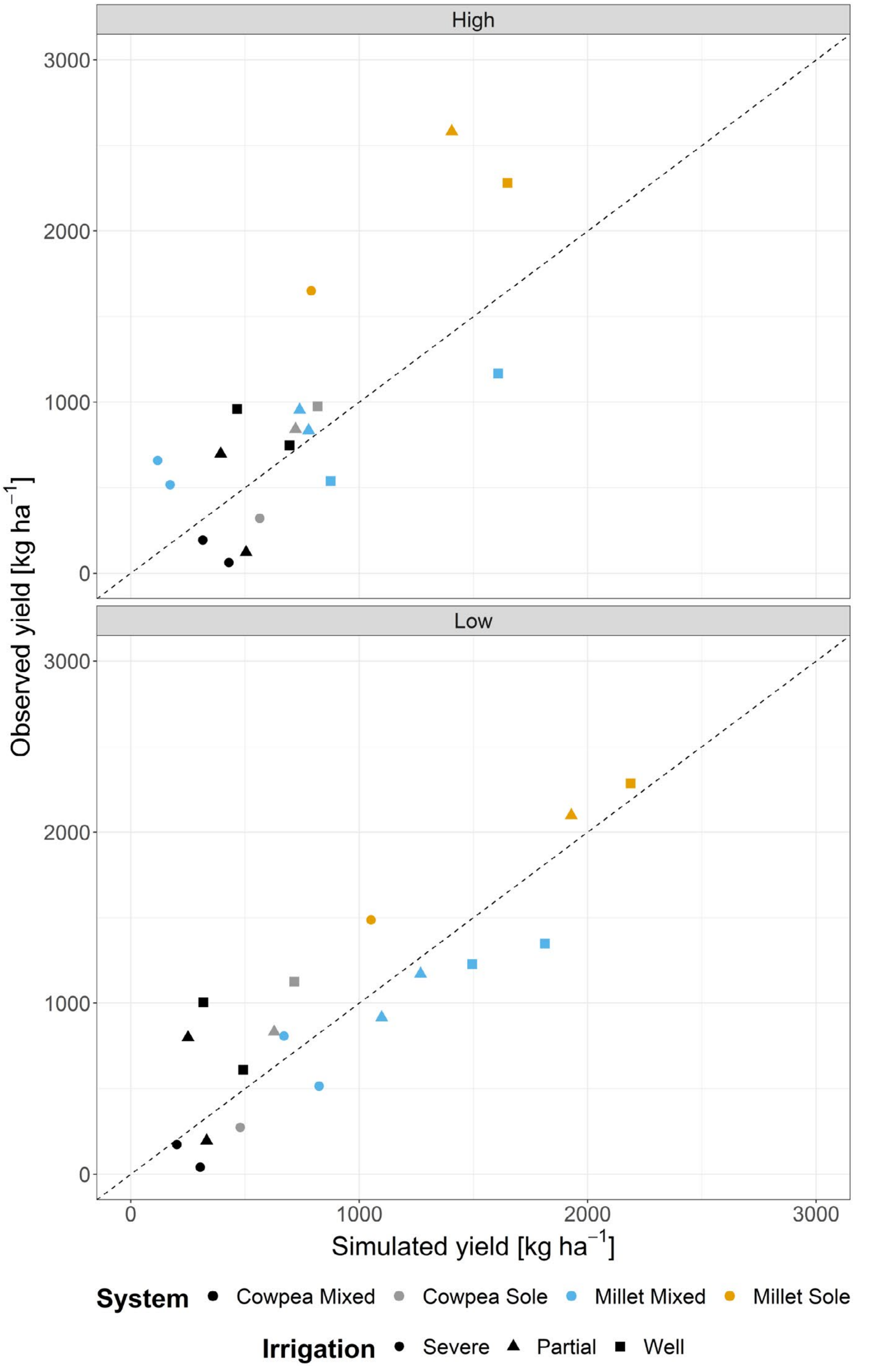

FIGURE 4 Simulated (*x*-axis) versus observed (*y*-axis) grain yield for cowpea and pearl millet sole crops and intercropped stands with high, 33, and low, 17 plants per m^{-2} planting densities in Patancheru—plots top and bottom respectively. Colours represent the cropping system; and shape the weekly irrigation treatments: severe, until pearl millet flowering (circles), partial, until cowpea flowering (triangles), and well-watered, until two weeks after cowpea flowering (squares)

with water supply and were driven by pearl millet yields, especially at high density, with regression slope values of 7.8 (mixed) and 7.5 (sole millet). The mean of the ten highest total intercrop yields was 3,100 kg/ha (pearl millet: 2,100 kg/ha; cowpea: 1,100 kg/ha—high plant density) and 2,900 kg/ha (pearl millet: 2,100 kg/ha; cowpea: 800 kg/ha—low plant density)—all at high water supply. The absolute highest total intercrop yield was just over 4,000 kg/ha (pearl millet: 2,900 kg/ha; cowpea: 1,100 kg/ha; high density, high water supply), i.e. a 70/30 share; the highest low density intercrop yield was 3,500 kg/ha with a 75/25 share (high water supply; Figures 9 and 10). In general, yields were slightly higher at high plant density but needed more water to perform well. The pearl millet shares of total intercrop yield dominated more when water supply increased at both densities.

Total biomass was not as strongly influenced by water supply or density (Figure S1). Under low water supply, pearl millet biomass was still reasonable.

Low-density intercropping achieved a 50/50 pearl millet-cowpea yield share with less water supply (the lowest treatment) than at high density (Figure 10). At high density, a 50/50 yield balance between the two intercrop components was only possible when at least 380 mm of water was supplied.

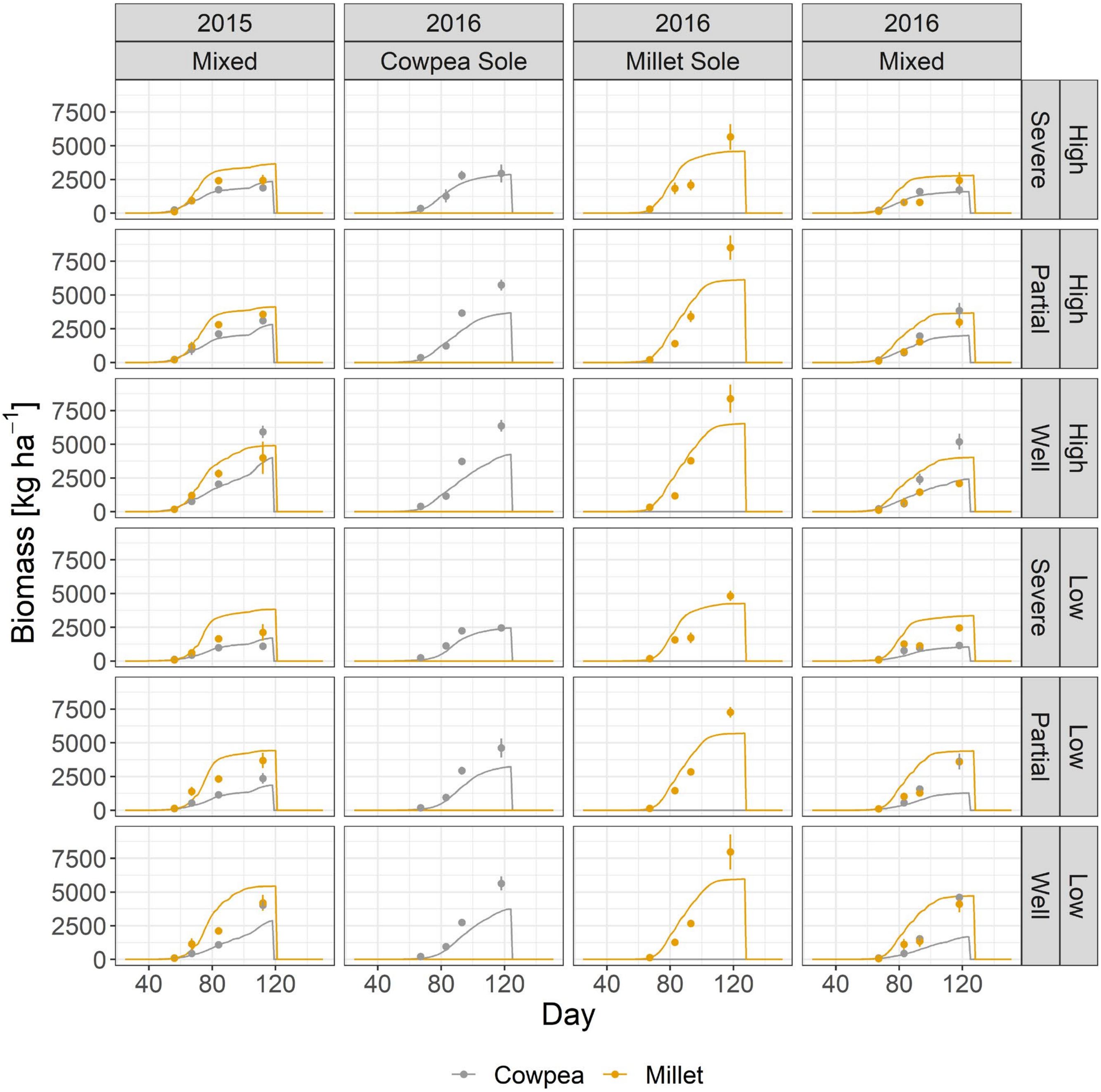

FIGURE 5 Simulated lines and observed points for biomass over time (Julian days) in Patancheru. Represented treatments, from left to right, are intercropped cowpea and pearl millet 2015, cowpea sole crop 2016, pearl millet sole crop 2016, and intercropped cowpea and pearl millet in 2016. The right-hand-side y-axis identifies both high, 33, and low 17 plants per m^{-2} planting densities; and weekly irrigation treatments: severe, until pearl millet flowering, partial, until cowpea flowering, and well-watered, until two weeks after cowpea flowering

4 | DISCUSSION

This study confirmed that APSIM is capable of reproducing the effects of management on crop performance; however, the accuracy of the prediction requires improvement. The simulation study showed that the total yields of intercropping are strongly linked to those of the sole cropped pearl millet. If farmers can accept a reduction of pearl millet yield under intercropping, food supply could be diversified with a protein rich crop. For the genotypes used in this study, intercropping could be a risk management strategy under drought, but only at low density.

4.1 | Model performance

Generally, yield dynamics were captured well by APSIM (IA of 0.87 for both crops), but were better captured for pearl millet than

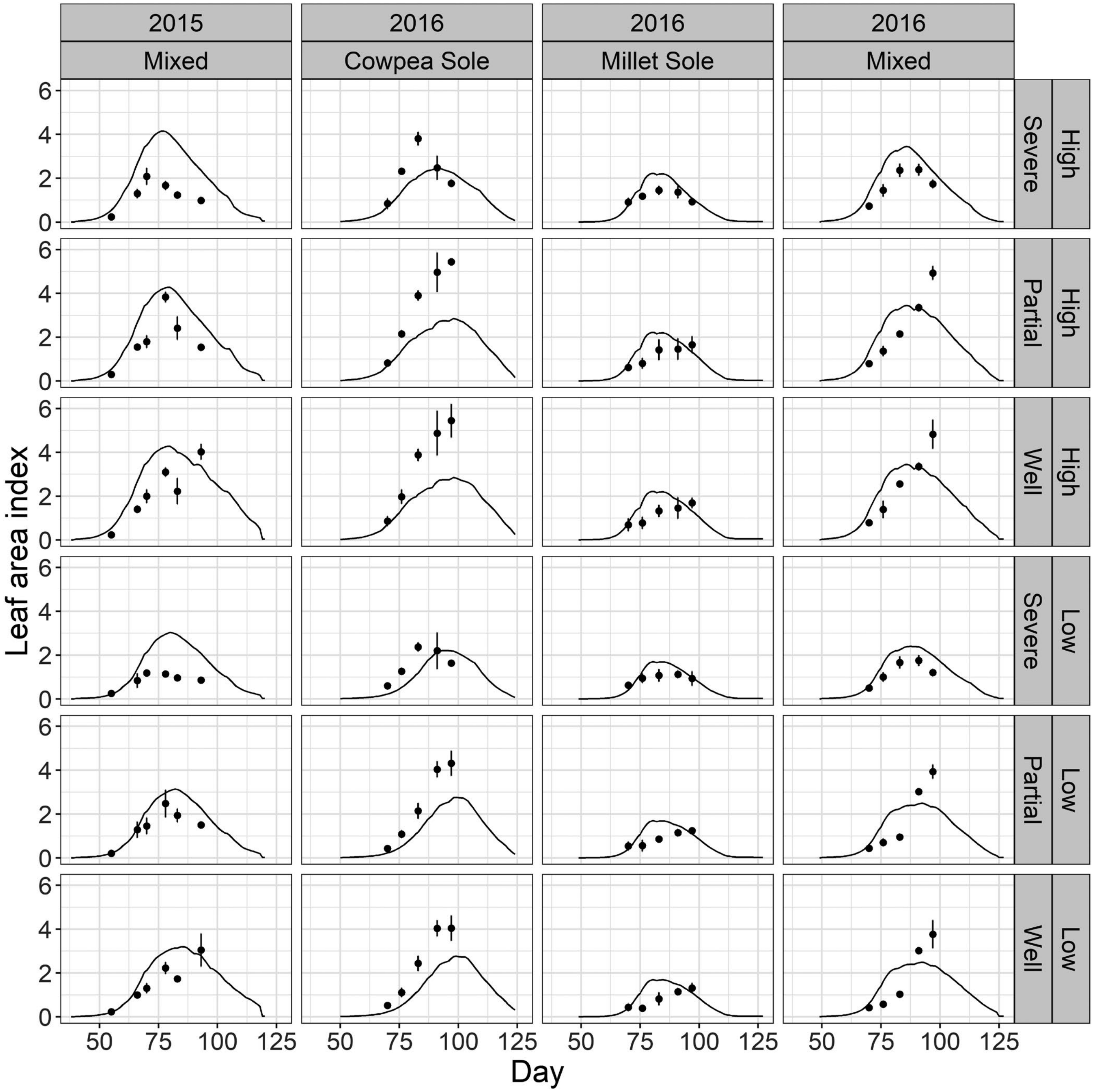

FIGURE 6 Simulated lines and observed points of the leaf area index shown over time (Julian days) in Patancheru. Represented treatments are intercropped cowpea and pearl millet 2015, cowpea sole crop 2016, pearl millet sole crop 2016, and intercropped cowpea and pearl millet 2016. The right-hand-side y-axis identifies both high, 33, and low 17 plants per m^{-2} planting densities; and weekly irrigation treatments: severe, until pearl millet flowering, partial, until cowpea flowering, and well-watered, until two weeks after cowpea flowering

cowpea, with values of 0.83 and 0.64, respectively (Table 3). The poor cowpea simulations inevitably reduced the accuracy of model predictions for intercrop treatments as a whole (Figure 3). Chimonyo et al. (2016) found the cereal component of their cereal–legume intercrop system (sorghum-cowpea) to be more accurately captured by APSIM. This emulates the findings of this study, albeit with a different cereal species, pearl millet. This potentially highlights two things: APSIM, and perhaps crop models in general have largely focussed on cereals in the past; and that legumes, cowpea in particular, can be unstable and highly sensitive to environment and management (Nelson et al., 2018). However, legumes and multispecies systems are promoted as important for our landscapes and food production systems (Franke et al., 2018; van Loon et al., 2018; Ngwira et al., 2012), increasing the need for detailed data that will help to accurately develop related models. Intercropping dynamics were generally well captured by APSIM, as both simulated and observed

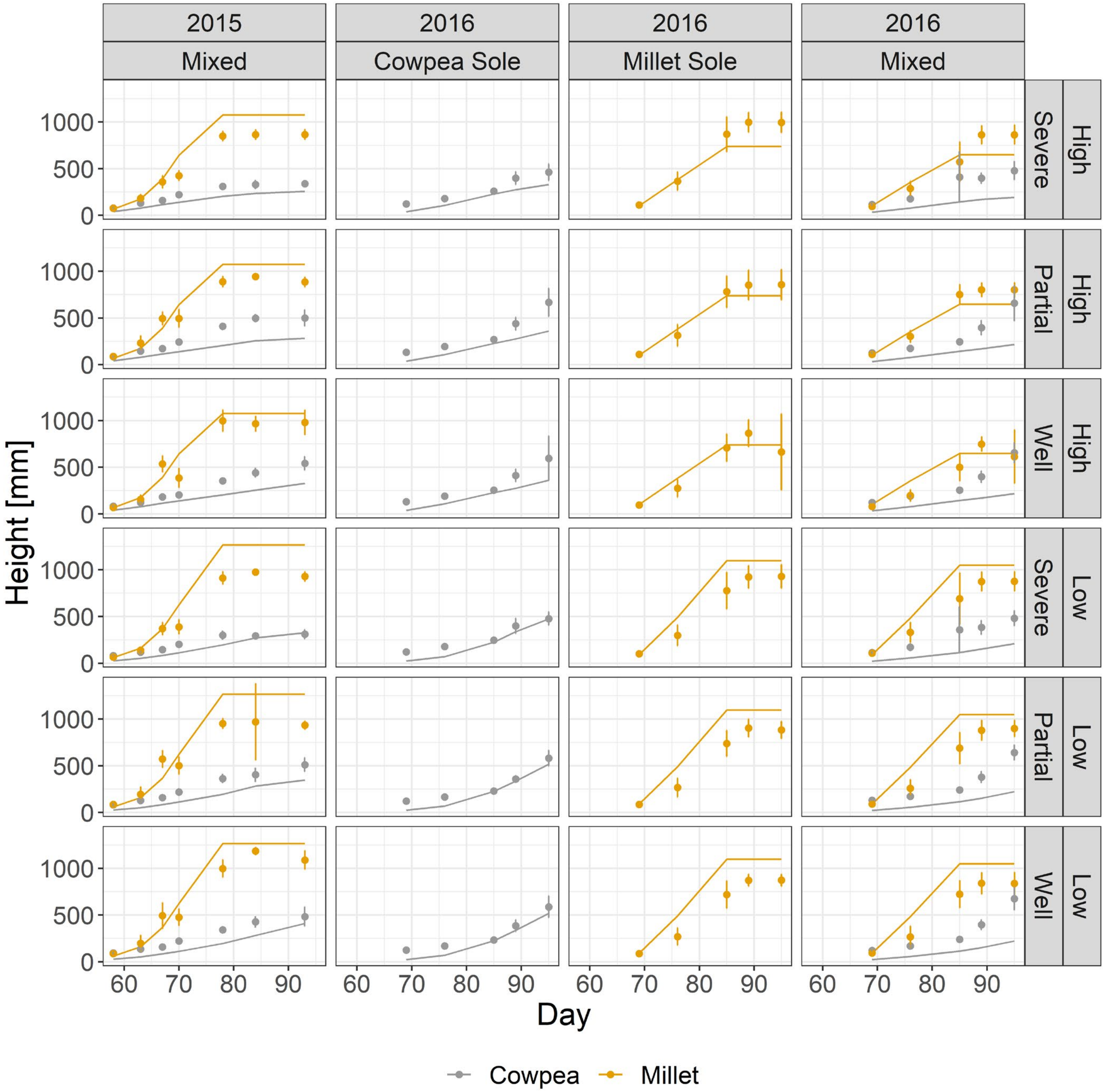

FIGURE 7 Simulated lines and observed points of the main stem height (mm) shown over time (Julian days) in Patancheru. Represented treatments are intercropped cowpea and pearl millet 2015, cowpea sole crop 2016, pearl millet sole crop 2016, and intercropped cowpea and pearl millet 2016. The right-hand-side y-axis identifies both high, 33, and low 17 plants per m^{-2} planting densities; and weekly irrigation treatments: severe, until pearl millet flowering, partial, until cowpea flowering, and well-watered, until two weeks after cowpea flowering

values showed how pearl millet yield and biomass production was compromised through competition from cowpea (Figures 4 and 5). Moreover, this lack of legume stability, and therefore predictability, emphasises the need to quantify scientific findings.

Key to this study is the way the model captured the dynamics of biomass observations, with high IA values at 0.91, 0.91, and 0.88 for both crops, pearl millet, and cowpea, respectively (Table 3). Both cowpea and pearl millet biomass production was lower when intercropped compared to sole crop equivalents (Figure 5). Chimonyo et al. (2016) reported inaccurate cowpea yields and biomass, whereby an overestimation of yield was linked to an overestimation of biomass. This study however slightly underestimated cowpea biomass, but more so for the high water supply treatments (Figure 5). Under severe stress treatments (those that received the least water), at both high and low densities, both crops, but particularly cowpea, were well simulated for biomass development (Figure 5). There was little difference between

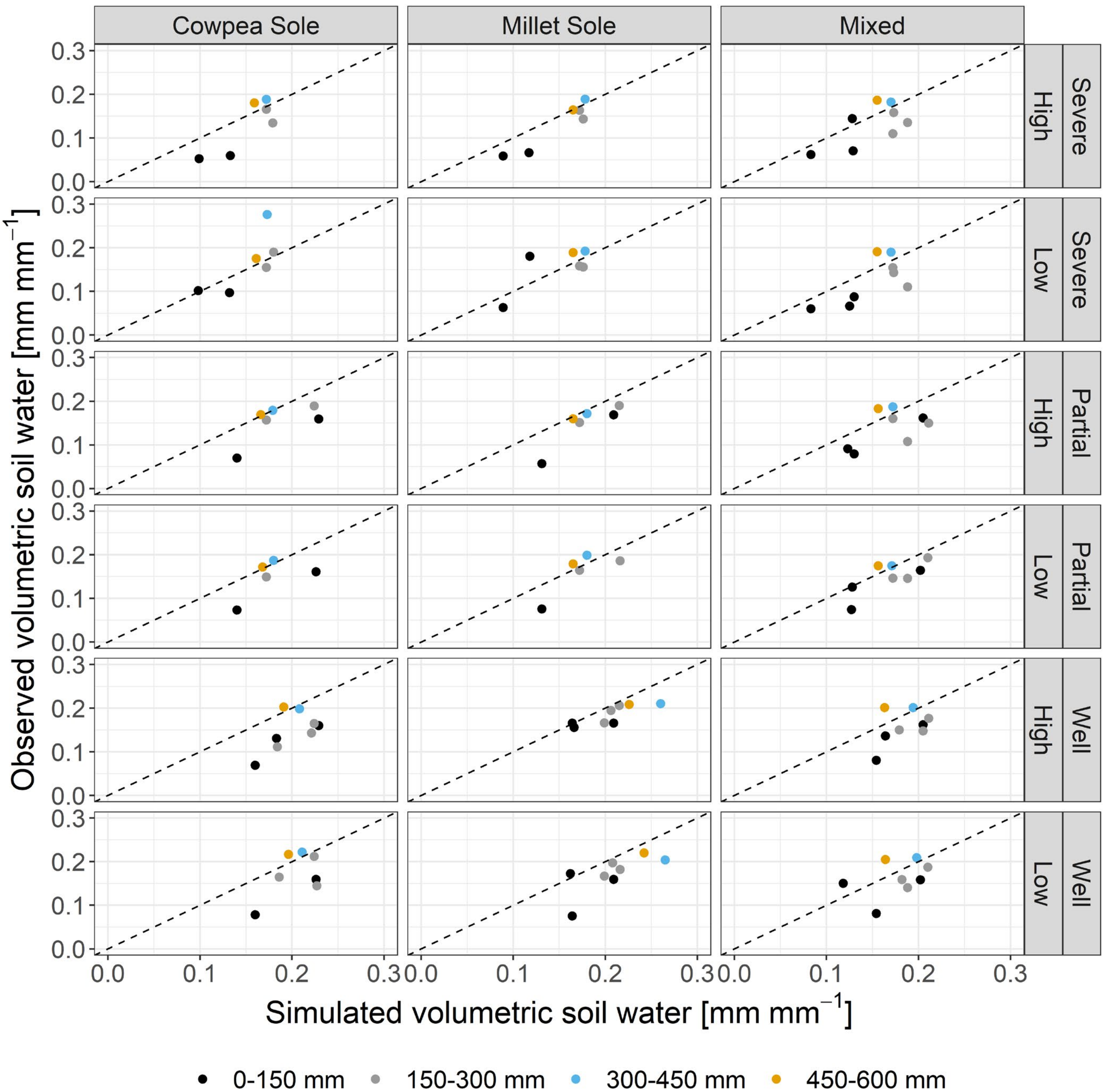

FIGURE 8 Simulated (*x*-axis) versus observed (*y*-axis) volumetric water content of soil water layers 0–150, 150–300, 300–450, and 450–600 mm for the experimental site in Patancheru. Represented treatments are cowpea sole crop 2015, pearl millet sole crop 2015, and intercropped cowpea and pearl millet 2016. The right-hand-side y-axis identifies both high, 33, and low 17 plants per m^{-2} planting densities; and weekly irrigation treatments: severe, until pearl millet flowering, partial, until cowpea flowering, and well-watered, until two weeks after cowpea flowering

the partial and well-watered treatments in terms of total water supply. It was therefore not surprising to see similarities between the inaccuracies of partial and well-watered biomass simulations (Figure 5). Clearly, APSIM was unable to capture the boost in above-ground vegetation production at later growth stages (Figure 5). Height was simulated especially well for pearl millet, with nRMSE and IA values of 0.31 and 0.94, respectively (Figure 7 and Table 3). The same can also be argued for cowpea, especially as a sole crop, although there were some deviations for intercropped cowpea height (Figure 7). Observations clearly demonstrated that the cowpea cultivar Russian Giant outcompeted the pearl millet more than the model simulated (Figure 5). The model underestimates yield performance of pearl millet high plant density for sole crop conditions (Figure 4). One reason may be that the model has not been sufficiently tested for higher densities, which might result in different growth patterns.

Trends found in simulated grain and biomass yields can be partly explained by canopy development. This data set confirmed key insights into cowpea biomass shortfalls (Figure 5), as they were mirrored by the

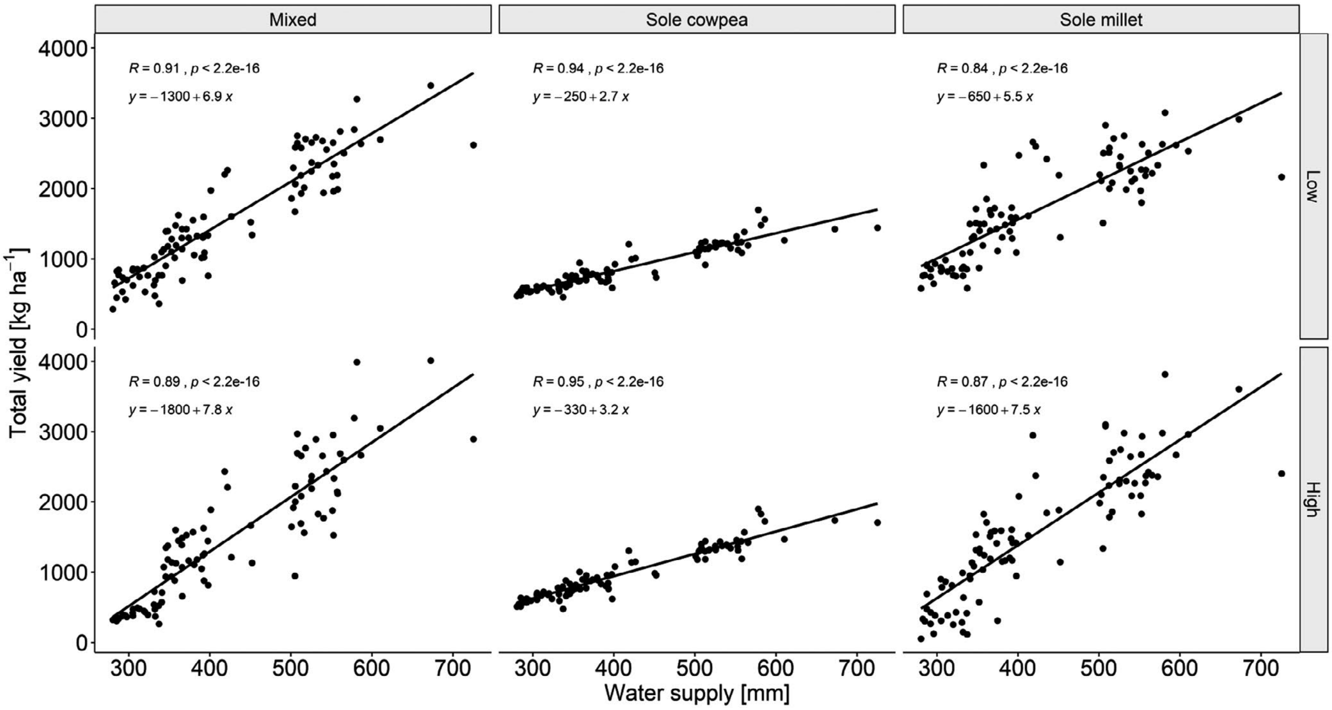

FIGURE 9 Simulated water supply (mm) (*x*-axis) versus total yield (kg/ha) (*y*-axis) for intercropped cowpea and pearl millet (mixed), sole cowpea, and sole pearl millet. The right-hand-side y-axis identifies both high, 33, and low 17 plants per m^{-2} planting densities. Each point represents one year of simulated results

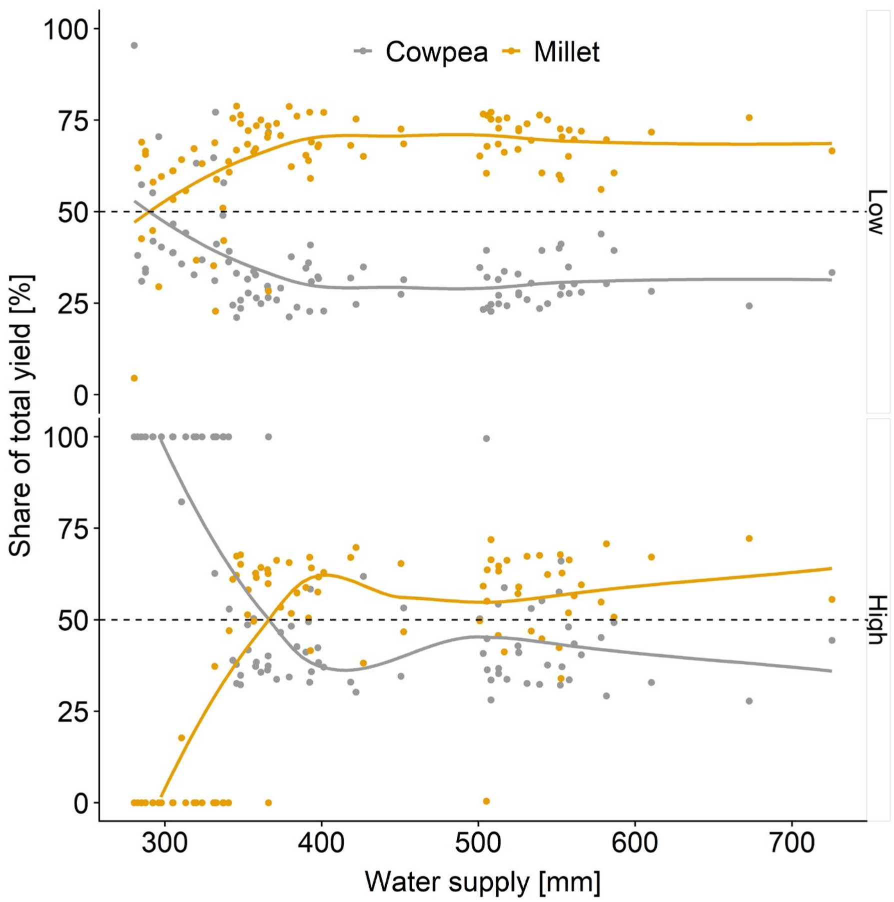

FIGURE 10 Simulated water supply (mm) (*x*-axis) versus share of total yield (%) (*y*-axis) for intercropped cowpea and pearl millet only. The right-hand-side *y*-axis identifies both high, 33, and low 17 plants per m^{-2} planting densities. Each point represents one year of simulated results. The horizontal dashed lines highlight the 50% mark across each plot

LAI of sole crop cowpea 2016 (Figure 6), but not stem height (Figure 7). However, it should be noted that while cowpea LAI was under simulated, values were still high and certainly represent a closed canopy, regardless of the poor fit to observations. A comparison with LAI values reported in Chimonyo et al. (2016) highlights inconsistencies, as their sorghum-cowpea intercrop system was overestimated by 36% and 15% for sorghum and cowpea, respectively. However, this was explained by late planting for experiments in 2013/14 that resulted in inadequate photoperiods and growth suppression (Chimonyo et al., 2016).

Due to the nature of the short growing season, the partial and well-watered treatments received similar amounts of irrigation water (Nelson et al., 2018). Simulations found very little difference between observed values under the partial and well-watered treatments (Figures 5 and 6), which highlights the usefulness of the model, albeit inaccurate in the final stages of high water input systems. Final biomass and grain yield were well simulated under the severe water deficit stress, agreeing with Chimonyo et al. (2016).

4.2 | Model improvement

While model simulations in this study were reasonable, in particular by capturing intercropping effects, there is room for improvement for the individual modelling of cowpea and pearl millet. Chimonyo et al. (2016) discussed APSIM's leaf area development model as a sigmoidal function of thermal time as inconsistent with their findings, which followed more of a power function form. Our study supports this argument for cowpea (Figure 6), which resulted in initial under estimation, also observed for APSIM wheat (Garrido et al., 2013). Inaccurate leaf area has knock-on effects in terms of potential radiation capture and therefore biomass and yield production. The simulation of cowpea canopy development is an important area for APSIM improvement (Akinseye et al., 2017) that should be supported due to the ease at which it can be measured in the field.

Leaf area index measurements illustrate plot-wise canopy cover, but not that of the individual crops when intercropped (Figure 6). While this means no decisive conclusions could be made for the intercropping treatments, as the ratios of cowpea and pearl millet that made up the intercrop LAI could not be quantified, analysis of LAI values for cowpea and pearl millet as sole crops offers insight into the underestimation of intercrop treatments. Sole crop cowpea simulations were not in line with observations (Figure 6). In 2016, intercrop simulations versus observations tend to have mirrored whatever happened in the sole crop cowpea treatments (Figure 6), perhaps as cowpea plants typically have a high LAI compared to pearl millet. This is particularly the case in our study, as the pearl millet cultivar used was bred to be short and should result in a more favourable harvest index (HI). Future experiments could measure the LAI of the pearl millet canopy above the lower cowpea canopy, and the LAI of the cowpea canopy, with measurements just above the soil surface. Although the lowest radiation interception measurements would be influenced by the lower canopy and that of the taller crop, this would offer insight into canopy structures and plant competition for light.

The model showed similar trends across all water treatments and simulations became less accurate as water supply increased (Figures 5 and 6). It is rare to run field trials in hot off-season conditions combined with high water supplies. This could help explain the suboptimal model performance, as such scenarios have rarely been tested, especially for cowpea. Inaccuracies in biomass and LAI in the higher water treatments occurred towards the end of the growing season, where APSIM simulated senescence, contrary to observations (Figures 5 and 6).

The APSIM cowpea model initiates leaf senescence due to age, light competition, water stress, and frost; a fraction of the oldest green leaf dies each day after flowering. Light competition causes leaf area loss with LAI values above 4.0 only—which was not reached for sole crop cowpea treatments—water was well supplied, and there was no frost. Senescence due to age was the only possible cause (Robertson et al., 2002). While this is visible from the model simulations, observations under partial and well-watered irrigation treatments showed no sign of senescence (Figure 6). Age-based senescence is calculated from daily thermal time, which was high in this experiment due to the heat and radiation exposure during the dry season. Its occurrence was in line with very high temperatures in 2016 (Nelson et al., 2018). While extreme conditions have rarely been tested, it is clearly important for model development when they are to investigate crop impacts under more frequent and severe climate extremes, such as heat and drought, which are amplified under global warming (Rötter et al., 2011). In terms of pearl millet, the model underestimated yields for high plant densities (Figure 4), highlighting the need for pearl-millet plant density experimentation.

4.3 | The effect of water supply and density on pearl millet-cowpea intercropping and sole cropping performance

The simulation experiment attempts to quantify the effects of crop specific differences to water supply and sole versus intercropped pearl millet and cowpea yield performance. Pearl millet is the main crop of the system studied with cowpea as a potential addition for protein, diversity and production risk aversion. Although mean total intercrop versus sole pearl millet yield differences were minimal at low and high water supply under low plant density, in terms of production risk, the lowest intercrop yields were higher than the lowest sole pearl millet yields (Figure 9). However, the low intercrop yields largely consisted of zero pearl millet yield (treatments: mainly high plant density and low water supply); pearl millet and the multi-species aspect of the intercrop system failed if water supply was too low or competition for water too high (low water supply and high plant density). Moreover, it is important to put intercrop productivity into context. For the intercrop system in question, a more balanced or pearl millet dominant total yield is likely preferred.

At low plant density, pearl millet yield was always present as part of total intercrop yield, even when water supply was low. The mean of the ten lowest intercrop yields at low plant density and low water supply was around 500 kg/ha (pearl millet 200 kg/ha; cowpea 300 kg/ha). The equivalent for sole pearl millet was 700 kg/ha (low density) and 200 kg/ha (high density). Clearly, high denisties and low water supplies are not condusive for high pearl millet yields, especially when competing for water from a vigorous intercrop component. However, this is of course specific to the genotypes used in this study. Yadav and Yadav (2000) found the pearl millet genotype used (HHB 67) to be less suppressive (less yield reduction of two intercropped clusterbean cultivars) than a long duration pearl millet (MH 179). Of course, the benefits of intercropping are not limited to grain yield, but relate to soil fertility and nutritional diversity (Daryanto et al., 2020). With this in mind, intercropping can make sense, but if drought conditions prevail, only at low densities. Rouw (2004) confirmed the same for sole pearl millet. Low densities ensure pearl millet has access to enough water for reasonable grain production.

To achieve high intercrop yields, pearl millet had to dominate the system, which involved supplying a threshold level of water that depended on plant density (Figure 10). Pearl millet intercrop yields suffered at high plant density under low water supply. Pearl millet dominance can refer to traits such as plant height. Yadav and Yadav (2000) discussed how pearl millet intercrop yield dominance could relate to light, whereby a tall, broad leaved pearl millet genotype—in this example MH 179—could cast more shade on an intercropped legume, therefore reducing its yield. We conducted an additional simulation experiment that assessed the relationship between intercrop component height differences and yield based on our model validation (details not shown). We found that while pearl millet was the driver of intercrop yield, it had to be 100 to 200 mm taller than cowpea—this was more pronounced with increased water supply. Cowpea yield, on the other hand, was not affected by the taller pearl millet intercrop. Designing multispecies systems clearly necessitates a thorough understanding of various interactions.

In terms of overall pearl millet biomass, water supply had less of an impact than it did on grain yield (Figures 9 and S1). This indicates that the crop was either not able to convert assimilates into grain under drought conditions, or there was not enough water left in the soil for grain filling. Cowpea yields, however, were less affected by density or water supply. This was due to high cowpea vigour at initial growth stages, i.e. cowpea was able to take up water early on in the growth period, leaving little remaining for pearl millet. Indeed, Aparna et al. (2014) found water stress to dramatically affect seed yield under severe drought conditions for the H77/833-2 (HHB 67) pearl millet genotype, as used in this experiment. Our findings were more pronounced at high plant density (intensified input). This is in line with Bado et al. (2021), who found that while mixed species systems improved agricultural production under low input conditions (including cowpea and pearl millet as intercrop components), intensifying input reduced production advantages. In our study, while yields were slightly higher at high plant density, increased water supply was needed. Marginal yield gains from intensified input are unlikely to be resource efficient, although this will be scenario specific (genotype-by-management-by-environment-by-socio-economic aspects).

5 | CONCLUSION

This study contributes towards quantifying the role of water supply for pearl millet-cowpea intercropping, providing insightful information for the development of intercrop adaptation systems for farmers. Intercrop yield was driven by pearl millet yield, which was dependant on water supply. We found intercropping could be a sensible risk management strategy under drought, but only at low density, although this is also subject to genotype vigour and resource use.

Field-based experimentation should further test the impact of resource competition on intercrop system performance. This could be implemented through experimentation with intercrop component genotypes that vary their resource use, or through management, via plant density or delayed sowing for instance. Crop model performance highlighted the need to run field trials for crop model improvement in extreme heat scenarios, with special attention paid to leaf dynamics and water use.

ACKNOWLEDGEMENTS

This study was conducted within the IMPAC^3 (grant number 031A351A) funded by the German Ministry of Education and Research. RPR, MPH, and MK received support from the German Ministry of Education and Research via the 'SALLnet' project (grant number 01LL1802A) within the SPACES2 Program. VV acknowledges the CGIAR Research Programs Grain Legumes and Dryland Cereals (GLDC) for funding his time. AMW acknowledges salary from the CGIAR Research Program Climate Change, Agriculture and Food Security (CCAFS) carried out with support from the CGIAR Trust Fund http://www.cgiar.org/funders/. The authors are grateful for the help of the field and laboratory staff from the Systems Analysis for Climate Smart Agriculture (SACSA) team at ICRISAT Hyderabad, India, for hosting the field trial on which this study is based.

DATA AVAILABILITY STATEMENT

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

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Nelson, W. C. D., Hoffmann, M. P., Vadez, V., Rötter, R. P., Koch, M., & Whitbread, A. M. (2021). Can intercropping be an adaptation to drought? A model-based analysis for pearl millet–cowpea. *Journal of Agronomy and Crop Science*, 00, 1–18. https://doi.org/10.1111/jac.12552