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Intercrop overyielding is maintained under estimated water and nitrogen stress in maize-cowpea on-farm trials in semi-arid Zimbabwe

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

Problem: Semi-arid regions of sub-Saharan Africa are characterized by highly variable rainfall and low inherent soil fertility. Maize-cowpea intercropping may offer the prospect of increasing and stabilizing crop productivity in these regions. However, the performance of such cropping systems often varies considerably in space and time.
Objective: The main objective of the study was to understand how farmer context and rainfall variability influence the performance of maize-cowpea intercropping, using on-farm field experiments together with soil-crop model simulations to compute water and nitrogen stress.
Methods: The data used in this study was generated from twelve on-farm trials during two cropping seasons (2021/22 and 2022/23) in semi-arid Zimbabwe. Three maize (Zea mays L.) varieties, one cowpea (Vigna unguiculata (L.) Walp.) variety and two cropping systems - either sole or intercropped - were tested. The STICS soil-crop model was parameterized to reproduce crop growth in the on-farm trials and compute water and nitrogen (N) stresses. Linear mixed-effects models were used to assess the impact of experimental treatments and simulated water and N stresses on intercropping performance.
Results: The Partial Land Equivalent Ratio (pLER – the ratio of intercropped productivity over sole crop productivity) for maize and cowpea greatly varied across farms and crop types. Maize variety did not significantly impact the pLER of maize and cowpea. Water stress and nitrogen (N) stress simulated by the model were significant predictors of variations in pLER: maize pLER for aboveground biomass significantly decreased with increasing simulated water stress, and maize pLER for grain yield significantly decreased with increased simulated N stress. Yet, average LER remained above one, regardless of the water or N stress on maize, because of a greater contribution of cowpea to LER when water and N stress on maize was high. Late planting was found to exacerbate maize water stress, while low total nitrogen in the top soil was significantly correlated with maize nitrogen stress.
Conclusion: Our study reveals that the production benefits of maize-cowpea intercropping can be maintained, in conditions of high water and nitrogen stress in multi-year and multi-location on-farm experiments.
Implications: Our findings confirm the assumption that intercropping is a useful approach to intensify and stabilize grain and fodder production in smallholder mixed crop-livestock farming systems in semi-arid environments.

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1. Introduction

Smallholder farmers produce a substantial share of the world's food (Ricciardi et al., 2018). In sub-Saharan Africa (SSA), maize (*Zea mays* L.) is the leading cereal crop grown, followed by millet and sorghum (Macauley and Ramadjita, 2015; Santpoort, 2020). A large proportion of smallholder households are food insecure (Frelat et al., 2016). A substantial share of these smallholder farms is located in semi-arid regions, characterized by low and erratic rainfall patterns, and sandy soils of low fertility. Most smallholder farms in semi-arid regions of SSA are mixed crop-livestock farms (Baudron et al., 2024; Hall, 2001). Increasing on-farm production of quality fodder, along with improved rangeland management and fodder conservation, are critical to improve crop-livestock integration.

Nitrogen is often the most limiting nutrient for crop production in semi-arid SSA. The use of mineral fertilizers by smallholders remains rather low (Chianu et al., 2012; Chikowo et al., 2014; Falconnier et al., 2023). The average maize yield in semi-arid regions under rainfed agriculture is about 1 t ha^{-1}, which is well below the water-limited yield range of 6–9 Mg ha^{-1} for semi-arid regions of SSA (www.yieldgap.org). To improve food and feed availability in mixed crop-livestock smallholder farming systems under rainfed agriculture, the yield gap between the actual yield and the water-limited yield must be reduced, through increased nutrient inputs and nutrient use efficiency. When nutrients are no longer a constraint, crops become more sensitive to climate variability – intensifying crop production through nutrient application, therefore, comes with greater inter-annual variability of the production (Affholder, 1997; Rötter and Van Keulen, 1997). In this context, cereal-legume intercropping is a relevant sustainable intensification option, because it involves crop species with potentially contrasting sensitivity to water stress, which could help stabilize crop production against climate inter-annual variability (Traore et al., 2023), while also providing additional high quality fodder without a need for more cropland.

In addition to temporal variability, short-range spatial variability of yields is very common for cropping systems in a smallholder context, due to differences in e.g., soil type, historical management, lack of resources, and crop management (Affholder et al., 2013; Tittonell et al., 2007a, 2007b). On-farm trials that encompass a diversity of farmers' contexts, repeated over several growing seasons, are critical to understand the drivers of the spatial and temporal variability in the performance of sustainable intensification options (Baudron et al., 2012a; Vanlauwe et al., 2019; Zingore et al., 2007a, 2007b). There are numerous studies dealing with the performance of cereal-legume intercropping on smallholder farms (Chimonyo et al., 2023; Kermah et al., 2017; Matusso et al., 2014; Namatsheve et al., 2021; Thierfelder et al., 2024). While such studies typically report on the mean benefits of intercropping, and highlight how specific management (e.g., planting date, intercropping pattern) influence these benefits, they rarely include a detailed analysis of the factors that drive the variability of performance, across farms and growing seasons. Understanding the pattern of water and nutrient stress offers the prospect to further explore the impact of contrasting climates and farmer' contexts, and come up with generic recommendations on what would work and where.

Water and nutrient stresses interact in a complex way in intercropping systems. For example, contrasting root systems (e.g., fibrous for cereal vs taproot for legumes) usually allow complementarity in the use of available water between cereal and legumes (Mugi-Ngenga et al., 2023), but a shift from complementarity to competition can occur in the case of very dry growing conditions (Senghor et al., 2023). Drought also impedes optimal N_2 Fixation by the legume (Sprent, 1972), which could disrupt the complementarity in the use of nitrogen between the legume and the cereal. Nitrogen input usually favours cereal growth at the expanse of the legume (Bedoussac et al., 2015), but this depends on the competitive ability of the legume (Mahmoud et al., 2022).

Soil-crop models can complement field-based experimentation to analyse how these stresses interplay (Affholder et al., 2003). Crop models allow for the simulation of potential growth, and water and nitrogen stresses. Current crop models, and the STICS soil crop model in particular, have proven useful (relative Root Mean Square Error, rRMSE in the range 8–42 %) in reproducing contrasts in water- and nitrogen-limited sole maize growth in a set of representative field experiments across sub-humid and semi-arid SSA (Falconnier et al., 2020a). In particular, the 'tipping bucket' approach used by STICS and several other models for water simulation, was found valid for models to reproduce accurately the dynamics of soil water in tropical soils. The STICS soil-crop model also accounts for the simulation of biological nitrogen fixation and its dependency on soil water, mineral nitrogen content and temperature conditions, and was helpful in understanding variability in legume growth in temperate (Falconnier et al., 2020b; Jégo et al., 2010) and tropical (Traoré et al., 2022) environments.

Intercropping models further include competition for light between tall and smaller plants, along with competition for water and nitrogen in the rootzone. A number of models can handle intercropping, with different levels of complexity, e.g., APSIM (Keating et al., 2003), LUCIA (Marohn et al., 2013), STICS (Brisson et al., 2004), MONICA (Nendel et al., 2011). Recent developments in STICS soil-crop model calibration for tropical cereals and legumes (Couëdel et al., 2024) and intercropping (Traoré et al., 2022) offer prospects to use the model to analyse water and N stresses in cereal-legume intercropping systems. The STICS model was calibrated for semi-arid conditions of southern Mali using detailed monitoring of soil and crop growth variables in intercropping systems (Traoré et al., 2022). The model reproduced the contrast in cereal and legume growth due to intercropping and nitrogen levels with good accuracy (rRMSE of 24 % for grain yield). The calibrated model helped explore how intercropping could stabilise productivity in the face of climate variability (Traoreé et al., 2023).

The current study aims at using a simulation model to better understand the variability in performance of maize-cowpea (*Vigna unguiculata* (L.) Walp) intercropping under farmer conditions. The study was part of a broader set of trials seeking to evaluate the feed and food productivity of drought tolerant and nutritious maize varieties grown in intercropping combinations with various legumes including cowpea and *Mucuna pruriens* in semi-arid conditions of Zimbabwe. This study specifically focuses on clusters of on-farm trials on maize-cowpea intercropping intensively monitored over two contrasting growing seasons to allow for crop growth characterization and detailed crop modelling. We hypothesized that the advantage of intercropping compared to sole cropping in terms of land productivity disappears under water and N stress.

2. Materials and methods

2.1. Study site

This research was conducted in Mutoko district, Zimbabwe (32°30′ 00″ E; 17°10′ 00″ S, altitude range of 900–1276 m a.s.l.). Mutoko is divided into two agro-ecological regions which include natural Region III and IV as described in the agroecological zoning of Zimbabwe by Manatsa et al. (2020). The study sites were located in the agro-ecological region (IV) characterized by a semi-arid climate where the rainy season in the area follows a unimodal pattern, starting in mid-November and ending in May. The area receives rainfall in the range 450–650 mm per year. Average annual air temperature ranges 27–32 °C. Farms are typically involved in mixed crop-livestock production (Baudron et al., 2024; Mutsamba-Magwaza et al., 2022). Maize is the dominant crop grown during the rainy season, and in some cases rotated with groundnut (*Arachis hypogaea* L.), cowpea, and other cereals such as pearl millet (*Pennisetum glaucum* (L.) R.Br.) and sorghum (*Sorghum bicolor* L. Moench). Farmers also raise cattle and goats for meat, milk, traction and manure.

2.2. Experimental design

The experiment was conducted on 12 farmers' fields during the 2021/22 season, and on 11 fields during the 2022/23 season, without changing the field and plot positions over the two growing seasons. All experiments were carried out on sandy soils (*Arenosols)*. The individual treatment plots were 6 m × 5 m, i.e., 30 m^2. The main experimental factors investigated were the maize variety and the cropping system. Three maize varieties, namely QPM623 (improved quality protein maize), ZS500 (provitamin A biofortified maize variety), both from Mukushi Seeds (Pvt) Ltd., and Seed Co. 403 (SC403, a local drought resistant variety from Seed Co (Pvt) Ltd.), were tested. The cowpea variety was a dual-purpose (grain and fodder) landrace locally referred to as '*Nyadawa'*. The cropping system factor had two levels: sole and intercropped, for both maize and cowpea. Sole maize, intercropped maize and sole cowpea received a compound basal fertilizer (Compound D: 7N, 14P_2O_5, 7K_2O) that was incorporated at 5 cm depth during planting to supply 12 kg N ha^{-1}, 10 kg P ha^{-1}, and 10 kg K ha^{-1}. Additionally, two splits of ammonium nitrate fertilizer were later applied to maize, equating to a total N application of 80 kg N ha^{-1}. In sole and intercropped treatments, top-dressing was only applied on maize sowing lines. At each of the farm sites, one additional control plot of SC403 variety was established, where no mineral fertilizer was applied. This control plot was used for model parameterization (see Section 2.4.2) of soil supply of N and maize N uptake, but was not included in the statistical analysis of the impact of experimental treatments on intercropping performance (see Section 2.4.3).

As a result of this design a total of nine plots were established on each farmer's field soon after land preparation in early November. Sole and intercropped maize were planted at 5 cm depth (from 24 November to 12 January in 2021/22 and 15 November to 20 December in 2022/23) at 0.90 m inter-row spacing and 0.60 m within-row spacing, with two maize plants per planting station (planting holes prepared with hand hoes, Fig. S1), leading to a maize plant population of 3.7 plants m^{-2}. Intercropped cowpea was planted two to three weeks after maize planting depending on soil moisture availability. Sole cowpea was planted at the same time as sole maize (D1) and also planted simultaneously with the intercropped cowpea (D2). Spacing for sole cowpea was 0.45 m × 0.30 m leading to 7.4 plants m^{-2} whereas for intercropped cowpea spacing was 0.9 m × 0.3 m, leading to half the density of the sole crop. In intercropping, cowpea was sown in between two maize rows. Farmers were advised to control weeds using hand hoes every two weeks, and were provided with carbaryl 85 % WP and malathion 50 % EC at 600–1200 ml/ha to control fall armyworms and aphids. Despite the fact that the experimental protocol advised on optimal weed and pests' control, the operations were left to the farmers, and in some cases not performed on time.

2.3. Data collection

2.3.1. Meteorological data

Daily rainfall was recorded using rain gauges installed at each of the farmer's field from November till harvest. Other climatic variables such as air temperature, solar radiation, wind speed and relative humidity were recorded using an automated weather station (ATMOS 41, Meter Group) located at a central place among the experimental farmers' fields. The weather data for November 2021, before planting the on-farm trials and installing the weather station, was retrieved from gridded NASA data (accessed from https://power.larc.nasa.gov/api/temporal/daily/point?parameters).

2.3.2. Soil nutrients and soil water

Before crop establishment, soil samples were taken for physical and chemical analysis in October 2021. Six sub-samples were randomly taken in each field to make a composite soil sample at a given depth. The soil samples were collected from 0 to 120 cm deep, at 20 cm depth intervals using an auger, resulting in 72 soil samples. Samples were air dried and passed through a 2 mm sieve. Soil organic carbon (SOC), soil total N, available P and K, and concentration of exchangeable Ca and Mg were determined from these soil samples (Table S1). The modified Walkley-Black method was used to determine SOC (Bahadori and Tofighi, 2016); total N was determined using the micro-Kjeldahl digestion method (Bremner, 1996). Resin-extractable P was used to quantify soil available P by extraction with an anion exchange membrane, coupled with a spectrophotometer (Almeida et al., 2018; Lajtha and Jarrell, 1999). The concentration of exchangeable K was analyzed using the flame emission spectroscopy with 1 M acidified ammonium acetate (Ziadi and Tran, 2007). Ca and Mg exchangeable concentrations were determined using ethylene diaminetetraacetic acid (EDTA) and atomic absorption spectrophotometry (Belal et al., 1998). Soil pH and texture were determined using the calcium chloride method and the hydrometer method, respectively (Jalali and Jalali, 2016).

Soil volumetric water content was measured using a Trime-PicoT3/IPH44 Time Domain Reflectometry (TDR) probe (manufactured by manufactured by IMKO Micromodultechnik GmbH) with PVC access tubes inserted at central point in each experimental plot before the first cropping season, in five of the twelve monitored farmers hosting the experiment. The depth of the installed access tubes ranged from 140 cm to 180 cm. Soil moisture was measured in 10 cm increments up to the maximum depth of each access tube. Measurements were taken twice a month until maize was physiological mature. The measured volumetric moisture content (%) was converted to millimeters (mm) by multiplying the volumetric soil water content, bulk density-obtained from Tsimba et al. (2007), and the corresponding layer thickness. The soil water content (mm) for the different soil horizons was then aggregated for the entire profile for each experimental plot per sampling date (data available on the link https://doi.org/10.18167/DVN1/G5TYUZ).

2.3.3. Plant growth, biomass and grain yield

Leaf Area Index (LAI) was measured using a Licor-LAI2000 (Licor, INC.) on four transects that covered three planting rows for both sole and intercropped plots (data provided on the link https://doi.org/10.18167/DVN1/G5TYUZ). The final LAI value for a given plot and date was computed as the average of the measured LAI on the four transects. The LAI measurements were taken at two to three weeks interval until maize physiological maturity. In intercropping treatments, below-canopy measurements were taken in cowpea canopy to obtain (maize + cowpea) total canopy LAI values. Dry matter accumulation was monitored by destructive harvests at peak flowering and physiological maturity. At flowering (from 60 to 69 days planting), maize aboveground biomass was sampled by cutting eight plants to ground level from four planting stations. For cowpea, a 'net' plot consisting of 1 rows × 4 m long, i.e. 3.6 m^2, was harvested. Sub-samples of cowpea and maize fresh biomass were taken and oven dried at 65 °C for 48 h for dry matter determination. At physiological maturity (from 25 March to 25 May in 2021/22 and 16 March to 17 May in 2022/23), aboveground biomass, grain and grain yield components were harvested from a 'net' plot of 11.2 m^2 consisting of two and four rows of 4 m lengths for maize and cowpea, respectively. The number of plants and cobs, and their fresh weight were determined from the harvested 'net' plot area, then computed to per hectare basis. Sub-samples of six maize cobs, and a weight of 0.5–1 kg of cowpea pods were randomly selected from each treatment for yield and yield components computation. All crop samples were oven dried at 65 °C for 48 h for dry matter determination.

2.3.4. Legume biological N_2 fixation

Biological N_2-fixation (BNF) in cowpea was determined on aboveground (stems + leaves) at peak flowering from sole and intercropping systems. Plant materials were harvested from a 'net' plot of 3.6 m^2. Sub-samples for fresh weight of aboveground biomass taken from the 'net' plot were oven dried, ground and passed through a < 1.0 mm sieve. The ground plant material samples were analyzed for total N content (%N) and isotopic composition ($\delta^{15}N$) at Catholic University of Leuven, Belgium, using an EA1110 elemental analyzer with a Delta V Isotope Ratio Mass Spectrometer via a ConFlo IV universal continuous flow interface (Thermo Fischer Scientific, Waltham, Massachusettes, USA). The percentage of N derived from the atmosphere (%Ndfa) was estimated from the $\delta^{15}N$ for aboveground biomass of cowpea using the ^{15}N-natural abundance method (Naab et al., 2009). ^{15}N values for unfertilized maize plot (control) and *Bidens pilosa* L. (a common weed species) collected from area surrounding the experimental plots were averaged and used as non-N_2-fixing reference plant N ($\delta^{15}Nref$). The percentage of N derived from the atmosphere (%Ndfa), i.e., derived from N_2-fixation, was computed as follows:

$$\%\text{Ndfa} = \frac{\delta^{15}Nref - \delta^{15}Nleg}{\delta^{15}Nref - B} \times 100 \tag{1}$$

where $\delta^{15}N$ is the % deviation from the standard of atmospheric N_2 (= 0.36637 atom% ^{15}N) and the $\delta^{15}Nref$ was the average from $\delta^{15}N$ for the non- N_2-fixing plants assessed under this study. $\delta^{15}Nleg$ is $\delta^{15}N$ of cowpea plants. The B value of − 1.759 was used (Naab et al., 2009). Total N fixed was then determined as a product of %Ndfa value and total plant N (kg N ha^{-1}).

2.4. Data analysis

2.4.1. Computation of Land Equivalent Ratio

The Land Equivalent Ratio (LER) is defined as the relative land area that would be required as sole crops to produce the yields achieved in intercropping. A LER value greater than 1 means that the intercrop is advantageous over sole cropping. LER values were computed as a ratio of grain yield (or aboveground biomass) in intercrop divided by the yield from sole crop of the corresponding crop:

$$\text{LER} = \frac{Yab}{Yaa} + \frac{Yba}{Ybb} \tag{2}$$

where (*Yaa*) and (*Ybb*) are the sole crop yields of crops (*a)* and (*b*), respectively, (*Yab*) is the intercrop yield of crop *a*, and *Yba* is the intercrop yield of crop (*b)*. In this calculation crop (*a*) is maize and crop (*b)* is cowpea. Plant observations of sole cowpea planted at the same time as maize (D1) were used for LER computation.

The partial land equivalent ratio (pLER) indicates how much each crop is contributing to the LER, and it was computed as follows*:*

$$\text{pLER} = \frac{Yab}{Yaa} \tag{3}$$

2.4.2. Simulation of water and nitrogen stresses

The soil-crop model STICS (v 9.2) was parameterized to simulate crop growth in the on-farm field experiments and compute indicators of water and nitrogen stresses.

2.4.2.1. Description of the STICS-intercrop crop growth model. STICS uses a daily time-step to simulate crop growth based on inputs related to climate, soil properties, and crop management (Brisson et al., 2003). Climate inputs include rainfall, temperature, solar radiation, relative humidity, and wind speed. Soil inputs include soil water holding capacity and topsoil characteristics influencing nutrient provision (e.g. total soil nitrogen). Crop management input include for example sowing date, fertilization date and quantity of mineral and organic nitrogen applied.

The model can be adapted to various crops, cereals and legumes (Falconnier et al., 2019 ; Falconnier et al., 2020b), and to intercropping (Brisson et al., 2009; Traore et al., 2023; Vezy et al., 2023). Plant development is driven by crop temperature depending on cumulative thermal time specific to species and varieties. The model dynamically simulate root growth, leaf area index, aboveground biomass, aboveground plant N uptake, grain yield, soil moisture content, and N_2-fixation for legumes. For legumes, parameters related to soil thermal time for nodule formation and life cycle, and plant growth rate determine the simulated potential N_2-fixation.

Water stress factor is defined as the ratio of actual to potential evapotranspiration and is calculated by the model from the LAI and daily potential evapotranspiration. N stress is defined as the ratio of supply of mineral nitrogen over plant demand. Plant demand corresponds to critical crop dilution of N, i.e., the specific level of nitrogen that a crop needs at a given time for optimal crop growth and development. Nitrogen supply is computed from available soil mineral N, N input from mineral and organic fertilizers, and N_2 fixation for legumes. The model computes these stress factors on a daily basis and the values ranges from 0 to 1, where zero is the completely stressed and one-without stress. Stress factors impact radiation use efficiency, LAI, plant transpiration and potential N_2-fixation for legumes. Detailed computation of stress factors can be found in Brisson et al. (2009).

In the STICS intercrop extension (Brisson et al., 2003), the dominant (maize) and the dominated plant (cowpea) are determined based on their relative height. A radiative transfer formalism is used to estimate direct and diffuse radiation and the fractions intercepted by the vegetative cover of maize and cowpea. Water and nitrogen uptake in the intercropping is computed based on root density of each crop at specific depths.

2.4.2.2. Parameterization of the soil-crop model. The farmer's fields, experimental treatments (combinations of cropping system, maize variety, fertilizer input, sowing date of cowpea), and year of experimentation, resulted in 207 simulation units that were used for plant and soil parameterization.

For soil parameterization, the soil profile was assumed to extend to a maximum depth of 180 cm, with five depth intervals (0–20, 20–40, 40–60, 60–80, 80–180 cm). Analysis of topsoil (0–20 cm) total nitrogen and pH (see Section 2.3.2) were used to determine the corresponding soil parameters for each farmer's field (Table S1). Soil C:N ratio was set at 12 and total carbonate content at zero in all the plots. Initial estimation of soil field capacity and wilting point values were obtained with pedo-transfer functions that rely on the soil texture analysis (Lidon and Forest, 1983). In a second step, the values were calibrated with trial and error to minimize the difference between observed and simulated soil water content. Preliminary simulations indicated a constant underestimation of plant N uptake. Therefore, the parameter *finert* that sets the fraction of stable organic nitrogen was set at 0.05 (instead of 0.65) and the maximum depth for soil organic matter mineralization was increased (from 30 cm to 60 cm) to allow for the simulation of more mineral N from soil organic matter mineralization, in line with the observation of maize N uptake in the control plots (Table 1).

For maize, the initial plant parameter values were the default values of the plant files provided with the model. For cowpea, plant parameter values were adapted from Traoré et al. (2022). Information from breeders on the time to maximum LAI, flowering, and maturity, was used to set the cultivar-dependent parameters of the model for the three maize varieties and cowpea variety used in this study (Table 1). With regard to N_2-fixation, thermal time between end of nodulation and end of nodule life (*stfnofvino*) was set at 1000 to match the duration of the reproductive phase of the legume (*stdrpmat* parameter). The parameter *fixmaxveg* for cowpea was set at 30 to match the observed maximum N fixed in the experiment. A summary of the calibrated plant parameter values used in this study can be found in Table 1. Calibration was done using both intercrop and sole crop data.

The determination coefficient (R^2) of the regression between simulated and observed plant variables was used to quantify the variability in observed variables explained by the crop model.

Table 1
Parameters description and values for maize and cowpea as calibrated in the STICS crop model for farmer's fields in Mutoko, Zimbabwe. Maize variety = V1 (QPM623), V2 (ZS500) and V3 (SC403). *Parameters *efcroijuv, efcroiveg, and efcroirepro* for left at their default values as per STICS generic maize plant file.

Parameters	Process	Acronym	Description	Unit	Maize			Cowpea	Target variable
					V1	V2	V3		
Plant	Crop development	*stlevdrp*	duration between emergence and start of grain filling	degree. days	880	880	700	800	Breeders information on cycle duration
		stdrpmat	duration between start of grain filling and maturity	degree. days	1250	1250	1100	1000	Breeders information on cycle duration
	Aboveground biomass	*efcroijuv*	maximum radiation use efficiency during the juvenile phase	g MJ^{-1}	1.9*	1.9*	1.9*	1.2	Literature values for cowpea (Traoré et al., 2022)
		efcroiveg	maximum radiation use efficiency during the vegetative stage	g MJ^{-1}	3.8*	3.8*	3.8*	1.7	Literature values for cowpea (Traoré et al., 2022)
		efcroirepro	maximum radiation use efficiency during the grain filling phase	g MJ^{-1}	3.8*	3.8*	3.8*	1.4	Literature values for cowpea (Traoré et al., 2022)
	Nitrogen fixation	*fixmaxveg*	maximal N symbiotic fixation rate per unit of vegetative growth rate	kg t^{-1}	-	-	-	30	Simulated N_2 fixed (kg/ha)
		stfnofvino	thermal time between end of nodulation and end of nodule life	degree. days	-	-	-	1000	Simulated N_2 fixed (kg/ha)
Soil	Water balance	*HCCF*	Soil field capacity	%	5.06	5.06	5.06	5.06	Simulated soil moisture down to measurement depth (mm)
		HMINF	Soil wilting point	%	2.27	2.27	2.27	2.27	Simulated soil moisture down to measurement depth (mm)
	Nitrogen uptake	*Finert*	Fraction of inert carbon in SOM	-	0.05	0.05	0.05	0.05	Simulated N uptake (kg/ha)
		profhum	Thickness of the active layer for mineralization	cm	60	60	60	60	Simulated N uptake (kg/ha)

2.4.3. Statistical analysis

The two experimental factors analyzed were (i) the maize variety and (ii) the cropping systems (sole vs intercrop). Covariates (uncontrolled factors) included topsoil total N, maize planting date (that varied across farmers for logistic reasons), days between maize and cowpea planting (that also slightly varied between farmers), growing season, and simulated water and nitrogen stresses during the vegetative and reproductive phase for sole and intercrops.

Firstly, linear mixed models were used to test for the impact of maize variety, cropping system, cowpea planting date, and growing season on maize and cowpea yield, and cowpea N_2 fixation. In the linear mixed models, maize variety and cropping system were the fixed experimental factors, the growing season was the co-variate (fixed effect), and farmer was included as a random effect.

$$(Model1)\,Yi = \mathcal{E}S_i \tag{4}$$

$$(Model2)\,Yi = \alpha M_{\mathrm{var}} + \mathcal{E}S_i \tag{5}$$

$$(Model3)\,Yi = \alpha CS_{fi} + \delta C_i \tag{6}$$

$$(Model4)\,Yi = \alpha M_{\mathrm{var}} + \delta C_i + \mathcal{E}S_i \tag{7}$$

where *Yi* represents the log transformed aboveground biomass and grain yield or total N fixed aboveground biomass or grain yield, M_{var} (maize variety) and CS_{fi} (cropping system) are the main treatment factors, C_i is the covariate (i.e., growing season). S_i is the farmer and (α, δ and Ɛ) represent fixed and random effects coefficients.

Secondly, linear mixed-effects models were used to assess the impact of experimental treatments and covariates on intercropping performance as indicated by the log (pLERs) and the log (LER), for aboveground biomass and grain yield. In the linear mixed-effect models, the fixed effects were the experimental factors and the covariates, while farmer was included as a random effect.

Mixed linear models were built as follows:

$$(Model5)\,Yi = \mathcal{E}F_i \tag{4}$$

$$(Model6)\,Yi = \alpha M_{zvi} + \mathcal{E}F_i \tag{5}$$

$$(Model7)\,Yi = \alpha M_{zvi} + \beta C_i + \mathcal{E}F_i \tag{6}$$

where *Yi* represents the log transformed pLER or LER for either aboveground biomass or grain yield, M_{zvi} is the main treatment (maize variety), C_i is the covariates (i.e., maize planting date, days between maize and cowpea planting, growing season average water and nitrogen stress factors during vegetative and reproductive phases for sole maize, sole cowpea, intercropped maize or intercropped cowpea), F_i is the farmer, and (α, β and Ɛ) represent fixed and random effects coefficients.

The *lmer()* function from the *lme4* package (Bates, 2010) in R software(Team, 2020), version 4.0.0 was used to fit these models.Visual assessment of residual plots revealed no deviations from normality after log-transformation of the data. *P*-values for determining the significance of effects were obtained using likelihood ratio tests of the entire model with the effect against the model without the effect using the *anova ()* function. A threshold value of 5 % was retained for significance.

For significant fixed effects, we the computed the marginal R squared value associated with the fixed effects using the *r.squaredGLMM()* function from the *MuMIn* package (Bartoń, 2022).

3. Results

3.1. Climate data

Rainfall varied considerably between farmers' field, even within a growing season (Fig. 1A). The cumulative rainfall received across farmers' fields ranged from 447 mm to 734 mm and 557 mm to 673 mm in the first and second growing season, respectively. Averaged across farmers' fields, the cumulative rainfall received in 2021/22 (543 mm) was comparable to that in 2022/23 (603 mm) (Fig. 1B). Yet, within season rainfall distribution differed between the two growing seasons: the first season received most rainfall in January, whereas in the second season, rainfall was better distributed across the months (Fig. 1B).

3.2. Impact of experimental factors on productivity – observed data

3.2.1. Productivity of maize and cowpea

Maize and cowpea aboveground biomass were significantly greater in sole cropping than in intercropping (Fig. 2A, Table S2): 31 % higher for maize, and 56 % higher for cowpea. Grain yield was also significantly greater in sole cropping than in intercropping for cowpea (45 % increase), but not for maize (Fig. 2C, Table S2). The aboveground biomass and grain yield of maize (either sole or intercropped) was not

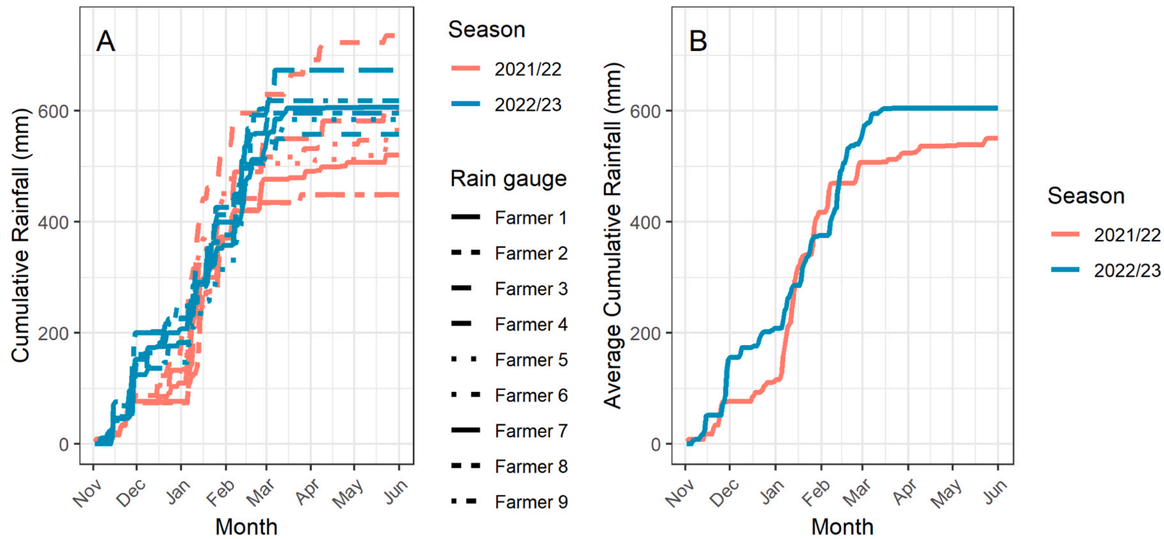

Fig. 1. Cumulative rainfall in all farmer fields (A) and average across fields, per season (B), from the time of maize planting to physiological maturity in Mutoko district, Mashonaland East Province, Zimbabwe. Acronyms in A refer to various farmers. In 2021/22 growing season planting was from 24 November 2021 to 12 January 2022 and harvesting was from 25 March to 25 May whereas in the 2022/23 growing season planting was from 15 November to 20 December and harvesting was from 16 March to 17 May.

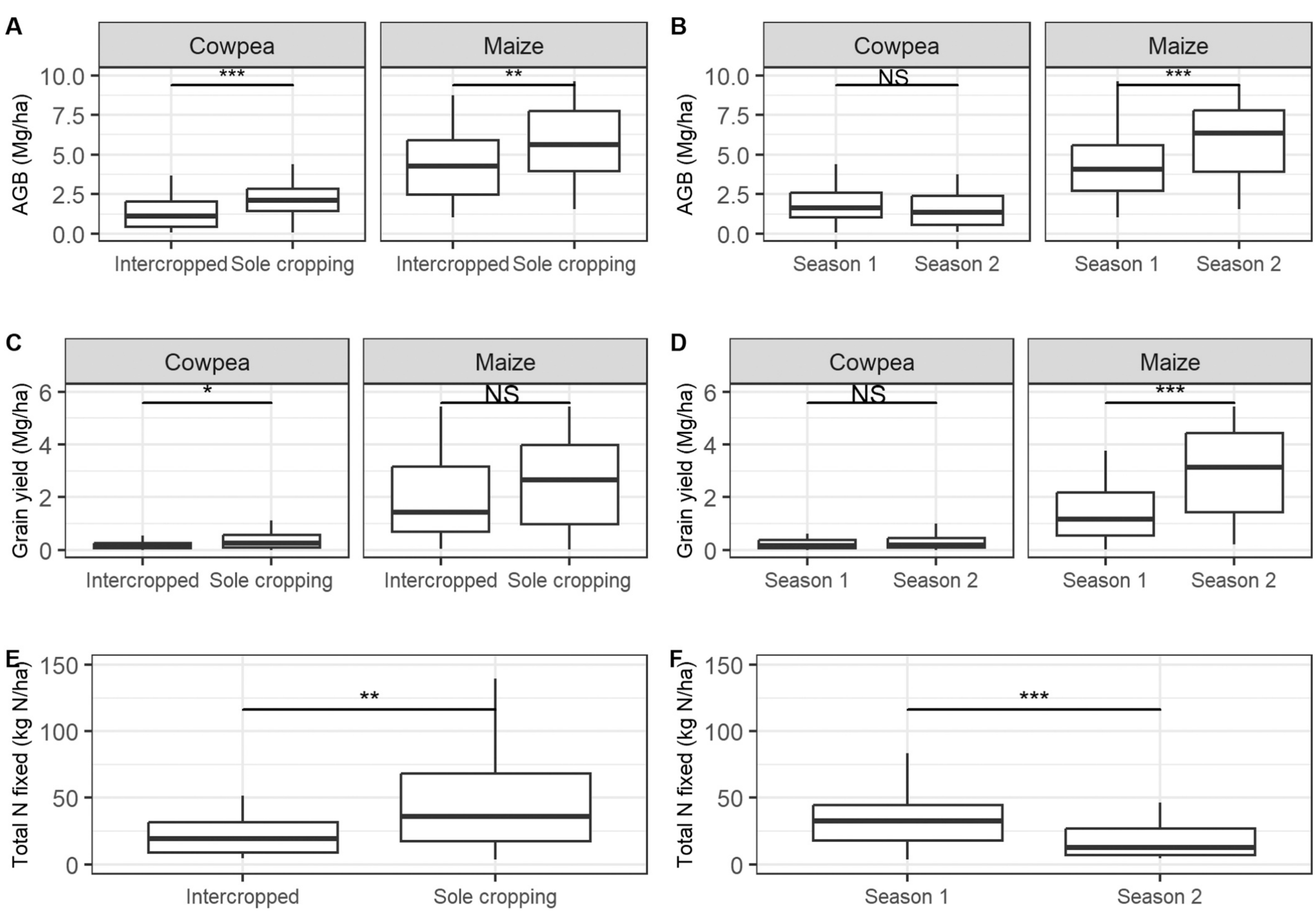

Fig. 2. Maize and cowpea aboveground biomass (AGB), grain yield and total N fixed by cropping system (across maize varieties, farmers, growing season, and cowpea planting date) (A, C and E), and by growing season (across maize varieties and farmers) (B, D and F). year_1 = 2021/22 and year_2 = 2022/23 growing season. Total N fixed was computed on aboveground biomass only at peak flowering. Stars represent significant differences (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$) between treatments. NS = not significant.

significantly impacted by maize variety (Table S2).

Maize aboveground biomass and grain yield were significantly larger in 2022/23 compared to 2021/22, with a 33 % difference for aboveground biomass, and 114 % for grain yield (Fig. 2B, D, Table S2). Cowpea aboveground biomass and grain yield were not significantly impacted by the growing season and by cowpea planting date (Fig. 2B, D, Table S2).

3.2.2. Nitrogen fixation by cowpea

Sole cowpea fixed significantly larger amounts of N compared to intercropped cowpea (Fig. 2E). Average %Ndfa (percentage of nitrogen derived from atmosphere) was 51 ± 20.3 % for sole cowpea, and only 39 ± 30.5 % for intercropped cowpea (data not shown). When averaged across all cropping systems, significantly more N was fixed in 2021/22 than in 2022/23 (Fig. 2F).

3.2.3. Maize and cowpea pLER and LER

The pLER of aboveground biomass and grain yield for maize and cowpea greatly varied from 0.1 to 2.4 across farms and crop types (Fig. 3A, B, D and E). Maize variety did not significantly impact the pLER of maize and cowpea (Table S2). The growing season significantly impacted the pLER (variation from 0.6 to 0.8) for maize aboveground biomass (Fig. 3A and Table S2). The growing season did not significantly impact the pLER for cowpea aboveground biomass and grain yield (Fig. 3D, E, Table S2).

The LER of aboveground biomass and grain yield varied widely from 0.6 to 2.4 across farmers with some of the farmers and maize variety combinations obtaining LER values below one (Fig. 3C, F). The median LER on aboveground biomass and grain yield (Fig. 3C, F) was above one in the two growing seasons.

3.3. Adequacy between plant/soil observations and model simulations

In the first season, observed and simulated soil moisture were much lower during the reproductive phase of the crops than during the vegetative phase (Fig. S2). The overall bias (i.e. model overestimating soil moisture) could be due to inaccuracies in soil moisture measurement due to soil disturbance when installing the access tubes. In the second season, there were no strong difference in observed soil moisture between reproductive and vegetative phase of the crops, a feature also simulated by the model (Fig. S2).

The observed maize and cowpea Leaf Area Index varied between 0 and more than 6. The calibrated model explained 18 % of this variability (Fig. S3). The observed maize and cowpea aboveground biomass during both growing seasons also varied widely (0.1–9.8 t ha^{-1}) due to differences in farmer's field characteristics, crop type, variety, planting date and cropping system. The calibrated crop model (that only accounted for water and nitrogen stresses) explained 43 % (coefficient of determination) of this variability (Fig. 4A). Plant N uptake in aboveground biomass at maturity varied from 1 to 198 kg N ha^{-1}. The calibrated crop model explained 24 % of that variability (Fig. 4B). Observed total N fixed by cowpea varied from 5 to 150 kg N ha^{-1} (Fig. 4C). The calibrated crop model explained 13 % of that variability (Fig. 4C). Observed grain yield varied greatly from 0.1 to 5.4 Mg ha^{-1} and the model depicted well the trend with 47 % of variability explained. In most cases the observed values were below simulated values, pointing possibly to stresses not simulated by the model, *e.g.* pest, diseases and/or weeds, macro (other than nitrogen) and micronutrients deficiencies.

The model, though overestimating yields overall, mimicked the observed increase in maize yield due to N input, and also the fact that yield increase due to N input was stronger in the second/wetter growing

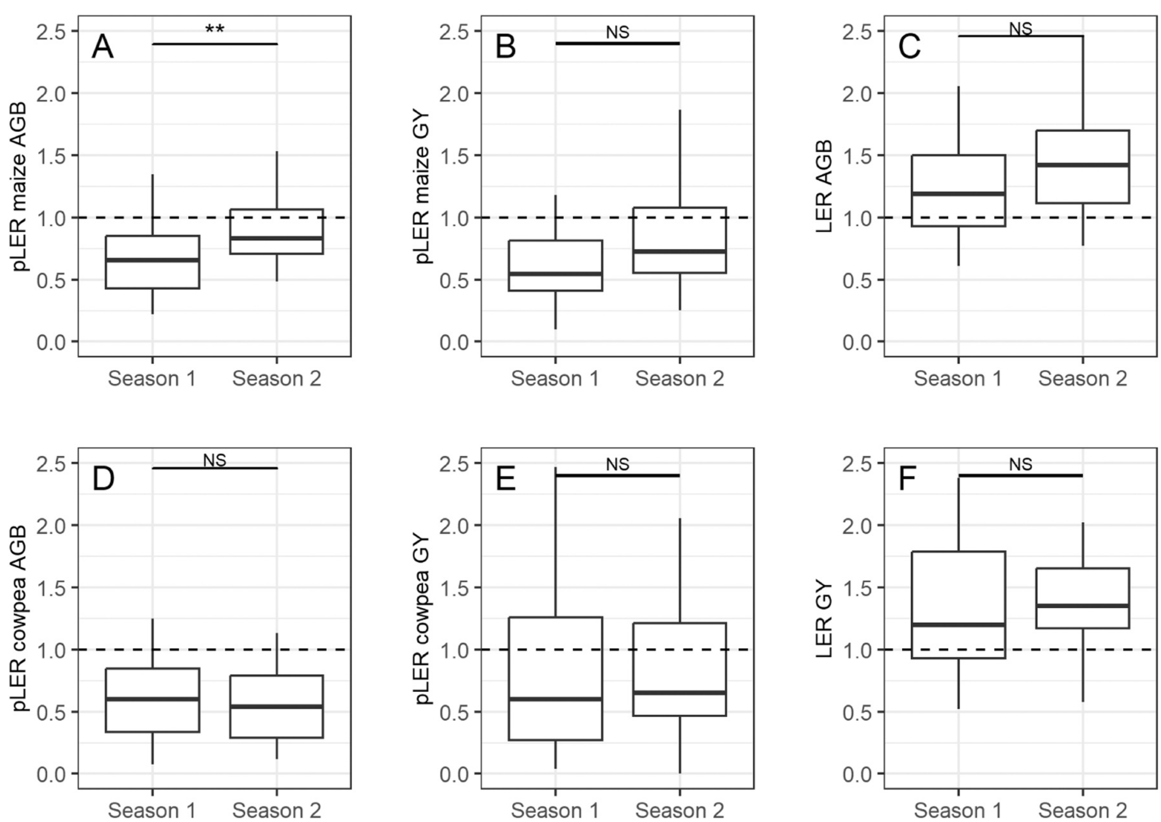

Fig. 3. Maize and cowpea pLER and LER (both crops combined) variability on aboveground biomass and grain yield for the two contrasting seasons. AGB is aboveground biomass and GY is grain yield. Season 1 is 2021/22 and Season 2 is 2022/23 growing season. Stars compare the pLER for each growing season. Stars represent significant differences (*$P < 0.05$, **$P < 0.01$, *** $P < 0.001$) between treatments. NS = not significant. Outliers (i.e. pLER values above 1.5 the interquartile range) are not displayed.

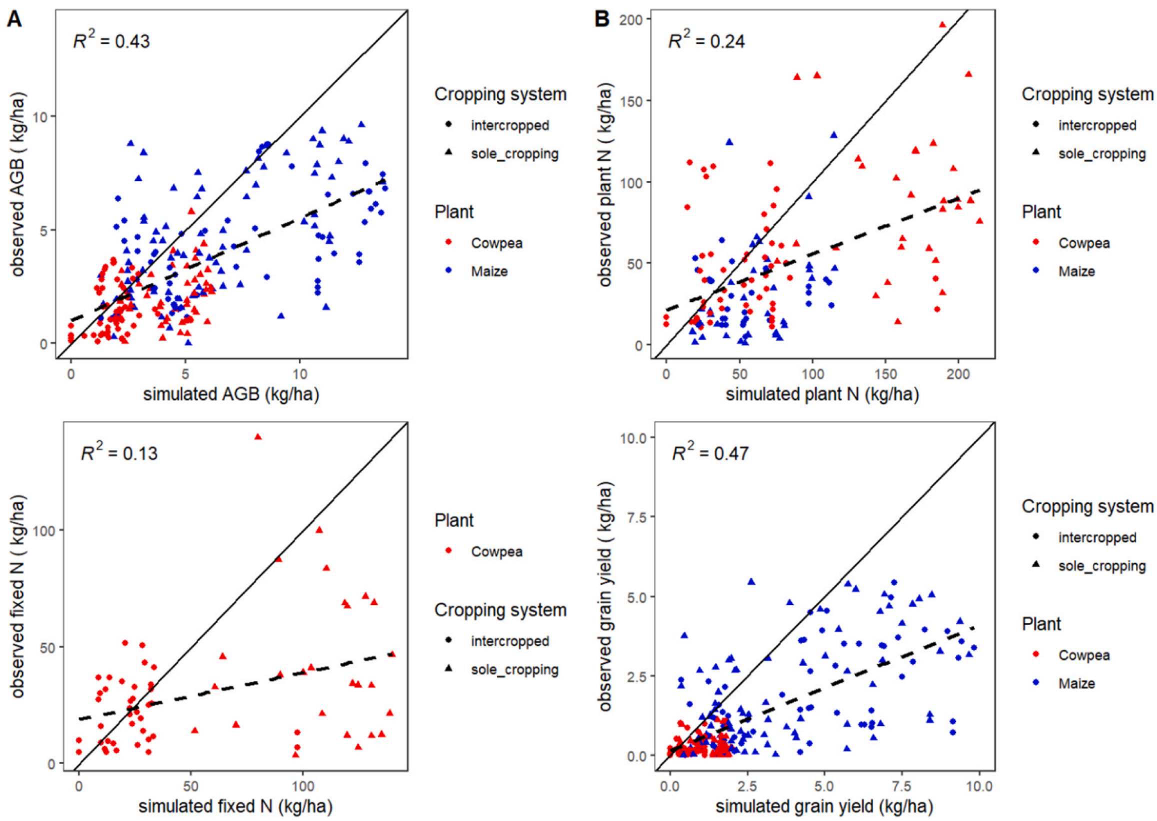

Fig. 4. Comparison of observed and STICS simulated aboveground biomass (A), plant N uptake (B), N_2-fixation (C) and grain yield (D) for all simulations units (207) for 2 years * 3 maize varieties * cropping systems * farmer (with 12 farmers in the first year and 11 farmers in the second year). AGB is aboveground biomass. The black solid line is the 1:1 line. The black dotted line represents the regression of observed against simulated values. Observations are shown on the Y-axis, so that the distance between the dot and the 1:1 line – and indicator of the influence of factors not accounted for by the model - can be easily visualized (as done in Affholder et al., 2013).

season (Fig. S4), indicating its usefulness in dealing with N stress. In some cases, the observed values were higher than the simulated ones, possibly suggesting that the model overestimated the impact of water and N stresses (Fig. 4).

3.4. Impact of simulated water and nitrogen stresses on pLER

The model simulated stronger water stress in 2021/22 than in 2022/23 (Fig. 5). Interestingly, water stress for maize was stronger with intercropping than with sole cropping (more so in the first season), while water stress for cowpea was similar with sole- and intercropping. Cowpea in intercropping systems did not experience more water stress than in sole cropping. Possibly, the shading of the cereal limited the growth of intercropped cowpea to the extent that water was not limiting. Simulated cumulated radiation interception by cowpea was substantially smaller in intercropping (median of 227 MJ/m^2) than in sole cropping (median of 718 MJ/m^2) (data not shown), which supports our hypothesis.

The simulated water stress (during reproductive phase) significantly explained variations in pLER on aboveground biomass for sole maize: a decrease in pLER values was associated with an increase in the water stress, with R^2 of 0.15 (Table S2, Fig. 6A). Late maize planting resulted in significantly lower pLER, with R^2 of 0.17 (Fig. 6C, Table S2). This impact could be explained by a significantly stronger simulated water stress that comes with late planting date (Fig. 6D, $R^2 = 0.49$). The majority of the farmer*maize variety combinations did not experience simulated water stress on cowpea. Therefore, the significant impact for cowpea simulated water stress on cowpea pLER (Table S2) was rather driven by a small number of outliers.

Nitrogen stress factor also significantly impacted pLER for maize grain yield (Table S2, Fig. 6B) – stronger simulated stress driving lower pLER values, with R^2 of 0.21. Topsoil total N in farmers' field did not significantly impact maize pLER (Table S2). Yet, topsoil total N was significantly correlated to the simulated nitrogen stress for sole maize (data not shown). The simulated nitrogen stress for sole maize was not significantly correlated to simulated N leaching (data not shown). Overall, simulated N stress on cowpea was not frequent, with majority of the farmer*maize combination experiencing no or very mild stress, so that the significant impact of cowpea nitrogen stress on cowpea pLER (Tables S2) was rather driven by a small number of outliers.

3.5. Impact of simulated water and nitrogen stresses on LER

Aggregating the farmer * maize variety combinations per level of simulated maize water and nitrogen stress helps identifying a clear pattern in the composition of the LER across the different farmers' cropping situations (Fig. 7). Increase in water and N stress drove down the pLER of maize, yet the pLER of cowpea was usually larger as the stress on maize increased (Fig. 7B and C). Possibly, cowpea was able to take the opportunity to intercept more light and hence grow better as maize growth was more constrained, as illustrated by the significant relationship between maize yield with intercropping and the simulated intercepted radiation by cowpea (Fig. S5). As a result, even in situations of high water and N stress on maize, average LER remained above one, indicating an advantage of the intercropping over the sole cropping. Under high simulated maize N stress conditions, the standard error bar crossed only in the case of LER for grain yield (Fig. 7D), indicating a LER not significantly greater than one.

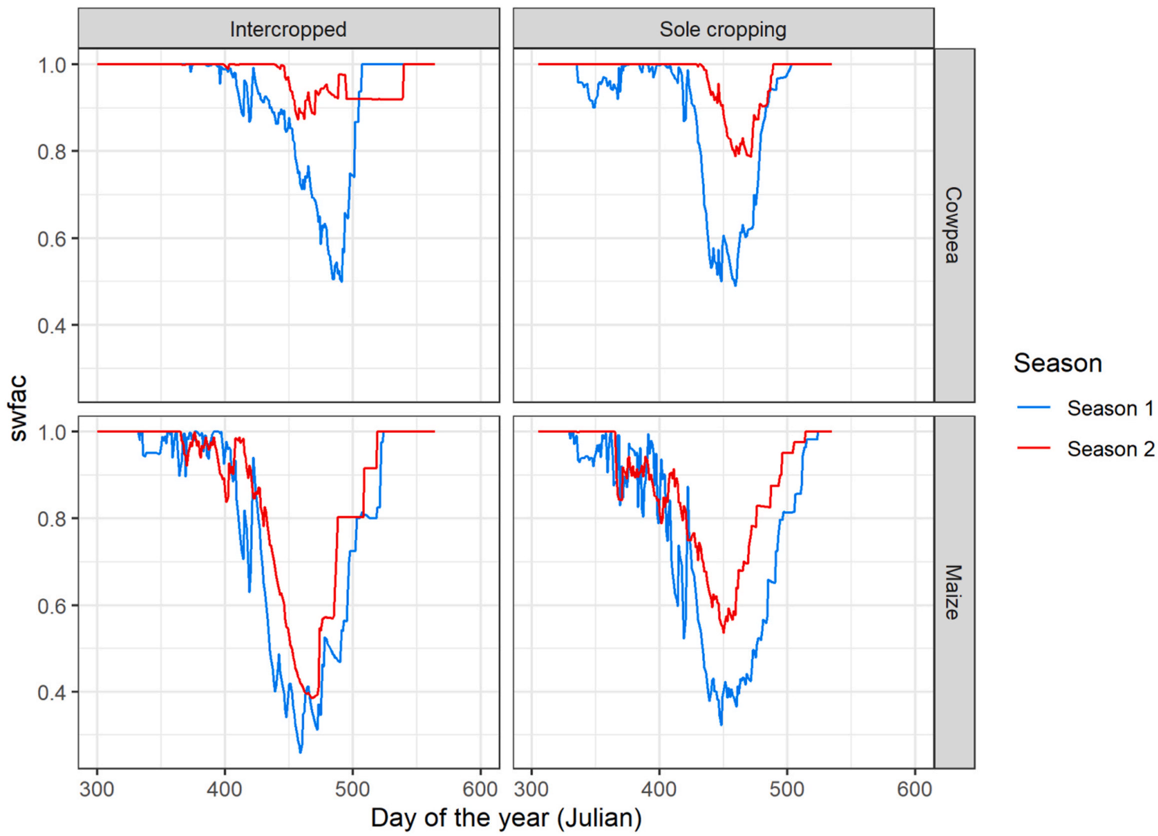

Fig. 5. Daily simulated dynamics of water stress factor (ratio of actual transpiration over potential transpiration) for maize and cowpea cropping systems (averaged across all simulation units for a given year). Swfac = daily simulated water stress factor, 1 means no stress and 0 means maximum stress. Red and blue lines are simulated water stress for year 1 (2021/22) and 2 (2022/23), respectively. The day of the year on the x-axis is cumulated over the two years of a given season.

4. Discussion

4.1. Variability in productivity across farmers' fields

Maize and cowpea productivity varied considerably across farmers' fields, a common feature of on-farm trials (Baudron et al., 2012; Falconnier et al., 2016). Median LER for aboveground biomass and grain yield was above one in the two growing seasons, despite a growing season with strong water stress that reduced maize productivity in the intercropping system relative to sole cropping. This indicates that cereal-legume is in general a good strategy to increase both grain and fodder production, without a need for cropland expansion. This echoes the finding of a recent meta-analysis on the benefit of maize-legume intercropping with average LER of 1.42 across 122 observations in SSA (Namatsheve et al., 2020).

Such advantage of intercropping is brought by complementarity in the use of available water and nitrogen between the cereal and legume. The deep tap root of the legume allows for complementarity in the use of water resources (Mugi-Ngenga et al., 2023), and N_2 fixation by the legume allows for complementarity in the use of nitrogen (Bedoussac et al., 2015). Yet, our computation of the percentage of nitrogen derived by intercropped cowpea (39 % on average) was slightly lower than the average 47 % found in the meta-analysis of Namatsheve et al. (2020). In our study, the additional N applications to maize in the intercropping system may have increased soil mineral N, which in turn possibly suppressed some of the fixation by the legume, leading to lower Ndfa values in the intercropping relative to sole cropping. On the other hand, comparing the delta15N values of the cowpea in the intercropping (that surely accessed some of the N fertiliser added on maize) with the unfertilized reference crop, may have led to overestimating N_2 fixation by cowpea in the intercropping, as the 15 N signature of N fertilizer resembles that of air.

4.2. Value of the soil-crop model

The parameterized crop model was useful in explaining a substantial amount of the observed variability in crop growth variables like aboveground biomass, N uptake, fixed N for cowpea, and grain yield. Yet, most of the observations were overestimated by the model, which is a known feature of the comparison of model simulation with on-farm observations (Affholder et al., 2013). The current crop model only accounted for water and N stress, and did not consider i) additional abiotic stress like macro, meso and micro nutrient (P, K, Ca and Zinc) deficiencies and water logging, and ii) reducing factors related to weed, pest and disease pressure. These additional biotic stresses and reducing factors could explain the deviation between model simulations and observations. Crop models are increasingly being used to understand causes of yield gap (*i.e.* deviation to water-limited yield) in a smallholder context (e.g. Silva et al., 2021). Because LAI dynamics reflect the impact of reducing factors, forcing the crop model with observed LAI values (as done in Gilardelli et al., 2019) could improve the match between field observations and crop model simulations, and ultimately the explanatory power of the water and N stress values derived from the crop model. Another possible source of uncertainty is the lack of within-field variability assessment. As a result, the pLER and LER computations of this study rely on un-replicated measurements of sole and intercrop yield. This can possibly inflate, or deflate LER estimates, when the sole crop is grown on a portion of the field with different characteristics (e.g. soil organic N related to past management) compared with the portion of the field where the intercrop is grown.

Despite these shortcomings, the simulated maize water and nitrogen stress in sole cropping significantly explained variations in maize pLER.

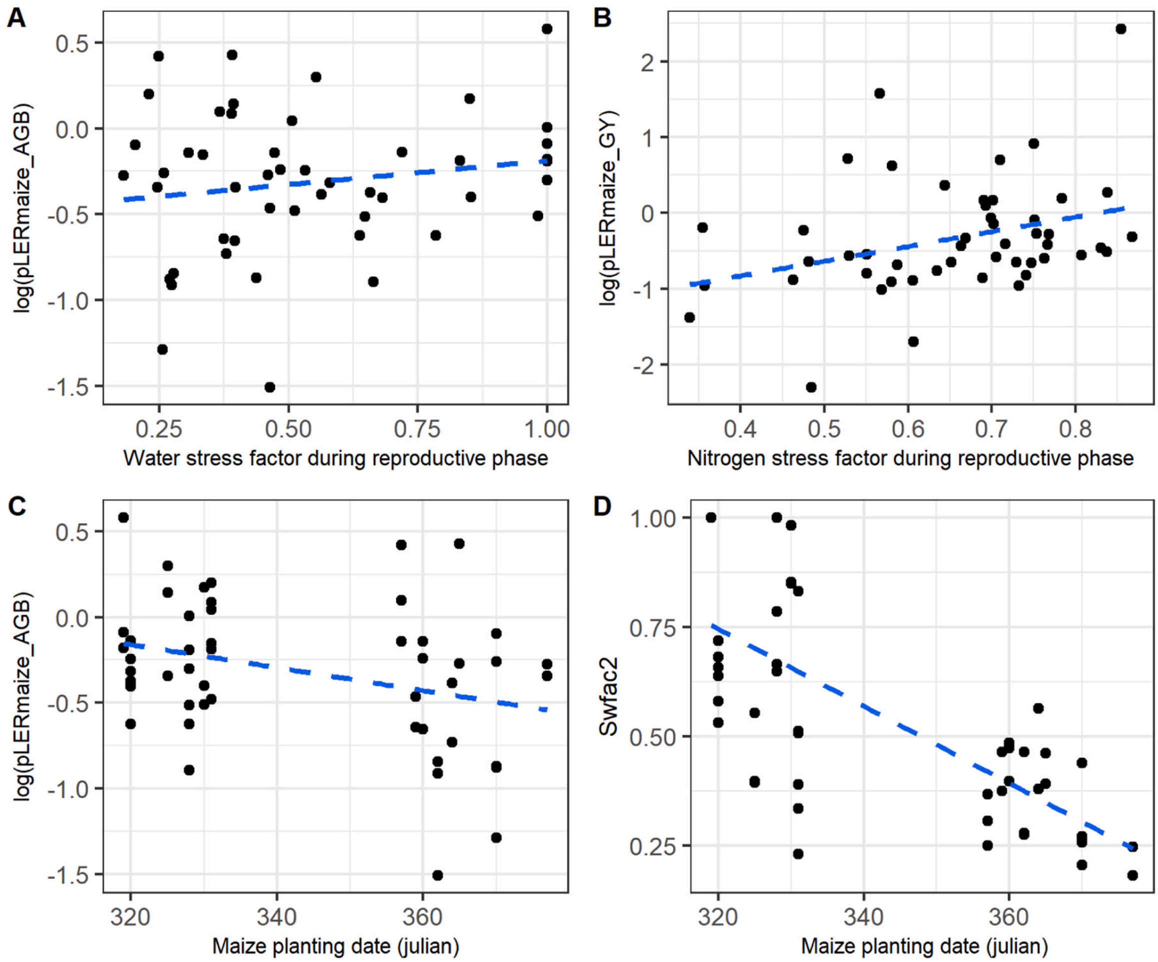

Fig. 6. Relations between observed pLER of aboveground biomass (A and C) and grain yield (B) for maize against simulated water (A), nitrogen stress (B) averaged during reproductive phases, and maize planting date (C). (D) simulated water stress (swfac2) averaged during reproductive phase against maize planting date. In A, B, C, and D, the log transformed values of the pLER (as used in the mixed models) are displayed.

Water and N stress explained 15–21 % of the variability in intercropping performance. A large proportion of the variability remains unexplained, yet these values are in the range of typical explanatory power of environmental and management factors in on-farm experiments (see e.g. Bielders and Gérard, 2015; Ronner et al., 2016). Covariates originating from crop model simulations can be used as covariate to explain variations in crop productivity (Shahhosseini et al., 2021; Supit, 1997). Yet, to the best of our knowledge, this is the first study using this approach to unravel the variability of intercropping performance. Noteworthily, the simulated stresses for intercropped maize and cowpea were not useful in explaining the observed variations in intercropping performance. This questions the necessity to rely on an intercropping model. Possibly, the competition between the cereal and the legume were not well represented, which could also explain the deviations between model simulations and observations. Yet, the model simulated stronger water stress in intercropping compared to sole cropping for maize, but not for cowpea, which is consistent with the observed changes in pLER of maize and cowpea as water stress increased. Intercropping models have not been extensively tested so far in the context of smallholder farms in the tropics, except for the studies of Fuchs et al. (2024) and Traoré et al. (2022). Further testing and improvement of intercropping models, using detailed on-station observation for contrasting water regimes will surely help improve their relevance.

4.3. *Impact of water and nitrogen stress on the functioning of intercropping*

The relationship between LER and water stress on maize was not significant. However, our results show that LER remained above one, even in situations of strong water stress on maize: the significant decrease in maize pLER with stronger water stress was compensated by an increase in cowpea pLER. This finding contrasts with some studies of the current literature that points to clear increase in LER with diminishing water availability. Zhu et al. (2023) found increase in LER with increases in water stress, using pot experiments of substitutive maize/grass pea intercropping. Using substitutive sorghum/groundnut intercropping design in water stressed environment, Natarajan and Willey (1986) found a 93 % increase in overyielding (i.e. productivity of the intercropping relative to sole cropping). This overyielding in water stressed conditions was attributed to the more successful competition of sorghum with the intercropped groundnut, than with itself in sole cropping (Harris et al., 1987). Possibly, the misalignment between the result of our study and the above-mentioned studies lies in the intercropping design that was considered. The above-mentioned studies considered a substitutive design, whereas the design in our study was additive. Testing additive millet-cowpea intercropping in semi-arid Senegal, Senghor et al. (2023) showed that the benefit of millet/cowpea intercropping decreased in the drier year of the experiment, because stronger water stress drove down the pLER of the millet, which

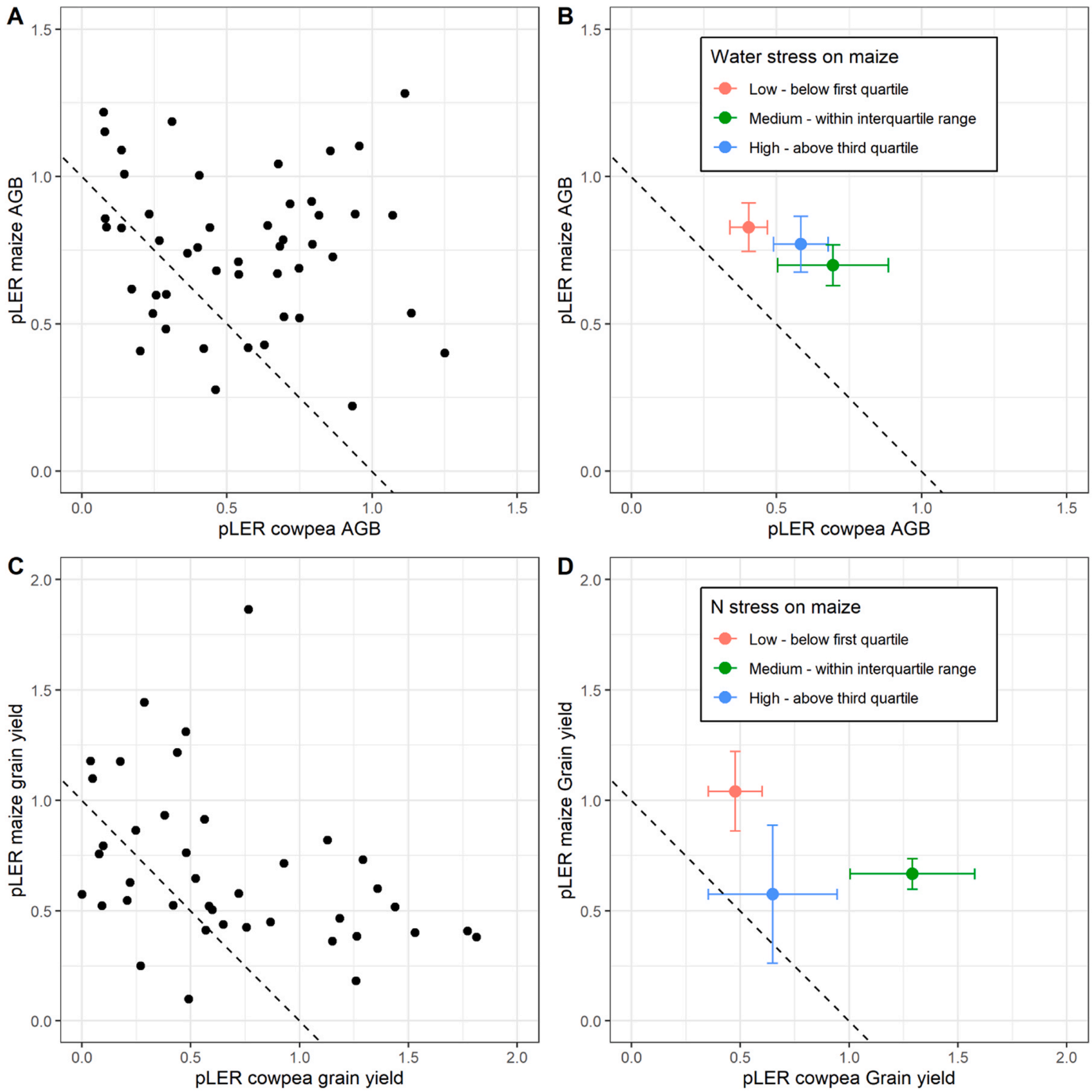

Fig. 7. A) Maize and cowpea pLER for aboveground biomass (AGB) – all farmer*maize variety combinations; B) Maize and cowpea pLER, averaged for high, medium and low simulated maize water stress; C) Maize and cowpea pLER for grain yield - farmer*maize variety combinations; B) Maize and cowpea pLER, averaged for high, medium and low simulated maize nitrogen stress. In all subplots, the dotted line is LER = 1. In B) and D), vertical and horizontal plain lines represent twice the standard error. In A), eight outliers (i.e. pLER values above 1.5 the interquartile range) are not displayed, and in B), six outliers are not displayed. These outliers were included in the computation (average and SE) displayed in B) and D).

aligns better with the finding of this study. However, in the study of Senghor et al. (2023), the decrease in millet productivity in the intercropping was not compensated by an increase in the pLER of the cowpea. Key discrepancies in intercropping sensitivity to water stress when considering additive and substitutive patterns, and contrasting planting densities for both the cereal and the legume, should deserve further scrutiny. Overall, smallholder farmers prefer additive patterns that favor the growth of the staple cereal (Falconnier et al., 2017).

With regard to nitrogen stress, better nitrogen availability (thanks to e.g. fertilization) was found to increase the competitive advantage of the cereal (Bedoussac et al., 2015). Very often, the grain yield of the intercropped legume (and pLER) decreases with fertilization, but this depends on the competitive ability of the legume (Mahmoud et al., 2022). This aligns with our finding, where stronger nitrogen stress on the cereal led to an increase in legume pLER. LER observed in farmers' fields became close to or below one, as nitrogen stress on maize increased. Low topsoil organic N was a significant driver of strong nitrogen stress on maize, despite the 80 kg N/ha applied in the experiment, indicating the critical impact of historical soil management on intercropping performance (Falconnier et al., 2016). Low soil nitrogen in 'outfields' that are less frequently fertilized is a common feature of smallholder settings in Zimbabwe (Zingore et al., 2007a, 2007b). This aspect would deserve further scrutiny, possibly trying to correlate simulated N stress (and possible pLERs) with simulated N leaching values.

4.4. Opportunities to expand the findings

Our study makes it clear that both water and nitrogen stress strongly vary from a field to another in a same small agricultural area, and from a growing season to another, and that this in turn impacts how the intercropping performs (i.e. more or less maize in the mixture). Yet, this on-farm study is based on a limited number of years and locations. Crops models make it possible to explore the impact of longer time series - with historical, and possibly future climate - to understand the frequency of strong water and nitrogen stress. Are there years that are constraining enough so that LER drops below one? What are typical thresholds in water and N stress at which intercropping systems cease to perform well? Modelling year-to-year variation in intercropping performance, as done in Guo et al. (2024) and Traoré et al. (2023), with crop models like STICS and APSIM that incorporate sufficient level of details, offers the prospect to answer these critical questions for smallholder farmers who want to engage with sustainable intensification. In these virtual experiments, contrasts in crop management strategies needs to be incorporated, for example different planting dates and nitrogen inputs. Under optimal conditions intercropping may not perform best, because of too much light competition between plants. Then virtual experiments could help identify whether intercropping performs best under intermediate stress conditions, where resource competition for light, water and nitrogen is more balanced.

5. Conclusion

Our study provides critical insights in how water and N stress drive the performance of maize-cowpea intercropping in semi-arid Zimbabwe. In situations with moderate water and N constraints, the cereal is favoured, and farmers obtained a substantial share of maize in the mixture. As water and N constraints become stronger, some of the maize production is replaced by cowpea production, but the LER of the intercropping remains above one. Maize cowpea intercropping therefore appears as a relevant land intensification and climate adaptation strategy.

CRediT authorship contribution statement

Angelinus C. Franke: Writing – review & editing, Visualization, Validation. **Isaiah Nyagumbo:** Writing – review & editing, Visualization, Supervision, Resources. **Antoine Couëdel** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Conceptualization. **Frédéric Baudron:** Writing – review & editing. **Stanford Mabasa:** Writing – review & editing, Visualization, Validation, Supervision. **Mathilde de Freitas:** Writing – review & editing, Visualization, Validation, Software. **Valentin Pret:** Writing – review & editing, Visualization, Validation, Software. **Regis Chikowo:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Rémi Cardinael:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **François Affholder:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization. **Souleymane Diop:** Visualization, Software. **Illiana W. Kwenda:** Writing – original draft. **Eleanor F. Mutsamba-Magwaza:** Writing – review & editing, Visualization, Validation. **Gatien N. Falconnier:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Illiana Winnemore Kwenda reports financial support was provided by European Union through the Livestock production systems in Zimbabwe (LIPS-ZIM), Research Platform Production and Conservation in Partnership (RP-PCP) and Resilience Building through Agroecological Intensification in Zimbabwe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109890.

Data availability

The data used in this study are available in the Cirad Dataverse (Kwenda et al., 2024).

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