Two crops are better than one for nutritional and economic outcomes of Zambian smallholder farms, but require more labour

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Abstract

Sustainable intensification practices suitable for smallholders in southern Africa will be needed to counteract the impact of future climate change and soil fertility decline in the region. Diversification of maize-based farming systems with grain legumes could play a key role. Here, we compared the performance of different maize-legume diversification strategies (single-row intercropping, strip cropping, and crop rotation) with sole cropped maize under conventional ploughing and Conservation Agriculture in four Zambian Districts in the Eastern and Southern Provinces. These options were assessed using the Sustainable Intensification Assessment Framework (SIAF), with metrics representing productive, economic, human, social, and environmental dimensions. Data were collected from on-farm trials over three growing seasons. We found no significant effect of cropping systems on individual maize and legume grain yield across growing seasons, but substantial nutritional and economic benefits of intercropping systems due to simultaneously growing two crops. In particular, maize-legume intercropping strategies (single-row intercropping and strip cropping) resulted in higher energy and protein yield at cropping system level than sole maize and maize-legume rotation, which had positive implications for human nutrition. Although there were increased labour requirements to manage the intercrops, and particularly the strip crops, these cropping systems had much higher net benefits and returns to labour and inputs than the other cropping systems tested. Farmer evaluations however did not show a preference for the intercropping systems over the maize-legume rotation or sole maize, most likely because labour and its availability may be as or more important for farmers than overall cropping system benefits. Soil organic carbon content and soil pH did not differ between the tested cropping systems at the start of the trials and after three cropping seasons but decreased over this period independent of the cropping system. Overall, the results indicate that maize-legume strip cropping, and single-row intercropping can increase food and nutrition security as well as gross margins from farming, but this comes at the expense of greater labour requirements throughout the growing season. The latter may be addressed through, e.g., appropriate-scale farm mechanization, if intercropping or strip cropping systems are to become a viable option for labour, not land, constrained farms in Southern Africa.

Keywords: words: Mbili Mbili; Conservation Agriculture; Sustainable Intensification, Integrated Assessment, On-farm Trials

1. Introduction

Managing the challenges presented by population growth, climate change, and soil fertility decline will require effective strategies to sustainably intensify smallholder farming systems in southern Africa and narrow existing yield gaps (Godfray *et al.*, 2010; Pretty *et al.*, 2011; Silva *et al.*, 2023). One such cropping system is Conservation Agriculture (CA;(Thierfelder *et al.*, 2015) , which relies on minimum soil disturbance, crop residue retention (mulching), and crop diversification (e.g., rotation, intercropping) amongst other complimentary good agricultural practices (Thierfelder *et al.*, 2018). Yet, finding suitable options for crop diversification that fit into local farming systems has remained complex (Thierfelder and Wall, 2010; Pretty *et al.*, 2011; Lipper *et al.*, 2014; Madembo *et al.*, 2020; Mhlanga *et al.*, 2021). Crop diversification contributes to agricultural productivity and resilience in various ways, including suppressing pests and diseases (Lin, 2011), buffering the effects of climate variability and extreme weather events (Lakhran *et al.*, 2017), and improving soil fertility (Choudhary, 2019), and is thus key to reaping the full benefit and potential of CA (Mhlanga and Thierfelder, 2021; Thierfelder and Mhlanga, 2022).

Previous research has shown that maize sole cropping, year after year, does not significantly improve livelihoods or nutrition due to the low economic and dietary value of maize (Nyakurwa *et al.*, 2017; Ekpa *et al.*, 2018). The dominance of maize can therefore have negative effects on nutrition, as maize provides mostly calories. In some areas of Zambia, and in much of Malawi, households consume more than 50% of their caloric intake from maize (Ngwira *et al.*, 2013; Mhlanga *et al.*, 2021). This has significant effects on the nutritional status of households (Mangani *et al.*, 2015; Ngaha *et al.*, 2020; Oladiran and Emmambux, 2022). A major aim of nutritional policies has therefore been to diversify maize-based diets by introducing legumes for higher protein content in daily food (Mzyece, 2020).

Attempts to diversify maize-based cropping systems have led to widespread experimentation with different forms of crop diversification (Woomer and Tungani, 2003; Woomer *et al.*, 2004; Madembo *et al.*, 2020; Kinyua *et al.*, 2023). Common to southern Africa are rotations and intercropping of maize with legumes, such as soybean, cowpea, pigeonpea, and groundnut. Crop rotations are widely practiced on commercial farms, but on smallholder farms, rotations are often unsystematic and more land area tends to be allocated to maize over legumes (Waddington, 2003; Waddington *et al.*, 2007a; Waddington *et al.*, 2007b). This may lead to superior maize yields in some areas (Nyagumbo *et al.*, 2020), but smallholders often cite a lack of available land to successfully rotate crops while harvesting enough maize to feed their families. This is particularly prevalent in southern Africa where the unimodal rainfall distribution over a period of 5 months only allows for one cropping season per year, which reduces the attractiveness of crop rotations, and impedes their widespread adoption (Thierfelder and Wall, 2010). Depending on land size, farmers either practice rotations within the same year or between different years. However, in southern Africa farmers have to either share the land between two crops or miss a year of one of the crops due to the unimodal rainfall pattern. They cannot compensate for the missed harvest within the same year.

In land-constrained situations, intercropping may be a more suitable diversification strategy due to the potential for higher land use efficiency (Daryanto *et al.*, 2020). An intercrop comprises two or more different crops grown together in time and space, and this can be more appealing to farmers because maize can still be grown alongside the second crop on the same land in every cropping season. However, competition for light and water between the maize and companion crops can compromise yields (Madembo *et al.*, 2020), and managing an intercrop can also have higher labour requirements. These issues pose significant challenges to successful intercropping in Southern Africa (Nyagumbo *et al.*, 2020).

An alternative strategy to intercropping that may reduce crop competition and make diversification more attractive is strip cropping. Strip cropping, an intercropping strategy whose objectives are to optimize plant arrangements in space beyond the traditional single row intercropping (Woomer et al., 2004, Thierfelder et al., 2018), has been developed since the early 2000s mostly in East and West Africa (Woomer et al., 2004). Strip cropping has been used in East Africa for more than two decades (Woomer and Tungani, 2003; Woomer *et al.*, 2004; Kinyua *et al.*, 2023), where it is known by the local name Mbili-Mbili (meaning "two-two" in the local vernacular). However, it has not been previously trialled on a larger scale in southern Africa. Strip cropping involves planting two or more rows of the same crop together in an alternating pattern, compared to conventional intercropping where single rows are alternated, or the second species is planted between the rows of the main maize crop. This double- or multi-row configuration aims to maintain high plant populations of both maize and the companion legume, while reducing competition by creating gaps in the maize canopy that increase light interception for associated crops at cropping systems level. Such arrangements are thus expected to have smaller yield penalties on intercropped maize compared to single-row intercrops by allowing for a greater light interception by the legume (Woomer and Tungani (2003).

In this study, we compared two-row and four-row strip cropping arrangements with single-row intercropping, crop rotations, and sole maize across a network of on-farm trials in Zambia using the Sustainable Intensification Assessment Framework (SIAF), which evaluates cropping systems from a five-domain perspective (Droppelmann *et al.*, 2017). The five domains in SIAF include productivity, economic, environmental, human, and to a certain extent also social indicators (Table 1). Notably, SIAF also includes an assessment of farmers' perceptions of innovations (such as strip cropping), which are essential to understand farmer decision making and adoption.

The aim of this study was therefore to assess the relative performance of maize-legume inter- and strip cropping systems relative to sole maize and maize-legume rotations based on the multiple SIAF indicators capturing different dimensions of sustainability. Both the monocrop and the diversified cropping systems were tested under CA and conventional tillage practices.

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Our expectation was that strip cropping would outperform sole cropping and single-row intercropping across most SIAF indicators due to the benefits of being able to grow two crops on the same land area with minimal competition and individual crop yield loss. We hypothesised that (a) individual crop yields would be higher in the strip crops than single-row intercrops and comparable to sole maize, (b) the higher yields of both maize and legumes would lead to strip crops providing more calories, protein, and having higher gross margins than other cropping systems, and (c) strip crops would have similar effects on environmental indicators as compared to the other cropping systems. We anticipated that these benefits combined with the opportunity to grow maize in each season would appeal to farmers, leading to our final hypothesis that (d) strip crops would be more highly rated by farmers than rotations, single-row intercrops, or sole crops.

2. Material and Methods

2.1. Study area

On-farm trials were conducted in four target communities in Zambia. Two communities were located in Southern Province, in the districts of Choma (Simaubi Camp) and Mazabuka (Dumba Camp), and two were located in Eastern Province, in the districts of Sinda (Nyanje 1 Camp) and Chipata (Chinjala Camp). Although all these sites are in Zambian Natural Region IIA, there is a gradient of increasing rainfall from the south to the north (Table 2). The growing season in these areas usually begins in November each year and runs until April or May. The trials were initiated in the 2019/20 growing season and we report data in this study since then until the 2021/22 growing season unless otherwise stated.

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2.2. Experimental design and crop management

The on-farm trials analysed in this study form part of a mother-and-baby trial set up (Snapp, 2002) with 6-10 mother trial replicates in each community, and each replicate located on a separate farm. In a mother-and-baby trial set up, the mother trial replicates test the full range of cropping systems at each site that are of interest (i.e., one plot per cropping system), while baby trials are smaller subsets of the mother trial located nearby, testing a pair of cropping systems chosen by the farmers as their preferred options (i.e., 2 plots in the trial). Here, we consider the mother trials only, as each of them contains the full set of cropping systems evaluated in this study. The mother trials were 0.3 ha in size and consisted of 8 plots (representing the different cropping system) each measuring 375m².

The mother trials tested seven cropping systems. These had two conventionally ploughed (CP) systems, in which the soil was prepared with a mouldboard plough, and maize was planted into plough-opened lines. The other five were CA-based cropping systems, in which weeds were controlled with one pre-planting glyphosate application at 3 litres ha^{-1}, and maize was planted into rip-lines. In all cropping systems, both maize and legumes were seeded on the same date in each farm in each growing season. All weeding after planting was carried out with hand hoes as frequently as needed to keep weeds not more than 10 cm tall or 10 cm in diameter for weeds with a stoloniferous growth habit. In the CA-based cropping systems, the soil was covered with maize crop residues at an initial rate of 2.5-3 t ha^{-1} before sowing in the first year, which translates to approximately 30% groundcover. After the first year, all crop residues on the CA-based cropping systems were left in situ*,* although some grazing of residues was observed in some instances. Crop residues were removed from the CP-based cropping systems after harvest.

The two CP cropping systems referred to are a sole maize crop **(CP-sole)** and a maize-legume intercrop **(CP-int).** In both, the maize was sown with 90 cm interrow spacing, and in the intercrop the legumes were sown in rows placed between the maize rows (leading to 45 cm spacing between maize and legume rows). These two cropping patterns were repeated in the first two CA cropping systems: **MT-sole** (consisting of sole maize under minimum tillage) and **CA-int** (consisting of maize-legume single-row intercropping under CA). The third CA cropping system consisted of a rotation with maize and a legume grown in alternating years **(CA-rot).** This cropping system occupied two plots so that both maize and legume phases were present in each growing season. Maize was sown with 90 cm interrow spacing and legumes with 45 cm interrow spacing.

The strip cropping systems were designed to keep the maize plant population equal to all other cropping systems, meaning maize interrow spacing was reduced to create space for legume strips without compromising on overall maize plant population per unit area. The first strip cropping system had maize sown in double rows **(CA-2-row)** which created space for three legume rows. Maize was sown with 50 cm between rows, and the legumes with 30 cm between rows, leaving 35 cm between the maize and legume rows (so in total, the legume strip occupied 130 cm between 50 cm maize strips). The second strip cropping system had four rows of maize alternating with four rows of legumes **(CA-4-row)**. Both crops were sown with 45 cm interrow spacing, so each strip of each crop was 180 cm wide in total. In both the CA-2-row and CA-4-row cropping systems, the position of the maize and legume strips alternated annually.

In all cropping systems, maize interrow spacing was designed to achieve a plant population of 44 444 plants ha^{-1}. Legume interrow spacing was designed to best suit each legume species in each cropping system. Groundnut was sown with 30 cm between plants within rows aiming at a plant population of 37,000 groundnut plants ha^{-1} in the strip and intercrops and 74,000 plants ha^{-1} in the rotational cropping system. Soybean was sown with 5 cm between plants, to achieve 222,222 soybean plants ha^{-1} in the strip and intercrops and 444,444 plants ha^{-1} in the rotational cropping system.

The medium maturing commercial maize hybrid PAN53, a widely grown maize variety in Eastern and Southern Zambia, was grown at all sites. Different legumes were planted in different provinces according to the rainfall regime and suitability. In Southern Province, we used groundnut, variety MG5, and in Eastern Province we used soybean, variety Dina.

In all cropping systems, maize was fertilized at the Zambian recommended rate of 108 kg N ha^{-1}, 14 kg P ha^{-1}, and 13 kg K ha^{-1} supplied as basal and top dressing. Legumes only received the basal fertilization of 16 kg N ha^{-1}, 14 kg P ha^{-1}, and 13 kg K ha^{-1}. Basal fertilization was applied at sowing and a top-dressing fertilization was applied to maize at 4-5 weeks after sowing. In the strip cropping and single-row intercropping systems, fertilizer was applied close to the maize row anticipating that the legumes would meet most of their N requirements through biological N_2 fixation (BNF). Soybean was inoculated with *Rhizobium* to promote BNF before use, as recommended for non-promiscuous soybean varieties.

2.3. Data collection

2.3.1. Harvesting procedures

Each crop was harvested at physiological maturity. For maize, 3 subsamples of 5 m by two rows were harvested from each maize plot, except for the 4-row strip cropping systems where 4 rows by 5 m were harvested. For legumes, 3 subsamples of 5 m by 4 rows were harvested. The grain and biomass subsamples were weighed exactly to the nearest 0.1 g, and one composite sample was then collected from the three sub-samples for each crop and weighed exactly. The samples were air-dried for approximately two weeks and weighed again for dry weight which was used to determined grain yield and biomass. Grain yield was adjusted to 12.5% for maize and legumes, respectively, while biomass was determined as is after air drying to a constant weight.

The strip cropping systems considered the area that the legume and the maize occupied, to avoid overestimating the yield of each crop in space. We maintained the number of samples per plot but measured the distance between the maize (legume) rows as well as the distance to the next cluster of maize (legume) rows to calculate the area coverage of both crops. The yield of each crop was then adjusted by the area coverage, so that the reported yield per ha for each crop was representative of the whole plot rather than of the specific strips.

2.3.2. Farmer evaluations of the cropping systems

Farmer evaluation meetings were conducted by the Ministry of Agriculture Camp Extension Officers on the maize plots for the third growing season i.e., 2021/2022, in the research sites. Overall, 428 female and 509 male farmers attended the evaluation meetings. One meeting was held per mother trial, attended by farmers who lived nearby the respective mother trial, so a different group of farmers was present at each meeting. The aim of the meetings was to understand farmers' perceptions and preferences of the cropping systems tested in the mother trials. Biophysical crop characteristics were rated by each farmer using a 10-point Likert scale according to the farmer evaluation protocol developed by International Maize and Wheat Improvement Center (CIMMYT) socioeconomics team, ranging from very bad (1) to excellent (10). The categories of the Likert scale are shown in Supplementary Material (Table S1). The average score for each characteristic per plot was recorded by the Camp Extension Officer. The evaluations were conducted per plot at three stages of maize growth:

i. *Early-season evaluations* – conducted about three weeks after planting to evaluate plant stand, weed control, crop growth, and crop colour; 150 and 162 female and male farmers attended these evaluations, respectively.
ii. *Mid-season evaluations* – conducted with 126 female and 192 male farmers at tasselling stage to evaluate crop growth, crop colour, crop uniformity and weed control, and,

iii. *End-season evaluations* – conducted with 152 female and 155 male farmers just before or at harvesting to evaluate the number of cobs per crop, cob size, cob-filling (proportion of the cob with grain) and weed control.

For all the three evaluations (early-, mid-, and end-season), we also obtained an 'overall choice' of cropping system. Farmers present at each mother trial were asked, as a group, to choose their top three cropping systems. Farmers were asked here to choose based on their perceptions of the cropping system at the time of evaluation of the mother trial and were not prompted to take total yields or inputs into account. Male and female farmers at each mother trial were asked separately. However, for the purposes of this analysis, both sets of answers were used but not distinguished from one another (gender differences will be explored in future work). The cropping systems chosen at each mother trial by each gender group were then aggregated to village level by counting the number of times each cropping system was selected, giving a final 'overall choice' score for each cropping system in each village.

2.3.3. Soil chemical analyses

Soil samples were collected for nutrient analyses in the top 20 cm of the profile from each trial and cropping system at two points in time: (1) prior to the establishment of the trials in the 2019/2020 growing season and (2) after three consecutive cropping seasons (i.e., at the end of the 2021/2022 growing season). In 2019/2020, samples were collected from 6 to 10 random positions within each plot using an auger, mixed, and combined to make one composite sample of 300-500 grams per cropping system. The samples were air-dried for at least 2 weeks and then sent for laboratory analysis at Mt. Makulu Research Station, Zambia Agriculture Research Institute. To assess soil quality changes over time and across the soil profile, the soil samples were collected at two soil depths (0-5 cm and 5-20 cm) at the end of the 2021/2022 growing season. In both cases, standard laboratory procedures were used to analyse the samples for pH, organic carbon (SOC), nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na) and cation exchange capacity (CEC), and textural properties (% sand, silt, and clay). The current study reports data for SOC and soil pH only.

Soil pH was measured using the standard calcium chloride ($CaCl_2$) method. Soil organic carbon was determined using the Walkley-Black method whereby a soil sample is oxidized by potassium dichromate solution in concentrated sulphuric acid (van Reeuwijk, 1986). The potassium dichromate reduced during the reaction with the soil is proportional to the oxidizable organic carbon present in the soil. Therefore, the soil organic carbon is then estimated by measuring the remaining unreduced dichromate by back-titrating with ferrous sulphate using diphenylamine as an indicator. To be able to determine SOC stocks, soil bulk density for each site was retrieved from Hengl *et al.* (2017), as this was not measured in the trials. We used bulk density to be able to explore cropping system differences in how much SOC stocks changed over time (described below). Given that the bulk density estimates are consistent within sites, imprecision on the absolute scale will not affect treatment comparisons. Soil bulk density, soil layer thickness, and SOC concentrations were used to calculate SOC stocks (t ha^{-1}) using the Equation [1] from Ellert and Bettany (1995):

$$SOC_{stock} = conc \times \rho b \times T \times 10\,000 \text{ m}^2 \text{ ha}^{-1} \times 0.001 \text{ Mg kg}^{-1} \quad [1]$$

where:

SOC_{stock} is the SOC mass per unit area (Mg ha^{-1}); conc is the element concentration (g kg^{-1}); ρb is the field bulk density (kg dm^{-3}); *T* is the thickness of soil layer (m).

2.4. Calculations

2.4.1. Cropping system productivity

To be able to compare the cropping systems with different crop intensities and temporal arrangements (i.e., sole *vs.* intercropping *vs.* rotation), and with different grain composition (i.e., maize and legumes), cropping system yields were expressed in terms of energy yield (GJ ha^{-1}) and protein yield (kg ha^{-1}) based on the measured crop-specific grain yield and standard energy and protein contents of the grain of each crop. The formulas used in the calculation of the energy and protein values for each cropping system are provided in Table S2. The energy values assumed for maize, groundnut, and soybean grain were 353, 578, and 428 kcal 100 g^{-1} seed (based on Global Expanded Nutrient Supply (GeNUS) database; http://projects.iq.harvard.edu/pha/genus; (Smith *et al.*, 2016b) while the protein contents were 10%, 26%, and 36%, respectively (based on the Food Nutrition Database; http://www.foodnutritiontable.com/; (de Jong, 2023).

2.4.2. Cropping system profitability

We calculated three main economic indicators for the 2021/2022 growing season using standard procedures from CIMMYT (1988), i.e., gross benefits (GB), production costs (PC), and net benefits (NB). A gross margin analysis was used to compare net benefits of different cropping systems per hectare at plot level using Equation [2]. The gross margin analysis quantified and monetized all the costs and benefits in individual plots as follows:

$$NB_i = \Sigma_j GB_{ij} - \Sigma_j PC_{ij} \quad [2]$$

where *NB* are net benefits, GB refers to gross benefits and PC to the production costs for crops *j* in cropping system × trial combination *i*. Production costs included all the costs related to labour (land clearing, land preparation, planting, weeding, fertilizer application, herbicide application, pesticide application, and harvesting) and material inputs (seed, fertilizers, herbicides, and pesticides) highlighted in Equation [3].

$$PC_j = (SQ_i \times CS) + (LQ_i \times w) + (PQ_i \times CP) + (HQ_i \times CH) + (\Sigma_f FQ_f \times CF_f) \quad [3]$$

where: PC indicates production costs (US$ ha^{-1}) for cropping system × trial combination *i*, SQ is seed quantity sown (kg ha^{-1}), CS is the unit cost of seed (US$ kg^{-1}), LQ is the labour quantity (person-days ha^{-1}, an eight-hour workday was used to calculate a person-day) measured in each mother trial, w is the cost of labour (wage rate; US$ day^{-1}) based on wage rates advised by the Ministry of Agriculture of Zambia, PQ is quantity of pesticide applied (litre ha^{-1}), CP is unit cost of pesticide (US$ litre^{-1}), HQ is quantity of herbicide applied (litre ha^{-1}), CH is unit cost of herbicide (US$ litre^{-1}), FQ is the quantity of fertilizer (basal and/or top dressing) applied (kg ha^{-1}), and CF is the unit cost of fertilizer (US$ kg^{-1}). The product $\Sigma_f FQ_f \times CF_f$ refers to the sum of basal and top-dressing fertilizer costs for *f* fertilizer types. The value of land was not taken into consideration in the gross margin analysis.

Gross benefits (Equation 4) were calculated using gross returns of all the crops in the plot by multiplying the total yield of the crops by their respective unit prices (US$ kg^{-1}):

$$GB_i = (MY_i \times MP) + (LY_i \times LP) \quad [4]$$

where GB refers to gross benefits (US$ ha^{-1}) in cropping system × trial combination *i*, MY to maize yield (kg ha^{-1}), MP to average maize price in the communities where the trials were conducted (US$ kg^{-1}), LY to legume yield (kg ha^{-1}), and LP to market legume price (US$ kg^{-1}). Crop prices were obtained from socio-economic surveys conducted annually in the communities hosting the trials.

2.4.3. Change in soil organic carbon and soil pH

Temporal changes in SOC and soil pH between the soil samples collected before the cropping systems were established and after three consecutive cropping seasons of their establishment was assessed using the ratio between the values of the latter sampling and those of the initial sampling as follows:

$$\Delta x_i = x_{ei} / x_{bi} \quad [5]$$

where Δx_i is the change in SOC (t ha^{-1}) or soil pH for cropping system × trial combination *I*, x_{ei} is the value of the respective soil property after three growing seasons of cropping systems' establishment, and x_{bi} is the value of the respective soil property prior to the establishment of the cropping systems.

2.5. Statistical data analysis

Statistical analyses were done using linear mixed models to assess the effects of cropping systems on the different performance indicators with the *lmer()* function of the 'lme4' package (Bates *et al.*, 2015) in R version 4.2.1 (Bates *et al.*, 2015; R-Core-Team, 2023). All models had a single fixed effect, i.e., cropping system, and the significance of this effect was tested using Type II Wald chi-square tests (due to the absence of interaction terms) using the *Anova()* function in the 'car' R package (Fox and Weisberg, 2019). Cropping system means were compared using multiple comparison with multiplicity adjustment through the *emmeans()* function of the 'emmeans' R package (Lenth, 2023). Random effects in each model differed depending on whether data were collected from multiple growing seasons or from a single growing season. All models were checked for homoscedasticity and normality of the residuals, and where data deviated from these, appropriate transformations were applied. Thus, transformations were done only for the soil data.

The effects of the different cropping systems on maize productivity, legume productivity, system energy yield, and system protein yield were assessed with cropping system as the fixed effect and farmer nested into community nested into province and growing season as random effects. Community and growing season were also combined in a new factor variable named ‘environment’ and used in the analysis as a random effect with cropping system nested into the factor to capture the context-dependency of the investigated variables. Biophysical conditions differ between locations and years, so each ‘environment’ represents a distinct combination of edaphic and climatic conditions.

The cropping system effects on production costs, net benefits, labour requirements, returns to labour, returns to inputs, and farmers’ ratings were also assessed using linear mixed models as described above. In these models, cropping system was included as a fixed effect and farmer nested into community nested into province as random effects. The significance of the fixed effect was assessed as described above. For the farmer choices analyses, cropping system was included as a fixed effect and province as a random effect.

SOC and soil pH from all trials were first analysed with linear mixed models for the first and second sampling moments separately to assess the baseline status of the soil and short-term differences between cropping systems between both sampling periods. In these models, farmer nested within community were included as random effects, cropping system was included as a fixed effect, and soil depth were also included as a fixed effects for the analysis of the data from the second sampling period (the first sampling period did not segregate samples for different soil depths). For the second step, linear mixed models were fitted to assess the change in soil chemical properties between the two sampling moments for each cropping system. For this analysis, the ratio of change in SOC and soil pH Δxi was first log-transformed to comply with homoscedasticity and normality tests. Cropping system effects on SOC and soil pH change was assessed considering cropping system as a fixed effect and farmer nested in community nested in province as random effects.

For all the analyses described above (i.e., for productivity, human, economic, social, and environmental assessments), we estimated the variance explained by the fixed effects (without the random effects), i.e., marginal pseudo-R-squared (mR^2), and the variance explained by both the fixed and random effects, i.e., conditional pseudo-R-squared (cR^2), using the *r.squaredGLMM()* function of the 'MuMIn' R package (Barton, 2023). Further, the variance explained by each of the random effects was extracted from the models using the *VarCorr()* function of the 'lme4' R package and the variance component for each random effect was expressed as a percentage of the total variance. The residual variance component describes any variation not described by the models, including interactions between the fixed and random effects (for example, where cropping systems had different relative outcomes among years, provinces, villages, and farms).

To explore relationships between productivity (crop yield), human (nutrition), economic, and environmental indicators across cropping systems a Principal Components Analysis (PCA) was conducted. We collated the maize grain and biomass yield, legume grain and biomass yield, energy and protein yields for each cropping system in each trial (across all three years) alongside the economic data per trial and the change in soil C and soil pH for each cropping system on each trial (available only for 2021/2022). These data were centred on their means and scaled by dividing by their value with the respective standard deviations. The PCA was run using the *prcomp()* function in the 'stats' R package (R-Core-Team, 2023). The results were visualised in a biplot, showing cropping system centroids (the average location of farms belonging to a cropping system in a multivariate space) and 95% ellipses (based on a normal distribution) calculated using the *fviz_pca_biplot()* function in the 'factoextra' R package (Kassambara and Mundt, 2020)

Radar plots were used to visually illustrate the relative trade-offs across different cropping systems following Droppelmann *et al.* (2017). Mean estimates for each SI indicator of the five analysed domains of sustainable intensification (i.e., maize and legume grain yields, energy, protein, net economic benefit, labour requirements, farmer overall rating, and change in SOC) in each cropping system were obtained from their respective models (described above). Each variable was scaled to a proportion of its maximum. For these assessments, labour requirements were reversed to labour savings, so that positive outcomes were always associated with higher values on the radar plots to avoid confusion on the directionality. Labour savings were calculated as the difference between the labour requirement of each cropping system and the maximum labour requirement across cropping systems and expressed as a proportion of that maximum value.

3. Results

3.1. Productivity domain: grain yield and biomass at crop level

Maize and legume grain yield and biomass did not differ significantly across cropping systems (Table 3, Fig. 1, Fig. S1). Cropping system explained little variance in these productivity outcomes (i.e., 1% of the variance), while substantial amounts of variance were explained by the random effects describing the year and location (Table 3), and around 15-20% variance remained as an unexplained residual (Fig. S2). Much of the variance explained by the random effects was attributed to growing season, either as a main effect or in interaction with the community (the community by growing season which is “environment”) (Fig. S2). The main effect of growing season explained more variance for maize grain yields and biomass, while for legumes the amount of variance described by the main effect and environment interaction were similar.

Average maize grain yield for each cropping system ranged between 3.4 and 4.0 t ha^{-1} while maize biomass ranged between 4.3 and 5.2 t ha^{-1} (Fig. 1a & Fig. S1a). Average legume grain yield for each cropping system ranged between 0.6 t ha^{-1} and 1.0 t ha^{-1} while legume biomass ranged between 1.2 t ha^{-1} and 1.8 t ha^{-1} (Fig. 1b, Fig. S1b).

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3.2. Human domain: Energy and protein yield

There were significant mean differences in energy and protein yield across cropping systems (Table 3). The highest energy yield was observed in the CA–4-row cropping system with a mean of 77.0 GJ ha^{-1} (Fig. 1c). This was followed by the other diversified cropping systems (CP-int, CA-int, CA-rot, and CA–2-row), for which energy yield was on averaged 64.4 GJ ha^{-1} across them (Fig. 1c). Sole cropping of maize either under CP or CA had the lowest energy yield with an average 23% lower than that of the CA–4-row cropping system. The CA–2-row and CA–4-row cropping systems had the highest protein yield with a mean of 0.5 t ha^{-1} across the three growing seasons and across all villages (Fig. 1d). This was followed by CP-int and CA-int cropping systems, for which protein yield was on average 0.48 t ha^{-1}, while the CA-rot cropping system had the lowest protein yield of 0.3 t ha^{-1} (Fig. 1d).

Cropping system alone explained a relatively small proportion of the variance in energy and protein yields, 2% and 5%, respectively, while growing season and location-related random effects explained about 80% and 75% of the variance (Table 3). Amongst the random variables, harvest year explained most variation, with contributions also from site by year interaction ('environment' variable), and the environment by cropping system interaction (Fig. S2b).

3.3. Economic domain: Profitability and labour requirements

There was a significant difference in the amount of labour required for crop management operations across cropping systems (Fig. 2). The strip and intercropping systems had the highest labour requirements for all cropping systems tested (Fig. 2a). In particular, the CA–2-row cropping system had the highest labour requirement of 59 person-days ha^{-1}, followed by the other strip and intercropping systems, for which labour requirements averaged 48 person-days ha^{-1} (Fig. 2a). The MT-sole and CA-rot had the lowest labour requirements, with an average of 32 person-days ha^{-1}. The fitted linear mixed models explained 68% (Table 3) of the observed variation in labour requirements across cropping systems while farmer nested in community nested in province explained most of the random effect variance (Fig. S2c). More labour was needed for weeding and harvesting than for other operations across all cropping systems (Table 4, Fig. 2b). The strip and intercropping systems required more labour for planting as compared to the sole cropping systems (Fig. 2b).

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The cropping systems with the higher labour requirements also exhibited higher production costs. Cropping system explained 43% and 69% of the variance, respectively, for labour inputs and production costs (Table 3), with further variation explained primarily by differences between farms for labour and between provinces for production costs (Fig. S2c). The significantly highest total production cost was that of the CA–2-row strip cropping system, which had an average production cost of US$660 ha^{-1} (Fig. 3a). This was followed by the CA–4-row, CA-int, and CP-int cropping systems, which had an average production cost of US$605 ha^{-1}. The CA-rot cropping system had the lowest production cost, which was ca. 40% lower than that of the CA–2-row strip cropping system.

Economic analyses showed that all intercropping systems (CP-int, CA-int, CA–2-row, and CA–4-row) had the highest net benefits per hectare compared to sole cropping systems, ranging from US$676 ha^{-1} to 877 US$ ha^{-1} (Fig. 3b), despite these cropping systems being associated with higher production costs (Fig. 3a). The driver behind this was the advantage of harvesting two crops from the same land area. The lowest net benefits were observed in the sole cropping systems, i.e., CP-sole and MT-sole, with an average of US$108 ha^{-1}. Nearly 20% of the variance in net benefits was explained by cropping system alone, while an additional 44% was explained by random effects and attributed to differences between provinces, villages, and farms (Table 3, Fig. 2d). As is the case with net benefits, gross benefits were higher under intercropping systems despite these cropping systems requiring more labour during planting (Table 4).

Returns to labour and returns to inputs were higher for the intercropping systems than for the sole cropping systems (Figs. 3c and 3d). The CA–4-row had the highest returns to labour of US$17.4 for each labour day invested, while the sole cropping systems (CP-sole and MT-sole) had the lowest returns to labour averaging US$4.4 (Fig. 3c). Returns to inputs were highest in all cropping systems with legumes (US$1.50 ha^{-1} for each dollar of inputs invested) and these, on average, were 275% higher than those of the sole cropping systems (Fig. 3d). However, cropping system explained only 13 and 17% of the variance in returns to labour and inputs, respectively, with differences between province, village, and farm explaining an additional 20-25% of the variance (Table 3, Fig. 2b).

------------------------------- Put Fig. 3 somewhere here -------------------------------

3.4. Environmental domain: Soil quality indicators

Changes in SOC and soil pH did not differ significantly between the cropping systems after three growing seasons of implementation (Table 3). However, there were decreases in both SOC and soil pH for all cropping systems with ratios below 1 indicating lower values after three consecutive cropping systems as compared to baseline values prior to establishment of the cropping systems (Fig. 4). There was a decrease over time of 36% and 10% for SOC and soil pH, respectively. The fitted linear mixed models accounted for 23% and 53% of the variation for SOC and soil pH, respectively, with cropping system accounting for less than 1% and 2% of variance, respectively (Table 3). The substantial residual variance (Fig. 2d) arises from differences between trials (within locations, years, and cropping systems) suggesting a high spatial variability in changes in soil properties across the on-farm trial network.

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3.5. Social domain: Farmers' evaluations of the cropping systems

Farmer ratings of different biophysical and management aspects of the tested cropping systems were assessed during the early-season, mid-season, and end-season (Table 5). For the early season evaluation, a significant difference in ratings between cropping systems were only noted for plant stand in which the CA–4-row cropping system was rated the highest (7.9), while the MT-sole cropping system was rated the lowest (7.2; Table 5). No significant differences were noted between the cropping systems in the rating of the biophysical and management aspects during the mid-season evaluations. In the late-season evaluations, significant differences in the rating of the cropping systems were noted for weed control only, where the CA-rot cropping system was rated highest and the CA-4-row cropping system was ranked lowest. In general, however, farmer ratings varied more between trials, and to a lesser degree between villages and provinces, than between the tested cropping systems (Table 5, Fig. S3).

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In addition to the biophysical and management ratings of different cropping systems, 'overall choice' scores were also determined for each cropping system in each village, based on how often different groups of farmers considered each cropping system to be among the top three performers. No significant differences were observed between the number of times each cropping system was chosen within any of the evaluation periods (Table 6). However, when these ratings were averaged across the evaluation periods, to get a seasonal evaluation, there was a significant difference in the choice rank. The CA-rot cropping system was chosen more often on average across villages while the MT-sole cropping system was chosen the least. The residual variance in the number of times each system was chosen was much greater than variance explained by either cropping system or identity of province (Table 6), indicating substantial variability in the most-chosen cropping systems between villages.

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3.6. Trade-offs and synergies between performance indicators

The PCA identified a dominant gradient in the data (PC1, explaining 46.3% of the variance) from trials with higher to lower legume yields, energy and protein yields, returns to inputs and labour, and net benefits (Fig. 5, Table S3). Typically, MT-sole and CP-sole cropping systems were associated with low values of these outcomes, while the diverse cropping systems were associated with higher outcomes on average, but spanned a much greater variation in outcomes, indicated by the relative size of their ellipses. The second PC (PC2, explaining 14.4% of the variance) described a gradient in maize grain yield and biomass, which varied more within than between cropping systems (see also Section 3.1). The third PC (PC3, explaining 12.0% of the variance) correlated most strongly with input and labour costs (Table S3), for which the strip and intercropping systems tended to have higher values than the rotation and sole cropping systems. Overall, the PCA shows that energy and protein yields were positively correlated with economic returns and benefits, and these reached their highest levels in the strip and intercropping systems, even though these cropping systems also had higher costs and labour requirements. Energy and protein yields and economic returns correlated with legume grain yields (PC1), but not maize grain yields (PC2), indicating that these benefits were driven by the presence of the legume in the cropping system.

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Radar plots facilitate the easy comparison of different cropping systems in terms of their overall performance across sustainability indicators (Fig. 6). There were similar patterns within each type of cropping system (Fig. 6): the pattern of responses for CP-sole was similar to MT-sole, whereas CP-int was similar to CA-int; CA–2-row was similar to CA–4-row, and finally CA-rot had a unique pattern. The intercropping systems had similar levels of energy and protein yield across the sites, regardless of the tillage method used, as compared to the sole crop and rotational cropping system. The CA–2-row and CA–4-row were the outright performers for all indicators, except for operational labour saved and farmer ratings, which were higher for the CA-rot cropping system (Fig. 6). Although changes in SOC were not significantly different across cropping systems, based on the linear mixed models, the CA–2-row cropping system showed potential to improve this indicator.

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4. Discussion

4.1. Benefits and challenges of intercropping systems

The focus of agriculture in smallholder farming systems in southern Africa is on maize, often neglecting the important contribution that can be expected from legumes in the cropping system, which are often grown as secondary crops. In our trials, we used both groundnut and soybean as companion crops to maize, both of which have potential to make an important contribution to livelihoods. While soybean is traditionally used as animal feed in southern Africa (Siamabele, 2021), recent nutritional campaigns in the region have made this crop more popular for human consumption (e.g., soya milk and meat, soya flower added as biofortification of porridge (Alamu *et al.*, 2017). Groundnut, on the other hand, is a popular women's crop in the region, which often generates extra income from farming (Owusu and Bravo-Ureta, 2022). Groundnut is eaten both boiled and roasted and as peanut butter, which is a cultural constant in children’s meals for protein fortification (Mupunga *et al.*, 2017). Thus, strip and intercropping systems can have an important contribution to the human and social dimensions evaluated in this study.

The results of this study showed that on average, intercropping and strip-cropping systems outperformed other sole maize cropping systems on outcomes that combined both maize and legume yields including energy and protein yield, net benefits, and returns to inputs and labour. This agrees with results from other studies and highlights the importance of a systems perspective in cropping systems research (Komarek *et al.*, 2021; Mhlanga *et al.*, 2021). In contrast, individual crop yields did not differ on average among cropping systems. This indicates that the benefits from intercropping and strip cropping compared to sole cropping and rotations arise from growing both crops together on the same unit of land within the same growing season, thus improving resource-use efficiency (Kinyua et al., 2023).

These benefits were however not consistently achieved across all on-farm trials and were often small relative to the total variation in outcomes across the trial network. Harvest year and location variables accounted for substantial variation in outcomes, indicating that spatial and seasonal factors such as weather patterns, soil type, and landscape position had larger impacts on the performance indicators than the cropping systems tested. Crop yields, in particular, varied between locations and growing seasons, which in turn affected energy and protein yields, net benefits, and returns to inputs and labour. The PCA results showed that legume yields were much more strongly correlated with these outcomes than maize yields, indicating that legumes were critical to enhancing cropping system performance.

It was surprising to see no difference in mean legume yields between the single-row intercrops and strip crops, given the differences in light reaching a legume strip compared to a legume single intercrop (Woomer and Tungani, 2003) and the known sensitivity of soyabean in particular to low light levels (Cober *et al.*, 1996). However, our data shows substantial variation in legume yields, suggesting that future research focusing on how legume yields can be stabilized within cropping systems and across sites and years could help to maximise the benefits of intercrops and strip crops.

Achieving higher nutritional and economic outcomes from intercropping and strip cropping systems required more labour and higher input costs than for the sole crop and the rotational cropping systems. These requirements were balanced out by greater net economic returns in these cropping systems, indicating that if farmers can invest more labour and accept slightly higher cost of production, they can disproportionately gain from applying an intercropping strategy such as strip cropping. Previous research from Zambia and Malawi also found higher returns on investment and returns to labour from intercropping systems (Thierfelder *et al.*, 2016a; Thierfelder *et al.*, 2016b; Mupangwa *et al.*, 2017; Mutenje *et al.*, 2019).

Our study included changes in SOC and soil pH over three consecutive growing seasons as two environmental indicators. No significant differences in these indicators were observed across cropping systems, indicating no short-term benefits or costs of specific cropping systems. However, a reduction in both SOC and soil pH was observed between the first and the second sampling period. The reduction in soil pH is likely associated with the low buffering capacity of Zambian soils and the types of fertilizer used which gradually increase soil acidity over time (Lungu *et al.*, 1993; Mitchell, 2005). Meanwhile, SOC under (sub-)tropical conditions can often not be maintained or improved, even under CA (Cheesman *et al.*, 2016), unless substantial amounts of crop residues and/or manure are returned to the field (Zingore *et al.*, 2005; Chivenge *et al.*, 2007; Nyagumbo *et al.*, 2022). Residue retention is hard to achieve for smallholders in Zambia where there is high demand for residues as livestock feed (Valbuena *et al.*, 2012), and residue levels on the trials studied here were frequently observed to be low due to livestock grazing.

4.2. Farmers' preferences and adoption potential

The social preferences of strip cropping were captured by periodic evaluations and ratings that farmers carried out during the cropping season. Overall, farmers favoured the CA-rot most often, despite our findings that nutritional and economic benefits were higher in intercropping systems. This may indicate farmer recognition of the increased labour and input requirements for planting and management in both strip and single-row intercropping systems. Since in these cropping systems two crops are grown simultaneously, extra labour is required for planting the crops as compared to the sole cropping systems (Dahlin and Rusinamhodzi, 2019). Although the rotational cropping system (CA-rot) also involved two crops, the spatial arrangement in the strip cropping systems (CA–2-row and CA–4-row) required intricate planting patterns complicating seeding, weed control, and field operations in general (Juventia *et al.*, 2022). However, farmers acknowledged a good plant stand in the early crop establishment phase (early evaluation) in the CA–4-row strip cropping. In contrast, CA-rot was rated highly for cob size and ease of weed control, as the rotational cropping system tended to result in good crop stands and did not create challenges during herbicide application and weed control. This most likely contributed to the rotational cropping system being rated the highest overall throughout cropping season, whereas the lowest rated was the CA-sole.

A tendency to favour the less labour-intensive CA-rot cropping system suggests that smallholders in Zambia are more labour constrained than land constrained (cf. Silva *et al.* (2023). This context is important to consider as farmers in Eastern and Southern Provinces of Zambia have more abundant land (Silva *et al.*, 2023), which preferentially supports crop rotations, whereas in other regions, where land is more limiting (e.g., Malawi), intercropping may be a more attractive option (Thierfelder *et al.*, 2013) and is therefore practiced more widely in maize/pigeonpea systems (Snapp *et al.*, 2010; Smith *et al.*, 2016a; Ngwira *et al.*, 2020). Such variation in land and/or labour availability may partially explain the variance observed in farmer preferences in our study. However, to reduce the labour burdens, animal traction mechanization for ripping has often been promoted and applied in CA cropping systems in Zambia. This can improve timely planting while providing greater labour productivity particularly among labour constrained households (Nyagumbo *et al.*, 2017).

Finally, farmers may not have considered the combined benefits received from a systems perspective over several growing seasons in their evaluation of the cropping systems, given the evaluations involved the wider community visiting the mother trials and assessing what they could see in the field at the time of evaluation. The scores for crop stand quality and weed management suggest the rotational cropping system generally looked good in the trials, and farmers were not prompted to consider the overall limitations in the economic and nutritional outcomes of the rotation in space and time when assigning an overall score. Future extension efforts could involve summarizing results at the cropping systems level, to help farmers to evaluate trade-offs of different cropping systems across different time horizons. However, where labour is more constraining than land, a rotational cropping system may remain a more attractive choice.

4.3. Further research

Our results suggest that although intercropping systems have better nutritional and economic outcomes on average, their adoption may be impeded by the extra labour of managing two crops instead of one especially considering the spatial patterns and complexities associated with these arrangements. Future research exploring how to overcome labour constraints could therefore be valuable, for example the possibility of mechanising strip cropping with small tractors (e.g., with a two-wheel tractor) and multi-crop post-harvest processing implements. Recent innovations in mechanization reduce the associated drudgery and high labour demands, which are common barriers to adoption. Appropriate scale farm mechanization with small two-wheel tractors and animal traction options, have been promoted in some parts of southern Africa, including Zambia and have been found to reduce labour demands (Baudron *et al.*, 2015; Baudron *et al.*, 2019) and this should be further explored and documented in future research. These mechanized solutions can potentially reduce the costs of production through reduction in labour requirements and increase profits through higher yields. Alongside practical interventions such as mechanisation, policy action may also be essential to incentivize diversified systems (Mortensen and Smith, 2020).

Another future research direction will be to investigate the causes of variance in the outcomes assessed in this study. All metrics assessed showed substantial variability between villages and/or farms, particularly within the intercropping systems, suggesting there may be key interactions with other factors that could be leveraged to further enhance the performance and reliability of these systems. In particular, our results suggest that identifying ways to reliably increase legume yields would also secure more reliable economic and nutritional benefits from the intercropping systems. Previous research suggests that inoculation and P fertilisation, and their interactions with soil properties, may be promising avenues to increase and stabilize legume productivity (Muoni *et al.*, 2022). The importance of diversification may also vary between climates, with several studies suggesting that diversity is particularly beneficial to buffer the impact of droughts and high temperatures on food production (Rusinamhodzi *et al.*, 2012; Renard *et al.*, 2023).

For a more holistic perspective on sustainability, future research could address the very limited set of environmental indicators considered so far (soil C and pH only). Future studies are planned to expand on this, including assessments on soil microbial activity, BNF, soil erosion, water infiltration and soil moisture, and biodiversity. Previous research suggests many of these metrics are likely to be higher in diverse CA treatments (Daryanto *et al.*, 2020; Iheshiulo *et al.*, 2023).

Finally, it is also essential that future studies investigate the management of pests and diseases in intercropping systems. The use of certain pest or weed control methods is impeded by the presence of two crops, especially if they are of different tolerance to the methods used. For example, the use of herbicides such as atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) in the control of weeds in maize-soybean or maize-groundnut cropping systems may result in residual effects of the herbicide, which negatively affects the development of legume crops in subsequent growing seasons (Reinhardt, 1995). On the other hand, depending on the crops used in intercropping systems, pests and diseases may find alternative hosts in one of the crops resulting in carryover into subsequent growing seasons, although intercrops are generally beneficial in disease and pest control (Trenbath, 1993; Huss *et al.*, 2022).

5. Conclusion

Diversification of maize-based cropping systems in Southern Africa needs to be tailored to prevailing farmers' conditions. Here, we assessed the performance of alternative spatial and temporal arrangements of maize-legume cropping systems across five domains of sustainable intensification: productivity, economic, social, human, and environmental.

We conclude that strip cropping, with 2 or 4 row arrangements (CA–2-row and CA–4-row), and single-row intercropping systems (CA-int and CP-int) performed relatively well across the different domains of sustainable intensification, generally with similar performance for the different domains. These cropping systems only scored worse than the rotation (CA-rot) and sole crops (MT-sole and

CP-sole) on input costs and labour requirements, but these were balanced out by greater returns on investment to inputs and labour due to larger net benefits. Overall, the sole crops performed worst, demonstrating that a legume crop adds substantial value to these cropping systems. Due to the temporal limitations, strip cropping and intercropping were a more efficient way to integrate legumes than the rotation.

Overall, these results confirmed our hypotheses that strip cropping would be a high-performing diversification option across productive, human, and economic domains. An unexpected finding was that single-row intercropping performed similarly well to strip-cropping, despite potentially greater competition between the maize and the legumes in single-row intercropping. However, farmers did not rate strip cropping or intercropping significantly higher than CA-rotation or CP-sole cropping, suggesting that issues such as labour may pose a barrier to adoption, and countering our final hypothesis that strip crops would be preferred. It remains to be seen whether ratings will change over time if farmers become more accustomed to the strip and single-row intercropping arrangements and their associated system-level benefits.

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Conflict of Interest

All authors confirm no conflict of interest whatsoever in conducting this study.

Author contribution

CT designed the study, supported its implementation, data taking, preliminary data analysis and wrote the first draft; BM, CM, and JVS supported the cropping systems analysis and contributed to writing the manuscript; HN, ES led the economic and social analyses; IN, KK, ES, MC contributed to design and field implementation and writing.

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Table 1: List of domain indicators quantified in this study following the Sustainable Intensification Assessment Framework (SIAF).

Domain	Indicator	Metrics	Measurement method
Productivity	Grain yield	kg ha^{-1} $season^{-1}$	Crop cuts
	Biomass yield	kg ha^{-1} $season^{-1}$	Crop cuts
	Total system productivity	kg ha^{-1} $season^{-1}$	Crop cuts
Economic	Gross margin	US$ ha^{-1} $season^{-1}$	Survey and productivity measurements
	Returns to labour and input	US$ $US\$^{-1}$	Survey and productivity measurements
	Labour requirement	Hours ha^{-1}	Field measurement
Human	Protein production	kg ha^{-1} $season^{-1}$	Survey and productivity measurements
	Energy production	calories ha^{-1} $season^{-1}$	Survey and productivity measurements
Social	Rating of technology by gender group	Rating	Focus group discussions, household surveys
Environment	Carbon sequestration (total Carbon)	% or Mg ha^{-1}	Soil measurement
	Soil pH	unitless	Soil measurement

Source: SIAF Framework: https://www.k-state.edu/siil/resources/framework/index.html

Table 2. Average growing season rainfall, soil texture, geographical location, and crops tested at the research communities in Southern and Eastern Zambia.

Province	District	Camp	Rainfall (mm)	Soil texture	Longitude	Latitude	Crops tested
Southern	Choma	Simaubi	664	Sandy loams	-16.256	26.822	Maize, groundnut
Southern	Mazabuka	Dumba	831	Sandy loams	-15.973	27.645	Maize, groundnut
Eastern	Sinda	Nyanje 1	951	Sandy clay loams	-14.426	31.840	Maize, soyabean
Eastern	Chipata	Chinjala	987	Loams	-13.631	32.498	Maize, soyabean

Table 3. Effect of cropping system on different performance indicators measured in the Eastern and Southern Provinces of Zambia during the 2019/20 and 2021/22 growing seasons.

Domain	Pseudo–R-squared‡	Indicator†	Degrees of freedom	Wald statistic	*P-value*¶
Productivity	$mR^2 = 0.01$; $cR^2 = 0.85$	Maize grain yield	6	7.89	0.25
	$mR^2 = 0.01$; $cR^2 = 0.79$	Maize biomass	6	8.82	0.18
	$mR^2 = 0.01$; $cR^2 = 0.77$	Legume grain yield	4	3.63	0.45
	$mR^2 = 0.01$; $cR^2 = 0.78$	Legume biomass	4	3.72	0.44
Human	$mR^2 = 0.02$; $cR^2 = 0.83$	System energy yield	6	18.72	0.005**
	$mR^2 = 0.05$; $cR^2 = 0.81$	System protein yield	6	22.73	0.000***
Economic	$mR^2 = 0.43$; $cR^2 = 0.68$	Labour requirements	6	264.79	< 2.2e-16 ***
	$mR^2 = 0.69$; $cR^2 = 0.89$	Total production costs	6	1226.3	< 2.2e-16 ***
	$mR^2 = 0.19$; $cR^2 = 0.63$	Net benefits	6	107.6	< 2.2e-16 ***
	$mR^2 = 0.13$; $cR^2 = 0.61$	Returns to labour	6	68.9	7.0e-13***
	$mR^2 = 0.17$; $cR^2 = 0.59$	Returns to inputs	6	83	8.77e-16 ***
Environmental	$mR^2 = 0.003$; $cR^2 = 0.23$	Soil organic carbon	6	0.87	0.99
	$mR^2 = 0.02$; $cR^2 = 0.53$	Soil pH	6	9.22	0.16

‡For the pseudo–R-squared, mR^2 represents the marginal R^2, which is variance explained by the fixed term (cropping system) only, while cR^2 represents the conditional R^2, which is variance explained by the fixed and the random terms (province, village, farmer, and/or year depending on the model). The residual variance (not explained by any of the terms) is obtained by subtracting the cR^2 from one.
¶Asterisks indicate statistical significance between groups at the following significance levels: ****P*< 0.001, ***P* <0.01.

Table 4. Economic benefits and production costs of the tested cropping systems across the whole growing season at the study sites during the 2021/22 growing season.

	Cropping system¶						
Activity	CP-sole	CP-int	MT-sole	CA-rot	CA-int	CA-2-row	CA-4-row
Benefits (US$)							
Maize yield (kg ha^{-1})	191.5	220.6	230.5	141.9	216.7	241.9	247.0
Legume yield (kg ha^{-1})	0.0	68.3	0.0	41.5	70.0	90.9	82.3
Price maize (US$ kg^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Price Legume (US$ kg^{-1})	0.8	0.8	0.80	0.8	0.8	0.8	0.8
Gross benefits (US$ ha^{-1})	**502.2**	**1,276.1**	**604.5**	**842.4**	**1,276.7**	**1,528.0**	**1,451.6**
Labour cost (US$ ha^{-1})							
Land clearing and preparation	12.9	14.6	8.5	11.1	11.7	23.9	11.9
Planting	10.2	21.8	8.4	11.3	18.9	25.9	23.5
Fertilizer, herbicide, and pesticide application	11.5	10.5	11.0	7.6	10.7	13.2	11.5
Mulching, ratooning, and thinning	0.5	0.2	1.2	0.6	1.0	0.5	0.4
Weeding	33.3	29.7	25.5	28.2	30.5	32.2	34.0
Harvesting	25.2	33.6	20.4	20.9	35.5	36.2	34.8
Total labour cost (US$ ha^{-1})	**93.4**	**110.3**	**75.0**	**79.7**	**108.4**	**131.8**	**116.0**
Input cost (US$ ha^{-1})							
Maize seed	46.4	46.4	46.4	23.2	46.4	46.4	46.4
Legume seed	0.0	112.0	0.0	56.0	112.0	137.3	112.0
Fertilizer cost	298.7	303.8	298.7	217.9	303.8	303.8	303.8
Herbicide costs	6.1	5.3	18.4	14.3	17.4	15.3	15.3
Pesticide costs	8.7	13.9	10.8	6.6	13.9	16.2	16.2
Total input cost (US$ ha^{-1})	**360.0**	**481.4**	**374.3**	**318.0**	**493.5**	**519.0**	**493.7**

¶CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping.

Table 5. Farmers' biophysical and management ratings of the different cropping systems during the early-season, mid-season, and end-season evaluations at the study sites during the 2021/22 growing season.

	Season evaluations											
	Early-season				Mid-season				End-season			
System¶	Plant stand	Weed control	Crop growth	Crop colour	Crop growth	Crop colour	Crop uniformity	Weed control	Cob number	Cob size	Cob filling	Weed control
CP-sole	7.4 abc	7.7 a	7.4 a	7.4 a	7.7 a	7.7 a	7.5 a	7.4a	7.1 a	6.5 c	6.9 a	6.6 abc
CP-int	7.3 bc	7.2 a	7.3 a	7.7 a	7.7 a	7.8 a	7.4 a	7.2 a	7.3 a	7.0 abc	7.2 a	6.1 bc
MT-sole	7.2 c	7.3 a	7.0 a	7.5 a	7.7 a	7.8 a	7.2 a	7.5 a	6.9 a	7.0 abc	7.0 a	6.7 ab
CA-int	7.2 bc	7.1 a	7.0 a	7.3 a	7.8 a	7.8 a	7.5 a	7.3 a	7.6 a	7.0 abc	6.8 a	6.24 bc
CA-rot	7.5 abc	7.3 a	7.0 a	7.7 a	7.9 a	7.5 a	7.5 a	7.6 a	7.9 a	7.5 a	7.7 a	6.9 a
CA-2-row	7.7 ab	7.4 a	7.1 a	7.8 a	7.9 a	7.5 a	7.5 a	7.1 a	7.4 a	7.3 ab	7.2 a	6.2 bc
CA-4-row	7.9 a	7.4 a	7.3 a	7.6 a	7.9 a	7.7 a	7.4 a	7.1 a	7.0 a	6.6 bc	6.8 a	6.0 c
Mean	7.5	7.3	7.2	7.6	7.8	7.7	7.4	7.3	7.3	7.0	7.1	6.4
P-value	**0.05***	0.51	0.32	0.60	0.64	0.77	0.92	0.19	0.12	0.09	0.21	**0.03***
SE	0.3	0.4	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5
mR^2	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.02	0.03	0.02	0.01
cR^2	0.58	0.71	0.67	0.63	0.82	0.82	0.82	0.90	0.53	0.48	0.52	0.80

¶CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping. For the pseudo–R-squared, mR^2 represents the marginal R^2, which is variance explained by the fixed term (cropping system) only, while cR^2 represents the conditional R^2, which is variance explained by the fixed and the random terms (province, village, farmer). The residual variance (not explained by any of the terms) is obtained by subtracting the cR^2 from one. †Asterisks, and dots in indicate statistical significance between groups at the following significance levels: *P <0.05.

Table 6. Farmer overall choices during the early-season, mid-season, end-season, and across-evaluations, and overall farmer's choice across the whole season at the study sites during the 2021/22 growing season. Total number chosen is the sum of the number of times a cropping system was chosen during the early-season, mid-season, and end-season evaluations.

Cropping system¶	Early-season	Mid-season	End-season	Seasonal	Total number chosen‡
CP-sole	7.5 a	6.3 a	4.5 a	6.1 ab	18.3
CP-int	5.0 a	6.8 a	5.3 a	5.7 ab	17.0
MT-sole	3.8 a	3.5 a	6 a	4.4 b	13.3
CA-rot	8.8 a	7.8 a	9.5 a	8.7 a	26.0
CA-int	5.5 a	4.8 a	6.5 a	5.6 ab	16.8
CA-2-row	6.3 a	6 a	6.8 a	6.3 ab	19.0
CA-4-row	6.8 a	8.5 a	5.0 a	6.8 ab	20.3
P-value†	0.4	0.2	0.4	**<0.05***	-
SE	1.6	1.5	1.6	0.9	-
mR^2	0.18	0.23	0.19	0.14	
cR^2	0.19	0.25	0.20	0.20	

¶CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping. For the pseudo–R-squared, mR^2 represents the marginal R^2, which is variance explained by the fixed term (cropping system) only, while cR^2 represents the conditional R^2, which is variance explained by the fixed and the random term (province). The residual variance (not explained by any of the terms) is obtained by subtracting the cR^2 from one. †Asterisks, and dots in indicate statistical significance between groups at the following significance levels: *P <0.05.

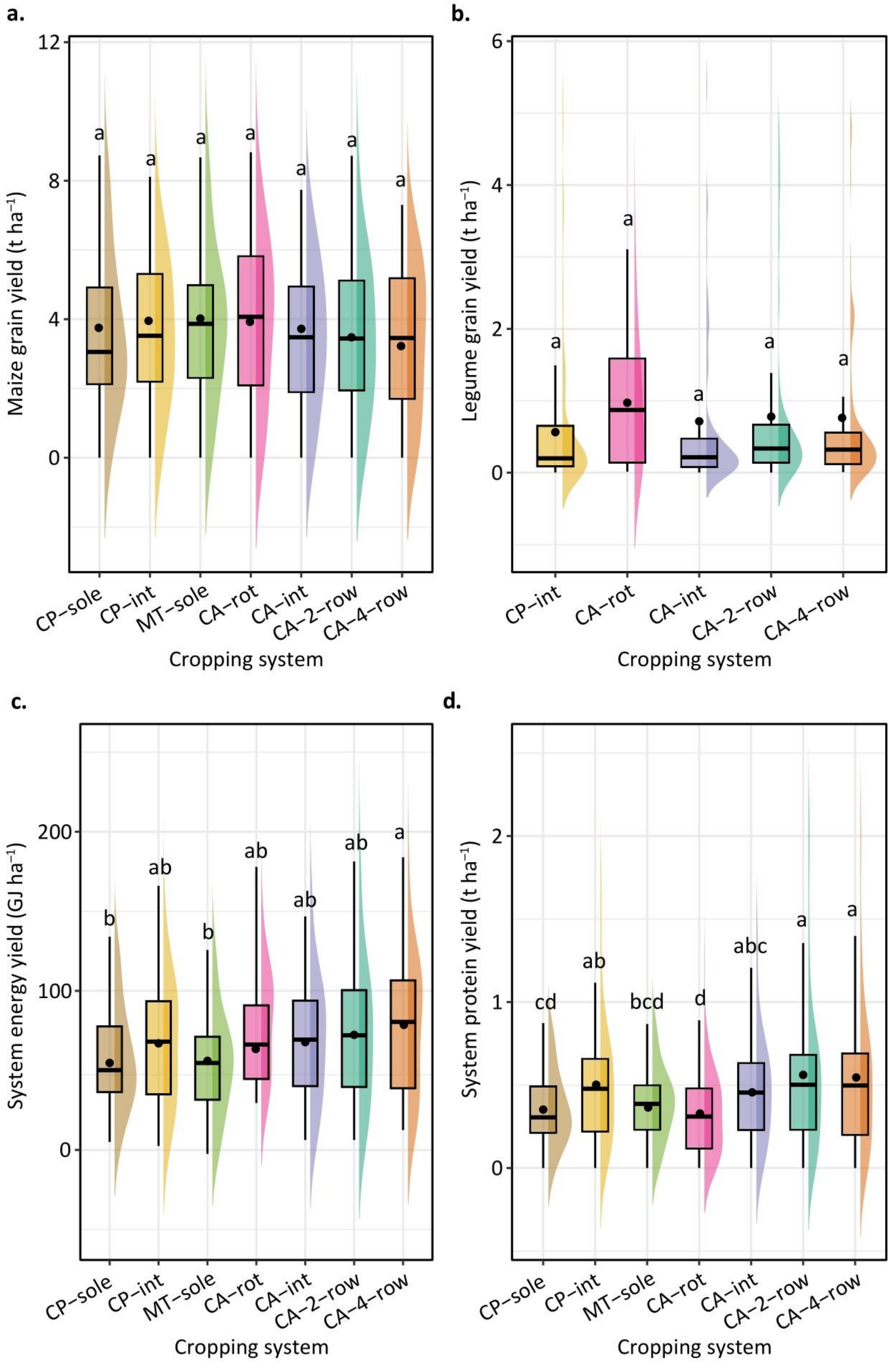

Fig. 1. Effect of the tested cropping systems on maize grain yield (a), legume grain yield (b), system energy yield (c), and system protein yield (d) during three consecutive growing seasons in the Eastern and Southern Provinces of Zambia. Different letters indicate statistically significant differences between groups at 5% significance level. The clouds beside each boxplot show data distribution. The dots within each boxplot represents the mean. Abbreviations: CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping.

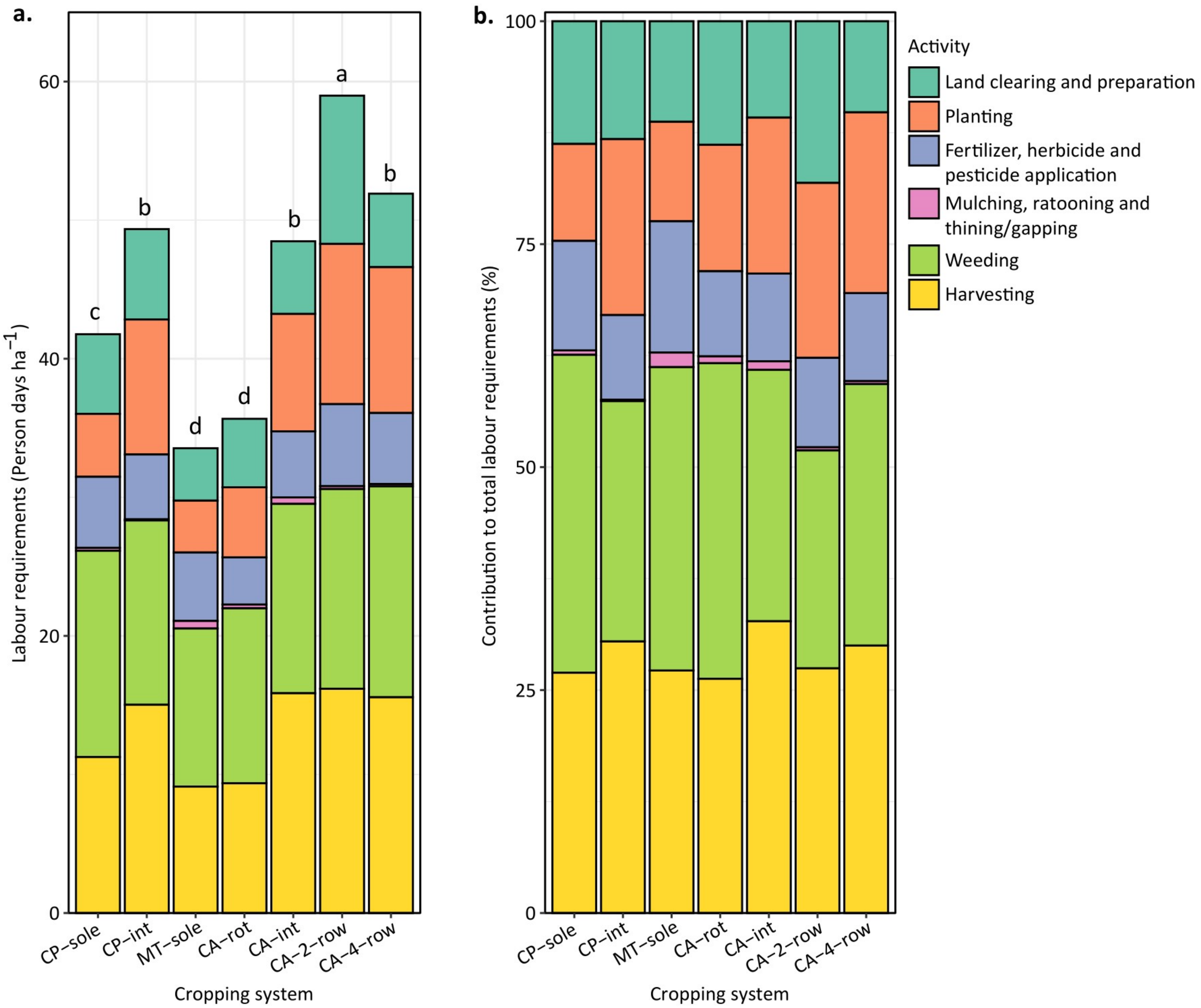

Fig. 2. Labour requirements per crop management operation across the tested cropping systems (a) and percentage contribution of each activity to the total labour requirements (b). Bars with different letters show significant differences in labour inputs between cropping systems at 5% significance level. Abbreviations: CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping.

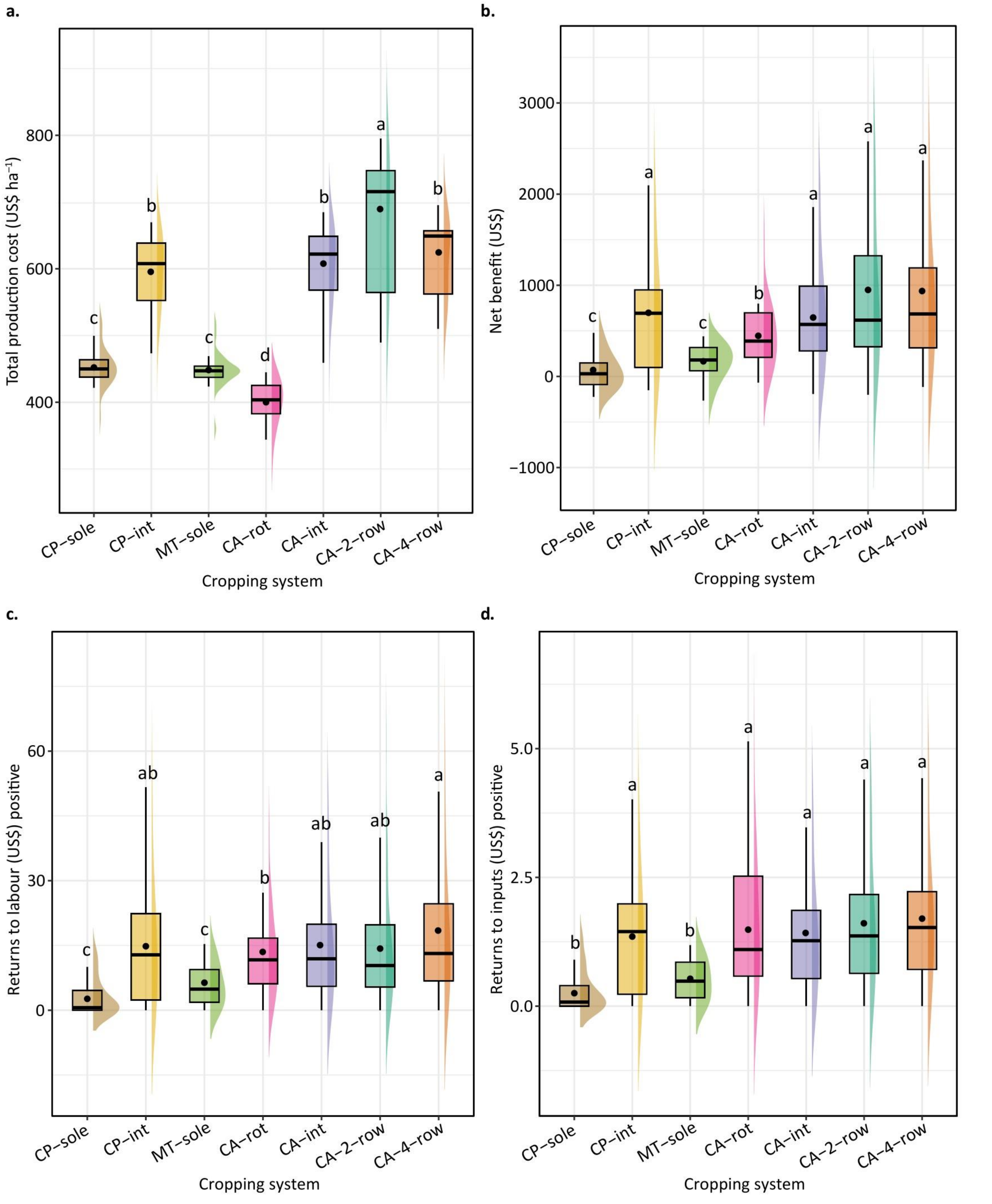

Fig. 3. Total production costs (a), net benefits (b), returns to labour (c), and returns to inputs (d) across the tested cropping systems during the three consecutive growing seasons in Southern and Eastern Zambia. Different letters indicate statistically significant differences between groups at 5% significance level. The clouds beside each boxplot show data distribution. The dots within each boxplot represents the mean. Abbreviations: CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping.

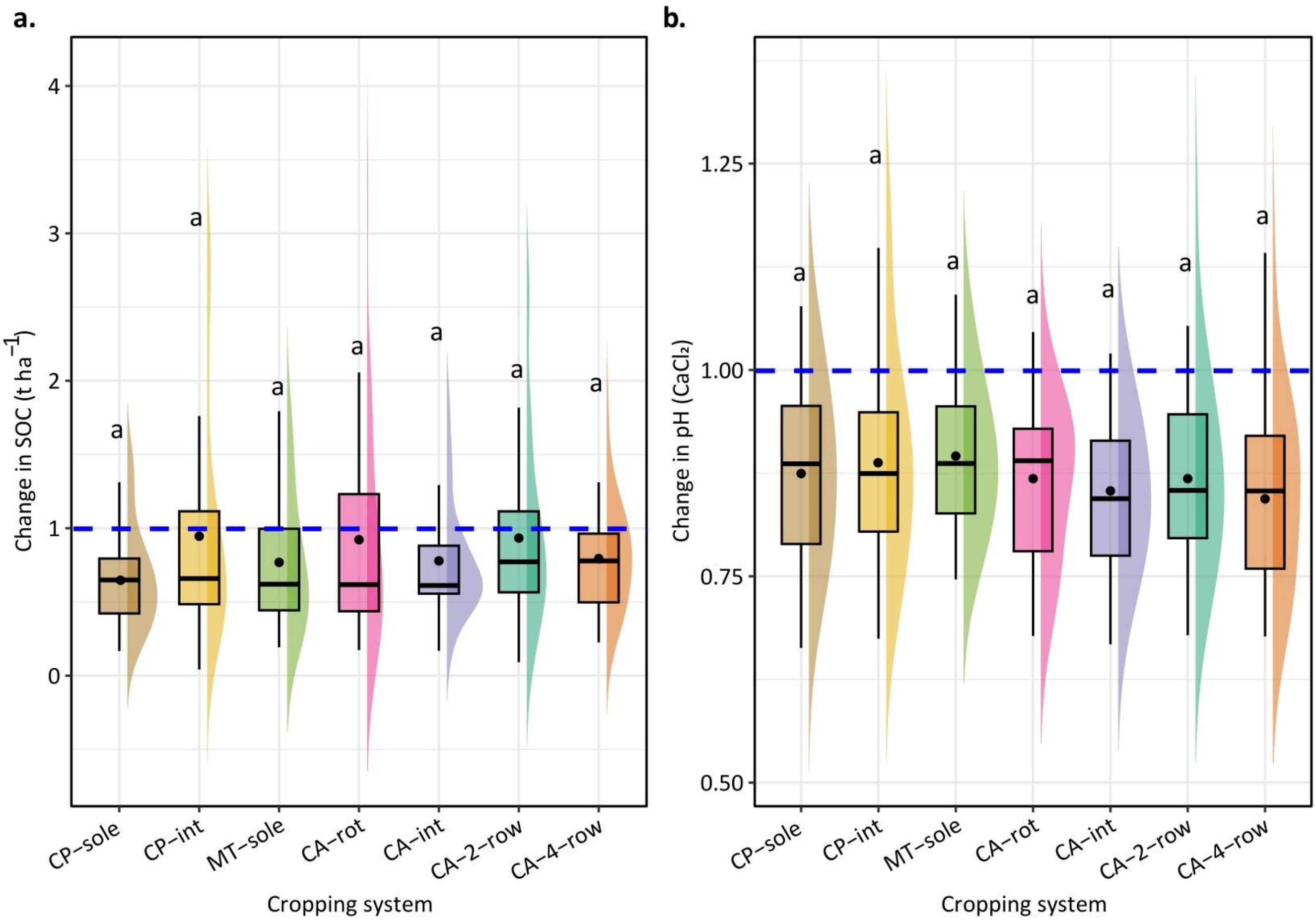

Fig. 4. Effect of the tested cropping systems on change in soil organic carbon (a) and change in soil pH (b) expressed as a ratio of samples measured in the 2019/20 growing season and samples measured during the 2022/23 growing season. Same letters indicate statistically non-significant differences between groups at 5% significance level. The clouds beside each boxplot show data distribution. The horizontal dashed blue line indicates a similar value for the soil property for both sampling moments. The dots within each boxplot represents the mean. Abbreviations: CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping.

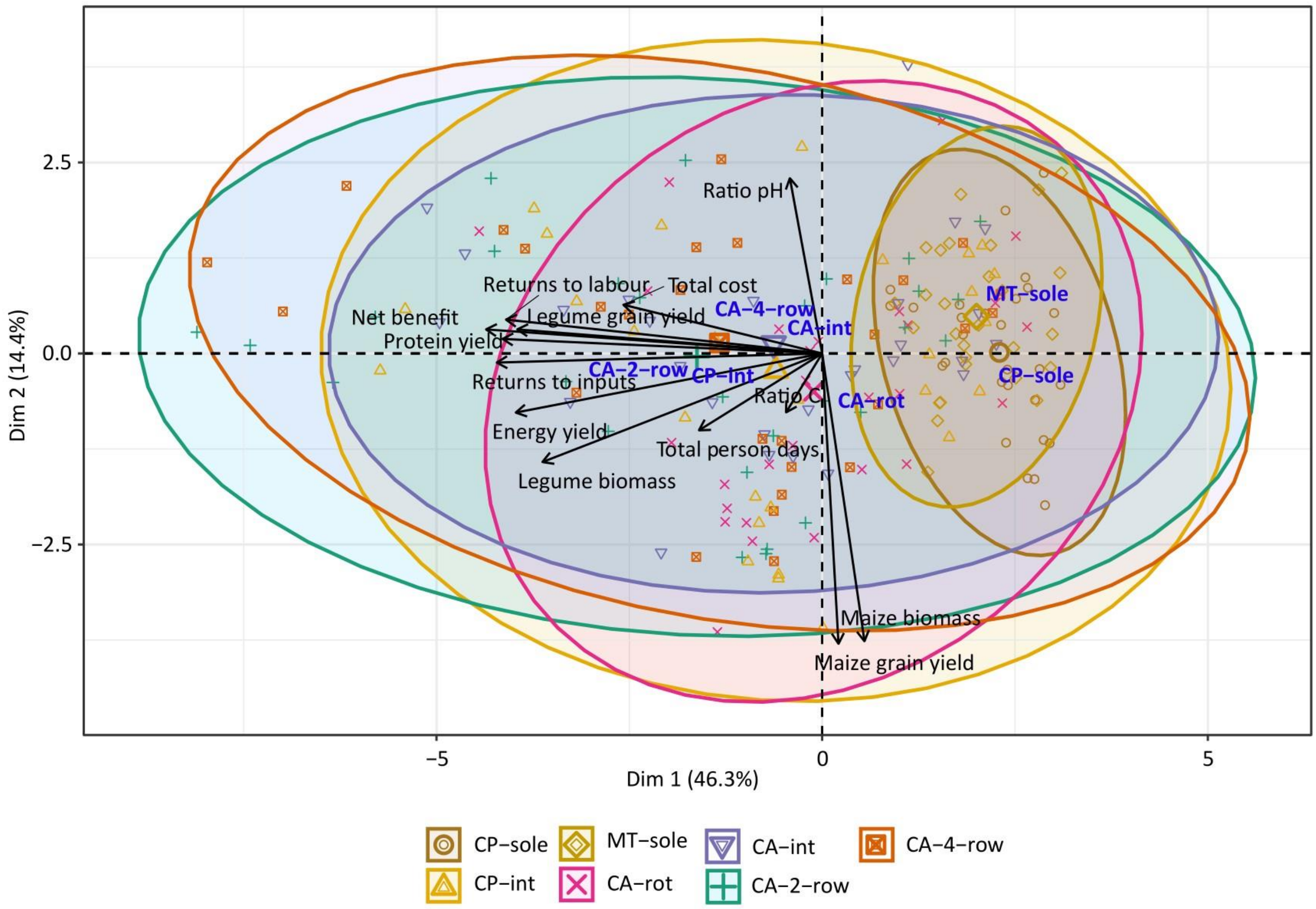

Fig. 5. Principal component analysis biplot of different performance indicators for all cropping systems, growing seasons, and villages (sites). The black arrows and labels indicate the correlation between each input variable and the first two principal components (PCs) of the PCA. The first PC represents a gradient in economic (returns and net benefits) and nutritional (energy and protein) outcomes, while the second PC reflects a gradient in maize productivity (biomass and yield) and change in pH. The small points indicate the scores of each treatment in each mother trial against the first two PCs. The blue labels and large points indicate the centroids, or mean locations, of each treatment in relation to PCs 1 and 2. 95% ellipses were generated for the distribution of each cropping system assuming a normal distribution of points. Abbreviations: CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping.

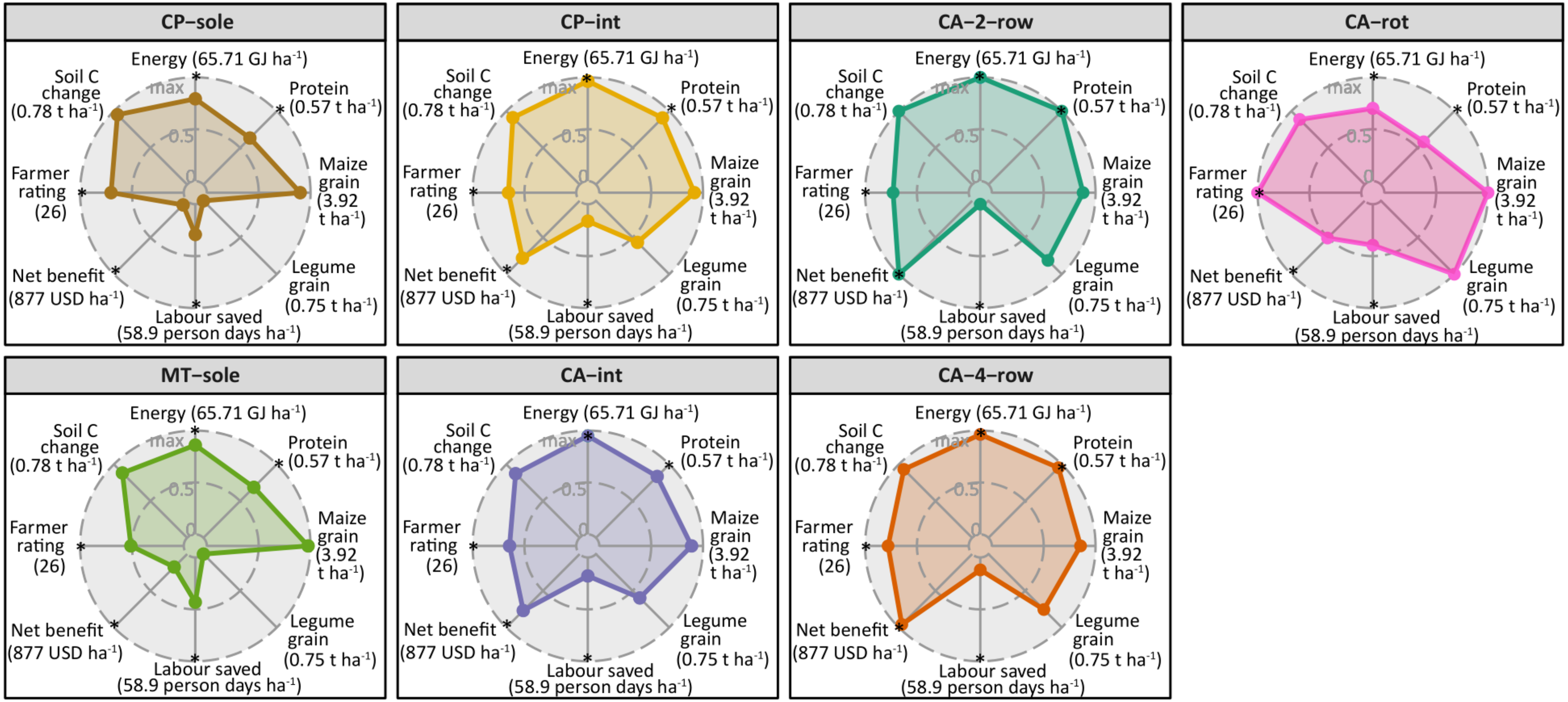

Fig. 6. Performance indicators within the tested cropping systems averaged across four growing seasons and four camps. Abbreviations: CP- sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping. The asterisks indicates that there was a significant difference between cropping systems for that indicator in prior mixed model analyses of that respective aspect.

Supplementary materials

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Table S1. Categories of the Likert scale used in the rating of biophysical crop characteristics by farmers. The Likert scale was according to the farmer evaluation protocol developed by the International Maize and Wheat Improvement Centre (CIMMYT) socioeconomics team

Category	Rating
Very bad	1–2
Bad	3–4
Good	5–6
Very good	7–8
Excellent	9–10

Table S2. Calculation of total system energy and protein yield for different treatments at each farmer field

Experimental treatments¶	System energy yield (GJ ha^{-1})†	System protein yield (kg ha^{-1})‡
CP–sole; MT–sole	$(MZ_{yield} \times Kcal_{maize} \times 10)/GJ_{Conv}$	$(MZ_{yield} \times \%Prot_{maize}$
CP–inter; CA–inter; CA–2-row; CA–4-row	$(MZ_{yield} \times Kcal_{maize} \times 10 + L_{intercrop} \times Kcal_{legume} \times 10) /GJ_{Conv}$	$(MZ_{yield} \times \%Prot_{maize} + L_{intercrop} \times \%Prot_{legume})$
CA–rot	$(½ \times MZ_{yield} \times Kcal_{maize} \times 10 + ½ \times L_{rotation} \times Kcal_{legume} \times 10) /GJ_{Conv}$	$(½ \times MZ_{yield} \times \%Prot_{maize} + ½ \times L_{rotation} \times \%Prot_{legume})$

¶The treatment abbreviations: CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; MT-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping. †MZ_{yield}, $L_{intercrop}$ and $L_{rotation}$ are yields of maize, intercrop legume and rotation legume, respectively while $Kcal_{maize}$ and $Kcal_{legume}$ are the kilocalories (kcal) 100 g^{-1} of maize and legumes seed, respectively. GJ_{Conv} is a conversion factor that converts kcal to gigajoules (GJ), where 1 GJ is 238845.897 kilocalories. ‡$Prot\%_{maize}$ and $Prot\%_{legume}$ are percentage protein content of the grain for maize and involved legume, respectively.

Table S3: Correlations between each variable included in the principal component analysis (PCA), and each principal component (PC). Correlation coefficients >0.33 or <-0.33 are in bold typeface to emphasise relatively strong relationships. The value in parentheses alongside each PC indicates the proportion of variance explained by that PC.

	PC1 (46.3)	PC2 (14.4)	PC3 (12.0)	PC4 (7.6)	PC5 (6.4)	PC6 (3.8)	PC7 (3.4)	PC8 (2.2)	PC9 (1.7)	PC10 (1.2)	PC11 (0.5)	PC12 (0.2)	PC13 (0.1)
Energy yield	**-0.35**	-0.12	0.17	-0.01	-0.02	0.34	-0.02	**0.51**	0.01	-0.22	0.60	0.01	0.19
Protein yield	**-0.37**	0.03	-0.05	0.06	0.02	0.28	-0.26	**0.46**	0.16	0.12	-0.63	-0.01	-0.26
Net Benefit	**-0.39**	0.05	0.06	-0.01	0.01	-0.25	-0.22	-0.15	-0.07	-0.09	-0.23	-0.37	0.71
Total Cost	-0.23	0.10	**-0.57**	0.17	0.04	0.13	-0.34	-0.27	0.23	**0.40**	**0.38**	-0.12	-0.09
Returns to labour	**-0.37**	0.07	0.22	0.00	-0.03	-0.28	-0.29	-0.21	0.04	-0.05	0.05	**0.77**	-0.04
Returns to inputs	**-0.38**	-0.02	0.19	-0.06	0.03	-0.30	-0.04	-0.16	-0.18	-0.27	0.14	-0.45	**-0.61**
Labour requirement	-0.14	-0.16	**-0.66**	-0.01	0.30	-0.05	0.16	0.07	**-0.45**	-0.38	-0.10	0.22	0.02
Change in pH	-0.04	**0.37**	0.16	**-0.47**	0.73	0.25	0.04	-0.13	0.03	0.08	0.02	0.00	0.01
Change in C	-0.04	-0.12	-0.21	**-0.84**	**-0.46**	0.05	-0.08	-0.03	0.02	0.03	-0.01	0.01	-0.01
Maize grain yield	0.02	**-0.61**	0.22	0.06	0.07	**0.51**	-0.25	-0.42	-0.26	0.01	-0.09	0.00	-0.01
Maize biomass	0.05	**-0.60**	0.02	-0.14	**0.38**	**-0.47**	-0.05	0.28	0.18	**0.36**	0.06	-0.02	0.01
Legume grain yield	**-0.35**	0.05	0.10	0.03	-0.13	0.03	**0.49**	0.00	**-0.47**	**0.62**	0.00	0.05	0.02
Legume biomass	-0.32	-0.23	-0.06	0.02	0.01	0.10	**0.59**	-0.28	0.60	-0.17	-0.10	0.03	0.02

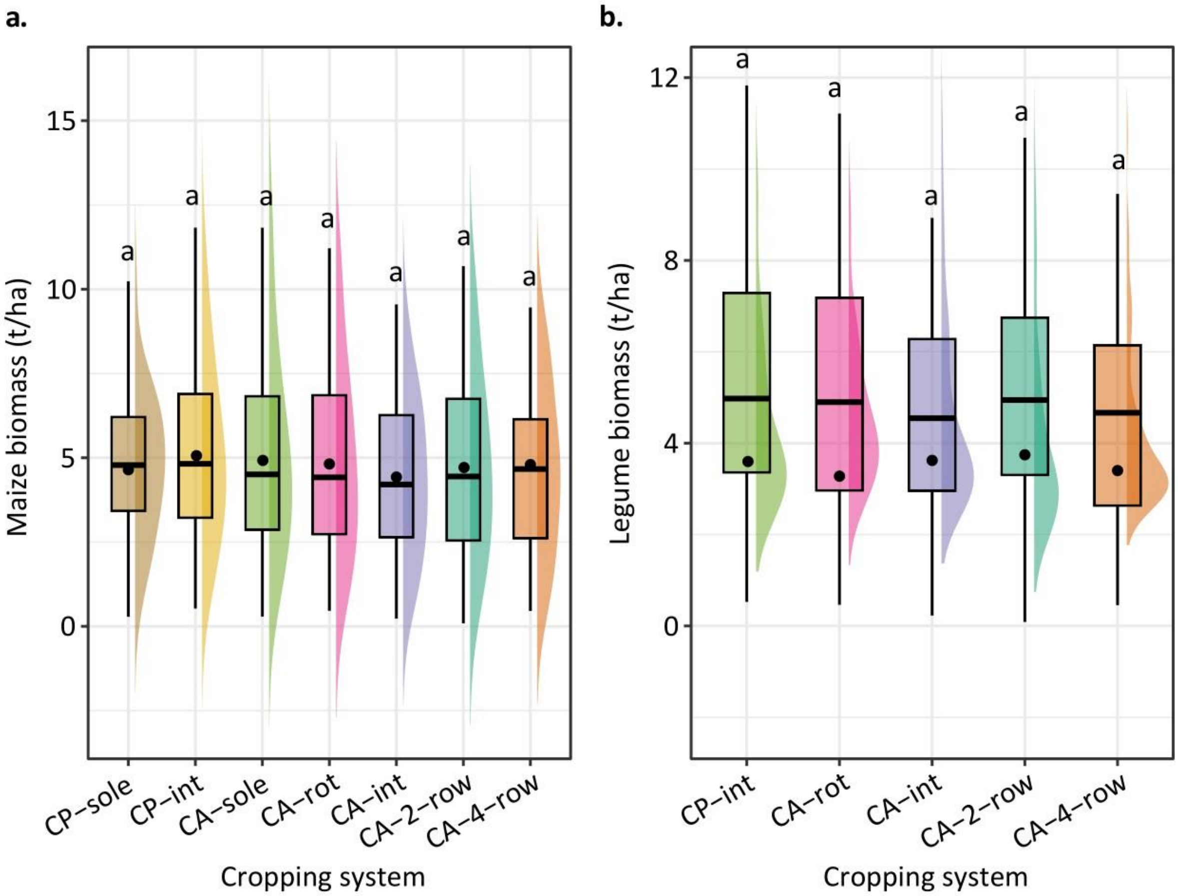

Figure S1. The effects of different cropping systems on (a) maize biomass and (b) legume grain yield during the four years of the study across Simaubi, Dumba, Nyanje 1, and Chinjala. Boxplots with different letters above them show systems significantly different from each other at 0.05 probability level. The clouds beside each boxplot show data distribution. The dots within each boxplot represents the mean. The treatment abbreviations: CP-sole = conventional ploughing with sole maize; CP-int = conventional ploughing with standard intercrop; CA-sole = ripping with sole maize; CA-rot = conservation agriculture with maize/legume rotation; CA-int = conservation agriculture with standard intercrop; CA–2-row = conservation agriculture with 2-row strip cropping; and CA–4-row = conservation agriculture with 4-row strip cropping.

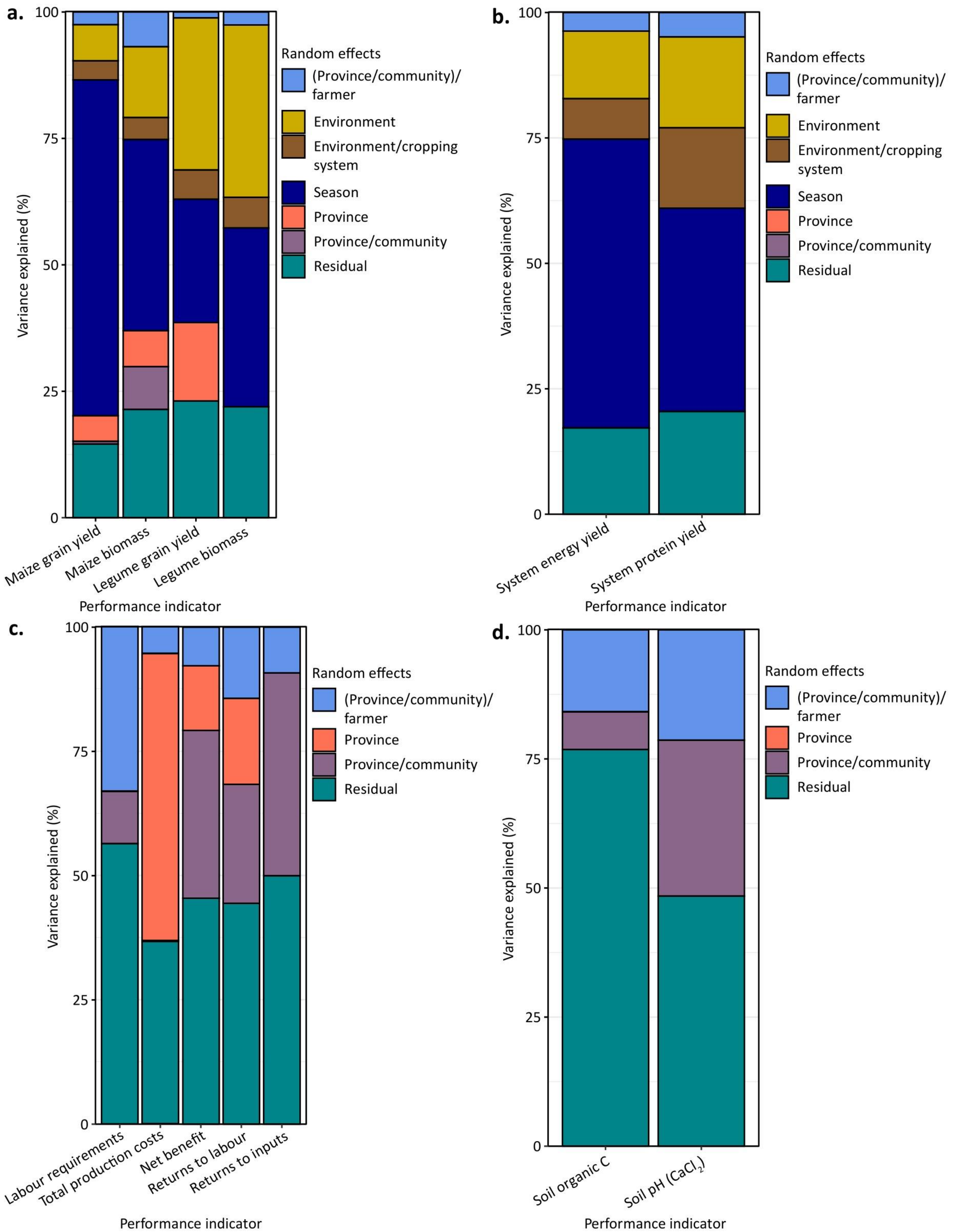

Figure. S2. Percentage of variation in productivity (a), human (b), economic (c), and environmental (d) indicators explained by location, cropping system, and year-specific differences accounted for by random effects in the models.

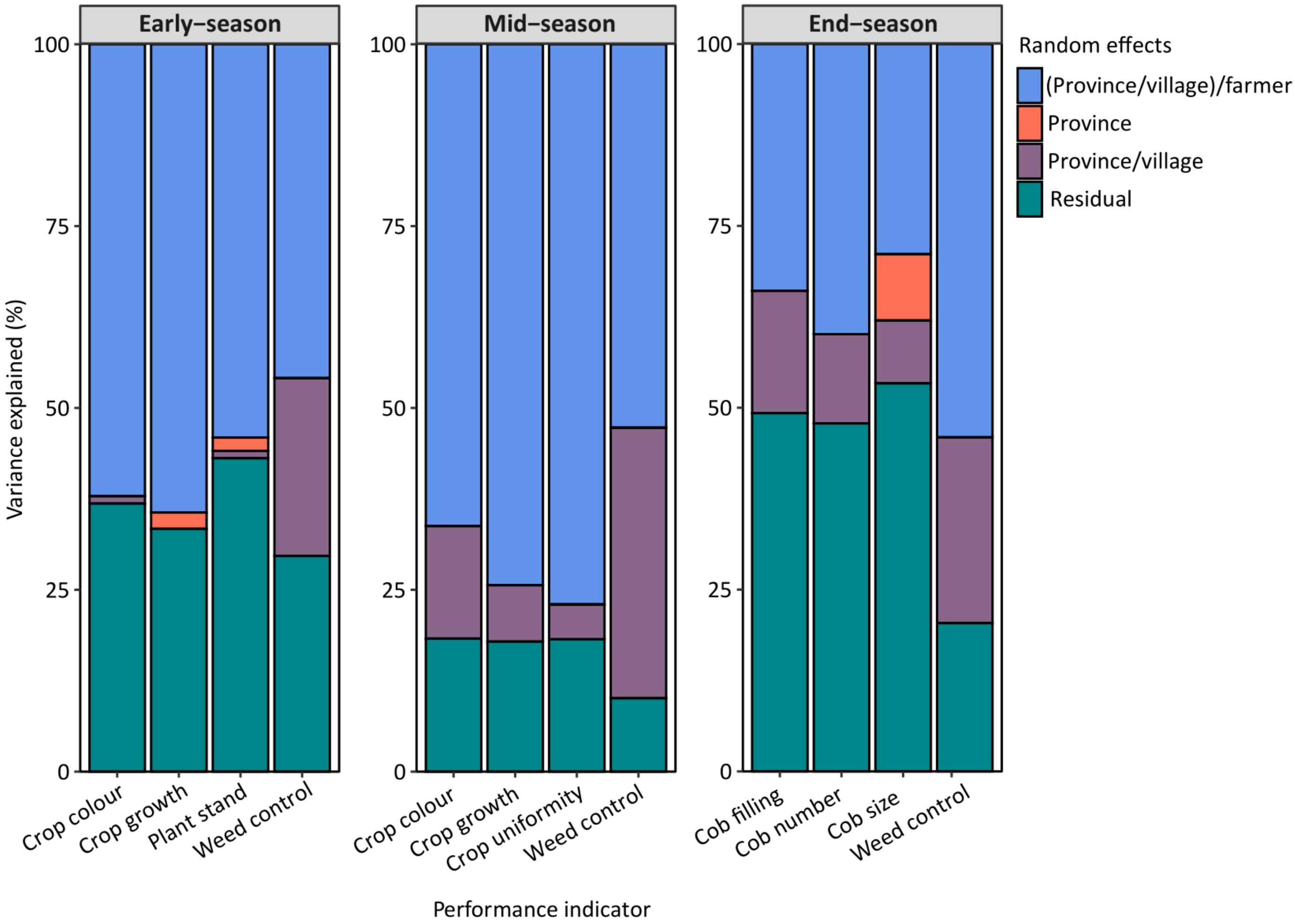

Figure. S3. Percentage of variation in ratings by farmers on different biophysical and management aspects (social indicator ratings) explained by location- and year-specific differences accounted by random effects during the early-season, mid-season, and end-season evaluations.

Declaration of Interest statement

All authors confirm no conflict of interest whatsoever in conducting this study.