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Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa?

Esther N. Masvaya[a,b,*], Justice Nyamangara[c], Katrien Descheemaeker[b], Ken E. Giller[b]

[a] International Crops Research Institute for the Semi-Arid Tropics, Matopos Research Station, P. O. Box 776, Bulawayo, Zimbabwe
[b] Plant Production Systems, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, The Netherlands
[c] Department of Environmental Science and Technology, Chinhoyi University of Technology, P. Bag 7724, Chinhoyi, Zimbabwe

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ABSTRACT

Intercropping cereals with legumes can potentially enhance productivity and soil fertility. There is limited experimental evidence on the mechanisms underlying benefits or risks in intercropping systems and below-ground interactions in intercrops remain largely unstudied. Such understanding can inform strategies towards maximising returns to investments, particularly in poor fertility soils on smallholder farms in semi-arid areas of sub-Saharan Africa. Additive intercropping experiments were established covering several seasons (2010/11–2014/15) and different conditions (on-station and on-farm) to determine effects on soil chemical variables, root dynamics and yield of intercrops. Maize was planted with the first effective rains and received either no fertiliser or 40 kg N ha^{-1}. Cowpea was planted on the same date as maize or three weeks after planting maize in intercrops or sole stands and received no fertiliser. End-of-season available N was highest ($P < 0.05$) under the late planted intercrop with 40 kg N ha^{-1} treatment in 2013/14. Addition of 40 kg N ha^{-1} significantly increased maize grain yield by 500–1100 kg ha^{-1} in the 2013/14 season. There was generally greater productivity and over-yielding in the intercrops compared with the sole crops; most intercrops had a land equivalent ratio > 1. Intercropping, however, resulted in compromised cowpea yields especially under the relay intercrop compared with the sole cowpea stands whilst maize yield was either not affected or improved. We attributed this to the lack of below-ground niche differentiation in root distribution between maize and cowpea. Maize–cowpea intercropping with low doses of N fertiliser resulted in over-yielding compared with monocropping. Intercropping proved to be a robust option across seasons and soil types, confirming that it is a promising option for resource-poor smallholders.

1. Introduction

Agricultural production in sub-Saharan Africa (SSA) is under increasing pressure to meet food and nutrition security needs of the growing population whilst contending with the challenges of climate change and variability, degraded and infertile soils (Hobbs, 2007; Ngwira et al., 2012). Smallholder farmers in SSA often grow cereal crops such as maize (*Zea mays* L.) in continuous monoculture for food security even when there is limited profitability (Baudron et al., 2012a). Raising agricultural production requires a shift towards more sustainable cropping systems to help reverse soil degradation, reduce labour investments and improve production.

Cultivation of legumes in smallholder farming systems either as components of rotations or intercrops has the potential to increase nitrogen (N) availability in the soil through biological N_2-fixation (BNF) (Giller, 2001). The inclusion of grain legumes in crop production is also beneficial for diversified diets and income generation (Ngwira et al., 2012; Rusinamhodzi et al., 2012). However, relatively small areas are allocated to legume production, restricting crop rotation (Mapfumo and Giller, 2001; Nhemachena et al., 2003) resulting in small benefits from the legumes (Ncube, 2007). Intercropping cereals with legumes is one practice that has potential to enhance productivity and soil fertility simultaneously (Jeranyama et al., 2000; Rusinamhodzi et al., 2012).

Intercropping systems involve growing two or more crop species or genotypes together and coexisting for a time (Brooker et al., 2014). Intercropping can increase aggregate yields per unit input, insure against crop failure particularly in dry regions and enhance the efficiency of land-use by complete and complementary utilisation of nutrients, water and solar radiation (Li et al., 2014). Intercropping helps to pre-empt resources being used by weeds and can suppress weed growth (Brooker et al., 2014). Cereal-legume intercrops result in increased N availability for the cereal because competition for soil N

* Corresponding author at: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT - Zimbabwe), P. O. Box 776, Bulawayo, Zimbabwe.
E-mail addresses: e.masvaya@cgiar.org, enmasvaya@gmail.com (E.N. Masvaya).

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from legumes is weak, and the non-legumes obtain additional N from biological N fixation by the legumes (Giller, 2001; Rusinamhodzi et al., 2006; Brooker et al., 2014).

Although intercropping may be beneficial, challenges may arise from strong interspecific competition for resources such as nutrients, water and light between the crops in time and space (Li et al., 2014). Ideal intercrops have complementary resource use and niche differentiation in space and time in order to optimise resource-use efficiency and crop yield simultaneously (Li et al., 2014). Studies in SSA on maize–cowpea intercrops resulted in poor cowpea yields attributed to shading by the maize especially when cowpea was planted at the same time as the maize (Jeranyama et al., 2000). When rainfall is plentiful shading out of the maize by the companion cowpea may occur (Shumba et al., 1990). The competition between crops can be managed by rearranging plant populations through substitutive or additive designs to maintain productivity of the main crop (Vandermeer, 1992). Competition between crops can also be managed by staggering the planting dates of the companion crops in relay intercropping. Relay intercrops are likely to increase labour demands (Rusinamhodzi et al., 2012; Brooker et al., 2014) but may provide the first crop with a higher chance for successful establishment and reduce the risk of total crop failure when rainfall is erratic within the season. However, there is limited experimental evidence on the mechanisms that lead to benefits or risks in intercropping systems (Li et al., 2014). In particular, the below-ground processes in intercropping systems remain largely unstudied in semi-arid areas in SSA although some work has been done in arid China (Mao et al., 2012). It is important to understand intercropping systems better to determine strategies that give the best returns to investments in poor fertility soils on smallholder farms in semi-arid areas in SSA.

In this study, we hypothesised that in risky rainfall environments and on different soil types (i) maize-cowpea intercropping results in over-yielding and therefore robust crop production; (ii) over-yielding in intercropping systems results from below-ground root distribution complementarity and (iii) relay intercropping results in temporal niche differentiation leading to improved land use efficiency compared with monocropping. The specific objectives of our study were: to determine the effects of intercropping on yields across seasons and in different contexts (on-station and on-farm under two management types − researcher and farmer managed), to assess the effect of intercropping on selected chemical soil variables and to understand the root dynamics of intercrop systems that contribute to observed effects on crop yield. Our study sites in semi-arid Zimbabwe are representative of larger areas in southern Africa that are characterised by poor soil fertility, low and unreliable rainfall and smallholder farming systems with many socio-economic constraints.

2. Materials and methods

2.1. Study area

The study was conducted in Matobo district, Matabeleland South Province located in south western Zimbabwe (Fig. 1). The region is characterised by semi-arid climatic conditions and lies in agro-ecological region IV, which receives 450–650 mm per annum rainfall in a single season between October and April. The region is subject to frequent seasonal droughts and extended dry spells during the rainy season and the probability of receiving annual rainfall above 500 mm is only 45–65% (Vincent and Thomas, 1961). The district has an annual mean temperature of 18.4 °C (Musiyiwa et al., 2015). Agro-ecological region IV is dominated by a semi-extensive farming system where crop production is strongly integrated with livestock production with the latter kept supporting crop production through the provision of draught power and manure, serve as a capital asset and diversify household income. Most smallholder farmers in semi-arid areas in Zimbabwe prefer to grow maize over sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* L.). Maize accounts for more than half of the total cropped area (Twomlow et al., 2006). Minor crops include cowpea (*Vigna unguiculata* (L) Walp.), groundnut (*Arachis hypogaea* L.) and Bambara nut (*Vigna subterranea* (L.) Verdc.) (Ncube et al., 2009). The dominant soils are sandy soils (Eutric Arenosols) derived from granite with pockets of clay soils (Chromic-Leptic Cambisols). In the smallholder areas of Zimbabwe, the arable fields are individually owned following allocation by the headmen. The fields are communally grazed during the dry season with the exception of securely fenced fields.

2.2. Research trials

Additive maize-cowpea intercrop trials were conducted both on-station at Matopos Research Station's Westacre Creek farm (2010/11–2012/13) and on-farm in Nqindi ward (2012/13–2014/15), both in Matobo district. On-farm, two sets of trials were set up, one farmer managed and the other researcher managed for two and three seasons respectively. The on-station trial was conducted on a clay soil (Chromic-Leptic Cambisols) while the on-farm trial was established on sandy soil (Eutric Arenosols) (IUSS Working Group, 2014). Both soil types are moderately deep to deep and well-drained. The on-station trial was researcher managed.

2.2.1. On-station researcher managed trial

An additive maize-cowpea trial was set up on-station for three seasons from 2010/11–2012/13. Maize was planted in planting basins and cowpea planted in furrows between the maize rows. Fertiliser was applied to all maize plots in this trial at 40 kg N ha^{-1} Details of plant spacing and fertiliser application are given in Section 2.2.4. The trial was set up as a randomised complete block design with four replicates. The treatments were: (a) sole maize; (b) maize – cowpea intercrop with cowpea planted the same date as maize; (c) maize – cowpea intercrop with cowpea planted 3 weeks after planting (3WAP) maize; (d) sole cowpea planted on the same date as maize and (e) sole cowpea planted 3 WAP maize. Each plot measured 10 m × 8 m and yield determinations were made from net plots of size 4.5 m × 5 m. Rainfall events were recorded daily and measured with a rainfall gauge in the experimental field.

2.2.2. On-farm researcher managed trial

An additive maize-cowpea intercrop trial (mother-trial) was established on a farmer's field in 2012/13 and ran for three seasons up to 2014/15. Plots measured 7.2 m × 6 m with each block measuring 7.2 m × 53 m with 1 m pathways between plots. Rip lines were made using an animal-drawn ripper at 0.9 m row spacing for the sole maize and 0.45 m for the intercrop and sole cowpea treatments. The fertiliser treatments 0 and 40 kg N ha^{-1} (0N and 40N) were used to simulate typical conditions in semi-arid areas of Zimbabwe where farmers do not apply fertilisers and small doses of N fertiliser through "microdosing" are promoted (Mupangwa et al., 2012; Nyamangara et al., 2014). The trial was set up as a randomised complete block design with three replicates. Treatments were: (a) sole cowpea planted on the same date as maize; (b) sole cowpea 3WAP; (c) sole maize (0 kg N ha^{-1}); (d) sole maize (40 kg N ha^{-1}); (e) maize-cowpea intercrop (0 kg N ha^{-1}) with cowpea planted on the same date as maize; (f) maize-cowpea 3WAP intercrop (0 kg N ha^{-1}); (g) maize-cowpea intercrop (40 kg N ha^{-1}) with cowpea planted on the same date as maize and (h) maize-cowpea

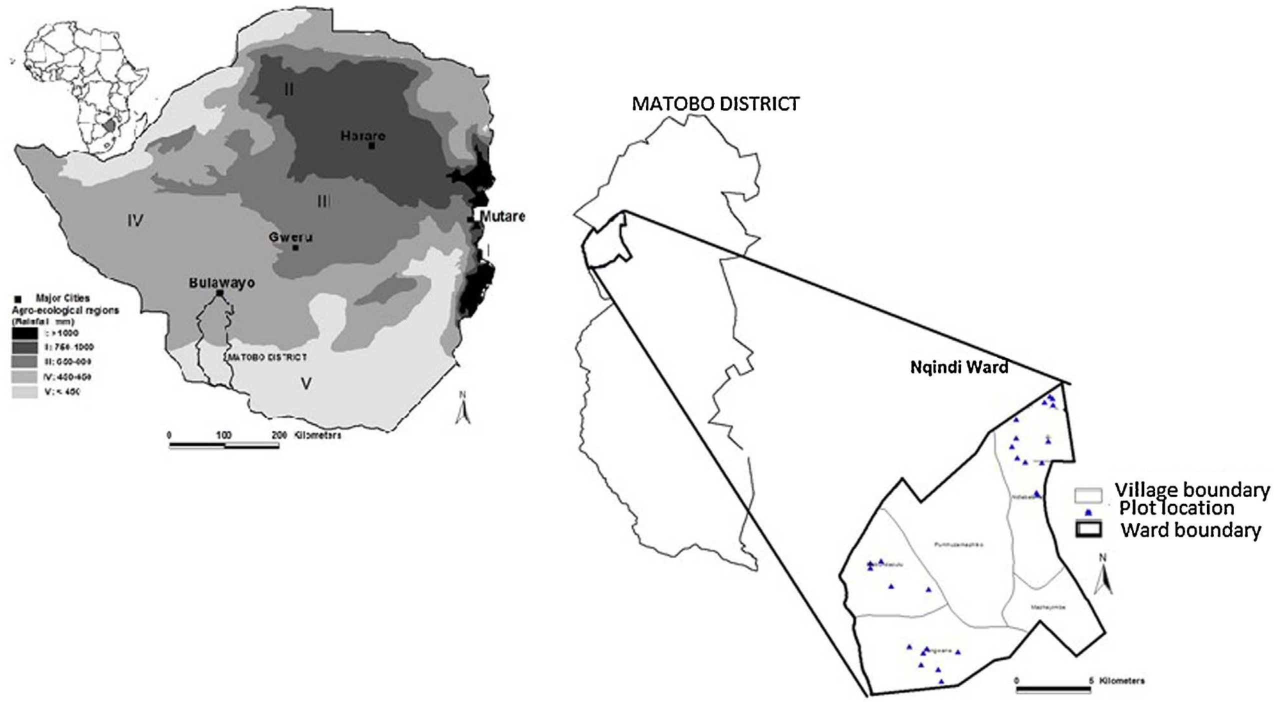

Fig. 1. Location of on-farm trials in Nqindi ward, Matobo District, Zimbabwe.

3WAP intercrop (40 kg N ha^{-1}). Yield was determined from net plots measuring 3.6 m × 4 m.

2.2.3. Farmer managed trials

A farmer research group comprising 24 farmers from two villages from Nqindi ward (Bazha and Fumugwe) was established in the 2013/14 season for participatory testing of intercropping for two seasons (Fig. 1). The villages were representative of the villages in the ward which have small to medium distances to the main tarred road which leads to the nearest city, Bulawayo or growth point (Maphisa). The research group farmers were selected with the assistance of the local extension agent, based on similar soil texture (sandy soils), the availability of draught power (for land preparation) and reliable labour for trial management. On each farm, five adjacent plots measuring 20 m × 10 m each were established and the same treatments applied as used in the researcher-managed on-farm trials. In each of the two villages, each farmer chose between the two cowpea planting dates such that in total, 12 farmers hosted the same date intercrop trial and the other 12, the 3WAP trial. A single replicate was planted on each farm and treatments were maintained on the same field for two seasons from 2013/14–2014/15. The treatments were as follows: (a) sole maize (0 kg N ha^{-1}); (b) sole maize (40 kg N ha^{-1}); (c) additive maize-cowpea intercrop (0 kg N ha^{-1}) with either cowpea planted on the same date as maize or 3WAP; (d) additive maize-cowpea intercrop (40 kg N ha^{-1}) with either cowpea planted on the same date as maize or 3WAP; (e) sole cowpea either planted on the same date as maize or 3WAP. Crop yields were determined from net plots measuring 9 m × 6 m. Farmers measured daily rainfall using provided rain gauges and kept record books of the dates and operations carried out in the trial plots.

2.2.4. General trial management

In the 40 kg N ha^{-1} treatment, a basal application of compound D fertiliser (14 kg N ha^{-1}, 12 kg P ha^{-1} and 12 kg K ha^{-1}) was applied in hand-hoe made planting basins (on-station) or planting furrows made by an animal drawn ripper (on-farm). The remainder of the N requirement for the 40 kg N ha^{-1} treatment was applied as a top dressing of 75 kg ammonium nitrate (AN, 34.5% N) ha^{-1} at the 5–6 leaf stage and or when there was enough soil moisture. The 0 kg N ha^{-1} treatment received a basal application of single super phosphate (12 kg P ha^{-1}) and muriate of potash (12 kg K ha^{-1}) fertilisers. The basins or rip lines were planted to a short duration maize variety SC403. In the basins, maize was planted at a spacing of 0.9 m × 0.6 m with two plants per station whilst under the ripper tillage, maize was planted at 0.9 m × 0.3 m with one plant per station.

Cowpea was planted in hand-hoe or ripper tine furrows made between the maize rows. Cowpea in sole stands was planted at 0.45 m × 0.30 m whilst in the intercrop it was planted at 0.9 m × 0.15 m. No fertiliser was applied to the cowpea in any of the experiments. The cowpea variety CBC 2 used is an erect, short duration variety, which takes 85 days to reach maturity. The variety has narrow leaves and is not very susceptible to aphid (*Aphis craccivora*) attack because of the relatively smaller leaf area. The target population for maize was 37,000 plants ha^{-1} whilst that of cowpea was 74,000 plants ha^{-1}. The plots were kept weed free by an initial application of glyphosate [*N*-(phosphono-methyl) glycine herbicide soon after planting and subsequent hand hoe weeding. Pests and diseases were controlled as needed. Maize stalk borer (*Busseola fusca*) was controlled using thionex (Endosulfan) and aphids were controlled using dimethoate (2-dimethoxyphosphinothioylsulfanyl-N-methylacetamide). Fungal rust (*Uromyces appendiculatus*) in cowpea was controlled by spraying copper oxychloride (85% WP).

2.3. Soil and plant sampling

Soil samples in Nqindi from the researcher managed and farmer managed trials were collected up to 1 m depth (depth intervals of 0.1 m) at the time of trial establishment. Fresh samples were split into two, with one subsample used to determine available N and the other sample air-dried, ground and passed through a 2-mm sieve. The fresh

Table 1
Selected soil chemical and physical properties (a) on-station at Westacre Creek, Matopos Research Station* and (b) on-farm in Nqindi ward, Matobo district.

(a) On-station

Depth (cm)	pH (0.01 M $CaCl_2$)	Available N ($kg\ ha^{-1}$)	Olsen P ($mg\ kg^{-1}$)	Organic C ($g\ kg^{-1}$)	Particle size analysis		
					% Sand	% Silt	% Clay
0–6	7.5	15.8	5.1	4.6	38	20	41
6–16	7.6	3.1	8.5	8.0	39	23	38
16–40	7.7	ND	4.5	3.7	36	17	47
40–60	7.8	ND	3.4	4.8	31	17	52

(b) On-farm

Depth (cm)	Bulk density ($kg\ m^{-3}$)	pH (0.01 M $CaCl_2$)	Available N ($kg\ ha^{-1}$)	Olsen P ($mg\ kg^{-1}$)	Organic C ($g\ kg^{-1}$)	Particle size analysis		
						% Sand	% Silt	% Clay
0–10	1430	5.4	7.7	18.1	2.6	90	8	2
10–20	1424	4.5	6.4	5.5	2.5	82	8	10
20–30	1421	4.6	6.5	2.6	2.3	84	6	10
30–40	1552	4.3	6.7	1.3	1.7	80	6	14
40–50	1558	4.4	6.8	1.0	2.0	80	8	12
50–60	1614	4.7	7.6	ND	1.4	76	8	16
60–70	1422	4.5	6.4	ND	2.1	80	0	20
70–80	1612	4.6	7.4	ND	1.6	80	0	20
80–90	1666	4.6	7.6	ND	1.1	90	2	8
90–100	1673	4.7	7.8	ND	2.1	88	8	4

*Adapted from Mupangwa et al. (2013).

soil samples for available N determination were refrigerated immediately after collection from the field and stored for a maximum of four days before N extraction. The dry soil samples were analysed for pH, texture, total N, total and available P and organic C using standard methods (Anderson and Ingram, 1993; Okalebo et al., 2002). Soil pH was determined in 1:5 soil suspension using 0.01 M $CaCl_2$. Soil texture was determined using the hydrometer method. Soil organic C was determined using dichromate oxidation (with external heat applied) method (the modified Walkley-Black method). Total N and P were determined colorimetrically after Kjeldahl digestion (H_2O_2/HCl) of the soil and available P after extraction with $NaHCO_3$ (pH 8.5). N was extracted from the refrigerated fresh soil samples by shaking the fresh sample in 0.5 M K_2SO_4, within four days of sampling, and the NH_4^+-N and NO_3^--N content was determined colorimetrically (Anderson and Ingram, 1993). Bulk density, calculated as mass of oven dry soil core divided by volume, was determined (Table 1) using undisturbed cores of 5 cm internal diameter and height. In subsequent seasons, soil samples for complete chemical analyses were collected at the end of the season, within two weeks of harvesting, in the on-farm researcher managed trial. Ten sub-samples were collected randomly from each plot from 0 to 30 cm depth and mixed to produce a composite sample for analysis. The soil properties from the on-station site at Westacre Creek farm are reported by Mupangwa et al. (2013) and are presented in Table 1. No additional soil analysis was done at this site.

At the maize silking and cowpea flowering stages, the spatial root distribution was studied in the researcher managed trial in Nqindi by destructive sampling with soil monoliths excavated from each plot at 0.2 m depth intervals up to 1 m in the 2012/13 season. The five monoliths were excavated from the space between the plants, from the middle of the inter- and intra-row spaces with each monolith measuring 0.45 m × 0.15 m × 0.2 m up to 1 m depth in each plot. In the 2013/14 season, to reduce soil disturbance, soil cores were excavated from 0.2 m depth intervals up to 1 m using a soil corer 8 cm in diameter (Böhm, 1979). In each plot, six cores per sampling depth were collected. The maize silking and cowpea flowering dates were chosen to capture the moment when roots would be fully extended in the profile. Root distribution studies for cowpea were only taken for the first cowpea planting date because the late planted cowpea established poorly in both seasons. The soil samples were soaked in water for at least an hour and then samples were stirred vigorously and poured through a 2-mm sieve. The sieves were suspended in a large water bucket and shaken continuously by hand until the roots were washed free of soil. The roots of the maize and cowpea were distinguished by their different colours and texture. The maize roots were white with a smooth surface whilst the cowpea roots were brownish. The modified Newman-line intercept method was used to determine the root length from the soil monolith and soil core samples by counting the number of intersections of roots with a 1-cm mesh grid (Tennant, 1975).

At harvest maize grain and stover yields were determined from net plots and grain and stover samples were subsampled for moisture correction. Stover samples were oven dried at 65 °C for two days then reweighed to determine stover dry weight. Grain moisture was determined using a grain moisture meter and yields were adjusted to 12% moisture content. Land equivalent ratios (LER) were calculated to evaluate the advantage of the intercropping to production as follows:

$$LER = \sum \left(\frac{Yi_i}{Ym_i} \right)$$

Where Yi_i is the yield of each crop in the intercrop and Ym_i the yield of each crop in the sole crop.

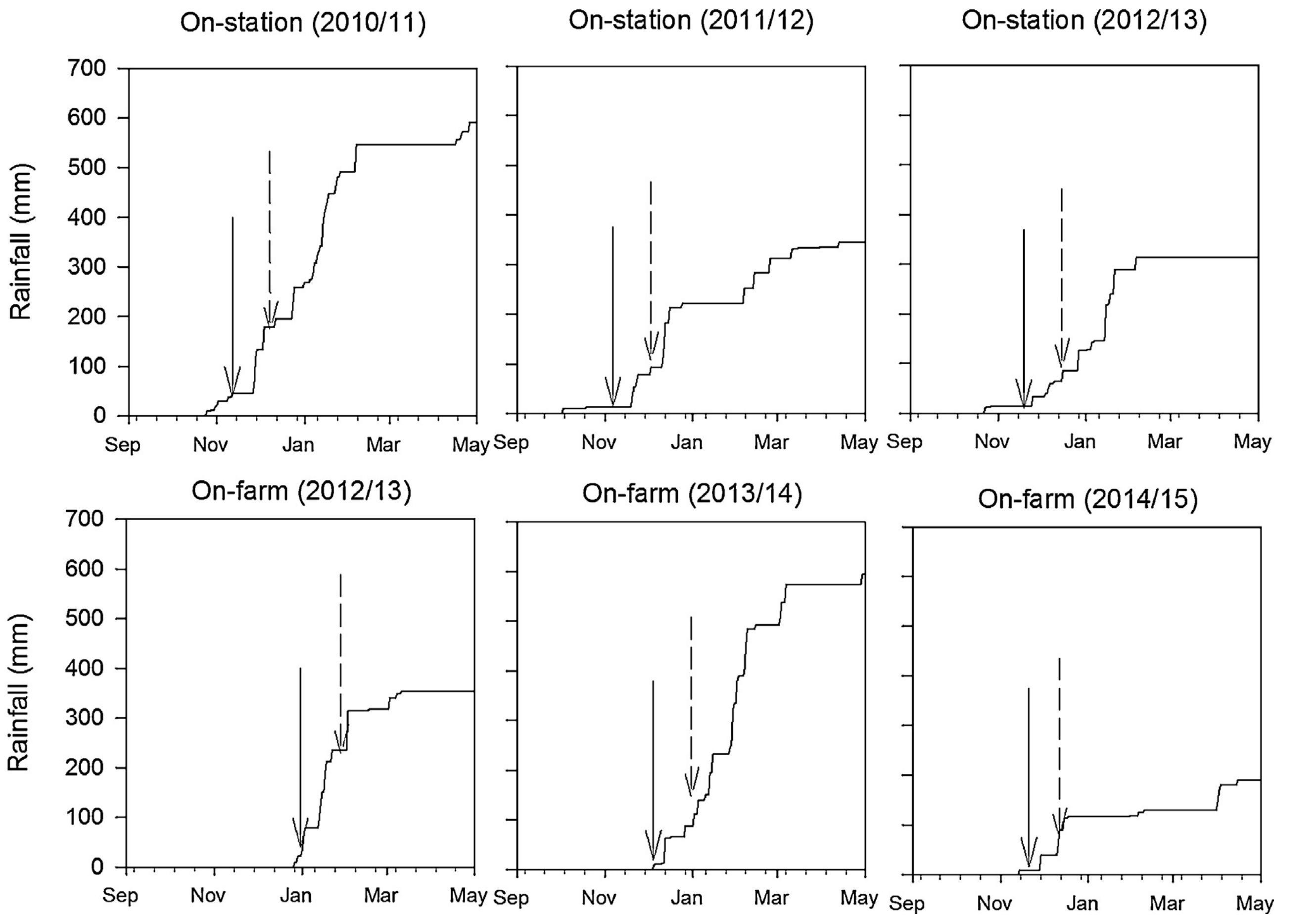

Fig. 2. Cumulative rainfall at Westacre Creek Farm (on-station) from the 2010/11–2012/13 seasons and the researcher-managed on-farm study site in Nqindi ward, Matobo district, Zimbabwe from the 2012/13–2014/15 seasons. The solid and dashed arrows show the planting date for maize and for cowpea planted 3 weeks after maize respectively.

2.4. Data analysis

Grain and stover yields, root length densities (RLD) and LER values were first tested for normality using the Shapiro-Wilk W test and found to be normally distributed (Shapiro and Wilk, 1965). The crop yields, RLD and LER values were then subjected to analysis of variance following a generalised linear model (GLM) procedure using Genstat version 14 to test the individual and interaction effects of intercropping treatment, cowpea planting date and fertiliser application. In the case of the farmer managed on-farm trials, the farmer's field was used as a random variable. Treatment means were separated using LSD at 5% level of significance.

3. Results

3.1. Rainfall distribution

The total rainfall on-station during the 2011/12 and 2012/13 seasons (345 and 314 mm respectively) and on-farm in the 2012/13 and 2014/15 seasons (354 and 190 mm respectively) was below the long-term average (590 mm per annum) for the Matobo district and also below the lower limit (450 mm per annum) for the agro-ecological region. These seasons were characterised by several extended dry spells (Fig. 2), which negatively affected crop performance. The total rainfall of 591 mm on-station in the 2010/11 season and 594 mm on-farm in the 2013/14 season were within the expected range for the region (450–600 mm). The 2013/14 season was characterised by high intensity storms but the rains stopped prematurely in mid-March.

3.2. Effect of intercropping on selected soil chemical properties of a sandy soil on-farm

In the on-farm researcher managed trial the end-of-season available N was significantly different ($P < 0.05$) between intercropping and fertiliser treatments only after the 2013/14 season (Table 2), with highest available N in the 3WAP intercrop + 40N treatment. The effect of intercropping and fertiliser treatments on available N was gone in the 2014/15 season. In the sole maize + 0N, available N decreased by 72% of initial N after three seasons. There were no significant differences in the other measured soil chemical properties (pH, Olsen P, organic C) resulting from intercropping, time of intercropping and fertiliser application and their interactions in all three seasons. Except for the same date intercrop + 0N, intercropping and fertiliser application resulted in a consistent but not significant increase in the soil organic C content by 16–69% from the initial organic C content in the researcher managed on-farm trial (Table 1b).

3.3. Effect of intercropping on root length densities on a sandy soil on-farm

The root lengths of maize were significantly different ($P < 0.05$)

Table 2
Soil analysis (0–30 cm depth) after the 2012/13–2014/15 seasons in the on-farm researcher managed trial in Nqindi ward, Matobo.

(a) 2012/13

Treatment	pH (0.01 M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})
Sole maize (0N)	4.9	11.7	18.0	2.4
Sole maize (40N)	5.2	6.1	4.4	3.0
Sole cowpea (same date)	5.0	11.7	5.2	4.2
Sole cowpea (3WAP)	4.9	11.7	3.3	3.3
Intercrop (0N same date)	4.8	6.5	11.3	2.9
Intercrop (40N same date)	5.0	8.2	13.7	2.9
Intercrop (0N 3WAP)	4.8	8.2	14.2	2.7
Intercrop (40N 3WAP)	4.9	7.4	7.8	2.8
P	NS	NS	NS	NS
SED	0.25	6.50	6.30	0.50

(b) 2013/14

Treatment	pH (0.01 M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})
Sole maize (0N)	4.9	5.2	1.3	3.0
Sole maize (40N)	4.9	20.4	3.3	4.2
Sole cowpea (same date)	5.1	26.0	2.8	4.0
Sole cowpea (3WAP)	4.8	21.7	13.4	3.6
Intercrop (0N same date)	4.9	23.4	4.7	3.4
Intercrop (40N same date)	4.9	25.6	5.5	4.2
Intercrop (0N 3WAP)	4.8	23.0	5.7	5.4
Intercrop (40N 3WAP)	4.8	33.8	3.6	4.5
P	NS	0.04	NS	NS
SED	0.10	6.63	4.26	0.67

(c) 2014/15

Treatment	pH (0.01 M $CaCl_2$)	Available N (kg ha^{-1})	Olsen P (mg kg^{-1})	Organic C (g kg^{-1})
Sole maize (0N)	4.4	3.5	0.0	1.1
Sole maize (40N)	4.0	10.0	0.7	3.0
Sole cowpea (same date)	4.5	25.6	ND	2.5
Sole cowpea (3WAP)	4.3	5.2	0.3	2.9
Intercrop (0N same date)	4.4	7.8	0.2	3.7
Intercrop (40N same date)	4.3	6.1	ND	2.3
Intercrop (0N 3WAP)	4.4	5.6	ND	2.5
Intercrop (40N 3WAP)	4.1	6.5	ND	3.3
P	NS	NS	NS	NS
SED	0.25	12.10	0.63	0.50

across depths, between sole and intercropped maize and between fertiliser rates in both the 2012/13 and 2013/14 seasons (Fig. 3). In 2012/2013, the RLD of maize was larger in the sole maize + 40N treatment than in the intercrop at most soil depths. In the same season, the maize roots for sole maize, regardless of fertiliser treatment, were mainly confined in the 0.2–0.4 m soil layer, whilst in the intercropped plots, maize roots were largely confined in the 0–0.2 m layer. In the wet season, 2013/14, the maize root length in both the sole and intercropped treatments was densest in the 0–0.2 m layer. Maize RLD was generally larger than that of cowpea in the intercrops in both seasons.

For cowpea, the sole crop roots were densest ($P < 0.05$) in the 0.2–0.6 m zone whilst in the intercrop the roots were densest in the 0–0.2 m zone in the 2012/13 season. The RLD for sole cowpea was greater than that of intercropped cowpea at most of the depths in the 2012/13 season. In the 2013/14 season, the RLD did not significantly differ between the intercropped and sole cowpea across the soil profile. Nevertheless, in this wetter season, the cowpea roots for the sole crop were confined to the 0–0.2 m zone whilst in the intercrop the roots were evenly distributed in the top 0.6 m.

3.4. *Effect of agronomic management on grain and stover yield*

3.4.1. *Researcher managed on-station trial*

On-station, in the 2010/11 and 2012/13 seasons, intercropping and time of planting cowpea had significant effects ($P < 0.05$) on both cowpea and maize yields (Fig. 4). The same date intercrop reduced cowpea grain yields by between 20 and 63% and the relay intercrop by 62–68% when compared with sole cowpea stands in the two seasons. In the 2010/11 season, maize yields were significantly larger in the sole maize when compared with the same date maize-cowpea intercrop. In subsequent seasons, the maize grain yields were low < 500 kg ha^{-1} but followed the same trend as in the 2010/11 season although the differences in yield between the sole and same date intercrop were not significant.

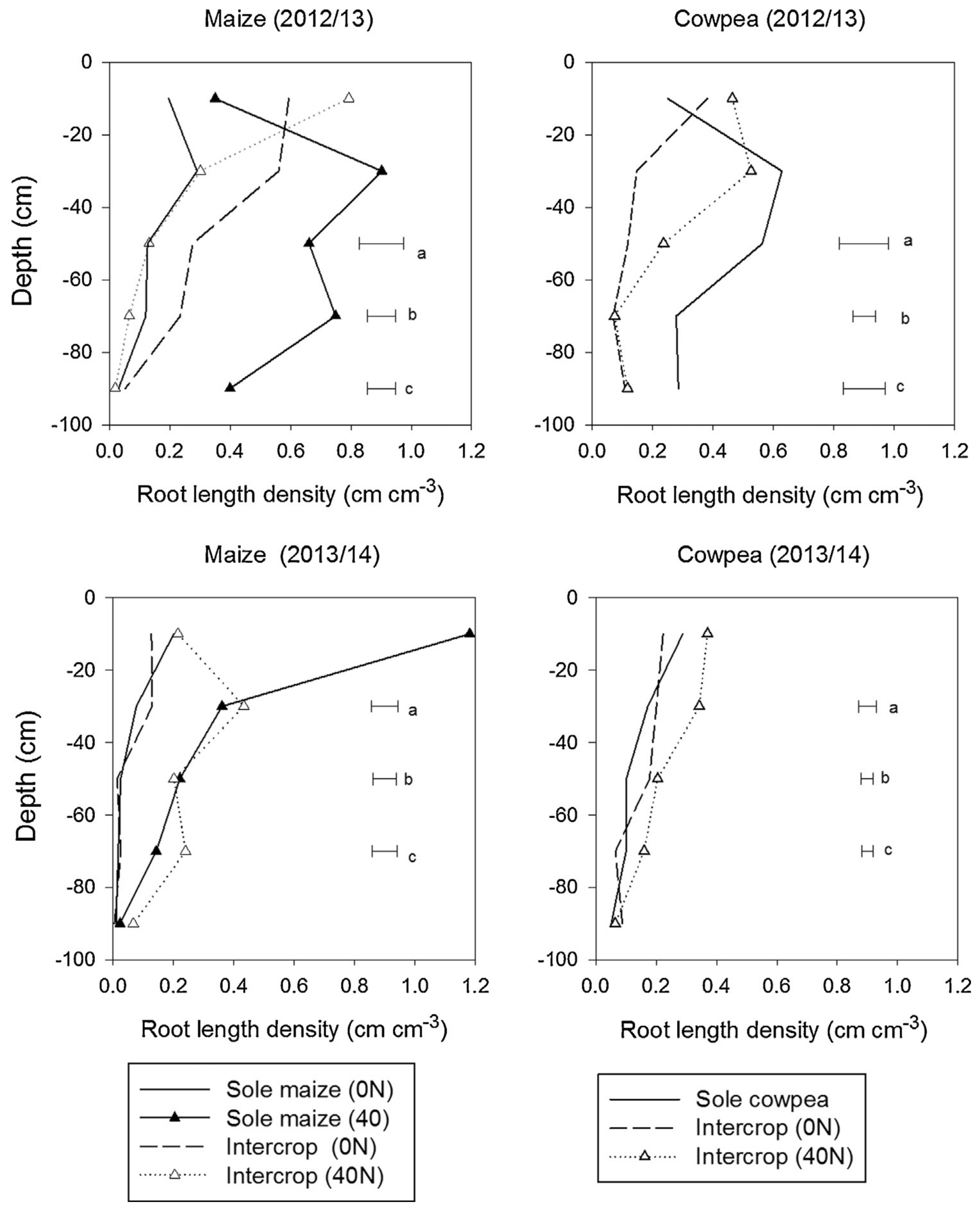

Fig. 3. Root length densities of maize and cowpea (planted at the same date as maize) in the 2013/14 season from the researcher managed on-farm trial. Error bars represent standard error of the difference of the means of factors: (a) depth, (b) intercropping and (c) N fertiliser rate.

Planting cowpeas three weeks after maize led to higher cowpea grain yields by 50–150% in 2010/11 and 2012/13 compared with cowpea in the same date intercrop. When cowpea was incorporated three weeks after maize, the maize yield (1500–2300 kg ha^{-1}) was higher when compared with the sole crop (1000–1800 kg ha^{-1}) implying that the late planted cowpea had a positive effect on maize growth.

3.4.2. *Researcher managed on-farm trial*

There was no maize and cowpea grain and very poor stover yields in the 2012/13 and 2014/15 seasons as a result of the low and poor rainfall distribution (Fig. 5). In the 2013/14 season, the same date intercrop + 0 N resulted in low maize grain yields. Application of 40 kg N ha^{-1} significantly increased maize grain yields ($P < 0.05$) with yields in the range 1250–1280 kg ha^{-1} compared with the 0N treatment with yields of 135–460 kg ha^{-1} regardless of intercropping. The 40N treatment also resulted in significantly larger maize stover yields in all three seasons compared to no fertiliser input (Fig. 5). Time of incorporating cowpea into an intercrop had significant effects on maize grain under the 0N fertility treatment and on stover yields under the 0N fertility treatment in the 2013/14 season and under the 40N treatment in the 2012/13 and 2013/14 seasons. For grain yields, the same date intercrop decreased maize yields by 163 kg ha^{-1} (55%) whilst the relay intercrop increased grain yields by 170 kg ha^{-1} (57%) compared with the sole maize crop. Relay intercropping generally decreased maize stover yields with the 40N treatment in 2012/13 and 2013/14 by between 40 and 380 kg ha^{-1} compared with both the sole crop and the same date intercrop. Under the 0N treatment in 2013/14, however, the relay intercrop increased stover yields by compared with the sole crop and the same date intercrop.

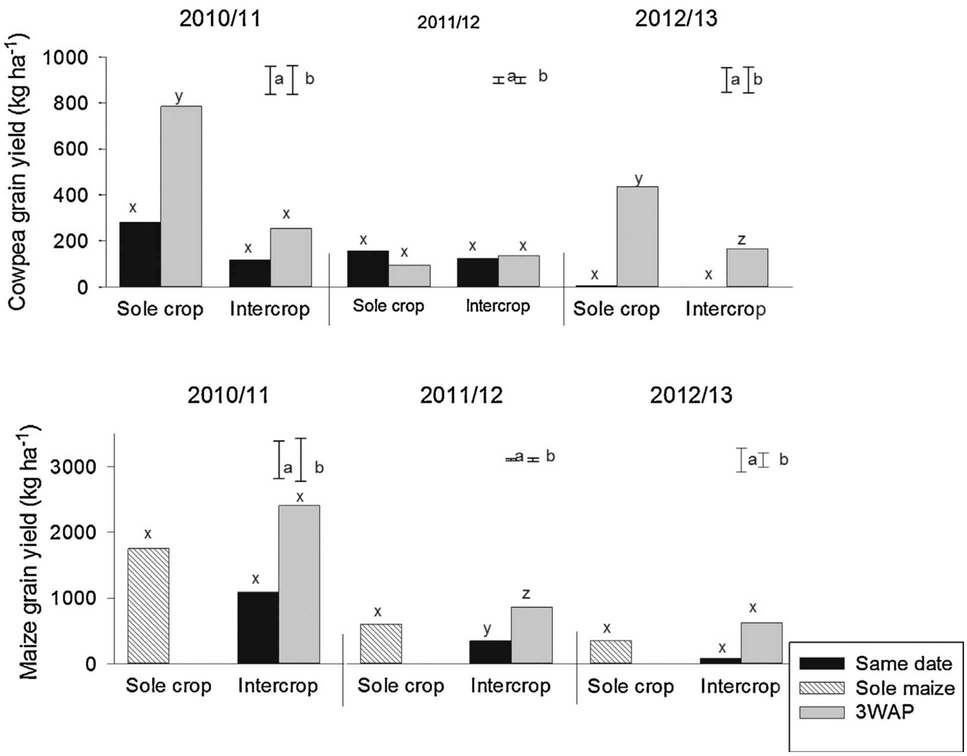

Fig. 4. Cowpea and maize grain yields by time of intercropping and intercrop type in a researcher managed on-station trial at Westacre, Matopos Research Station. Error bars represent standard errors of the difference of the means of factors: (a) intercropping and (b) intercropping time. Means with the same letter are not different at $P < 0.05$ for the interaction of intercropping and intercropping time.

Cowpea grain (2013/14) and stover yields (2013/14 and 2014/15 seasons) were affected significantly by time of planting ($P < 0.05$) (Fig. 6). Generally, the later the cowpea was planted the poorer the yields regardless of whether the cowpea was planted as a sole crop or intercropped with maize. In the 2013/14 season, cowpea grain yield for the early planted crop ranged from 400 to 700 kg ha^{-1}. There were no cowpea yields recorded for the second cowpea planting date (3WAP) following poor establishment of the crop as the planting coincided with a 10 day long dry spell in the 2013/14 season. In the 2014/15 season, planting cowpea late reduced the stover yield by an average of 77% compared with planting cowpea with the first effective rains. Intercropping significantly reduced cowpea grain and stover yields in the 2013/14 season by 5–35% when compared with the sole cowpea stands although the average root length densities between the two crop stands were similar. There were no significant treatment effects on the cowpea yields resulting from the addition of fertiliser to maize although both grain and stover yields were higher when fertiliser was applied in the 2013/14 season.

3.4.3. *Farmer managed on-farm trial*

There were no significant maize yield penalties resulting from intercropping or time of incorporating cowpea into an intercrop. Addition of 40 kg N ha^{-1} significantly increased grain yield ($P < 0.05$) by 500–1100 kg ha^{-1} and stover yields by 1500–1700 kg ha^{-1} whether maize was planted as a sole crop or in an intercrop in the 2013/14 season (Table 3). The highest maize grain yields were obtained when cowpea was relayed by three weeks with the application of 40 kg N ha^{-1}.

Intercropping and time of intercropping significantly affected cowpea grain yields in the farmer managed trials (Table 4). Planting cowpea in sole stands gave the highest grain and stover yields in both the 2013/14 and 2014/15 seasons. Planting cowpea with the first rains together with maize (the same date intercrop) also resulted in higher cowpea grain and stover yields in both seasons compared with the later planting. Similar to the researcher-managed trial, the late planted cowpea was negatively affected by dry spells.

3.5. *Effect of agronomic management on land equivalent ratios*

The total yield was generally higher in the intercrops than the sole crops of either maize or cowpea. As such, most intercrop treatments both on-station and on-farm had LER > 1 pointing to the greater land-use efficiency of the maize-cowpea intercrop system compared to sole cropping (Fig. 7; Supplementary Table). The intercropping treatments both on-station and on-farm generally resulted in over yielding especially under the 40N treatments (Figs. 7 and 8). However, the poorer the season in terms of rainfall distribution and amount, the smaller the LERs. There was considerable variability in monoculture maize and cowpea yield as well as in LER values between farms (Fig. 8). The on-station relay intercrop (3WAP) performed significantly better with LER ranging from 1.8–2.5 compared with the same planting date intercrop with LER 0.5–2.4 in all three seasons. The smallest LER was obtained in the drought season of 2012/13. On-farm the LER trends were variable in both the farmer and researcher managed trials and a significant interaction effect was found between time of intercropping and fertiliser application in the researcher managed trial in the 2013/14 season. The same date intercrop was favourable if N fertiliser was applied whilst the relay crop was a better alternative under the treatment without fertiliser.

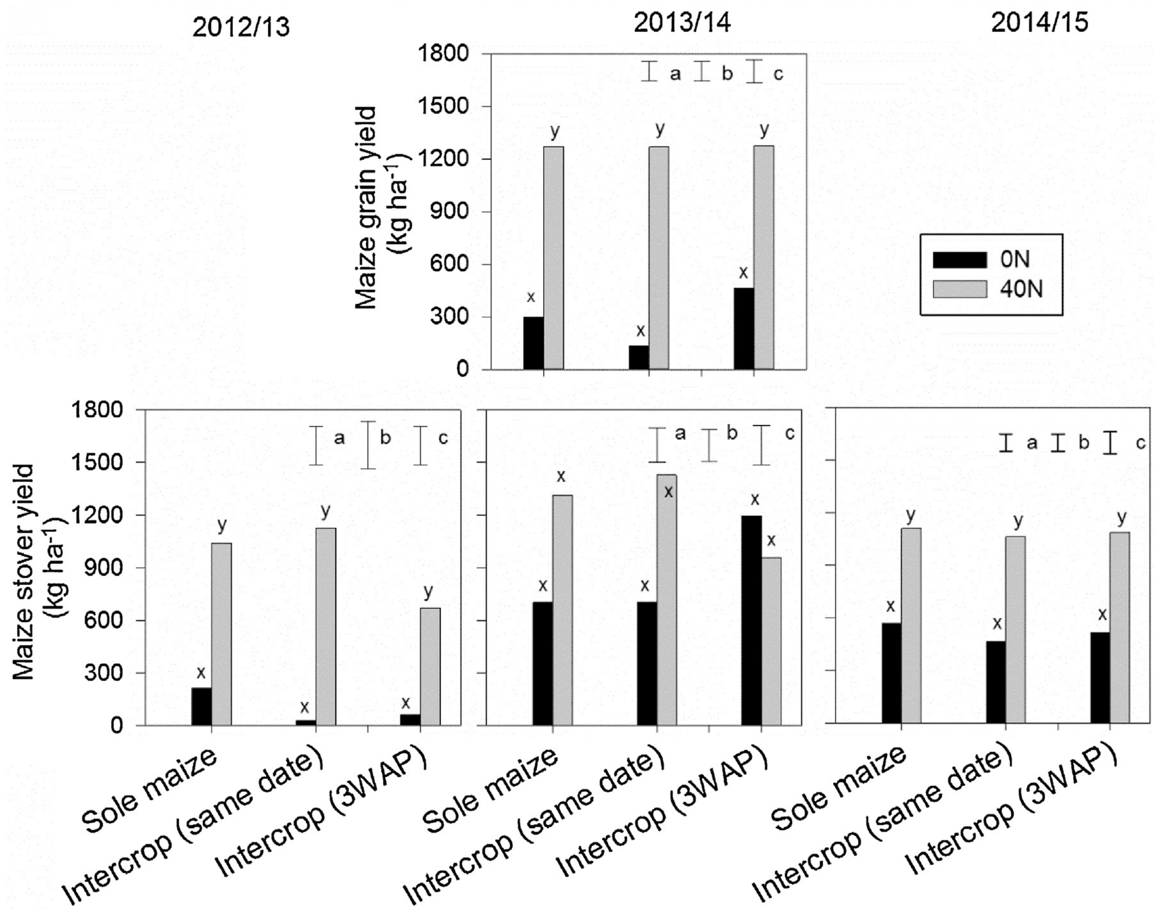

Fig. 5. Effect of intercropping, time of sowing of cowpea and fertiliser application on maize grain and stover yields in on-farm researcher managed trials in Nqindi ward, Matobo district. Error bars represent standard errors of the difference of the means of yields for factors: (a) intercropping (b) N fertiliser and (c) intercropping time. Means with the same letter are not different at $P < 0.05$ for the interaction of intercropping, N fertiliser rate and intercropping time.

4. Discussion

4.1. Maize – cowpea intercrops and over-yielding

Improved crop and soil productivity can be realised with intercropping in conjunction with low rates of N fertiliser. In general, intercropping maize and cowpea resulted in over-yielding with LER values above 1 although crop yields were highly variable depending on the rainfall distribution in the different seasons. Enhanced productivity of intercrops has been recorded elsewhere in Zimbabwe and in the region (Jeranyama et al., 2000; Ngwira et al., 2012; Rusinamhodzi et al., 2012; Thierfelder et al., 2012). Maize yields were generally not compromised as a result of adding cowpea either planted together with the maize or as a relay crop. This was true both on the heavy textured clay soil and the light textured sandy soil, regardless of the season. However, in the first season in the on-station trial the maize yield was reduced by planting maize and cowpea on the same date whilst in the researcher managed on-farm trial, in 2013/14, the treatment without fertiliser maize yields were also reduced by intercropping. Cowpea yield penalties due to intercropping were more common and occurred in all experiments and seasons.

The total biomass (maize + cowpea stover) in intercrops was higher than in sole maize or cowpea stands. This increased biomass production is seen as a benefit of intercropping in the mixed crop-livestock systems, which are characterised by competing uses of crop residues mainly for livestock feed and for maintaining soil organic matter (Baudron et al., 2012b; Ngwira et al., 2012; Thierfelder et al., 2012). Maize-cowpea intercropping results in greater vegetative cover compared with the sole crop stands and therefore a reduction in soil evaporation and increased water use efficiency (Mao et al., 2012). Where LER > 1, water may have been used more effectively as more water was used by the crop through transpiration than lost due to evaporation or weeds. As such, there with higher output (kg grain/biomass) in intercrop systems per unit of rainfall compared with the monocrops.

In addition, intercrops with N_2-fixing legumes may reduce the C:N ratio of the resulting mulch mixture. The decomposition of this mulch will release nitrogen, as opposed to the decomposition of high C:N materials such as maize stalks, which require that soil microbes use the available N for their own metabolic needs resulting in temporary N immobilisation (Giller et al., 2011; Grahmann et al., 2013). This may explain our finding of increased available N in the sole cowpea and intercrop plots. Legume-fixed N may be less susceptible to loss from the soil system when compared with chemical fertiliser, thus improving the ability of the soil to supply N (Crews and Peoples, 2004). The increased production of high quality biomass plays a vital role for crop-livestock farmers by improving the quantity and quality of animal feed in the dry

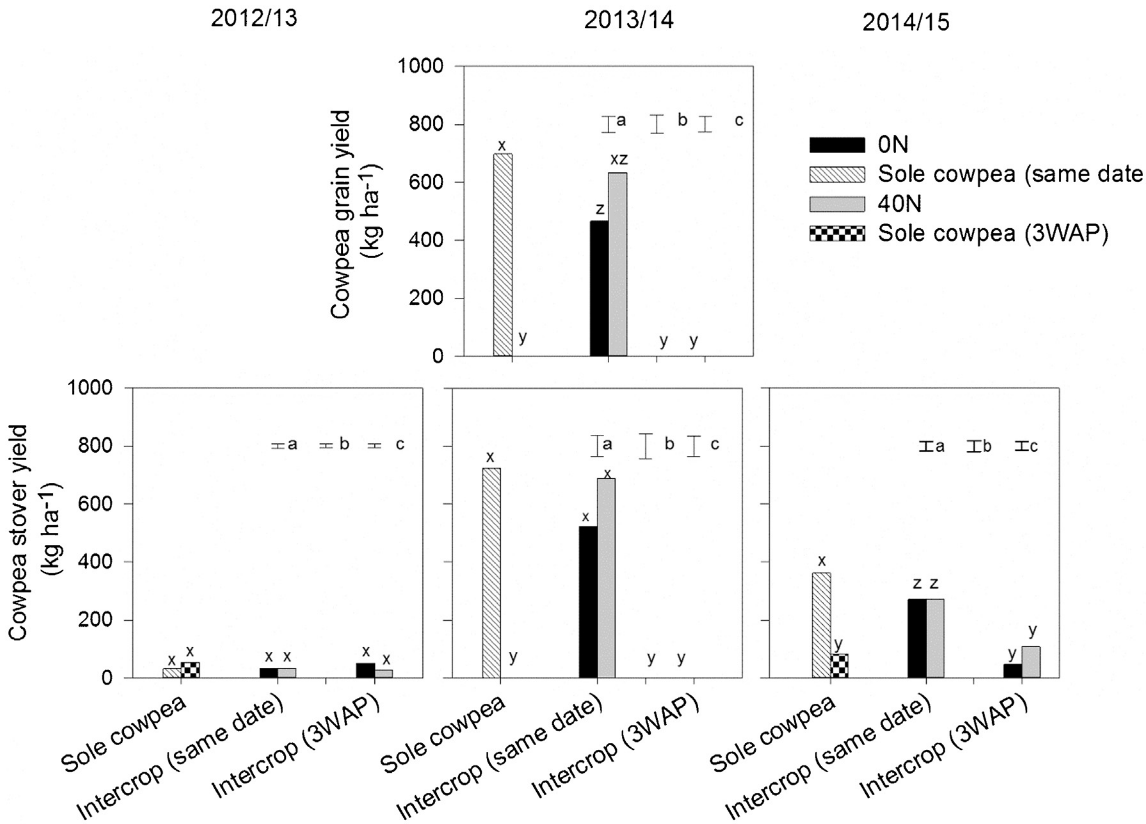

Fig. 6. Effect of intercropping and date of planting on cowpea grain and biomass yields in an on-farm researcher managed trial in Nqindi ward, Matobo district. Errors bars represent standard error of the difference of the means of factors: (a) intercropping (b) N fertiliser and (c) intercropping time. Means with the same letter are not different at $P < 0.05$ for the interaction of intercropping, N fertiliser rate and intercropping time.

season while maintaining grain yield from the same piece of land. Even in case of poor grain yields, the production of large amounts of high-quality feed in the intercrops may allow to maintain animal production and farmers will be able to sell excess animals or livestock products to purchase cereal grain (Belel et al., 2014).

Maize yields responded to N fertiliser application more than to intercropping meaning that although planting legumes may improve soil N (Jeranyama et al., 2000), in the short term N fertiliser is required on the degraded sandy soils. This finding is similar to that of a study on similar sandy soils in humid Zimbabwe (Dunjana et al., 2014). Indeed, intercropping non-legumes with N fixing legumes alone cannot replace the role of N fertiliser in these cropping systems if the priority is increased yields. Under semi-arid conditions in Zimbabwe, maize generally requires approximately 50 kg N ha^{-1} (Piha, 1993). Rusinamhodzi et al. (2006) measured 68–138 kg N ha^{-1} fixed through BNF yet little was transferred to the companion crop in an intercrop and the majority of the fixed N is used by the legume itself (van Kessel and Hartley, 2000). Although not significant, cowpea performed better with larger grain and stover yields in intercrops where 40N was applied. The application of a small quantity of N enhances vegetative growth and root activity in the legume, leading to the observed higher yields (Burris, 1959). Rusinamhodzi et al. (2012) also observed a significant response of cowpea yields to applied N and P fertiliser, which they attributed to well-timed staggered planting which saw the maturity of cowpea coinciding with adequate moisture conditions. The latter was, however, not the case in our study.

4.2. Does below-ground root complementarity explain over-yielding in intercrops?

Component crops in an intercrop may have different use of resources resulting in complementarity (Tsubo et al., 2005). In our study, however, we found only marginal below-ground complementarity in the maize-cowpea intercrop on the poor sandy soil as the roots of both crops were densest in the same depth zones in both the drier and the wetter season. As such, there was a lack of niche differentiation in terms of root growth with high competition for nutrients and water as a result. This also means that below-ground root complementary cannot serve as an explanation for the over-yielding observed in the maize – cowpea intercrops. Zhang et al. (2014) suggested that additional processes such as mycorrhizal colonisation and or above-ground complementarity or competition should be taken into account to understand complementarity which is not only defined by crop rooting patterns but also nutrient and water requirements and thus uptake. Maize had a higher RLD in the intercrop compared with the monocrop when grown without fertiliser in 2012/13. The maize RLD in the intercrop was generally larger compared with the cowpea. This may explain the asymmetric interspecific facilitation in the intercrops illustrated by the negative effect on the cowpea grain yields compared to no (on the sandy soil) or a positive (on the clay soil) effect on maize grain and stover yields. However, the actual mechanism of the facilitation in the intercrop was unknown in the present study. According to Hayes et al. (1999) under conditions of P deficiency, as was the case in our study, acid phosphates secretion from roots is

Table 3
Effect of intercropping, time of incorporation of cowpea into intercrops (same date – cowpea planted on the same date as maize; 3WAP – cowpea planted 3 weeks after planting maize) and N fertiliser application on maize (a) grain and (b) stover yield in farmer-managed intercrop trials in Matobo district in the 2013/14 and 2014/15 seasons.

(a) Maize grain yield (kg ha^{-1})

N treatment	2013/14			2014/15		
	Sole maize	Intercrop maize		Sole maize	Intercrop maize	
		Same date	3WAP		Same date	3WAP
0N	354 (12) [§]	363 (8)	334 (9)	0 (12)	0 (12)	0 (12)
40N	1202 (14)	933 (7)	1402 (10)	183 (12)	158 (12)	209 (12)

	P	SED	P	SED
Intercropping	NS	154.7	NS	34.6
N treatment	< 0.001	153.3	0.001	34.6
Intercropping time	NS	216.6	NS	42.3
Intercropping*N treatment interaction	NS	274.6	NS	48.9
N treatment *intercropping time interaction	NS	274.6	NS	59.9

(b) Maize stover yield (kg ha^{-1})

N treatment	2013/14			2014/15		
	Sole maize	Intercrop maize		Sole maize	Intercrop maize	
		Same date	3WAP		Same date	3WAP
0N	756 (12)	769 (8)	746 (9)	569 (12)	466 (12)	518 (12)
40N	2340 (14)	2367 (7)	2392 (10)	1110 (12)	1064 (12)	1087 (12)

	P	SED	P	SED
Intercropping	NS	284.7	NS	101.2
N treatment	< 0.001	282.2	< 0.001	101.2
Intercropping time	NS	353.9	NS	124.0
Intercropping*N treatment interaction	NS	505.4	NS	143.1
N treatment *intercropping time interaction	NS	505.4	NS	143.1

[§] Number in parenthesis represents the number of observations in that treatment (*n*).

increased. It is possible that cowpea roots could secrete acid phosphates facilitating P nutrition in maize therefore increased RLD and generally increased growth. Rates of transfer of fixed N from legumes to companion cereal crops are considered to be small (van Kessel and Hartley, 2000; Giller, 2001) and is unlikely to be important in this case. Further research on possible mechanisms for interspecific facilitation in intercrops is needed.

4.3. Relay intercropping and its effects on land use efficiency

The relay intercrop studied here resulted in a temporal niche differentiation with maize having a head start in development compared to the late planted cowpea. This resulted in cowpea grain and stover yield penalties as the plantings coincided with dry spells on the sandy soils on-farm. In the 2013/14 season, both the sole and intercrop 3WAP cowpea crop completely failed to establish. The dry spells resulted in soil crusting, which impeded crop emergence and resulted in poor cowpea stands. The relay intercrop, however, resulted in benefits in maize grain yield on-station on the clay soil (Fig. 4; Supplementary Table) and no effect on the maize on-farm on the sandy soil (Fig. 5; Supplementary Table). This is because by the time cowpea is introduced into the intercrop, the maize root system would have been well developed. The clay soils on-station have a high water holding capacity (Mupangwa et al., 2012) such that growth of the late planted cowpea in this soil is possible even in drier seasons like 2012/13. On-farm, the sandy soil, typical of two-thirds of Zimbabwean soils, has a poor water holding capacity (Mapfumo and Giller, 2001; Moyo, 2001), which may explain the poor yields associated with the late planted cowpea on sandy soils. In addition to the differences in soil type, planting basins used on-station tend to hold more water than rip lines especially at the beginning of the season. Mupangwa et al. (2015) showed that planting basins start off with marginally higher soil water contents compared with other tillage methods like ripping or single conventional ploughing although this changed as the season progressed both on a clay and sandy soil.

4.4. Maize-cowpea intercropping in the context of smallholder farmers in semi-arid areas

With LERs generally above one, maize-legume intercropping increases household food security and leads to dietary diversification. However, the benefits of intercropping were depended on the rainfall pattern in the different seasons and trials. For example, in the on-station trial in the first season and the researcher-managed on-farm trial in the second season without fertiliser, maize yields were reduced when both crops were planted together at the same time. This risk may discourage

Table 4
Effect of intercropping and time of planting cowpea on cowpea grain and stover yield (same date – cowpea planted on the same date as maize; 3WAP – cowpea planted 3 weeks after planting maize) in farmer managed intercrop trials in Matobo district (2013/14 and 2014/15 seasons).

(a) Cowpea grain yields (kg ha^{-1})

	2013/14			2014/15		
	Sole	Intercrop		Sole	Intercrop	
		0N	40N		0N	40N
Same date	1040.9	697.8	754.3	122.5	46.7	71.7
3WAP	573.0	427.1	418.4	0	0	0

	2013/14 P	2013/14 SED	2014/15 P	2014/15 SED
Intercropping	0.009	96.1	0.03	14.1
Intercropping time	< 0.001	99.7	< 0.001	13.3
Interaction	NS	140.4	0.03	19.9

(b) Cowpea stover yields (kg ha^{-1})

	2013/14			2014/15		
	Sole	Intercrop		Sole	Intercrop	
		0N	40N		0N	40N
Same date	1146	722.0	811.0	362.1	225.7	226.6
3WAP	637.0	452.0	509.0	83.8	28.3	89.3

	2013/14 P	2013/14 SED	2014/15 P	2014/15 SED
Intercropping	NS	214.1	0.015	31.8
Intercropping time	0.047	218.0	< 0.001	30.0
Interaction	NS	3061	0.088	44.8

smallholder farmers to invest and change their production system from monocropping of maize to intercropping. This is because of the importance of maize, which guarantees food security at household level and can always be marketed in case of excess production (Baudron et al., 2012a; Thierfelder et al., 2012).

Our study focused on two fixed planting times for cowpea, whereas farmers in reality observe the rainfall patterns before making the decision on whether or not to plant (Musiyiwa et al., 2015). This helps to avoid the challenges we encountered in our study of cowpea planting times coinciding with dry spells, and resulting very small cowpea yields or complete cowpea failure especially on-farm on the sandy soil. Whether farmers adopt intercropping is dependent on several factors which include soil fertility status, climate, land and livestock holding, labour availability and farmers' goals and attitudes (Zingore et al., 2007; Giller et al., 2011). Resource poor farmers may not be able or willing to invest seed, fertiliser/manure and labour in a second crop if there is a possibility of the crop failing. Although farmers appreciated the concept and potential benefits of intercropping, the relay intercrop was not viewed as a practical option. The associated risk of poor cowpea yields and the additional labour required when planting the second crop were mentioned as disincentives. Production of legumes in smallholder farming systems remains a challenge also because of farmers lacking access to markets to purchase improved legume seed and sell their produce (Mazvimavi and Twomlow, 2009). Although cowpea grows well in most smallholder areas and even on granitic sandy soils, it is very susceptible to pests, especially aphids, which can significantly affect the overall performance of the crop. In our study, we controlled pest attacks on the cowpea with pesticides which, however, are not readily available locally and beyond the reach of resource poor farmers.

Soils in the study area were nutrient poor (Table 1) and intercropping may reduce the quantity of fertiliser N required by the cereal in the short term. This is appealing for resource poor farmers who cannot afford large fertiliser quantities. In our study the addition of small amounts of N fertiliser, typical of smallholder farmers, in conjunction with intercropping led to positive responses in yields. However, once N is made available, the resulting vigorous plant growth may exacerbate other nutrient deficiencies. In our study, NPK or PK fertiliser was added to the maize but not to the cowpea which is typical of smallholder farmers who apply little or no fertility amendments to legume crops (Ronner et al., 2016). With the intensification of the cropping system as with intercropping, nutrient requirements for the legume need to be addressed especially as soils in the study area are nutrient poor (Table 1). As such manure, if available, is a key nutrient resource on smallholder farms as it provides both macro- and micronutrients (Zingore et al., 2008).

While our study presents the technical performance of intercropping at plot level, farmers in semi-arid Zimbabwe with farm sizes of 3.5–5 ha with different crop and livestock enterprises look beyond the plot for household food security (Ncube et al., 2009). Interactions between the different parts of the farm and the trade-offs between different economic or production objectives, especially with the mixed farming practice in semi-arid Zimbabwe, may cause the production efficiency of a farm to be different from what may be inferred at lower scales such as the plot.

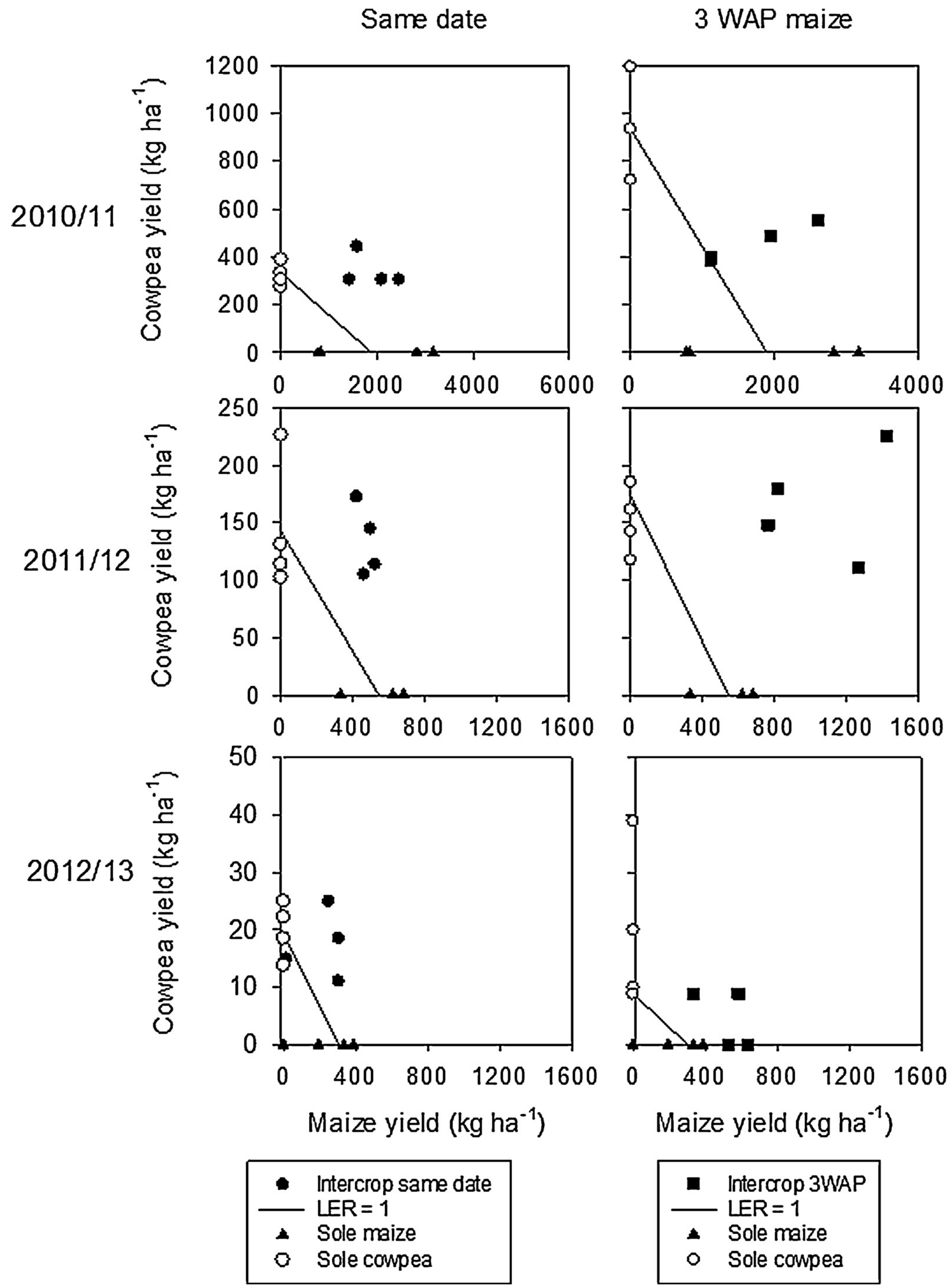

Fig. 7. Maize and cowpea yield in the 2010/11, 2011/12 and 2012/13 seasons at Westacre Creek, Matopos Research Station. All points falling above the lines connecting the two monocrops (mean LER = 1) represent yield combinations that resulted in overyielding and all points below represent combinations for intercrops that were inferior to the monocrop alternatives. (Note: The axes scales are different for each season).

5. Conclusions

Maize-cowpea intercropping has the potential to improve land-use efficiency through over-yielding compared with maize monocropping regardless of time of intercropping, season quality and soil type in smallholder systems where the use of external inputs such as fertiliser is restricted. Although productive, the intercrop resulted in compromised cowpea yields especially under the relay intercrop compared with the sole cowpea stands whilst those of maize were either not affected or improved. We attributed the poor cowpea yields in the intercrops to the lack of below-ground niche differentiation in root distribution between maize and cowpea. As such, over-yielding in the intercrops could not be attributed to below-ground root complementary in root patterns. Maize had a high root length density meaning it explored more soil volume and therefore more resources required for crop growth and as such performed better than the cowpea. As trends were consistent over different seasons, the maize – cowpea intercrop with small doses of N fertiliser is a robust system for food and livestock feed production. Nevertheless, for intercropping to be attractive to smallholder farmers, current constraints with respect to reliable access to input and output markets and credit schemes would have to be removed.

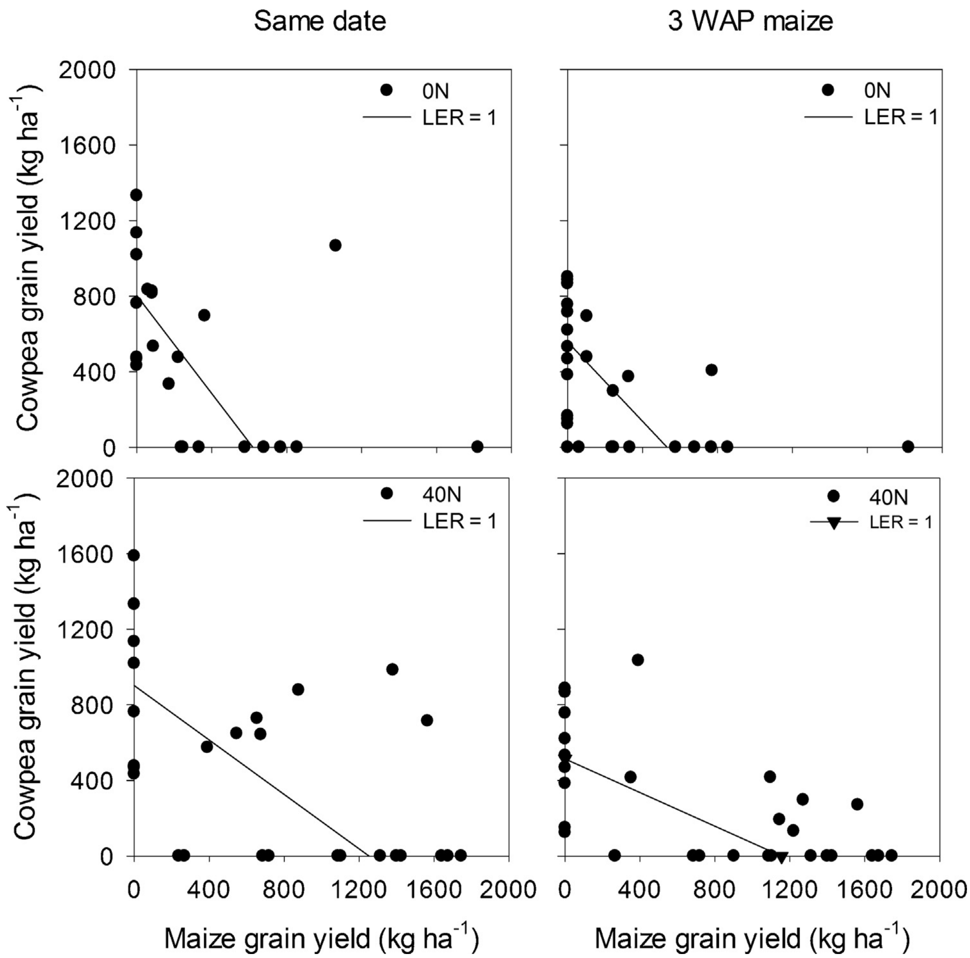

Fig. 8. Maize and cowpea yield sets from intercropped treatments (evaluation of yield advantage in intercropping systems) in farmer managed intercrop trials in the 2013/14 season. Each dot represents each yield set observation. The straight line connecting the two monocrops represents the average LER = 1 for the study sites for each trial set (the average was obtained by averaging the monocrops). All points falling above the LER = 1 represent yield combinations that resulted in overyielding and all points below represent combinations for intercrops that were inferior to the monocrop alternatives.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2017.04.016.

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