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Productivity and biological N₂-fixation in cereal-cowpea intercropping systems in sub-Saharan Africa. A review

Talent Namatsheve¹ · Rémi Cardinael^{1,2,3} · Marc Corbeels^{2,3,4} · Regis Chikowo^{1,5}

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Abstract

Intercropping is a common practice among farmers in sub-Saharan Africa, regarded as a sustainable way of improving land productivity to meet food and nutritional requirements for a growing population, especially in marginal areas. Cowpea (*Vigna unguiculata* L. Walp) is often intercropped with major cereal crops, maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench) and pearl millet (*Pennisetum glaucum* L.R.Br). Here we conducted a systematic literature review on cowpea intercropped with maize, sorghum or pearl millet reported in sub-Saharan Africa with the objectives (i) to determine yield and productivity of component crops and (ii) to quantify biological N₂-fixation in sole or intercrops. We retrieved 60 unique publications combining 1196, 998 and 25 observations of yields, land productivity and N₂-fixation, respectively, for crops grown as intercrops and monocrops. The major results are as follows: (1) land productivity of cowpea intercropped with maize, sorghum and pearl millet is favourable, with average land equivalent ratios of 1.42 ± 0.47 , 1.26 ± 0.35 and 1.30 ± 0.32 , respectively; (2) no significant differences between the proportion of nitrogen derived from the atmosphere (%Ndfa) for sole or intercropped cowpea were found, with average values of 56.00 ± 4.89 and 46.62 ± 7.05 , respectively; (3) however, the total amount of fixed nitrogen was higher in cowpea monocropping systems due to higher biomass production; nitrogen fixation was 57 kg N ha^{-1} and 36 kg N ha^{-1} in monocrops and intercrops respectively. We conclude that cereal-cowpea intercropping is a pathway for intensification for the low nutrient input systems of smallholder farmers in sub-Saharan Africa. Our review also suggests potential for improvement of these systems, based on the choice of the associated varieties, planting patterns and sowing time, cowpea leaf harvesting as a vegetable, and fertilization.

Keywords Crop yield · Land equivalent ratio · Legume crops · Low inputs systems · Smallholder farmers

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1 Introduction

Sub-Saharan Africa (SSA) is facing food insecurity, and crop yields of major cereal crops lag behind those of other regions (Cairns et al. 2013; Fischer et al. 2014). Recurrent droughts, infertile soils and lack of adequate machinery and other inputs are putting crop production into jeopardy (Sánchez 2010). Improving food and nutrition security must be prioritized and requires the deployment of effective agricultural technologies. In the face of limited external resources, the question on how to effectively utilize the available resources in a continuum of circumstances becomes critical (Giller et al. 2011).

Integration of grain legumes as intercrops with cereals for low-input farming systems in SSA increases nitrogen (N) cycling and availability through biological N₂-fixation for smallholder farmers that generally lack external nutrient inputs on farms (Nezomba et al. 2015). When companion crops are compatible, with interspecific facilitation and niche complementarity, intercropping increases land and labour productivity (Watiki et al. 1993; Fridley 2001; Peoples et al. 2009; Kermah et al. 2017; Yang et al. 2017). Moreover, it offers a means to balance environmental and socio-economic objectives of farming (Musumba et al. 2017). On the other hand, observed yield reduction in intercrops is often due to competition for resources such as light, water and soil nutrients (Blade et al. 1991; Senaratne et al. 1995; Peoples et al. 2009). For example, shading by taller plants in mixtures reduces the photosynthetic rate of the understorey legumes, thereby reducing their yields.

Cowpea (*Vigna unguiculata* L. Walp) is one of the major grain legumes cultivated by millions of smallholder farmers in SSA. It is a drought-tolerant crop that performs better than other legumes under erratic rainfall (Timko and Singh 2008). Cowpea can be incorporated into cropping systems as a sole crop in legume-cereal rotations, but the increased climate risk-related crop failure with sole cropping threatens food security (Kermah et al. 2018). Diversification and intensification through inclusion of cowpea as intercrops with staple cereal crops represents a key technology in the drive towards sustainable intensification of agriculture (Ojiem et al. 2014; Kermah et al. 2018), and risk management on smallholder farms. Cowpea is often intercropped with maize (*Zea mays* L.) in the sub-humid regions of SSA (Fig. 1), whilst in semi-arid regions, cowpea is intercropped with drought-tolerant cereals, sorghum (*Sorghum bicolor* L. Moench) and pearl millet (*Pennisetum glaucum* L.R.Br) (Singh et al. 2005; Ewansiha et al. 2014a).

Direct mutual benefits of legume-cereal intercropping involve below-ground processes which increase the bioavailability of mineral nutrients (Xue et al. 2016); in some cases, small direct N transfer benefits from legumes to companion crops were reported (Giller et al. 1991; Senaratne et al. 1995; Laberge et al. 2011). This N transfer is in the form of root

exudates, the sloughing off of root cells and nodules, and through the turnover of roots during the growing season. Notably, root turnover increases with root N content, and N₂-fixers have particularly high root turnover rates (Fujita et al. 1992; Sanginga 2003). Intercropping is also ideal for pest and disease management, which can have a significant impact on crop yields (Ajeigbe et al. 2005; Chabi-Olaye et al. 2005). Inclusion of N₂-fixing legumes in intercropping systems can also improve soil organic carbon (SOC) content and phosphorous (P) availability, which are key determinants of soil fertility (Ntare and Bationo 1992; Vesterager et al. 2008; Ngwira et al. 2012).

In SSA, smallholder farms are mostly 0.5 to 2 ha and farmers prioritize growing staple crops. Therefore, intercropping staple cereal crops with legumes provides a pathway for further enhancing crop diversification on these small farms as well as improving land productivity (Waggoner 1995) that is usually expressed in terms of land equivalent ratio (LER) (Mead and Willey 1980; Martin-Guay et al. 2018). LER is the relative land area that is required under sole cropping to produce yields that can be achieved under intercropping (Rusinamhodzi et al. 2012; Smith et al. 2016; Martin-Guay et al. 2018).

The productivity of cereal-cowpea intercrops can be explained by a range of management practices e.g., plant arrangements, crop density, crop varieties, leaf harvesting for consumption and fertilization regimes that collectively determine the level of mutual benefits and competition between component crops (Saidi et al. 2010; Rusinamhodzi et al. 2012; Masvaya et al. 2017). Cowpea varieties have varied architecture, including erect and spreading types (Timko and Singh 2008) that perform differently as intercrops. Varietal selection in intercrops is therefore of paramount importance. Smallholder farmers often consume cowpea leaves as a vegetable, which is known to be a rich source of minerals. However, periodical leaf harvesting during the cropping season can have different outcomes on grain productivity depending on crop growth characteristics and intensity of pruning (Saidi et al. 2010).

In this paper, we reviewed literature on the effect of intercropping cowpea with cereals (maize, sorghum, pearl millet) across SSA. The objectives of this systematic literature review were to (i) determine the performance of cereal-cowpea intercrops in terms of yield of component crops and LER compared with sole crops and (ii) compare biological N₂-fixation of cowpea grown in both monocropping and cereal-based intercropping systems.

2 Methodology

A comprehensive literature search was done in February 2020 using Scopus, Web of Science and Google Scholar for peer-

Fig. 1 Maize-cowpea intercropping system in Goromonzi District, Mashonaland province, Zimbabwe



reviewed publications on cereal-cowpea intercropping systems that were reported in SSA, excluding South Africa. By restricting our scope to cereal-cowpea intercrops in SSA, we excluded many articles on cowpea-based intercrops reported worldwide. The search was carried out for literature published between 1980 and early 2020 using the following search string: (TITLE-ABS-KEY (cowpea AND (maize OR sorghum OR millet) AND intercrop* AND (Africa or any country in SSA)). A total of 217 articles were retrieved from this literature search. We further selected papers which met the following first two criteria in addition to any one of the last two criteria below.

Firstly, field experiments must have been conducted in SSA, and involving cowpea intercropped with maize, sorghum or pearl millet. Secondly, referenced literature must be a peer-review journal article only, excluding conference papers and book chapters. Thirdly, the studies must report on grain yields of the sole crops and that of the intercrops. When yields of component crops were presented without land productivity, partial and total LERs were calculated. However, some papers reported LER values only and they were included in this review. Lastly, for biological N_2 -fixation, only papers showing N_2 -fixed in both intercropped cowpea and monocrops were considered.

In total, 60 unique publications that assessed the effect of cereal-cowpea intercropping on crop productivity and/or biological N_2 -fixation in SSA met the above-mentioned selection criteria. Fifty-five papers reported on cereal-cowpea productivity only, four papers reported on both productivity and N_2 -fixation and one paper reported on N_2 -fixation only. Retrieved papers were mainly from Western Africa (43), followed by Southern Africa (9) and Eastern Africa (8). We gathered 1196 observations on yields and 998 observations on LER of cereal-cowpea intercrops (Namatsheve et al. 2020). For N_2 -fixation, we gathered 25 observations, from four articles on maize-cowpea intercrops, one article on millet-cowpea intercrops and no data was recorded on sorghum-cowpea

intercrops. Four of the reviewed articles reported yields of more than one cereal species intercropped with cowpea. Studies on yields and productivity of cereal-cowpea intercropping systems in SSA are generally focused on planting patterns, varieties of component crops, planting intervals, tillage, weed management and pest control practices (Table 1). The most commonly studied treatments are row arrangements (24 articles) and cowpea genotypes (19 articles) (Table 1). Retrieved studies reporting yield and LER in maize-cowpea intercrops are shown in Table S1. Studies on sorghum-cowpea and millet-cowpea intercropping are listed in Tables S2 and S3, respectively. Studies on biological N_2 -fixation are listed in Table S4. The full dataset is available in the CIRAD repository (Namatsheve et al. 2020).

When data in the retrieved articles were not presented in tables, they were extracted from the graphs, using the WebPlotDigitizer software (<https://automeris.io/WebPlotDigitizer/>). Student *t* tests were used to compare crop yields in intercropping and monocropping systems, to determine if LER values were significantly higher than 1 and to compare N_2 -fixation between cowpea intercrops and sole crops. The significance level used was $P < 0.05$. Statistical analyses were performed using R software, version 3.1.1 (R Development Core Team 2013).

3 Does cereal-cowpea intercropping increase yield and land productivity?

Overall, cereal-cowpea intercropping improved total crop productivity regardless of crop arrangements, varieties and rainfall patterns in these low-input systems, where nutrient inputs and irrigation are restricted. A wide array of cereal-cowpea intercropping systems have been studied (Tables S1, S2, S3), both on-farm and on-station, with variable responses across the sites. In maize-cowpea intercrops, maize yields ranged from 0 to 5852 kg ha⁻¹ and cowpea yields ranged from

Table 1 Main factors that have an effect on yield and productivity of cereal-cowpea intercrops across SSA

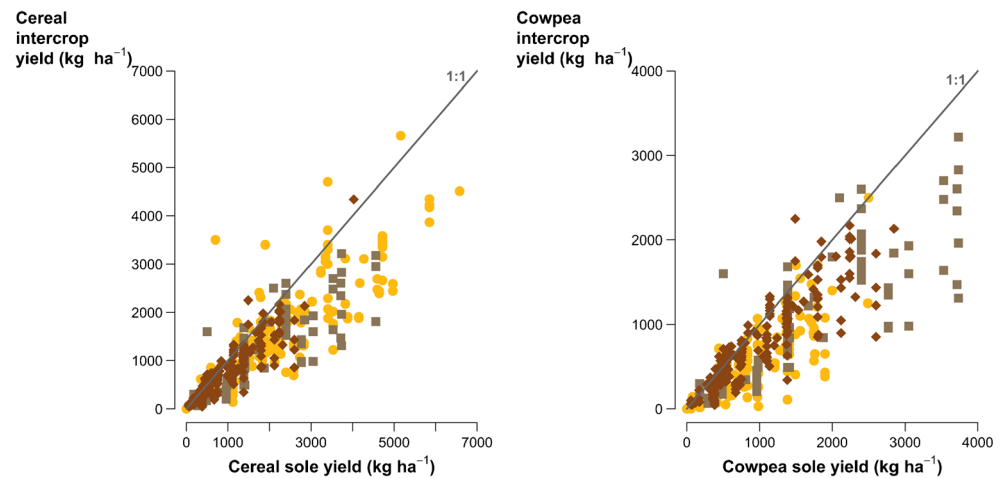
Factor studied	References	Number of references
Row arrangements	Ajeigbe et al. (2005); Ajeigbe et al. (2006); Dube et al. (2014); Falconnier et al. (2016); Kermah et al. (2017); Khan et al. (2007); Kombiok et al. (2006); Kouyate et al. (2012); Lamessa et al. (2015); Ntare (1990); Nyagumbo et al. (2015); Oseni (2010); Oseni and Aliyu (2010); Osman et al. (2011); Reddy et al. (1992); Rusinamhodzi et al. (2012); Sarr et al. (2008); Sikirou and Wydra (2008); Singh and Ajeigbe (2007); Takim (2012); Takim et al. (2014); Vesterager et al. (2008); Watanabe et al. (2019); Zougmore et al. (2010)	24
Crop density/proportions	Alemseged et al. (1996); Ewansiha et al. (2015a); Ewansiha et al. (2015b); Mariga (1990); Osman et al. (2011); Shumba et al. (1990); Sibhatu et al. (2015); Takim (2012)	8
Fertilizers/soil fertility level	Jeranyama et al. (2000); Kermah et al. (2017); Maman et al. (2017); Masvaya et al. (2017); Oluwasemire et al. (2002); Rusinamhodzi et al. (2012); Sanou et al. (2016); Sibhatu et al. (2015)	8
Cowpea genotype	Adeniyani et al. (2011); Ajeigbe et al. (2005); Ajeigbe et al. (2006); Diangar et al. (2004); Egbe et al. (2010); Ewansiha et al. (2014a); Ewansiha et al. (2014b); Ewansiha et al. (2015a); Ewansiha et al. (2015b); Haruna et al. (2018); Katsaruware and Manyanhaire (2009); Kouyate et al. (2012); Miriti et al. (2012); Mohammed et al. (2008); Ntare (1989); Ntare (1990); Ntare and Williams (1992); Reda et al. (2005); Sanou et al. (2016); Trail et al. (2016)	19
Cereal genotype	Abayomi (2000); Diangar et al. (2004); Ewansiha et al. (2014b); Grema and Hess (1994); Haruna et al. (2018); Khonde et al. (2018); Ntare (1989); Sanou et al. (2016); Singh and Ajeigbe (2007)	9
Planting date	Ewansiha et al. (2015b); Lawson et al. (2013); Masvaya et al. (2017); Ntare (1990); Ntare and Williams (1992)	5
Leaf harvesting/detasseling	Katsaruware and Manyanhaire (2009); Saidi et al. (2010)	2
Rain season type	Chabi-Olaye et al. (2005); Khan et al. (2007); Munyuli et al. (2007)	3
Weed management	Carsky et al. (1994); Munyuli et al. (2007); Wright et al. (1991)	2
Pest management	Ajeigbe et al. (2005); Ajeigbe et al. (2006); Chabi-Olaye et al. (2005); Miriti et al. (2012); Nyagumbo et al. (2015); Subbarao et al. (2000); Wright et al. (1991)	7
Tillage type	Kirchhof and Salako (2000); Takim and Fadayomi (2010)	2

0 to 3062 kg ha⁻¹. The zero yield were reported by Masvaya et al. (2017) during a long dry spell in Zimbabwe. In sorghum-cowpea intercrops, sorghum grain yields ranged from 808 to 4560 kg ha⁻¹ whilst cowpea grain yields ranged from 20 to 1315 kg ha⁻¹. For millet-cowpea intercrops, millet yields were 50–4341 kg ha⁻¹ whilst cowpea yields ranged from 10 to 2850 kg ha⁻¹. Generally, intercropping decreased yields of cowpea and cereal crops across the studies although at different magnitudes (Fig. 2).

Productivity of cowpea-based intercropping systems was determined using LER. In most cases, cereal partial LER was higher than cowpea partial LER (Fig. 3). In the majority of the studies reviewed, LER values were > 1 (Fig. 4, Tables S1, S2, S3). The highest LER values of > 2 were recorded in maize-cowpea intercropping experiments (Adeniyani et al. 2011; Dube et al. 2014). On N-deficient soils, which is a common characteristic in SSA, legume-based

intercropping systems are generally more productive than sole crop systems and this is largely due to the ability of legumes to fix atmospheric N₂ (Wang et al. 2014). LER increases with decreasing levels of soil N (Searle et al. 1981; Ahmed and Rao 1982; Kermah et al. 2017), suggesting increased performance of legume-based intercropping systems in poor soils. Mechanisms underlying overall yield increase in intercrops compared with monocrops have been explained as interspecific facilitation and niche complementarity (Soltani et al. 2013; Xue et al. 2016). Increase in plant density through intercropping systems might also improve land productivity through improved resource capture and use efficiency especially in low N input systems (Morris and Garrity 1993; Bedoussac and Justes 2011). However, in some studies, LER values of < 1 were recorded (Grema and Hess 1994; Ajeigbe et al. 2006; Singh and Ajeigbe 2007; Masvaya et al. 2017). Application of N fertilizers results in vigorous cereal

Fig. 2 Comparison of yields of cowpea and cereals grown in monocrops and intercrops in SSA. Yellow circles, grey squares and brown diamonds are for maize-cowpea, sorghum-cowpea and millet-cowpea intercropping systems, respectively



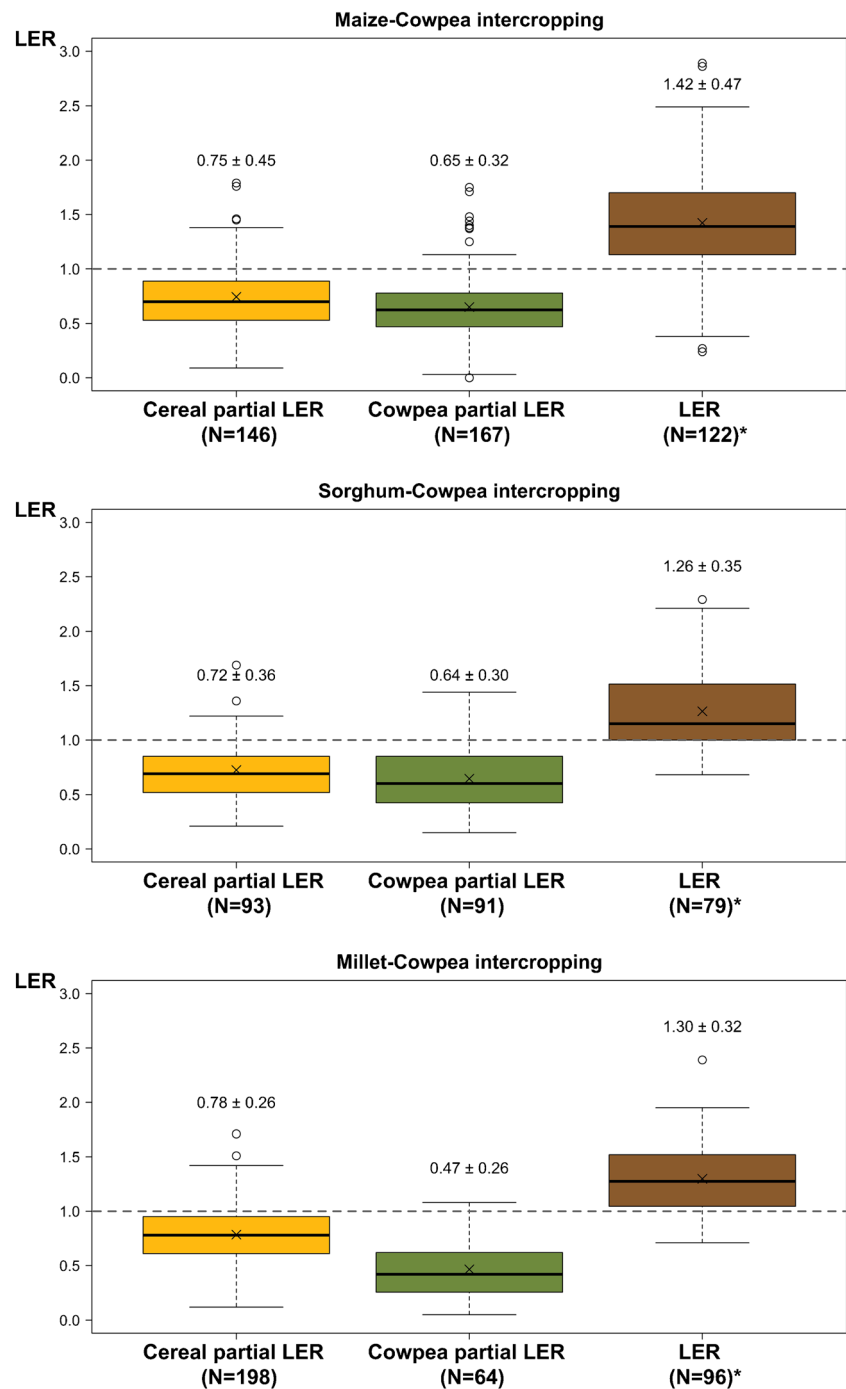
growth whilst suppressing the growth of the understorey legume crop (Yu et al. 2015). When cowpea is severely suppressed and cereal growth is increased, LER values become lower due to reduced cowpea yields (Mead and Willey 1980; Bedoussac and Justes 2011; Bitew et al. 2019). In such cases legume yield becomes a main determinant of LER; therefore, LER values become lower (Ofori and Stern 1987). Generally, productivity of intercropped legumes is reduced when farmers improve their agronomic practices and access to improved seeds, fertilizers and herbicides (Martin-Guay et al. 2018).

3.1 Maize-cowpea intercrops

Intercropping significantly reduced ($P < 0.05$) maize and cowpea yields (Fig. 2, Table S1). However, LER was overall significantly enhanced ($P < 0.001$) and the mean LER reached 1.42 ± 0.47 (Figs. 3 and 4). Several studies carried out in Western Africa (Ajeigbe et al. 2006; Kombiok et al. 2006; Sikirou and Wydra 2008; Takim 2012), Southern Africa (Mariga 1990; Shumba et al. 1990) and Eastern Africa (Alemseged et al. 1996; Khan et al. 2007; Vesterager et al. 2008) reported a yield reduction of maize grown in different planting patterns and row arrangements in intercropping systems with cowpea (Table S1) (Namatsheve et al. 2020). As the proportion of maize rows to cowpea rows increases in intercrops, maize yields increased whilst cowpea yields were reduced (Ajeigbe et al. 2006; Vesterager et al. 2008; Dube et al. 2014). In a semi-arid agro-ecology in Zimbabwe, Shumba et al. (1990) showed that intercropping maize and cowpea resulted in a large yield penalty on the maize crop. However, some cases of maize yield increments in intercrops were reported by Takim et al. (2014). Nyagumbo et al. (2015) found similar maize yields when intercropped with cowpea in planting basins (1802 kg ha^{-1}) or as a sole crop (1789 kg ha^{-1}) in Central Mozambique (Table S1). Yield gains in maize-cowpea intercrops may be attributed to better moisture conservation and weed control in intercrops as compared with

sole crops. Besides, intercropping also reduces niches available for weed growth and associated water loss through transpiration by weeds (Lawson et al. 2013; Dube et al. 2014). Soil moisture conservation in intercropping systems can be attributed to early ground cover by the legume that reduces raindrop impact and soil water evaporation (Trail et al. 2016; Muoni et al. 2020). Also, temporal differences in peak demand for nutrients and water at critical growth stages such as grain filling reduce competition for resources between the component crops (Trail et al. 2016). In addition, cowpea varieties had a large effect on the yield and LER of maize-cowpea intercropping systems (Table S1). Varietal selection determines yield and productivity in both intercrops and monocrops. Cowpea varieties that are less competitive are ideal for intercropping as the farmers' primary production goal is to have a staple cereal grain for subsistence consumption. Maize yields were reduced from 3300 to 1500 kg ha^{-1} (Adeniyani et al. 2011) and from 2233 to 1735 kg ha^{-1} (Haruna et al. 2018) when intercropped with spreading cowpea as compared with erect cowpea (Table S1). Spreading cowpea varieties are often indeterminate with a long growth duration. In intercrops, maize provides a structural support where the vines climb and have access to photosynthetically active radiation which promotes growth and yield of cowpea. Therefore, the extent of maize yield depression acceptable to farmers, and the associated cowpea yield increases are key determinants for selection of cowpea cultivars for intercropping. Some studies reported that erect and early maturing cowpea out yielded spreading cowpea in intercrops (Mohammed et al. 2008; Adeniyani et al. 2011; Haruna et al. 2018). More cowpea yield reduction was reported when intercropped with a late maturing maize variety as compared with an early maturing maize variety (Ewansiha et al. 2015a). Late maturing maize varieties are more competitive, and they require more resources thereby compromising cowpea yields in intercrops.

Fig. 3 Partial land equivalent ratio (LER) and total LER for different cereal-cowpea intercropping systems. Upper and lower edges of boxes indicate 75th and 25th percentiles, horizontal lines within boxes indicate medians, whiskers below and above the boxes indicate the 10th and 90th percentiles and crosses indicate mean LER. Mean LER values and associated standard deviations (SD) are also presented. Outliers are plotted as individual points. Asterisks represent LERs significantly higher than 1 ($P < 0.05$)



Some authors reported that cowpea leaf harvesting and planting intervals had an effect on yield and LER of maize-cowpea intercrops (Table S1). In Kenya, Saidi et al. (2010) recorded a lowest LER of 1 when leaves of intercropped cowpea were not harvested and highest LER of 1.35 when were harvested at 3 weeks after emergence. Therefore, defoliation of cowpea seems relevant to increase productivity. Finally, although application of N fertilizers inhibits N_2 -fixing capacity of cowpea (Malunga et al. 2018), it reduces competition for N

between component crops thereby increasing yields (Jeranyama et al. 2000; Masvaya et al. 2017) (Table S1).

3.2 Sorghum-cowpea intercrops

Sorghum and cowpea yielded more in monocrops as compared with intercrops in most of the cases (Table S2, Fig. 2). Average sorghum yields in monocrops and intercrops were 2059 kg ha^{-1} and 1355 kg ha^{-1} respectively, and average cowpea yields were 759 kg ha^{-1} and 434 kg ha^{-1} in

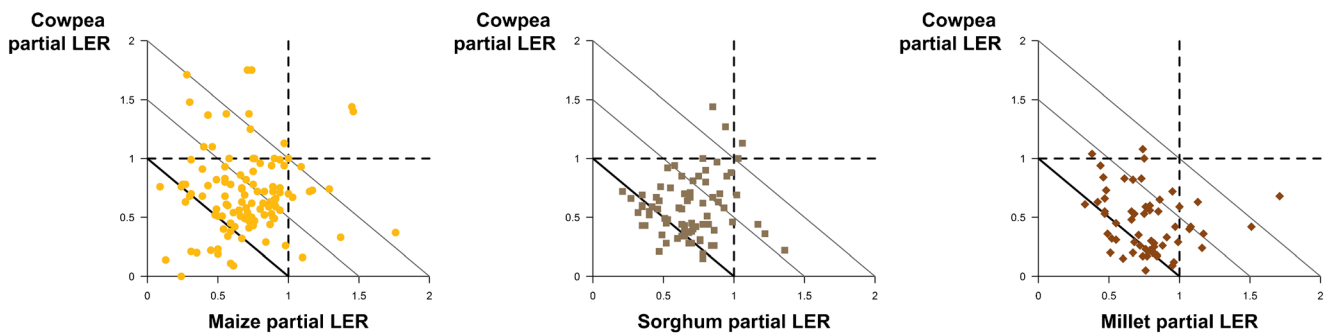


Fig. 4 Comparison of partial land equivalent ratio (LER) of cowpea with those of intercropped cereals in SSA. The solid black lines represent total LER = 1, 1.5 and 2. The vertical dashed line represents partial cereal LER = 1, and the horizontal dashed line represents the partial cowpea LER = 1

monocrops and intercrops. LER was significantly enhanced ($P < 0.01$), and the mean LER reached 1.26 ± 0.35 (Figs. 3 and 4). Row arrangements and crop varieties were major determinants of sorghum-cowpea yields (Table S2). Increasing cowpea rows in relation to sorghum rows in intercrops increased cowpea yields whilst reducing sorghum yields (Ajeigbe et al. 2005; Oseni 2010). Pronounced yield reduction was observed when sorghum was intercropped with a late maturing cowpea variety (Mohammed et al. 2008).

3.3 Millet-cowpea intercrops

Overall, in millet-cowpea intercrops LER was significantly improved ($P < 0.05$), with a mean LER of 1.30 ± 0.32 (Figs. 3 and 4). Intercropping millet with cowpea reduced millet yields (Grema and Hess 1994; Ajeigbe et al. 2006; Singh and Ajeigbe 2007; Sarr et al. 2008) (Table S3). Given the dry climates where millet is typically grown under moderate to severe water stress conditions, introducing cowpea as an intercrop should be based on a relative small depression of millet grain yield, whilst guaranteeing some cowpea grains. Cowpea grain yield from intercrops therefore represents an increase in the efficiency of the utilization of the limited seasonal rainfall.

Cowpea yield was also reduced in millet-cowpea intercropping systems ($P < 0.05$) compared with sole cowpea, from 714 to 309 kg ha^{-1} on average (Grema and Hess 1994; Ajeigbe et al. 2006; Singh and Ajeigbe 2007) (Table S3). Mutual shading by millet especially under relay intercropping results in reduced cowpea yields. However, the relative yield reduction of cowpea in millet-cowpea intercrops depends to a great extent on the varieties. Short-growth duration cowpea varieties suffer more yield reduction as they are often strongly shaded by millet, as similarly observed in maize-cowpea and sorghum-cowpea intercrops. Varietal selection is an important factor; millet had a large yield penalty when intercropped with spreading cowpea varieties (Ntare 1989, 1990; Grema and Hess 1994). Cowpea varieties with long growth duration suffer less competition as they

are more competitive in intercrops as reported in a study by Grema and Hess (1994) where cowpea yield in intercrops was reduced by only 6% (Table S3). On the other hand, Trail et al. (2016) reported a millet yield increment of 27% when millet was intercropped with an upright cowpea variety.

Generally, LERs of millet-cowpea intercropping systems were productive as indicated by LER values of > 1 (Figs. 3 and 4, Table S3), as observed in the other intercropping systems. Varietal selection, row arrangements and better fertility management were reported to increase productivity of millet-cowpea intercropping systems (Oluwasemire et al. 2002; Sanou et al. 2016; Maman et al. 2017). However, LER values of < 1 were reported by Grema and Hess (1994), Ajeigbe et al. (2006) and Singh and Ajeigbe (2007).

3.4 General aspects of cereal-cowpea intercrops

Yield reduction under intercropping is associated with competition by component crops for nutrients, light and moisture (Kermah et al. 2018). Yield reductions are more pronounced for cowpea than for the cereal crop, and this could be attributed to lack of belowground niche differentiation in root distribution and mutual shading (Ajeigbe et al. 2006; Mohammed et al. 2008). In addition, cowpea density in intercrops is generally lower than the cereal crop density; this resulted in lower partial LER values for cowpea than for the cereals (Ofori and Stern 1987; Jeranyama et al. 2000; Masvaya et al. 2017).

Whilst we have relied on LER as the index of assessing intercropping productivity, this may be faulty in some studies. Willey (1979) stated that yields of the sole crop obtained at optimum plant density are required in the computation of LER. This is not always the case in experiments that compare sole crops with intercrops. Plant density of the intercrops is often altered as an experimental variable to determine optimum densities of the intercropping system. Therefore, it is expected that when the yield of the sole crop at optimum planting density of the intercropping system is compared with the yield in the intercropped system, LER values, and thus the

advantages of intercropping, would be overestimated in many experiments.

4 Does intercropping influence biological N₂-fixation in low input systems?

Incorporation of grain legumes into cereal-based systems replenishes soil fertility through N₂-fixation whilst supplying protein rich grains for household food and nutrition (Giller 2001). Biological N₂-fixation contributes N to legume growth and grain production under different environmental and soil conditions. In this systematic review, we found no significant differences $P < 0.05$ between the proportion of N derived from the atmosphere (%Ndfa) for sole or intercropped cowpea, with average values of 56.00 ± 4.89 and 46.62 ± 7.05 , respectively (Table S4). On the other hand, cowpea grown in monocrops significantly ($P = 0.017$) fixed more N than cowpea grown in intercrops due to higher biomass production (Kombiok et al. 2006; Vesterager et al. 2007, 2008; Sarr et al. 2008; Kermah et al. 2018); on average 57 kg N ha^{-1} was fixed in monocropped cowpea and 36 kg N ha^{-1} was fixed in intercropped cowpea (Table S4). Only one millet-based intercropping experiment was reported, in Senegal, where cowpea fixed 35 kg N ha^{-1} and 45 kg N ha^{-1} in intercrop and as sole crop respectively (Sarr et al. 2008) (Table S4). In maize-cowpea intercropping experiments, the highest total amount of fixed N of 101 kg N ha^{-1} was reported by Vesterager et al. (2008), in monocrops where P was applied. Phosphorus provides the mechanism for energy storage in the form of ATP (adenosine triphosphate) and the transfer of that energy source to fuel vital plant functions such as biological N₂ fixation (Tairo and Ndakidemi 2013; Nyoki and Ndakidemi 2014). Application of inorganic fertilizers stimulates larger shoot dry matter yields and the corresponding shoot N accumulated by crops. Giller (2001) and Peoples et al. (2009) also stated that the amount of N₂-fixation depends on accumulated shoot and biomass yield. In weed free monocrops, there is no interspecific competition for available resources such as NP, and this may result in an increase in nodule number and weight which causes stronger leghaemoglobin activity that is directly related to an increase in N₂-fixation (Sarr et al. 2015). Good soil fertility can enhance production of shoot dry matter, which also leads to more N fixed. In an experiment that was carried out in Ghana at two sites with different soil types, Kermah et al. (2018) reported that more N was fixed in cowpea grown in fertile soils than in poor soils (Table S4). Soils with adequate N enabled vigorous above-ground growth, which helps cowpea to intercept ample solar radiation. Low N₂-fixation of 4 kg N ha^{-1} was reported by Kombiok et al. (2006) in intercropped cowpea in Ghana (Table S4). Even though the %Ndfa is larger when cowpea is grown on poor soils, the

overall benefits are limited due to relatively poorer productivity than on more fertile soils. Vesterager et al. (2008) also reported a relatively low fixation rate of 52 kg N ha^{-1} in intercropping systems. In intercrops, especially when an additive design is used, cereals are more competitive as they are tall and they overshadow cowpea. As a result, mutual shading reduces cowpea growth and this has a negative effect on N₂-fixation and growth of the legume. In addition, infertile soils do not support crop growth, thereby reducing N₂-fixation in intercropped cowpea. However, Marschner (1995) reported that the presence of a cereal exploiting more soil nutrients stimulates legumes to fix more N. Finally, the benefits for integrating cowpea in cereal-based systems are often underreported as N contained in senesced leaves is often missed in N balances. Whilst mechanisms of direct N transfer to cereals from legumes in intercropping systems can be elaborated, what remains in question is whether this process results in meaningful N supply to maize in marginal soils.

5 Conclusions

This systematic literature review was conducted to assess the effect of cereal-cowpea intercropping on productivity and biological N₂-fixation in conditions of sub-Saharan Africa. As expected, the yields of cowpea and the associated cereals were mostly reduced in intercropping systems compared with sole crops. However, maize-cowpea, sorghum-cowpea and millet-cowpea intercropping systems all proved to be significantly more productive, with average LER values of 1.42, 1.26 and 1.30, respectively. We found no significant differences between the proportion of N derived from the atmosphere (%Ndfa) between sole or intercropped cowpea, but the total amount of fixed N was higher in cowpea monocropping systems due to higher biomass production. Intercropping cowpeas with cereals provides an opportunity for subsistence farmers to intensify the land productivity, especially on low fertile soils. However, adoption of intercropping by farmers depends on many factors, such as the perceived value of component crops, access to market and labour issues. Further studies should investigate how to unlock the potential of cereal-cowpea intercropping.

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Authors' contribution TN prepared the original draft of the manuscript. RC, MC and RCH conceptualized the idea and MC defined the literature search criteria. TN and RC managed the literature search and curated the data. RC performed the formal analysis and the data visualization. All the authors reviewed, commented and edited the paper for submission. RC acquired the funding for this work.

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Data availability The datasets generated and analysed during the current study are available in the CIRAD dataverse repository, doi: <https://doi.org/10.18167/DVNI/DXDR1R>

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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