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META-ANALYSIS

Yield and fertilizer benefits of maize/grain legume intercropping in China and Africa: A meta-analysis

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Abstract

Maize/annual grain legume intercropping is pivotal in achieving sustainable intensification in developing countries like China and some African countries. It remains unclear whether and to what extent the benefits of intercropping on crop yield and land-use efficiency vary between the two regions. This meta-analysis compared the performance of intercropping maize with six annual grain legumes (soybean, common bean, groundnut, cowpea, pea, and faba bean) commonly grown in China and Africa. Data extracted from 73 publications were used to analyze land equivalent ratio (LER), yield gain, nitrogen, and phosphorus fertilizer equivalent ratio. The overall values of LER, nitrogen, and phosphorus fertilizer equivalent ratio were significantly >1 for both China and Africa. The overall yield gain was 1.45 ± 0.07 t ha^{-1}, with China having a higher mean (2.3 ± 0.13 t ha^{-1}) than Africa (0.90 ± 0.07 t ha^{-1}). Relay-strip intercropping had the highest LER and yield gain in China, while Africa's yield gain was lower in both strip and alternate row intercropping compared with that of China. Maize/common bean intercrop had the highest yield gain in Africa, while maize/faba bean produced high yield gain in China. The yield gain for maize/peanut and maize/soybean was higher in China than in Africa. Increasing nitrogen and phosphorus rates reduced LER in both regions. Here, we show for the first time that while additional phosphorus increases yield gain for Africa it can reduce absolute yields in China. Therefore, the African farmers are recommended to adopt strip or relay-strip intercropping, common bean insertion into intercropping or moderate phosphorus fertilizer application to substantially improve yield gain and income. For China, minimizing fertilizer use by including intercropping with more legume diversity may contribute to reduced environmental problems while achieving high yield gain.

Keywords Land equivalent ratio · Yield gain · Nitrogen fertilizer equivalent ratio · Phosphorus fertilizer equivalent ratio

1 Introduction

By 2050, Africa's population is predicted to increase by approximately 2.5 billion (Godfray et al. 2010; Gerland et al. 2014). Despite having 14.2% of the world's arable land, feeding Africa remains a challenge due to low agricultural yields, and the region will most likely fail to relieve hunger and malnutrition by 2030 (FAO 2022; Ray et al. 2022). Meanwhile, despite having only 9% of arable land, China has managed to feed 20% of the world's population, owing to intensive irrigation, improved varieties, better soils, and more importantly to extensive fertilizer use (Larson 2013). Recent figures indicated that China's inorganic fertilizer consumption decreased from 463 to 393 kg/ha between 2016 and

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2018. Fertilizer consumption in Africa increased from 17.5 to 20 kg/ha during the same period but remained low when compared to China (World Bank 2022). China's cereal yield in 2018 was 6.1 t/ha, higher than the global average (4.1 t/ha) and Africa's (1.4 t/ha). While in Africa, too little fertilizer is the cause of low crop output, in China, too much fertilizer has been related to several environmental problems (Yusuf et al. 2017; Jiao et al. 2018, 2020; Xu et al. 2018).

China's high food production comes at the expense of poor fertilizer use efficiency and excessive soil residual fertilizer, resulting in groundwater contamination and air pollution (Zhu and Chen 2002; Gong et al. 2011; Wang et al. 2014). African soils, on the other hand, are inherently poor with low organic matter and high nutrient fixation capacity due to continuous monoculture, and efforts to restore soil fertility through fallowing have failed due to rising population density and the resulting demand for land (Tittonell et al. 2007; Ngwira et al. 2012; Vanlauwe et al. 2014, 2015). There is a growing interest in more sustainable ways of producing food in both China and Africa to address these challenges while fulfilling the increased need for calories and nutrients, with a focus on intercropping (Chen et al. 2017; Ingram 2017; Chen et al. 2019).

Intercropping, defined as the cultivation of two or more plant species in the same field either for a specific period or the entire growing season, provides about 15–20% of the global food supply (Willey 1990; Bybee-Finley and Ryan 2018; van Oort et al. 2020). Intercropping is common in countries characterized by low input agricultural systems, lower yields, and small land areas (Ngwira et al. 2012; Woomer et al. 2014). It has been practiced in China for more than 1000 years, and it is still widely adopted in different forms (Zhang et al. 2014). Because traditional row intercropping is labor-intensive (Feike et al. 2012), mechanized strip intercropping has become the most widely practiced form of intercropping today in the country (Qian et al. 2018). In Africa however, the majority of smallholder farmers prefer either in-row or alternate row intercropping to minimize manual weeding (Fig. 1) (Mudita et al. 2008). Maize (*Zea mays* L.) is commonly intercropping with common bean (*Phaseolus vulgaris* L.), soybean (*Glycine max* (L.) Merr.), groundnut (*Arachis hypogaea* L.), and cowpea (*Vigna unguiculata* (L.) Walp.) in Africa (Waddington et al. 2004; Mhlanga et al. 2016; Vanlauwe et al. 2019). While maize/common bean or maize/cowpea intercropping is not popular in China, peanut, soybean, faba bean (*Vicia faba* L.), and pea (*Pisum sativum* L.) intercropping with maize have been widely studied (Fig. 1) (Li et al. 2009; Zhao et al. 2016; Yang et al. 2017).

Intercropping maize with legumes has several benefits including flexibility in planting and soil conservation (Ghosh et al. 2007; Thierfelder et al. 2012), soil carbon sequestration, better soil erosion and weed control, and efficient use of resources (Bilalis et al. 2010; Eskandari and Kazemi 2011; Li et al. 2011; Cong et al. 2015; Verret et al. 2017). Legumes may fix nitrogen when grown as monocultures; but, when intercropped with maize, nitrogen fixation is boosted, ensuring nutrient cycling and long-term viability (Fan et al. 2006). Because maize root exudates increases the expression of genes related to nodulation, intercropping maize/legume has been reported to increase nitrogen fixation (Li et al. 2016; Hu et al. 2021). Greater nitrogen use efficiency in intercropping has been reported to reduce the requirement for inorganic fertilizer nitrogen by about 26% globally (Jensen et al. 2020). As a result, intercropping can be one of the cropping systems that can assist reduce the "ecological yield gap" by increasing soil fertility and lowering fertilizer expenditures (Bonilla-Cedrez et al. 2021).

Even though both Chinese and African farmers practice intercropping, the production settings differ significantly between the two regions in terms of crop species planted, input use, row configurations, soil fertility, and climatic conditions (Fig. 1). Unlike China, some parts of Africa still have food deficits due to unsatisfactory yield gain to fulfill domestic demand. There has been no attempt to comprehensively assess the yield gain in Africa's intercrop systems yet. To the best of our knowledge, the key causes of the differences in absolute yield gain for grain between China and Africa have not been established. Quantitative studies of intercropping between regions with different production contexts, such as China and Africa, could provide new perspectives on China's pollution problems. While low fertilizer use has resulted in less pollution in Africa, China's intercropping management, which has contributed to food self-sufficiency, may give important lessons for Africa farmers. The objectives of this meta-analysis were (1) to determine the productivity of maize/annual grain legume intercropping on overall LER and yield gain (hereafter referred to as net effect) between China and Africa; (2) to ascertain how various intercropping combinations, configurations, and management practices affect productivity for both China and Africa; and (3) determine the contribution of maize/annual grain legume intercropping to efficient fertilizer use.

2 Materials and methods

2.1 Data collection and extraction

We used the Web of Science database (https://apps.webofknowledge.com/) to search for relevant studies on the topic from 1980 to 2020. The search terms (maize* OR corn*) AND (soybean* OR bean* OR faba bean* OR cowpea* OR peanut* OR pea*) AND (intercrop*) AND (yield*) AND (China OR Africa) were employed in the topic field. In total, 1138 articles were retrieved for further refinement (Fig. S1). Only research articles reporting primary data based on field

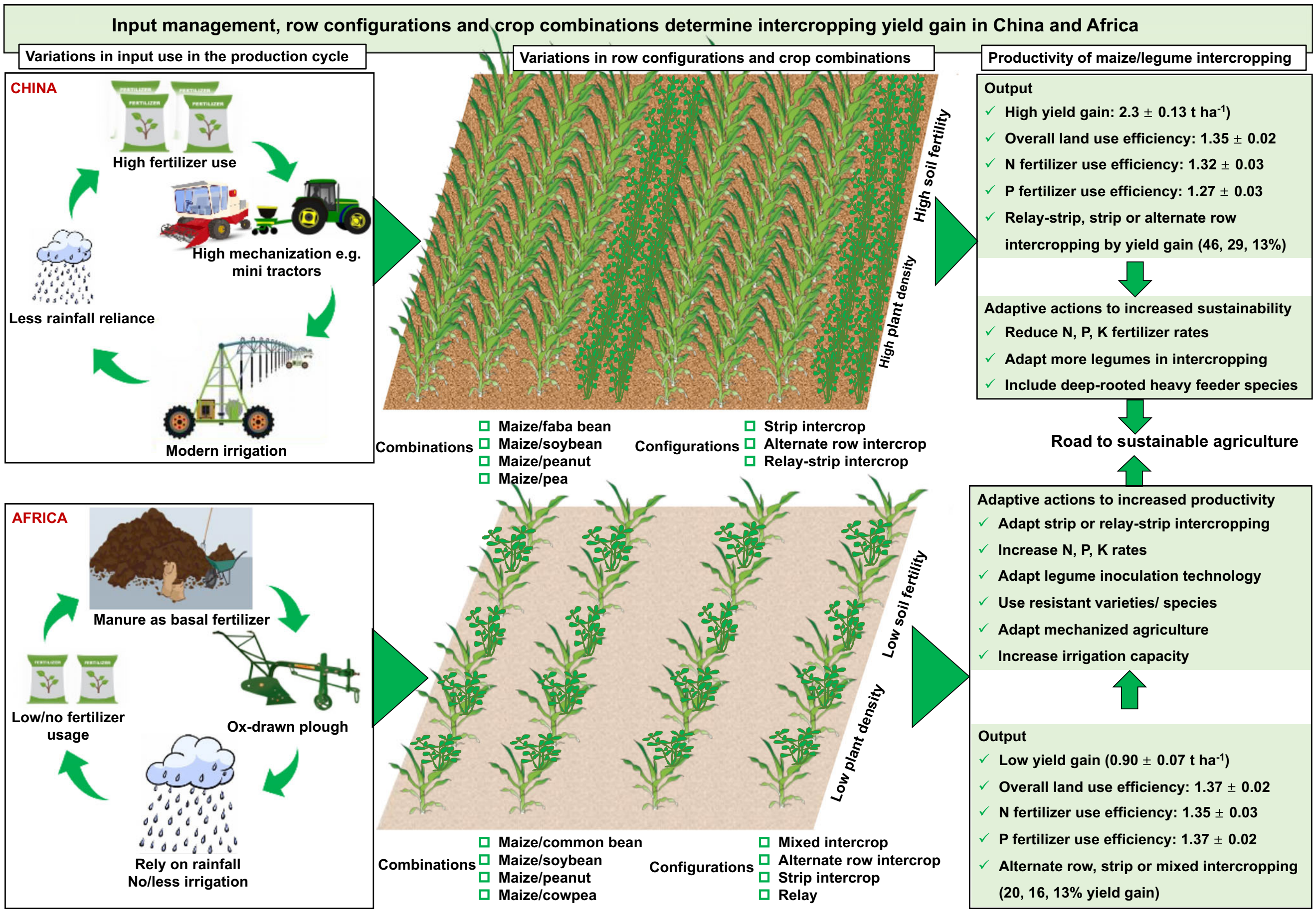


Fig. 1 Schematic view of various management practices and intercropping configurations in China and Africa. NPK represents nitrogen, phosphorus, and potassium. High fertilizer usage in mechanized strip intercropping system is popular in China. Mini-tractors compatible with strip intercropping carry out plowing, planting, pest, and weed control throughout the season. Harvesting can be done by mini-combine harvesters. Farmers in China rely more on irrigated agriculture. For Africa, farmers depend on cattle manure for application before planting, sometimes with additional inorganic fertilizer. Land preparation is done by ox-drawn plows, and crop production is predominantly rainfed.

experiments on maize and annual grain legume yields either as sole or intercrop in China and Africa and published in English were considered for meta-analysis. Articles in press and conference papers, reviews, meta-analyses, or research reporting greenhouse or pot experiments were excluded. Data reported in tables were extracted directly while graphical data were mined using *WebPlot Digitizer 4.3*. A database was created containing key information including (i) intercropping arrangement (e.g., alternate row, strip intercropping, etc.); (ii) experimental site and its soil properties (e.g., soil organic matter, pH); (iii) crop management (e.g., row spacing, planting densities, sowing, and harvesting dates), (iv) nitrogen, phosphorus, and potassium fertilizer rate; and (iv) response variables (i.e., grain yield and LER). If an eligible study contained multi-year field trials conducted across different experimental sites and/or with different crop species (grain legumes), the data was treated separately. A global map was generated using *QGIS 3.16.1* that showed the experimental sites of the studies included in this meta-analysis (Fig. S2).

2.2 Response variables

The yield benefits of intercropping maize with annual grain legumes were expressed using the land equivalent ratio (LER):

$$\mathrm{LER} = \frac{\mathrm{Y1}}{\mathrm{M1}} + \frac{\mathrm{Y2}}{\mathrm{M2}} \quad (1)$$

where Y1 and Y2 represent the yield of maize (species 1) and grain legumes (species 2), M1 and M2 are corresponding sole crop yields (Mead and Willey 1980).

Ideally, LER is a dimensionless indicator of relative grain yields in intercropping compared with sole cropping and, as such, it does not provide a true reflection on the absolute grain yield increase per unit area achieved by intercropping (Li et al. 2020b). To understand the benefits of maize/annual grain–legume intercropping we calculated the net effect, defined as the difference between the observed and the expected yield (Loreau and Hector 2001; Tang et al. 2021).

$$\text{Net effect} = (Y_1 + Y_2) - (\text{EY}_1 + \text{EY}_2) \tag{2}$$

where Y_1 and Y_2 are the observed yields in the intercrops and EY_1 and EY_2 are the expected yields of species 1 and 2 in the intercrop. The expected yield was calculated as the product of the monoculture yield and the land share (Li et al., 2020a).

$$\text{EY}_1 = M_1 \times LS_1 \tag{3}$$

$$\text{EY}_2 = M_2 \times LS_2 \tag{4}$$

where M_1 and M_2 are the yields (per unit area of the respective sole crops) of species 1 and 2 in monoculture whereas LS_1 and LS_2 are the land shares of species 1 and 2 in intercropping. The land share was calculated based on the densities of a species in the intercrop and the sole crop (Li et al. 2020a). Complementarity effect and selection effect were calculated as described by Li et al. (2020a) and their sum results in net effect (Loreau and Hector, 2001). When species differ in resource use and niche differentiation in space or time, complementarity effects arise, resulting in better resource consumption (Hector et al. 2002). Facilitation happens when one species enhances the growth of the other through various mechanisms (Callaway 2007). Direct (e.g., shade or protection from adverse weather) or indirect facilitative effects are possible (e.g., when one species reduces attack by pathogens or herbivores on other species) (Maron et al. 2010; Schnitzer et al. 2011). The complementarity effect is calculated by multiplying the total increase in relative yield in a mixture by the average yield or biomass of the individual crops. The selection effect calculates the relationship between a species' sole crop yield and its change in relative yield in a mixture (Loreau and Hector 2001). The selection effect value indicates to what extent the more productive species' biomass or space occupancy dominance is responsible for overyielding in the mixture. It is a metric for determining how much of the yield increase due to overyielding is attributable to component species with high versus low sole crop yields. If the species in the mixture are complimentary or facilitative in terms of resource acquisition, the overall resource uptake in the mixture will be more than expected from the sole crops (Malézieux et al. 2009).

We used relative indicators to determine the efficiency of intercropping in fertilizer savings. In analogy with LER and water equivalent ratio (Mao et al. 2012), we defined the nitrogen and phosphorus fertilizer equivalent ratio (NFER and PFER, respectively) as the level of nitrogen and phosphorus fertilizer needed in sole crops to produce the same yields in intercropping.

$$\text{NFER} = \frac{\text{Nfert1} \times \frac{Y1}{M1} + \text{Nfert2} \times \frac{Y2}{M2}}{\text{Nfertic}} = \text{pLER1} \times \frac{\text{Nfert1}}{\text{Nfertic}} + \text{pLER2} \times \frac{\text{Nfert2}}{\text{Nfertic}} \tag{5}$$

$$\text{PFER} = \frac{\text{Pfert1} \times \frac{Y1}{M1} + \text{Pfert2} \times \frac{Y2}{M2}}{\text{Pfertic}} = \text{pLER1} \times \frac{\text{Pfert1}}{\text{Pfertic}} + \text{pLER2} \times \frac{\text{Pfert2}}{\text{Pfertic}} \tag{6}$$

where Nfertic and Pfertic are nitrogen and phosphorus fertilizer input per unit area (kg ha^{-1}) of the intercrop (Li et al. 2020a); Nfert1 and Pfert1, and Nfert2 and Pfert2 are nitrogen and phosphorus fertilizer input per unit area of species 1 and 2, respectively in monoculture. pLER represents the partial land equivalent ratio. The nitrogen and phosphorus fertilizer equivalent ratio express the relative amount of nitrogen and phosphorus fertilizer that would be required if sole crops were used to achieve the same yields as a unit area of intercrop. Values of these two metrics larger than 1 indicate fertilizer savings in intercropping. A nitrogen and phosphorus equivalent ratio equal to the LER indicate that the nutrient use efficiency gains of intercropping are primarily due to higher production on less land (Xu et al. 2020). If the fertilizer input in the intercrop is intermediate between those in the sole crops, the nitrogen and phosphorus equivalent ratio will tend to be larger than the LER. If the fertilizer amount in the intercrop is higher than those in the sole crops, the both metrics will tend to be smaller than the LER.

2.3 Calculations on gross income

The weighted mean of grain yield in monoculture systems was determined to compare the total productivity of monoculture and intercropping systems in China and Africa with different crop species:

$$\text{Weighted means of grain yield} = \text{GYmono}_1 \times \text{LS}_1 + \text{GYmono}_2 \times \text{LS}_2 \tag{7}$$

where GYmono_1 and GYmono_2 are grain yields of crops 1 and 2 in monoculture, respectively. LS_1 and LS_2 are the land shares of crops 1 and 2 in the intercropping (Li et al. 2021).

The price per 1000 kg of grain yield of all crop types was based on official producer prices collected from (FAOSTAT 2022). Since there was a wide variation in the price of the same crop across different African countries, all prices were collected first, and an average was calculated. This average producer price was then used to calculate the gross income per hectare for all African countries.

2.4 Explanatory variables

Six explanatory variables were used: (1) intercropping legume species, (2) location, (3) intercropping design, (4) nitrogen fertilizer application rate, (5) phosphorus rate, and (6) potassium rate. Intercrops were also grouped on whether the legume included received fertilizer nitrogen or not. Intercropping designs were treated as relay-strip, strip, mixed, or alternate row intercropping. A few studies from Africa reported as relay intercropping were treated separately from relay-strip as they lacked information on row spacing or planting dates.

2.5 Statistical analysis

Relationships between LER, net effect, nitrogen, and phosphorus fertilizer equivalent ratio with explanatory variables were estimated via mixed-effects modeling using restricted maximum likelihood (REML) as the estimation method. Fifteen models were fitted to the analyzed data (Table S1). Comparisons were done using Fisher's test at a 95% confidence level. Only regression lines with p values less than 0.05 were shown in the figures in the regression analysis. Any records consisting of missing data were excluded in the analysis if required for that variable. All analyses were conducted in *Minitab 17*. Bootstrapping was iterated 1000 times once at an alpha level of 0.05 using the Command Line Editor. Due to insufficient information on measures of precision extracted from the literature, we did not weigh the studies. The analysis of intercropping data with unweighted studies is widely accepted (McDaniel et al. 2014; Yu et al. 2016), and this increases the number of studies available for meta-analysis. A funnel plot relating effect sizes to sample sizes was used to test for publication bias (Philibert et al. 2012).

3 Results and discussion

3.1 Overall effects of intercropping on LER, net effect and its components, gross income, nitrogen, and phosphorus fertilizer equivalent ratio

There were 38 publications on China's intercropping systems, with 35 articles from Africa in our database. There was slight publication bias within the analyzed studies as shown by asymmetrical distribution pattern of the funnel plot (Fig. S3). This was likely attributed to a few studies which had small sample sizes and low LERs. The overall LER was 1.36 ± 0.012 (mean ± standard error), with median, first and third quartile values of 1.33, 1.15, and 1.54, respectively (Fig. 2a). The average net effect for grain yields was 1.45 ± 0.07 t ha^{-1}, with median, first and third quartile values of 1.11, 0.43, and 2.34, respectively (Fig. 2b). Most of the overall yield gain was due to the complementarity effect (1.21 ± 0.06 t ha^{-1}, Fig. 2c), while the selection effect contributed less (0.25 ± 0.04 t ha^{-1}, Fig. 2d). Significant differences in net effect (yield gain) were observed between China (2.3 ± 0.13 t ha^{-1}) and Africa (0.90 ± 0.07 t ha^{-1}). The overall financial analysis indicated that high yield gain in China resulted in a huge gross income of US$3188 ha^{-1} in intercropping than US$1946 ha^{-1} in monocropping. For Africa, gross income in intercropping was US$1519 ha^{-1} and US$948 ha^{-1} in monocropping (Table 1). Maize/soybean intercropping combination had the highest gross income value of US$4124 ha^{-1} for China, while in Africa, maize/common bean intercropping gave the highest income of US$1932 ha^{-1}. Overall, the nitrogen fertilizer equivalent ratio was 1.34 ± 0.02 with a median of 1.29 (Fig. 2e), and phosphorus fertilizer equivalent ratio was 1.33 ± 0.03 with a median of 1.28 (Fig. 2f). The nitrogen fertilizer equivalent ratio was slightly higher for Africa (1.35 ± 0.03) than China (1.32 ± 0.03) although the differences were not significant. Phosphorus fertilizer equivalent ratio, on the other hand, was substantially greater in Africa (1.37 ± 0.02) than in China (1.27 ± 0.03).

High LER found in this study is an indication that there are land sparing benefits derived from growing maize with grain legumes which consequently result in better resource use efficiency. This means that intercropping can produce the same yields while utilizing a smaller land area. The nitrogen and phosphorus fertilizer equivalent ratio represent the ratio of the fertilizer levels used in sole cropping to that used in intercrops to produce equal amounts of yield (Li et al. 2020). The findings on high gross income indicate that farmers have a chance to gain more income from intercropping than monocultures. However, the time of sell is important, as reports have shown that selling immediately after harvesting can reduce returns since demand will be low due to high supply (Rusinamhodzi et al. 2012). Others have suggested that reliable access to inputs and output markets, including functional credit schemes should be provided (Masvaya et al. 2017). Our results highlight that sole crops used 34% more nitrogen and 33% more phosphorus to achieve the same yield as intercrops, indicating increased nitrogen and phosphorus use efficiency. High fertilizer use efficiency can, therefore, be achieved by intercropping, which is particularly important for African smallholders who lack sufficient finances to acquire fertilizers. For China, there is an opportunity to maintain high yields while reducing the excessive use of fertilizers especially in high input-high output systems, hence mitigating several fertilizer-related problems (Gong et al. 2011; Li et al. 2011; Wang et al. 2014).

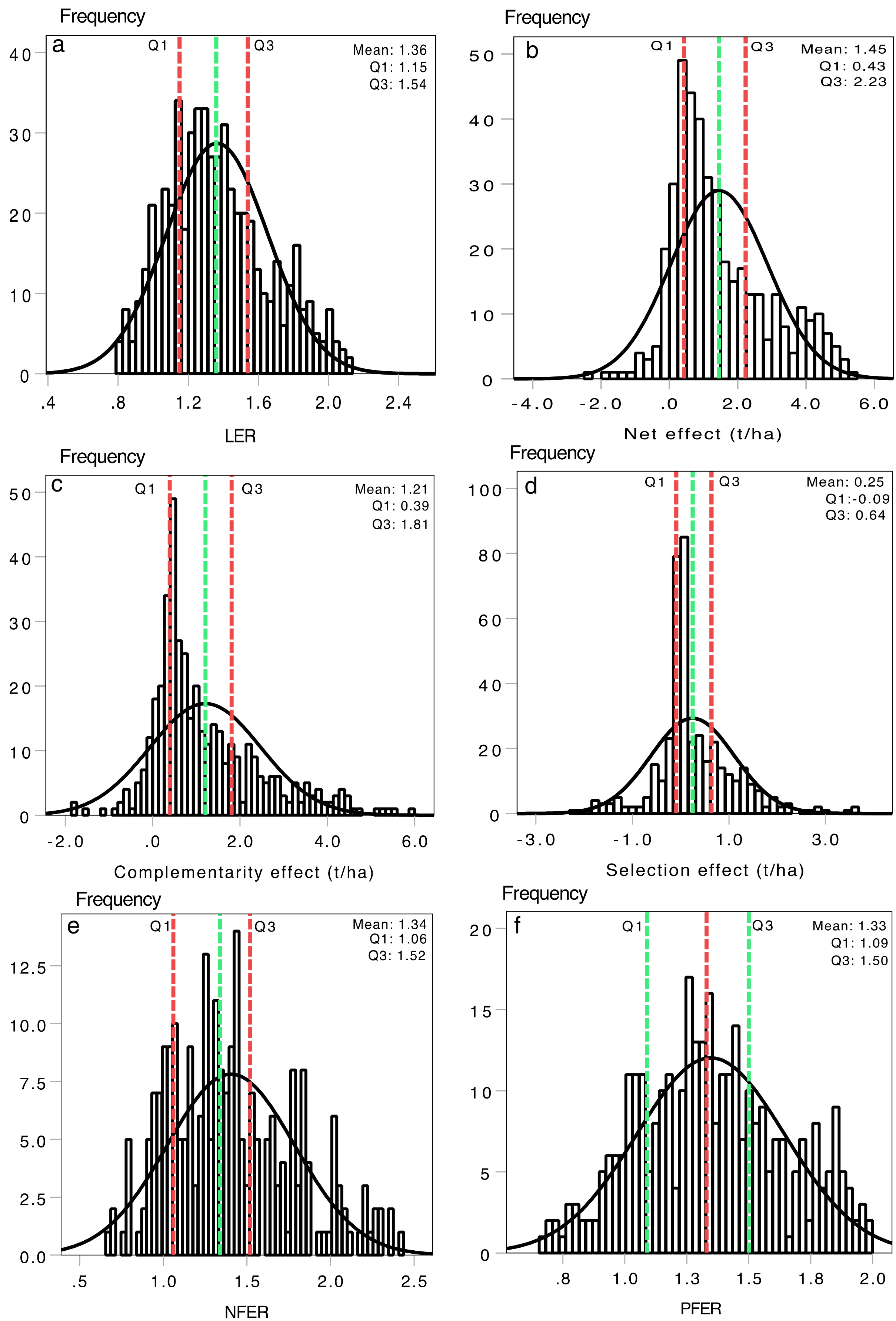

Frequency
a
Q1
Q3
Mean: 1.36
Q1: 1.15
Q3: 1.54
LER
b
Mean: 1.45
Q1: 0.43
Q3: 2.23
Net effect (t/ha)
c
Mean: 1.21
Q1: 0.39
Q3: 1.81
Complementarity effect (t/ha)
d
Mean: 0.25
Q1:-0.09
Q3: 0.64
Selection effect (t/ha)
e
Mean: 1.34
Q1: 1.06
Q3: 1.52
NFER
f
Mean: 1.33
Q1: 1.09
Q3: 1.50
PFER

Table 1 Gross income of crop species under monoculture and intercropping in Africa and China

Region	Crop combination	*n*	Gross income (US$/ha)			
			Monoculture	Intercropped	Increase (%)	*P*
China	Maize/soybean	122	2316	4124	78	<0.001
	Maize/peanut	23	1885	2752	46	<0.001
	Maize/peas	19	2129	3748	76	<0.001
	Maize/faba bean	33	1453	2126	46	<0.001
	Mean		1946	3188	62	
Africa	Maize/soybean	96	644	1044	62	<0.001
	Maize/peanut	25	712	1375	93	0.035
	Maize/common bean	40	1439	1932	34	<0.001
	Maize/cow pea	88	997	1723	73	0.004
	Mean		948	1519	66	

n represents number of observations. Gross income is the income from grain yields of crops. Gross income in the monoculture is the expected, which is the weight of the means of the two monoculture crops based on the land shares occupied by the two crops in the intercropping. Gross income increase (%) is calculated as (Gross income in intercropping – Gross income in monoculture)/Gross income in monoculture × 100.

3.2 LER and yield gain as affected by maize/annual grain-legume intercropping combinations

We estimated the LER for six-grain legumes, each intercropped with maize (Fig. 3a). Two legume species (soybean and peanut) were present in both China and Africa. The data were also analyzed on legume species unique to China (faba bean and pea), and Africa (common bean and cowpea). The LER varied with the grain legume species, and it was higher for maize/peanut intercrop in Africa (1.50 ± 0.05) compared with China (1.03 ± 0.02). China's maize/soybean LER was 1.38 ± 0.03 compared with 1.35 ± 0.02 of the Africa. For China, the maize/faba bean LER was 1.31 ± 0.04 and that for maize/pea was 1.47 ± 0.03. For Africa, the LER for maize/cowpea was 1.37 ± 0.03 and that for maize/common bean was 1.34 ± 0.03. The net effect was significantly higher in China (2.43 ± 0.02) than in Africa (0.79 ± 0.01) for maize/soybean. Similarly, the net effect was 1.45 ± 0.06 for China and 0.61 ± 0.02 for Africa in maize/peanut intercrops (Fig. 3b). In China, net effect was high for maize/faba bean (2.30 ± 0.29) while it was lowest for maize/peanut (1.45 ± 0.03). The highest net effect was observed in maize/common bean (1.89 ± 0.05), and the lowest in maize/peanut (0.70 ± 0.01) for Africa (Fig. 3b).

The global average LER for maize/grain legume intercropping has been estimated to be 1.22 ± 0.02 (Yu et al. 2015) with the highest of 1.30 reported by others (Martin-Guay et al. 2018). Several meta-analyses indicate better crop yield stability and productivity of intercropping compared with sole cropping (Wang et al. 2014; Raseduzzaman and Jensen 2017). The maize/peanut intercropping system for Africa had a significantly higher LER compared with China. This could be because African farmers mostly grow peanut in mixed intercropping system which increases facilitative effects between maize and peanut. The secretion of root exudates by both plants ensures the availability of phosphorus which is generally limiting in African soils. These results concur with Daryanto et al. (2020) who reported higher LER (1.57) for peanuts in Africa and attributed it to the shading effect of maize on peanut which promotes photosynthetic activity and flowering of peanuts. Our study also showed that LER was higher for China in maize/soybean than for Africa although with no significant difference. Nevertheless, significantly higher LER values for maize/soybean intercropping have been reported in many regions of the world including China, although this was not the case for North America (1.06), South America (1.04), and Australia (0.95, Xu et al. 2020). The reasons for low land-use efficiency among the three latter regions have not yet been established. The yield gain in Africa's maize/cowpea was much lower than that of maize/common bean. The high yield gain in maize/common bean intercropping offer new insights into crop species selection for intercropping in Africa. Even though all legume species produce considerable land savings, a choice has to be made for selecting legumes that offer better prospects of improved absolute yields for food security or high-income benefits (Table 1). Adopting more grain legumes with a high potential for better yield gain (e.g., common bean) may improve Africa's food production. In other African regions suitable for cool-season crops, maize/faba bean intercrop can also be adopted to achieve high yield gain.

◀ **Fig. 2** Frequency distribution plots for LER, net effect, complementarity effect, selection effect, nitrogen, and phosphorus (NFER, and PFER) fertilizer equivalent ratio (**a**–**f**, respectively). Vertical lines represent the first quartile (Q1), mean and upper quartile (Q3), respectively. Frequency distributions were estimated using model 1 (Table S1).

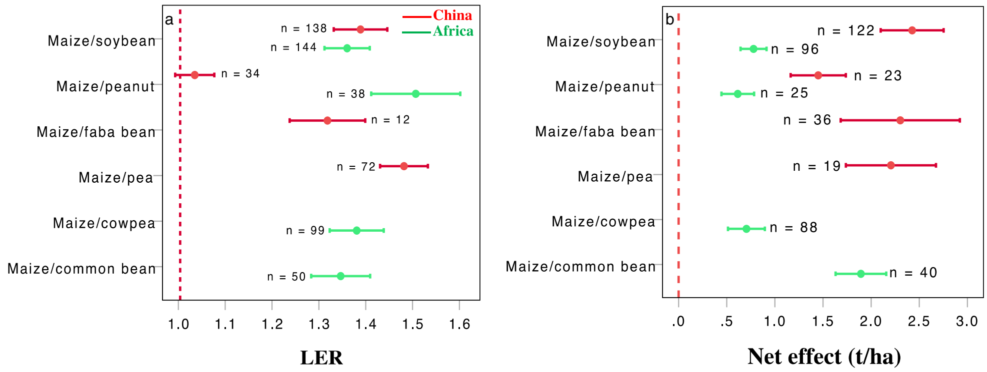


Fig. 3 Land equivalent ratio for maize annual grain-legume intercropping (**a**) and net effect (**b**) between Africa and China. The horizontal lines and symbols (**a** and **b**) represent the confidence interval and mean LER at 95% level. Means of LER and net effect across all legume species in Africa and China were estimated using models 4 and 6 (Table S1), respectively.

Our results on overall net effect value for maize/annual grain legume intercropping concur with the previous research that reported values ranging from 1.5 ± 0.1 t ha^{-1} to 2.14 ± 0.16 t ha^{-1} for different intercropping systems (cereal/cereal, cereal/legume, and legume/legume) (Li et al. 2020a). In particular, China's net effect was significantly higher than that of Africa, which may explain why Africa is still struggling to achieve food self-sufficiency even if it has high land sparing opportunities. Coupled with severe droughts and poor soil fertility problems, the productivity of continuous monocropping remains low. During droughts, a process called "hydraulic lift" allows water to be carried upward through root systems from moister subsurface to dry surface soil (Sekiya and Yano 2004). On a hot and dry day, as transpiration increases, the moisture that has been hydraulically lifted supports crop growth when released into the soil. Because most smallholder farmers live far from water sources that can be used for agricultural irrigation, hence 95% of African agriculture is rainfed (Rockström and Falkenmark 2015). Only about 20% of Africa's cropland is equipped for irrigation, compared to China's 55% (FAO 2022). Therefore, deep-rooted species introduced into intercropping systems can help shallow-rooted crops to access water sources deep in the soil layers that would otherwise be unavailable, hence reducing total crop failure for African farmers (Li et al. 2013; Brooker et al. 2015). However, more research is needed to identify the best species combinations, species densities, and row designs to ensure high water use efficiency in dry conditions (Sekiya and Yano 2004). Increased usage of legumes by Chinese farmers, on the other hand, can help to alleviate water shortages. Intercrops decrease excessive fertilizer use, which reduces eutrophication, a problem that leads to water shortages (Liu et al. 2015).

3.3 Using row configuration variations to explain land-use efficiency and yield gain

The performance of intercropping systems on LER varied significantly depending on the row arrangements (Fig. 4a). The LER for strip intercropping was 1.43 ± 0.03 for China and 1.30 ± 0.05 for Africa. Alternate row intercropping had a LER of 1.37 ± 0.02 for Africa and 1.10 ± 0.02 for China. Mixed intercropping had a LER of 1.48 ± 0.04 while that of relay intercropping was 1.35 ± 0.04 for Africa. Relay-strip intercropping was unique to China, with the highest LER (1.65 ± 0.26). The results on net effect indicated that China's alternate row intercropping provides a higher net effect (1.03 ± 0.02) than Africa's 0.90 ± 0.01 (Fig. 4b). While relay-strip and strip had higher net effect in China, the net effect was significantly lower in both strip (0.56 ± 0.03) and mixed intercropping (0.71 ± 0.01) for Africa. Africa's relay intercropping had a higher net effect (2.34 ± 0.13) than other systems.

When comparing China and Africa, the LER and net effect in strip intercropping were higher for China than for Africa. Farmers in Africa rarely practice strip intercropping while Chinese farmers efficiently manage this system under advanced mechanization. Farmers in China, as well as the Chinese government and the Ministry of Agriculture, have adopted strip intercropping as an environmentally friendly method, and it has already been expanded to 21 provinces (Iqbal et al. 2018). Meanwhile, our results show that even when strip intercropping is done in Africa, the observed benefits are still much lower than those obtained in China. The reason for this could be that Africa continues to employ the conventional strip intercrop method, which has low light use efficiency, radiation use efficiency, low competitive profitability of particular legumes like cowpea, and mechanization incompatibility (Lv et al. 2014). China has created a new mechanized-based maize/soybean strip intercropping model that includes two systems: regular strip intercropping and relay-strip intercropping and has been linked to high productivity (Yu et al. 2015). In a maize/soybean strip or relay-strip intercropping system, the model uses a 200-cm bandwidth, with 2:2 maize-to-soybean rows (Iqbal et al. 2018). This model promotes improved planting and fertilizer application scheduling, which saves fertilizer input, thanks to its interoperability with farming activities. The relay-strip intercrop's temporal structure will thus assure lower nitrogen input during the early co-growth period, which has been shown to promote

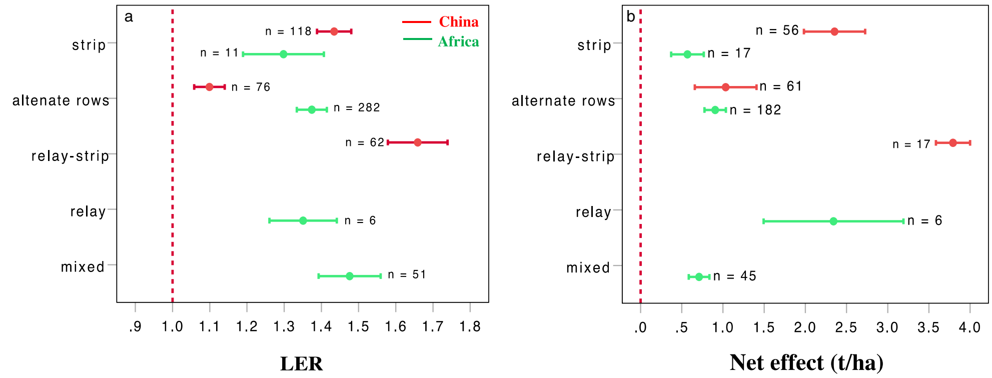


Fig. 4 Land equivalent ratio in China and Africa (**a**), and net effect (**b**) as affected by row arrangements. The horizontal lines and symbols (**a** and **b**) represent the confidence interval and mean LER at 95% level. Means for LER and net effect were fitted using models 8 and 10 (Table S1), respectively.

nitrogen fixation in maize/pea intercrops (Yu et al. 2015; Hu et al. 2016). Greater uptake capacity of belowground resources, due to larger total root length and biomass in relay-strip intercropping compared to that in conventional intercropping systems, has been reported elsewhere (Cong et al. 2015). Furthermore, reports show that in modern mechanized strip intercrop systems, reduced pest loads, weeds, better irrigation, and harvesting practices mechanically in China further increases productivity (Feike et al. 2012; Qian et al. 2018; Alarcón-Segura et al. 2020).

Although Africa had a high LER in the alternate row systems compared with China, the net effect was larger for China than for Africa. Most farmers in Africa grow maize and grain legumes within rows or in alternate rows (Mudita et al. 2008). However, in such cases, both interspecific and intraspecific competition is high since both component crops are grown at the same time leading to suppression of crop yields. Moreover, unlike in China, the inherent soil fertility in Africa is very poor, which may also explain why yield gain was larger in China than in Africa. Strip or relay-strip mechanized intercropping can increase food production in semi-arid regions of the world such as Africa (Qian et al. 2018). However, various obstacles may hamper the goal of increasing yield gain in Africa. The majority of smallholder farmers in Africa lack appropriate mechanization and rely on manual labor, which is less efficient and time-consuming (Rusinamhodzi et al. 2012). Even so, mechanical operations are achievable with suitable crop width configurations and appropriate crop densities in intercropping systems (Xiwen et al. 2015). However, in the context of African intercropping, the incorporation of advanced machinery may be difficult due to incompatible row configurations. Furthermore, the progress in breeding for legume species adaptable to various intercropping designs has been slow in Africa. Meanwhile, the use of semi-dwarf and shade-tolerant soybean cultivars in maize/soybean mechanized intercropping in China is beneficial in reducing the impact of shade (Chen et al. 2017).

Despite the fact that the tested intercropping designs in our study have shown promising outcomes, we must point out that they are based on the majority of studies using intercropping patterns that are effectively maintained by researchers utilizing regionally adapted approaches. The results of researcher-managed trials are frequently positive and promising. However, some features of researcher experimentation may differ from what farmers do during the production cycle. For example, one research indicated that 98% of farmers in South Africa rarely follow a particular design, rather grow maize and other legumes haphazardly (Silwana and Lucas 2002). In our database, just a few studies (26 %) were conducted as on-farm trials, including three studies focused on farmer management on different designs. Farmers' perceptions towards using an intercrop design differed in those few trials. Some farmers in Zimbabwe, for example, appreciated the concept of relay intercropping but failed to implement it deeming it not practical. Farmers rejected the design because of the significant risk of decreased yields in intercropping under stress, less revenue, and the increased labor requirement in intercrop systems compared to monoculture (Masvaya et al. 2017). With good yields in maize and legumes under farmer-managed research in Mozambique, however, 86% of farmers favored within-row intercropping compared to distinct row intercropping, despite the greater labor required (Rusinamhodzi et al. 2012). In this regard, it may be necessary to make farmers actively participate and assume leadership roles in their fields during the adoption of new systems such as mechanized strip or relay strip intercropping. This will acclimatize them to the system while they identify during the process what works best for them for maximum productivity. Nevertheless, when the majority of farmers in Africa have access to the farm machinery required for strip or relay-strip intercropping, increased land-use efficiency and higher absolute yield gain can still be realized. African governments, like China, have a vital role to play in assisting farmers with financial assistance and providing adequate skills for mechanized agriculture. While strip or relay-strip intercropping can be the better options for Africa, soil fertility must be considered, and efforts to increase soil fertility such as residue retention, manuring, and optimum inorganic fertilizer application promoted.

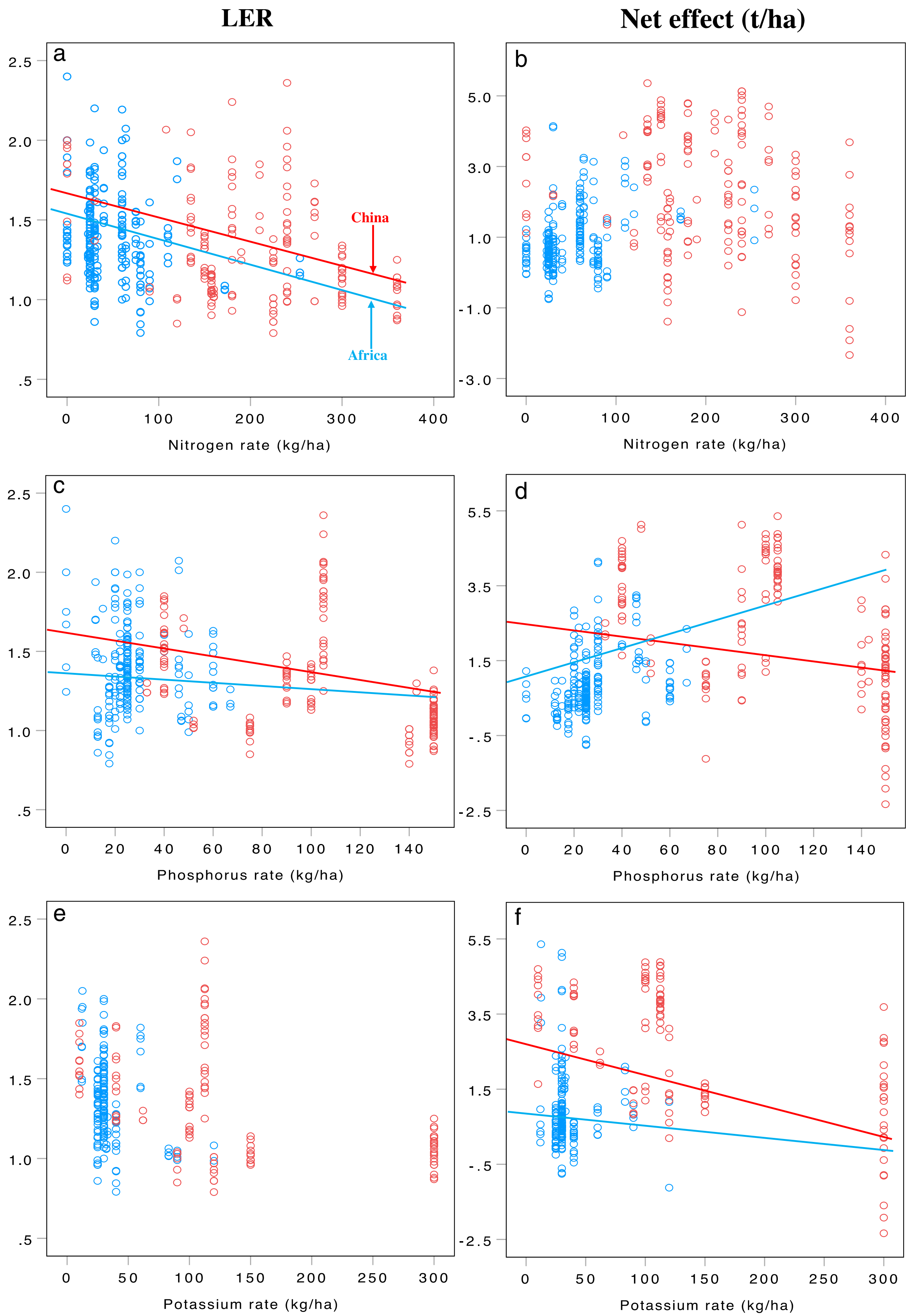
3.4 Nitrogen, phosphorus, and potassium rates in relation to LER, and net effect

LER decreased with additional nitrogen in both China and Africa although China's LER remained higher than that of Africa's (Fig. 5a). Increasing nitrogen reduced net effect for China, but this practice resulted in higher net effect for Africa (Fig. 5b). LER decreased with an increase in phosphorus in both regions although it remained higher for China compared with Africa (Fig. 5c). Significant reductions in net effect were observed in China when the phosphorus rate increased. In Africa, however, an increase in phosphorus rate significantly improved absolute yields (Fig. 5d). Increasing potassium rate caused reductions in LER and net effect for both China and Africa (Fig. 5e–f). The decline in both metrics was more pronounced in China than in Africa.

Overall, our findings are consistent with the results of (Yu et al. 2015), who reported the negative effect of high nitrogen on LER. Under favorable conditions (high nitrogen input), interspecific competition is heightened, while legumes lose their advantage in fixing atmospheric nitrogen. In good conditions, facilitative interactions in maize/legume intercropping are thus less important than competitive ones (Li et al. 2013; Yu et al. 2015). The rate of applied nitrogen did not significantly affect net effect between China and Africa. Li et al. (2020) reported that the yield gain of maize/cereal intercropping is hinged on nitrogen input while yield gain in maize/legume intercropping is independent of nitrogen application. The use of a high nitrogen rate may not, therefore, be warranted in legume intercropping as legumes can fix free atmospheric nitrogen. Inoculation with the appropriate Rhizobium strain enables efficient nitrogen fixation, which benefits the maize crop in intercropping. Maize nitrogen uptake was shown to be 20.2% higher in maize/soybean relay strip intercropping in a previous study (Yong et al. 2014). To reduce nitrogen application in intercrop systems, farmers can take advantage of inoculation and biological nitrogen fixation. Recent studies have focused on the importance of nitrogen application in yield increase while much less attention has been paid to other minerals. Here, we show that the productivity of maize/annual grain legumes is not limited by nitrogen availability, but rather by phosphorus unavailability. Meanwhile, increasing the phosphorus rate improved net effect for Africa whilst reducing the net effect for China (Fig. 5c and d). This finding suggests an opportunity for farmers in Africa to improve yield gain by applying considerably more phosphorus, which is also crucial for nitrogen fixation and compensating for these losses in their maize/grain legume intercropping systems (Fig. 1) (Kanomanyanga et al. 2021).

In Chinese soils, phosphorus accumulation and leaching have increased dramatically, with roughly 67% of phosphorus sources resulting in water contamination (Zhong et al. 2004). As Chinese soils are high in phosphorus, adopting legume species and maize types that are highly efficient in phosphorus acquisition can reduce the need for excessive fertilizer. African soils are severely affected by degradation due to expansion and intensification (Fig. 1) (Chikowo et al. 2010; Tully et al. 2015). Phosphorus losses from soils occur in agricultural landscapes all over the world, mostly as a result of applied phosphorus being bonded in soil surfaces and hence not directly labile for plants and microorganisms like Rhizobia (Turner et al. 2007). Furthermore, African soils lose phosphorus due to erosion (9.6 kg ha^{-1} year^{-1}), and this problem is worsened by expensive phosphorus costs, leading to low phosphorus applications (1.7 kg ha^{-1} year^{-1}) as compared to China (19 kg ha^{-1} year^{-1}) (Alewell et al. 2020). Maize/legume intercropping can be a sustainable option to provide the required phosphorus in African soils. Different plant species obtain phosphorus from the soil in various ways. In comparison to phosphorus-inefficient species, phosphorus-efficient species accumulate significantly more insoluble soil phosphorus or organic phosphorus (Li et al. 2013). Faba bean has been proven in previous studies to assist maize in acquiring more phosphorus than when grown as a monocrop, hence resulting in maize overyielding under intercrop systems. The faba bean's release of protons and organic acids makes phosphorus available for maize uptake in low phosphorus soils. Overyielding due to this facilitative interaction was averaged 46% for maize and 26% for faba bean in a 4-year experiment (Li et al. 2007). In maize/peanut intercrop systems, similar findings have been observed before (El Dessougi et al. 2003). Therefore, breeding and adoption of highly phosphorus-efficient legume species for intercropping with maize can help African farmers achieve higher yield gain. Finally, maize/annual grain legume intercropping represents a promising pathway for sustainable intensification while addressing the pressing demand for food security both in China and Africa (Lithourgidis et al. 2011; Brooker et al. 2015).

Fig. 5 Land equivalent ratio and net effect as affected by nitrogen ▶ rate (***a–b***) and phosphorus (***c–d***), and potassium rate (***e–f***) and net effect in China and Africa. The relationship between LER and net effect with nitrogen, phosphorus, and potassium was estimated using models 12 and 14 and 16 (Table. S1), respectively. The regression equations: (LER = 1.45–0.00126*nitrogen rate, LER = 1.55–0.00126*nitrogen rate, $P < 0.001$; net effect = 0.95–0.0019*nitrogen rate, net effect = 2.67–0.0019*nitrogen rate, $P > 0.05$); (LER = 1.47–0.003193*phosphorus rate, LER = 1.63–0.003193*phosphorus rate, $P < 0.001$; net effect = 1.23 + 0.0148*phosphorus rate, net effect = 3.85–0.0148*phosphorus rate, $P < 0.05$); (LER = 1.54–0.00175*potassium rate, LER = 1.36–0.00322*potassium rate, $P > 0.05$; net effect = 0.78–0.00194*potassium rate, net effect = 3.83–0.01*potassium rate, $P < 0.001$) (***a–f***), for Africa and China, respectively.


LER
Net effect (t/ha)
a
b
c
d
e
f
China
Africa
Nitrogen rate (kg/ha)
Phosphorus rate (kg/ha)
Potassium rate (kg/ha)

4 Conclusion

This study gives crucial lessons from the intercropping systems in the two regions with contrasting production contexts. It has demonstrated that, while intercropping saves land in both China and Africa, the absolute yield increase differs greatly between the two regions. China's intercropping system has a substantial yield gain (2.3 ± 0.13 t ha^{-1}) compared to monocultures, resulting in a 62% increase in gross income. In contrast, Africa's yield gain (0.90 ± 0.07 t ha^{-1}) is lower than China's but with a 68% benefit in gross income. We demonstrate that, while Africa's alternate row intercropping may result in significant land savings, the yield benefit is still relatively low (Fig. 1). Second, our results suggest that intercropping maize/grain legumes is significant for increasing fertilizer use efficiency in both regions. Here, we show that intercropping can significantly reduce fertilizer overuse problems in China thereby minimizing environmental impacts of agriculture while maintaining high food production. Third, this study found that African farmers have the potential to increase intercropping yields by increasing phosphorus application. As a result, excellent grain yields and income can be reached in Africa with adequate inoculation, variety selection, and phosphorus addition (Himmelstein et al. 2017). Finally, we reveal that different legumes have varying yield and income gains with maize/common bean being the most promising in high grain yields for Africa. For future sustainable intercropping, a better focus on relay-strip or strip intercropping, coupled with high phosphorus fertilizer and breeding for legume species that can fit into these systems could improve soil fertility, food production, and income generation in Africa. It is worth noting that to achieve high yield gain in Africa, the governments, scientists, and key agricultural organizations, as well as farmer collaboration and assistance, are greatly required. Chinese farmers are also advised to plant a variety of legumes, ideally varieties with high nutrient acquisition capabilities, in an intercrop system to take advantage of residual soil fertility and biological nitrogen fixation. However, they should avoid overuse of fertilizers, particularly nitrogen, as this limits nodule formation and nitrogen fixation by intercropped legumes. To the best of our knowledge, this is the first meta-analysis to compare maize/grain legume intercropping systems between China and Africa to identify possible avenues to sustainable intensification. We, therefore, believe that the findings presented herein are important for agronomists and policymakers for the betterment of future food production and environmental sustainability.

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Data availability The data used in this study is available from the corresponding author upon reasonable request.

Code availability Not applicable

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

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