Field Crops Research 270 (2021) 108208

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Maize/peanut intercropping increases land productivity: A meta-analysis

Chen Feng[a], Zhanxiang Sun[a,**], Lizhen Zhang[b], Liangshan Feng[a], Jiaming Zheng[a], Wei Bai[a], Chunfeng Gu[c], Qi Wang[b,c], Zhan Xu[b,c], Wopke van der Werf[c,*]

[a] *Tillage and Cultivation Research Institute, Liaoning Academy of Agricultural Sciences, Shenyang, 110161, China*
[b] *College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China*
[c] *Centre for Crop Systems Analysis, Wageningen University, P.O. Box 430, 6700AK, the Netherlands*

ARTICLE INFO

Keywords:
Intercropping pattern
Temporal niche differentiation
Relative sowing time
Nitrogen input
Mixed effects model
Random effects

ABSTRACT

Intercropping cereals and legumes can increase agricultural productivity and reduce inputs of nitrogen fertilizer but there is a need for further literature synthesis on the size of intercropping advantages and the factors affecting these advantages. Here we present a global meta-analysis of 36 studies, 66 experiments and 260 treatments addressing the land productivity of maize (*Zea mays* L.) and peanut (*Arachis hypogaea* L.) intercropping. Data were extracted from the literature and analyzed with mixed effects models to assess the land equivalent ratio (LER) and the factors affecting LER. The worldwide average LER of maize/peanut intercropping was 1.31 ± 0.03. The LER did not vary with continent, intercrop planting pattern and temporal niche differentiation, but sowing maize earlier than peanut (relative sowing time: RSTm<0) increased the partial LER of maize without significantly decreasing the partial LER of peanut. Increased N rate increased the partial LER of maize and decreased the partial LER of peanut but did not affect the total LER. This meta-analysis shows that maize/peanut intercropping is more land use efficient than the sole crops, it attains on average a "win-no win" yield advantage and mainly due to the maize.

1. Introduction

Intercropping is the cultivation of two or more crop species simultaneously in the same field for the whole or a part of their growing period (Willey, 1990; Hauggaard-Nielsen et al., 2008). The advantages of intercropping comprise yield increase (Ofori and Stern, 1987), higher resource use efficiency (Yu et al., 2015; Mao et al., 2012; Zhu et al., 2015), building of soil organic matter, improved N cycling (Cong et al., 2015), and suppression of insect pests (Letourneau et al., 2011), weeds (Liebman and Dyck, 1993), and diseases (Trenbath, 1993; Boudreau, 2013; Zhang et al., 2019). The need for chemical inputs (e.g. N fertilizer, pesticides, herbicides) is often lower in intercrops than in sole crops (Martin-Guay et al., 2018; Xu et al., 2020). Thus, intercropping provides an opportunity to intensify agriculture in a sustainable way (Li et al., 2020a; Tilman, 2020).

Cereal/legume intercropping is practiced worldwide (Rao et al., 1987; Gaba et al., 2015; Yu et al., 2015; Martin-Guay et al., 2018). The key reasons for mixing cereals and legumes in an intercrop are to increase long-term land productivity by biological fixation of atmospheric N by the legumes and to enhance diversity of product and reduce climate risk (Kermah et al., 2017). Cereals may perform better when intercropped with legumes than as a sole crop, especially at low N supply, due to reduced competition for soil N as legumes can obtain their nitrogen from the atmosphere and are not strong competitors for soil N (Cowell et al., 1989; Hauggaard-Nielsen et al., 2001). Furthermore, a high uptake of inorganic N by cereals may enhance the biological N fixation of legumes (Hauggaard-Nielsen et al., 2003), thus enhancing soil fertility by incorporating legumes in cropping systems in the long term (Giller, 2001).

Maize (*Zea mays* L.) is a major cereal grain crop used for food, fuel, starch, and biofuel (Gore et al., 2009) but it requires high water and N inputs due to high productivity (Ju et al., 2009). Continuous maize cropping often leads to a poor and declining soil fertility (Dakora et al., 1987; Sanginga, 2003), which increases the risk of crop failure (Kermah et al., 2017). In China, farmers often apply excessive amounts of N fertilizer to maize, with serious environmental impacts (Tan et al., 2017; Xiao et al., 2019).

* Corresponding author at: Centre for Crop Systems Analysis, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, the Netherlands.
** Corresponding author at: Tillage and Cultivation Research Institute, Liaoning Academy of Agricultural Sciences, No.84 Dongling Road, Shenhe District, 110161, Shenyang, China.
E-mail addresses: sunzx67@163.com (Z. Sun), wopke.vanderwerf@wur.nl (W. van der Werf).

https://doi.org/10.1016/j.fcr.2021.108208
Received 26 March 2021; Received in revised form 7 June 2021; Accepted 14 June 2021
Available online 29 June 2021

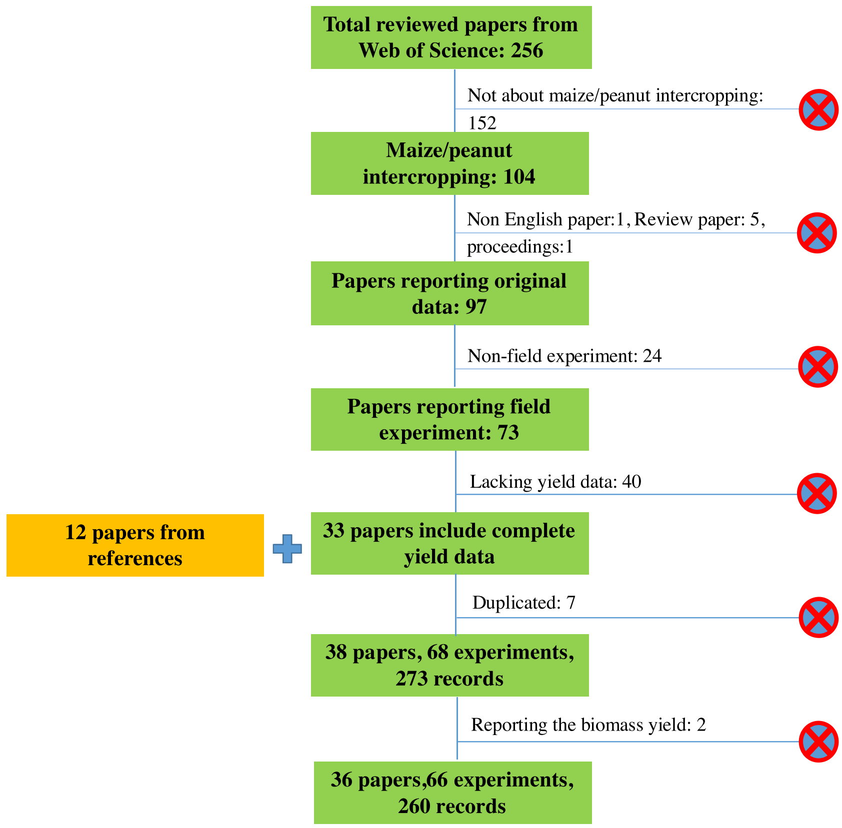

Fig. 1. Paper selection procedure.

Peanut (*Arachis hypogaea* L.) is a high value crop which is a source of protein and cooking oil (Settaluri et al., 2012; Davis and Dean, 2016). Peanut requires less water and fertilizer than maize, it can fix N from the atmosphere and its residues provide N to the following crops (Dakora et al., 1987).

Given interspecific complementary, maize/peanut intercropping has a potential to increase crop yields, reduce risk and improve soil fertility. Cereal/legume intercropping is a good way to improve system productivity as well as resource use efficiency (Searle et al., 1981; Li et al., 2001; Ghosh, 2004; Li et al., 2009), but trade-offs exist. In the maize/-peanut intercropping system, maize is often a dominant crop species, achieving a better growth and higher yield per plant in the intercrop than in the pure stand (Mandimba et al., 1993). Peanut is shaded and dominated by maize with often reduced yield per plant in intercrops (Jana and Saren, 1998; Ghosh, 2004), which may reduce or even nullify the benefit of maize yield increase in intercropping. A synthesis of existing data across the world is required to obtain an overall assessment of the importance of advantages and disadvantages of intercropping maize and peanut.

Only few meta-analyses of intercropping have been done so far, and these showed an average land equivalent ratio (LER) of around 1.22 $\pm$ 0.02 (Yu et al., 2015), 1.30 $\pm$ 0.01 (Martin-Guay et al., 2018) or 1.29 $\pm$ 0.02 in intercrops with maize and 1.16 $\pm$ 0.02 in intercrops without maize (Li et al., 2020a). These previous studies were global meta-analyses that consider a wide range of species combinations, while they contained only a small sample of studies on maize/peanut intercropping, e.g. four out of 100 publications in the study of Yu et al. (2015) and 35 out of 939 data records (126 publications) in Martin-Guay et al. (2018). No meta-analysis has been made of the potential yield advantages that might be achieved by intercropping maize and peanut.

Because of the global importance of maize and peanut as food crops and the recognized potential for complementarity between these species, we conducted a specific meta-analysis on the land use efficiency in maize/peanut intercropping. The land equivalent ratio (LER) is used in this analysis to represents the potential land sparing of intercropping as compared to monocrops. Design and management characteristics of an intercrop such as the intercropping pattern (strip, row, mixed), co-growth period of two species, sowing order of maize and peanut and nitrogen fertilizer input are likely to influence intra- and interspecific interactions by changing the plant growth condition in intercrops, such as light interception, water and nutrient distribution and uptake. Consequently, those agronomic practices are likely to affect the LER. These influences have not before been synthesized in an overarching analysis.

Therefore, in this study, we address two main questions: (1) What is globally the land equivalent ratio of maize/peanut intercropping? (2) How is LER affected by intercrop management, particularly, the intercropping pattern, co-growth period, relative sowing time of two species and fertilizer-N input?

2. Materials and methods

2.1. Data collection and synthesis

A literature search was conducted on the Web of Science on 5th March 2019. We used the search terms (*intercrop* OR (*mix** AND *crop**) OR *polycult* not (fish* or shrimp**)) AND (*maize* OR *corn* OR *zea*) AND (*peanut* OR *groundnut* OR *arachis*) in the topic field. We concentrated on studies performed between 1945 and 2019. The search yielded 256 publications. We selected only those studies that met four inclusion criteria: (1) data were from field experiments (excluding pot experiments); (2) papers reported original data (no reviews); (3) papers were written in English; (4) papers included both the grain yield of intercrops and sole crops, or reported the LER directly. A total of 36 publications were retained (Fig. 1, Appendix: S1, S2).

Multiple data records were extracted from each publication. Different data records from the same publication represent separate experiments

Table 1
Variables extracted from publications.

Variable	Definition	Data type/ Unit
Title	Title of publication	Text
Authors	Authors of Publication	Text
Continent	Continent where experiments were carried out	Text
Latitude and longitude	Latitude and longitude of the experimental site	Text
Intercropping pattern	In which way the two species were intercropped: - **Strip intercropping** two species planted in alternative strips and at least one strip includes more than one row; - **Row intercropping** two species planted in alternate rows; - **Mixed intercropping** two species planted in the same field without any distinct row or strip pattern.	
Sowing and harvesting date	Sowing and harvesting date of intercropped species or information on total period and overlap period of intercrops to calculate relative sowing time (RST) or temporal niche differentiation (TND)	Date
Fertilizer-N rate	Amount of N applied as fertilizer to intercrops and sole crops per unit area of the whole field	kg/ha
Yield (or LER)	Grain yield of sole crops and intercrops, or LER of intercropping	ton/ha

and different treatments within an experiment. An experiment was defined as a unique combination of site and year. Treatments were defined by differences in crop variety, crop density, crop configuration, intercropping pattern, sowing dates and fertilizer amount within an experiment. We individually coded each publication and each experiment in order to use publication and experiment as random factors in the analysis to account for factors affecting the response variables that were either not reported or not included in our statistical models. Data were extracted from tables or from figures using the GetData Graph Digitizer version 2.26 (Table 1). The final data set included data from 36 publications, 66 experiments and 260 records (treatments within experiments).

2.2. Response variables

The response variables were the LER (Mead and Willey, 1980) and partial land equivalent ratios (PLER) for maize (PLERm) and peanut (PLERp), calculated according to the Eqs. (1) and (2).

$$\mathrm{LER} = \frac{Y_m}{M_m} + \frac{Y_p}{M_p} \tag{1}$$

$$\mathrm{PLERm} = \frac{Y_\mathrm{m}}{M_\mathrm{m}} \;\&\; \mathrm{PLERp} = \frac{Y_\mathrm{p}}{M_\mathrm{p}} \tag{2}$$

Where Y_m and Y_p are the yields of maize and peanut in intercropping, while M_m and M_p are the corresponding sole crop yields.

We also calculated the relative yield advantage of maize (ΔRYm) and peanut (ΔRYp) to further quantify the contribution of the component crops to the intercropping system (Loreau and Hector, 2001):

$$\begin{aligned} \Delta\mathrm{RYm} &= \frac{Y_\mathrm{m}}{M_\mathrm{m}} - \frac{\mathrm{EY}_\mathrm{m}}{M_\mathrm{m}} = \mathrm{PLERm} - \mathrm{LSm} \\ \Delta\mathrm{RYp} &= \frac{Y_\mathrm{p}}{M_\mathrm{p}} - \frac{\mathrm{EY}_\mathrm{p}}{M_\mathrm{p}} = \mathrm{PLERp} - \mathrm{LSp} \end{aligned} \tag{3}$$

Where EY_m and EY_p are the expected yields of maize and peanut, which were calculated as the product of the monoculture yield and the land shares, LSm and LSp. The land share was calculated on the basis of the densities of a species in the intercrop and in the sole crop or on the basis of the row or plant arrangement (Li et al., 2020b). There is a relative yield advantage for a species if the relative yield is greater than the land share. Based on the sign of the relative yield advantage of the two component species, a mixture could be classified as win-win (both species have a relative yield advantage), win-lose (maize has a relative yield advantage but peanut has not), lose-win (maize has a relative yield loss but peanut has a relative yield advantage) and lose-lose (both species suffer a yield disadvantage).

2.3. Explanatory variables

In the analyses, we used five explanatory variables, i.e. (1) continent, (2) intercropping pattern (categorical with 3 levels: strip, row, mixed), (3) temporal niche differentiation (TND, Eq. 4), (4) relative sowing time (RST, Eq. 5), (5) amount of fertilizer-N applied to intercrops. The information on continent, intercropping pattern, and amount of N fertilizer was obtained directly from the publications, while the TND and RST were calculated according to Eqs. (4) and (5) (Yu et al., 2015, 2016):

$$\mathrm{TND} = \frac{P_\mathrm{system} - P_\mathrm{overlap}}{P_\mathrm{system}} = 1 - \frac{P_\mathrm{overlap}}{P_\mathrm{system}} \tag{4}$$

Where P_overlap refers to the length of the period of overlap in the growing periods of maize and peanut in the maize/peanut intercropping, while P_system refers to the duration from sowing of the first crop species to harvest of the second crop species. This index quantifies the proportion of time that the two species in the intercrop are growing separately, resulting in competitive relaxation due to the empty space left by the not yet sown or already harvested companion species. When TND is zero, the growing periods of maize and peanut are identical, i.e. simultaneous intercropping. When TND is greater than 0, there is temporal differentiation in growing periods, i.e. relay intercropping. TND would be one in the case of no overlap (co-growth), i.e. double cropping. Double cropping was not addressed in this analysis.

Relative sowing time (RST) of a species was calculated as the difference in sowing time between a focal species and its companion, expressed as a proportion of the growing period of the focal species (Yu et al., 2016):

$$\mathrm{RSTm} = \frac{S_\mathrm{m} - S_\mathrm{p}}{H_\mathrm{m} - S_\mathrm{m}} \tag{5}$$

where RSTm represents relative sowing time of maize with respect to peanut. S_m is the sowing date of maize, S_p is the sowing date of peanut, and H_m is the harvest date of maize with all dates based on the Julian calendar. Negative values of RSTm characterize the time, relative to the total growing period of maize, that maize is growing before, and therefore without competition from peanut. If maize was sown later than peanut or if, maize and peanut were sown simultaneously, then RSTm $>= 0$. We expect that a species can escape from strong competition from the companion species if it is sown before the other species, i.e. if its RST < 0.

2.4. Statistical analysis

All analyses were conducted in R Core Team (2021). Linear regression with mixed effects models (R package nlme; Pinheiro et al., 2021) was used to quantify the relationships of LER and PLER with the explanatory variables (continents, intercropping pattern, TND, RST, N input). We assumed normal error structure and homoscedasticity and validated the model assumptions by checking residuals (Zuur et al., 2009). We used publication and experiment within publication as random effects to account for differences between the studies (publications) and between experiments (sites*years) within studies. The best random effects structure was identified by fitting different structures and comparing them using Akaike's information criterion using the R functions anova and AIC. Fourteen mixed-effects models were fitted to the data (Table 2). Data records with missing values of a variable were

Table 2
List of final best models fitted to the data.

Model	Equations
1	$LER_{ijk}=\beta_0+a_i+b_{ij}+\varepsilon_{ijk}$
2	$PLERm_{ijk}=\beta_0+a_i+b_{ij}+\varepsilon_{ijk}$
3	$PLERp_{ijk}=\beta_0+a_i+b_{ij}+\varepsilon_{ijk}$
4	$LER_{ijk}=\beta_0+\beta_1{*}continent_i^2+\beta_2{*}continent_i^3+\beta_3{*}continent_i^4+a_i+b_{ij}+\varepsilon_{ijk}$
5	$LER_{ijk}=\beta_0+\beta_1{*}Pattern_{ijk}^2+\beta_2{*}\ Pattern_{ijk}^3+a_i+b_{ij}+\varepsilon_{ijk}$
6	$LER_{ijk}=\beta_0+\beta_1{*}TND_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
7	$PLERm_{ijk}=\beta_0+\beta_1{*}TND_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
8	$PLERp_{ijk}=\beta_0+\beta_1{*}TND_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
9	$LER_{ijk}=\beta_0+\beta_1{*}RSTm_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
10	$PLERm_{ijk}=\beta_0+\beta_1{*}RSTm_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
11	$PLERp_{ijk}=\beta_0+\beta_1{*}RSTm_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
12	$LER_{ijk}=\beta_0+\beta_1{*}N_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
13	$PLERm_{ijk}=\beta_0+\beta_1{*}N_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$
14	$PLERp_{ijk}=\beta_0+\beta_1{*}N_{ijk}+a_i+b_{ij}+\varepsilon_{ijk}$

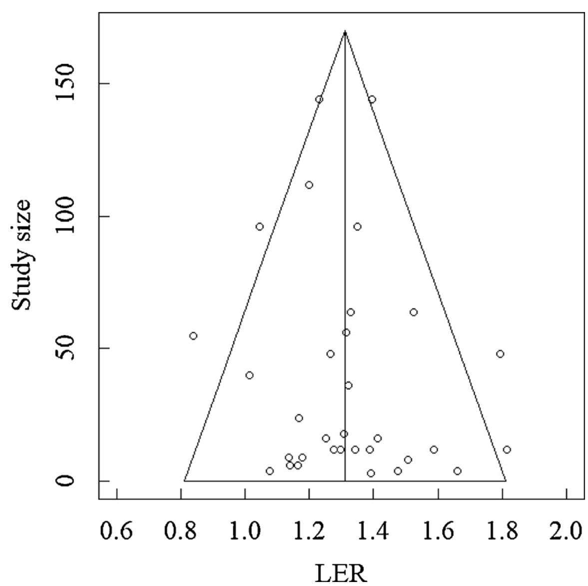

Fig. 2. Funnel plot of study size against land equivalent ratio. The vertical line represents the estimated mean LER via the mixed effects model. Study size is defined as the total number of plots across all replications, treatments and experiments in a study.

excluded from analyses which required that variable.

The indices, *i, j* and *k* represent publication, experiment and treatment, respectively. In all mixed models, the regression coefficients are denoted by β whereby β_0 denotes the intercept while other coefficients β denotes the effects either of a covariable (in which case β represents a

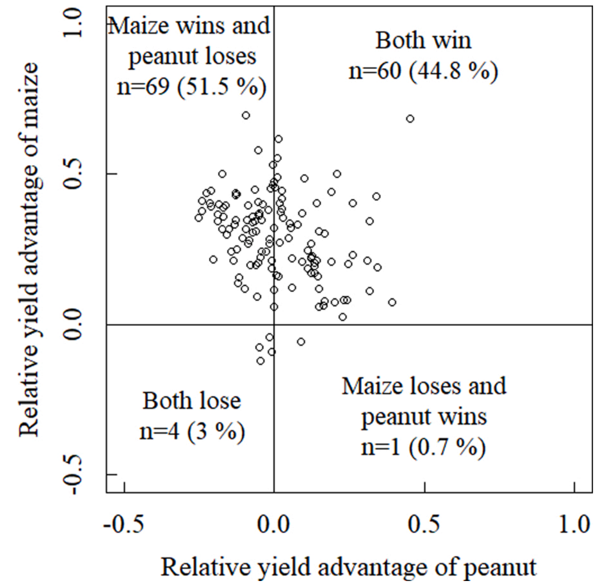

Fig. 4. Scatter plot of the relative yield advantage of maize (ΔRYm) versus the relative yield advantage of peanut (ΔRYp).

slope) or a categorical effect (in which case β represents a difference in intercept between categories). a_i is a random publication effect and b_{ij} is a random experiment effect. a_i and b_{ij} are assumed normally distributed with constant variances. ε_{ijk} is a residual random error assumed normally distributed with constant variance. The variance terms a_i, b_{ij} and ε_{ijk} were all assumed independent. Superscripts 2, 3, 4 in model 4 (Table 2) indicate different continents while superscripts 2 and 3 in model 5 indicate different intercropping patterns.

We made a funnel plot (Duval and Tweedie, 2000) for LER to assess publication bias. For the funnel plot, we plotted study size against LER of each study as a proxy for study accuracy. The study size was calculated by summing the number of experimental units over all experiments and treatments underlying the mean LER calculated from the publication (Yu et al., 2015). The funnel shape was almost symmetrical (Fig. 2), indicating absence of publication bias (Peters et al., 2008).

Because many publications did not include sufficient information (e.g. standard deviation or standard error) to estimate SEs of the LER per each treatment, we did an unweighted analysis in which all studies had an assumed equal variance, consistent with earlier meta-analyses on intercropping (Yu et al., 2015; Martin-Guay et al., 2018; Xu et al., 2020; Li et al., 2020a). The advantage of an unweighted analysis is that a greater number of source papers is suitable for analysis, thus increasing the sample size of studies that is available for this meta-analysis.

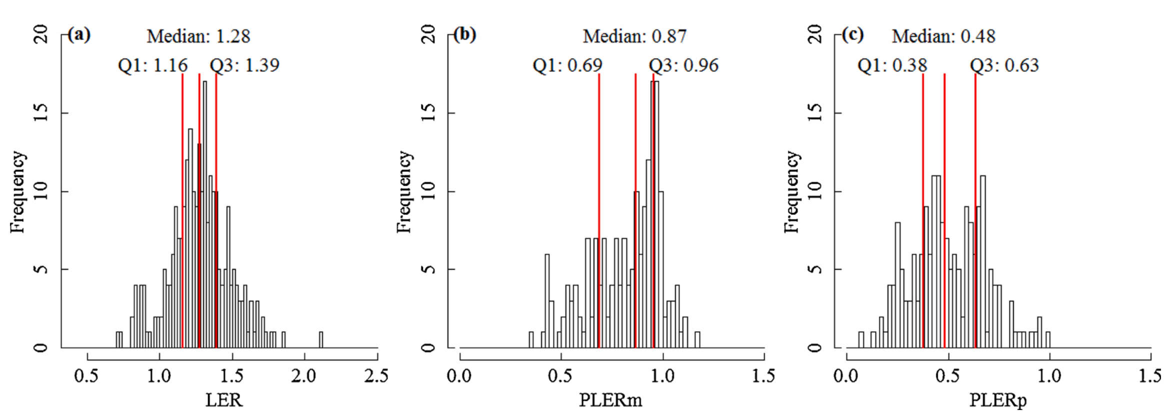

Fig. 3. Frequency distribution of LER (a), PLERm for maize (b) and PLERp for peanut (c). Vertical lines indicate the first (Q1), median and the third (Q3) quartile (transition value) of LER, PLERm and PLERp, respectively (Model 1, 2 and 3, Table 2).

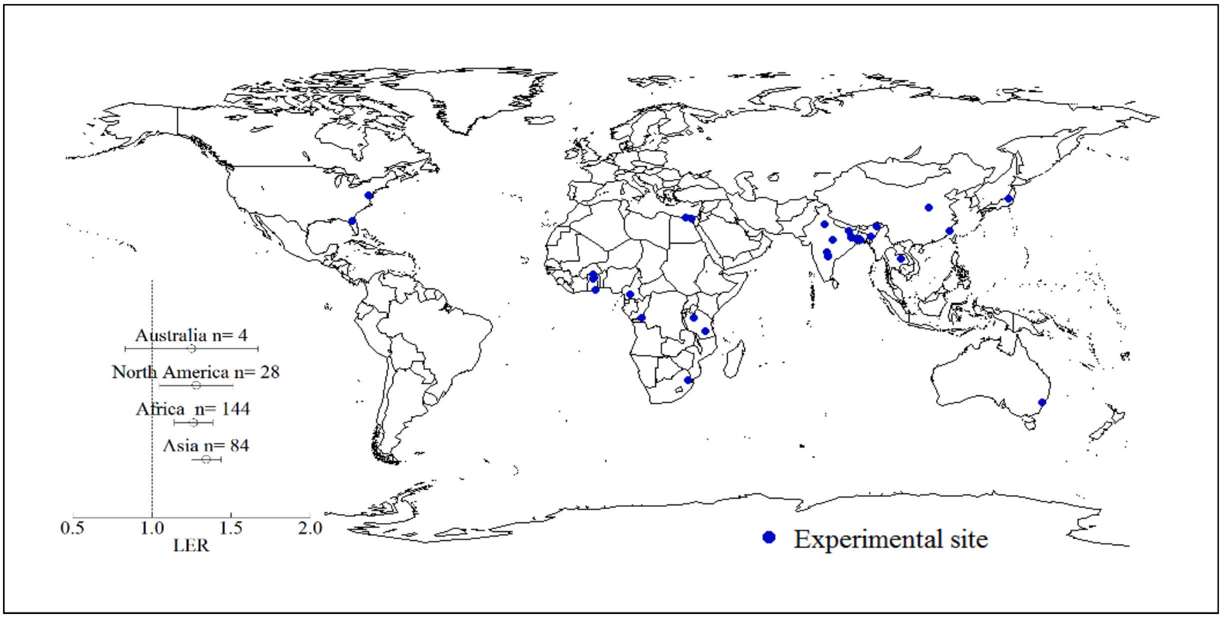

Fig. 5. Estimated means and global distribution of studies on the LER of maize/peanut intercropping. The horizontal bars represent 95 % confidence intervals; the dashed lines indicate LER = 1. Mean LERs for each continents were estimated with model 4 (Table 2).

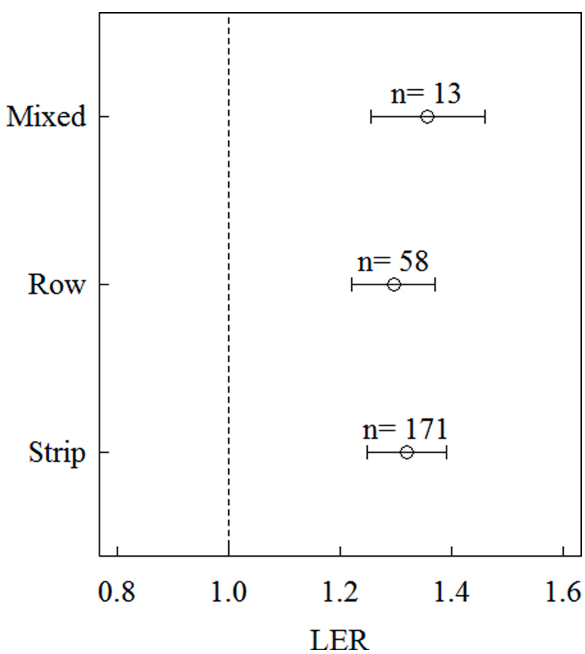

Fig. 6. Estimated mean LER in three intercropping patterns, mixed, row and strip. The horizontal bars represent 95 % confidence intervals; the dashed line indicates LER = 1. Mean LERs in different intercropping patterns were estimated with model 5 (Table 2).

3. Results

3.1. Land equivalent ratio

The first quartile of LER was 1.16, the median LER was 1.28, and the third quartile was 1.39 (Fig. 3a). The mean LER was 1.31 ± 0.03. There were 238 LER values (92 %) greater than one, indicating that in a large majority of cases, maize/peanut intercropping gave a higher land use efficiency than sole crops. The mean PLER of maize was 0.85 ± 0.03 and the mean PLER of peanut was 0.49 ± 0.03, while the median PLER of maize was 0.87 and the median PLER of peanut was 0.48 (Fig. 3b and c). The high relative yield of maize contributed more to the high LER than the more modest PLER of peanut. The mean relative yield advantage of maize was 0.29, while the mean relative yield advantage of peanut was 0.01 (Fig. 4). Maize had a relative yield advantage in the far majority of cases (96.3 %) while peanut had slightly more often a relative yield disadvantage (54.5 %) than a relative yield advantage (45.5 %).

The maize/peanut intercropping studies analysed here were distributed over Africa (144 records), Asia (84 records), North America (28 records) and Australia (4 records). The mean LER was 1.26 ± 0.06 in Africa, 1.35 ± 0.05 in Asia, 1.28 ± 0.11 in North America, and 1.25 ± 0.21 in Australia (Fig. 5), with no significant difference among continents ($P = 0.7112$). Generally, maize/peanut intercropping increased land use efficiency across different parts of the world.

3.2. Effect of different factors on the LER

There was no significant difference in the LER between the three intercropping patterns ($P = 0.3236$), ranging from 1.30 ± 0.04 in row intercropping to 1.36 ± 0.05 in mixed pattern (Fig. 6). The configuration also showed no significant effect on the relative yield advantage of maize ($P = 0.0609$) and peanut ($P = 0.3721$). There was no response of the LER and PLER to TND, but the PLER of peanut tended to increase with TND (Fig. 7c), suggesting that relative yield of peanut was more sensitive to TND than the relative yield of maize.

Sowing maize earlier than peanut increased the PLER for maize by 0.63 units as the RST decreased by one unit (Fig. 7e). There was no effect of RST on the PLER of peanut or the total LER (Fig. 7d, f). Increased fertilizer-N rate increased the PLERm ($P = 0.0213$), decreased the PLERp ($P = 0.0106$) and had no effect on the total LER indicating an N rate benefit to intercropped maize but a negative effect on peanut (Fig. 7g, h, i).

4. Discussion

This is the first meta-analysis on the land use efficiency of maize/peanut intercropping. Based on the information of field studies in a global database, we found that maize/peanut intercropping is a means to increase land productivity (LER = 1.31 ± 0.03 with a maize PLER of 0.85 and a peanut PLER of 0.49). Martin-Guay et al. (2018) and Yu et al. (2015) reported worldwide average LERs of 1.30 ± 0.01 and 1.22 ±

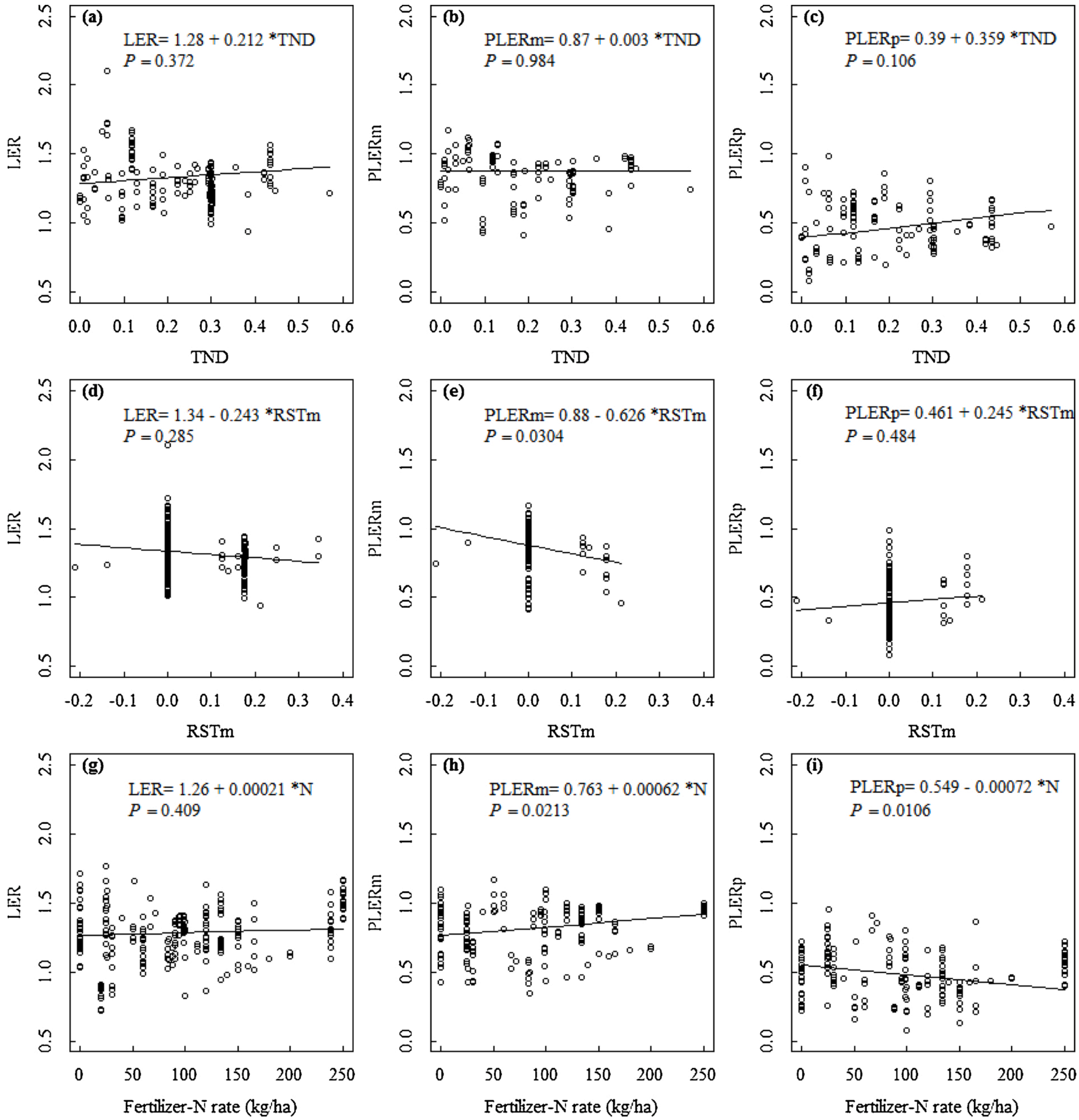

Fig. 7. Relationship between the LER and TND (a), the PLERm and TND (b), the PLERp and TND (c), the LER and RSTm (d), the PLERm and RSTm (e), the PLERp and RSTm (f), the LER and fertilizer-N rate (g), the PLERm and fertilizer-N rate (h), and the PLERp and fertilizer-N rate (i). *P*-values refer to the slopes of the regressions. The relationships between response variables (LER, PLERm and PLERp) and explanatory variables (TND, RSTm, Fertilizer-N rate) was estimated by mixed effects model 6-8, 9-11, 12-14.

0.02, respectively, while Li et al. (2020a) found an average LER of 1.29 ± 0.02 in maize based intercrops. The average LER in this study of 1.31 ± 0.03 was in line with the results of these meta-analyses that were based on multiple species combinations. It confirms the general belief that cereal/legume intercropping has a land use advantage.

Maize/peanut intercropping attains on average a "win-no win" yield advantage, with a relative yield advantage for maize of 0.29 and for peanut of a scant 0.01. In about 52 % of the records maize showed a relative yield gain while peanut lost, while 45 % of the records showed a relative yield gain for both maize and peanut (Fig. 4). Overall, a comparatively high maize yield in the intercrop was the main reason for an overall yield advantage in maize/peanut intercropping.

There was no response of the LER to TND, which is not consistent with previous studies. Yu et al. (2015) found that LER increased with TND. Xu et al. (2020) also found a positive effect of TND on the LER in maize/soybean intercropping. The lack of relationship between the LER and TND in our dataset could be due to the comparatively narrow range of TND in the extracted studies which was from 0 to 0.57 (Appendix: S3) compared to 0 to 0.95 in Yu's dataset (2015), where the wider range of the independent variable increases the chance to find a significant response. Yu et al. (2015) furthermore mentioned that when conditions are favorable for crop growth (high N input), competition for light is strong, and high LER is achieved by allowing TND to mitigate this strong competition. On the other hand, when nutrients are limiting (0 or low N), the effect of temporal niche differentiation on LER was not as strong as under more favorable conditions. In the studies in our database, the N input was relatively low (Appendix: S4), 90.8 ± 12.1 kg/ha in the intercropping system. This moderate input may also be a reason why temporal niche differentiation did not show a significant positive effect on LER. However, we still found a slight positive trend of PLERp to TND, suggesting that relative yield of peanut was more sensitive to TND than maize by reducing the shaded time.

We found that PLERm increased with larger negative values of RSTm (earlier sowing for maize), while there was no effect of RSTm on PLERp. This means that sowing maize earlier will result in a higher relative yield of maize, but it will not strongly influence the relative yield of peanut. Thus, our analysis indicates that the sowing order of species in maize/peanut intercropping could be a better predictor for intercrop maize performance than the duration of the co-growth period. Sowing maize earlier than peanut can improve the relative yield of maize of this intercropping system.

We found no response of the LER to the fertilizer-N rate. However, the PLER of maize increased and the PLER of peanut decreased with higher N rate. Higher N input leads to a more vigorous growth of maize, which negatively affects peanut by competition for light and water. Peanut is less responsive to N input than maize because it can fix N from atmosphere. Thus, with greater input of N, the competitive balance between the species is tilted towards greater advantage for maize. Possibly in an attempt to attain high maize yield, researchers in most of the experiments in our dataset used a relative high N input for intercropping without considering the shading effect on peanut and the biological N fixation of peanut. New experiments are needed with moderate N input in intercropping to maintain peanut yield and achieve the N saving potential of maize/peanut intercropping.

5. Conclusions

Maize/peanut intercropping is a promising practice to achieve sustainable high crop yield. It is important not only for smallholder agriculture to meet the demands for food and protein, but also for land sparing in developing countries. Maize had substantial relative overyielding, while peanut had not. The dominant crop species, maize, makes the largest contribution to the high LER of maize/peanut intercropping. The intercrop planting patterns and temporal niche differentiation had no effect on land equivalent ratio, while sowing maize earlier than peanut in intercropping increased the relative yield of maize without jeopardizing the yield of peanut. The LER did not respond to fertilizer-N rate, however, PLER of maize increased and of peanut decreased with increased N rate.

Declaration of Competing Interest

The authors declare that there are no competing interests.

Acknowledgements

We acknowledge the financial support by the National Key Research and Development Program of China (Grant numbers: 2016YFD0300202), Liaoning Revitalization Talents Program (XLYC2007041, XLYC1807056), the National Natural Science Foundation of China (Grant numbers: 41807388, 31461143025), the State Administration of Foreign Experts Affairs of the People's Republic of China (P182006002), and the European Union's Horizon 2020 Programme for Research & Innovation under grant agreement no. 727217 (ReMIX: Redesigning European cropping systems based on species MIXtures). We thank staff of the crop system analysis group of Wageningen University for help, and we thank the reviewers for helpful suggestions for improvement.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2021.108208.

References

Boudreau, M.A., 2013. Diseases in intercropping systems. Annu. Rev. Phytopathol. 51, 499–519.
Cong, W.F., Hoffland, E., Li, L., Six, J., Sun, J.H., Bao, X.G., Zhang, F.S., van der Werf, W., 2015. Intercropping enhances organic carbon and nitrogen in soil. Glob. Change Biol. 21, 1715–1726.
Cowell, L.E., Bnnuen, E., Van Kessel, C., 1989. Yield and N_2 fixation of pea and lentil as affected by intercropping and N application. Can. J. Soil Sci. 69 (2), 243–251.
Dakora, F.D., Aboyinga, R.A., Mahama, Y., Apaseku, J., 1987. Assessment of N_2 fixation in groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* L. Walp) and their relative N contribution to a succeeding maize crop in Northern Ghana. MIRCEN J. Appl. Microbiol. Biotechnol. 3 (4), 389–399.
Davis, J.P., Dean, L.L., 2016. Peanut composition, flavor, and nutrition. Peanuts. AOCS Press, pp. 289–345.
Duval, S., Tweedie, R., 2000. Trim and fill: a simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. Biometrics 56 (2), 455–463.
Gaba, S., Lescourret, F., Boudsocq, S., Enjalbert, J., Hinsinger, P., Journet, E.P., Navas, M.L., Wery, J., Louarn, G., Malezieux, E., Pelzer, E., 2015. Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. Agron. Sustain. Dev. 35 (2), 607–623.
Ghosh, P.K., 2004. Growth, yield, competition and economics of groundnut/cereal fodder intercropping systems in the semi-arid tropics of India. Field Crops Res. 88 (2–3), 227–237.
Giller, K.E., 2001. Nitrogen Fixation in Tropical Cropping Systems. CABI Publishing. CAB International, Wallingford, UK.
Gore, M.A., Chia, J.M., Elshire, R.J., Sun, Q., Ersoz, E.S., Hurwitz, B.L., Peiffer, J.A., McMullen, M.D., Grills, G.S., Ross-Ibarra, J., Ware, D.H., Buckler, E.S., 2009. A first-generation haplotype map of maize. Science 326 (5956), 1115–1117.
Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2001. Interspecific competition, N use and interference with weeds in pea–barley intercropping. Field Crops Res. 70 (2), 101–109.
Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2003. The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. Nutr. Cycl. Agroecosyst. 65 (3), 289–300.
Hauggaard-Nielsen, H., Jørnsgaard, B., Kinane, J., Jensen, E.S., 2008. Grain legume–cereal intercropping: the practical application of diversity, competition and facilitation in arable and organic cropping systems. Renew. Agric. Food Syst. 23 (1), 3–12.
Jana, P.K., Saren, B.K., 1998. Dry-matter accumulation, yield attributes and yield of summer maize (*Zea mays*) and groundnut (*Arachis hypogaea*) intercropping systems as influenced by irrigation. Indian J. Agron. 43 (1), 18–22.
Ju, X.T., Xing, G.X., Chen, X.P., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proc. Natl. Acad. Sci. 106 (9), 3041–3046.
Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D., Abaidoo, R.C., Giller, K.E., 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. Field Crops Res. 213, 38–50.
Letourneau, D.K., Armbrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutiérrez, C., López, S.D., Mejía, J.L., Rangel, A.M.A., Rangel, J.H., Rivera, L., Saavedra, C.A., Torres, A.M., Trujillo, A.R., 2011. Does plant diversity benefit agroecosystems? A synthetic review. Ecol. Appl. 21 (1), 9–21.
Li, L., Sun, J.H., Zhang, F.S., Li, X.L., Yang, S., Rengel, Z., 2001. Wheat/maize or wheat/soybean strip intercropping: I. Yield advantage and interspecific interactions on nutrients. Field Crops Res. 71 (2), 123–137.
Li, Y.Y., Yu CB, Cheng X., Li, C.J., Sun, J.H., Zhang, F.S., Lambers, H., Li, L., 2009. Intercropping alleviates the inhibitory effect of N fertilization on nodulation and symbiotic N_2 fixation of faba bean. Plant Soil 323 (1–2), 295–308.
Li, C.J., Hoffland, E., Kuyper Th, W., Yu, Y., Zhang, C.C., Li, H.G., Zhang, F.S., van der Werf, W., 2020a. Syndromes of production impact yield gains in intercropping. Nat. Plants 6, 653–660.
Li, C.J., Hoffland, E., Kuyper Th, W., Yu, Y., Li, H.G., Zhang, C.C., Zhang, F.S., van der Werf, W., 2020b. Yield gain, complementarity and competitive dominance in intercropping in China: a meta-analysis of drivers of yield gain using additive partitioning. Eur. J. Agron. 113, 125987.
Liebman, M., Dyck, E., 1993. Crop rotation and intercropping strategies for weed management. Ecol. Appl. 3 (1), 92–122.
Loreau, M., Hector, A., 2001. Partitioning selection and complementarity in biodiversity experiments. Nature 412, 72–76.
Mandimba, G.R., Galandzou, C., Guenguie, N., 1993. Effect of plant population densities on the growth of *Zea mays* L. and *Arachis hypogaea* L. in intercropping systems. Biol. Agric. Hortic. 10 (2), 141–154.
Mao, L.L., Zhang, L.Z., Li, W.Q., van der werf, W., Sun, J.H., Spiertz, H., Li, L., 2012. Yield advantage and water saving in maize/pea intercrop. Field Crops Res. 138, 11–20.
Martin-Guay, M.O., Paquette, A., Dupras, J., Rivest, D., 2018. The new green revolution: sustainable intensification of agriculture by intercropping. Sci. Total Environ. 615, 767–772.
Mead, R., Willey, R.W., 1980. The concept of a 'land equivalent ratio' and advantages in yields from intercropping. Exp. Agric. 16 (3), 217–228.
Ofori, F., Stern, W.R., 1987. Cereal–legume Intercropping Systems, Advances in Agronomy, 41. Academic Press, pp. 41–90.

Peters, J.L., Sutton, A.J., Jones, D.R., Abrams, K.R., Rushton, L., 2008. Contour-enhanced meta-analysis funnel plots help distinguish publication bias from other causes of asymmetry. J. Clin. Epidemiol. 61 (10), 991–996.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team, 2021. nlme: Linear and Nonlinear Mixed Effects Models. https://CRAN.R-project.org/package=nlme.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R foundation for statistical computing, Vienna, Austria. http://www.R-project.org/.

Rao, M.R., Rego, T.J., Willey, R.W., 1987. Response of cereals to nitrogen in sole cropping and intercropping with different legumes. Plant Soil 101 (2), 167–177.

Sanginga, N., 2003. Role of biological nitrogen fixation in legume based cropping systems; a case study of West Africa farming systems. Plant Soil 252 (1), 25–39.

Searle, P.G.E., Comudom, Y., Shedden, D.C., Nance, R.A., 1981. Effect of maize+ legume intercropping systems and fertilizer nitrogen on crop yielding and residual nitrogen. Field Crops Res. 4, 133–145.

Settaluri, V.S., Kandala, C.V.K., Puppala, N., Sundaram, J., 2012. Peanuts and their nutritional aspects—a review. Food Nutr. Sci. 3 (12), 1644.

Tan, Y.C., Xu, C., Liu, D.X., Wu, W.L., Lal, R., Meng, F.Q., 2017. Effects of optimized N fertilization on greenhouse gas emission and crop production in the North China Plain. Field Crops Res. 205, 135–146.

Tilman, D., 2020. Benefits of intensive agricultural intercropping. Nat. Plants 6, 604–605.

Trenbath, B.R., 1993. Intercropping for the management of pests and diseases. Field Crops Res. 34 (3–4), 381–405.

Willey, R.W., 1990. Resource use in intercropping systems. Agric. Water Manage. 17 (1–3), 215–231.

Xiao, G.M., Zhao, Z.C., Liang, L., Meng, F.Q., Wu, W.L., Guo, Y.B., 2019. Improving nitrogen and water use efficiency in a wheat-maize rotation system in the North China Plain using optimized farming practices. Agric. Water Manage. 212, 172–180.

Xu, Z., Li, C., Zhang, C., Yu, Y., van der Werf, W., Zhang, F., 2020. Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use: a meta-analysis. Field Crops Res. 246, 107661.

Yu, Y., Stomph, T.J., Makowski, D., van der Werf, W., 2015. Temporal niche differentiation increases the land equivalent ratio of annual intercrops: a meta-analysis. Field Crops Res. 184, 133–144.

Yu, Y., Stomph, T.J., Makowski, D., Zhang, L.Z., van der Werf, W., 2016. A meta-analysis of relative crop yields in cereal/legume mixtures suggests options for management. Field Crops Res. 198, 269–279.

Zhang, C.C., Dong, Y., Tang, L., Zheng, Y., Makowski, D., Yu, Y., Zhang, F.S., van der Werf, W., 2019. Intercropping cereals with faba bean reduces plant disease incidence regardless of fertilizer input; a meta-analysis. Eur. J. Plant Pathol. 1–12.

Zhu, J., van der Werf, W., Anten, N.P., Vos, J., Evers, J.B., 2015. The contribution of phenotypic plasticity to complementary light capture in plant mixtures. New Phytol. 207 (4), 1213–1222.

Zuur, A., Ieno, E., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology With R. Springer Science & Business Media.