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The new Green Revolution: Sustainable intensification of agriculture by intercropping

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HIGHLIGHTS

- Global productivity potential of intercropping was determined using a meta-analysis.
- Global land equivalent ratio of intercropping was 1.30.
- Land equivalent ratio of intercropping did not vary through a water stress gradient.
- Intercropping increases gross energy production by 38%.
- Intercropping increases gross incomes by 33%.

GRAPHICAL ABSTRACT

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ABSTRACT

Satisfying the nutritional needs of a growing population whilst limiting environmental repercussions will require sustainable intensification of agriculture. We argue that intercropping, which is the simultaneous production of multiple crops on the same area of land, could play an essential role in this intensification. We carried out the first global meta-analysis on the multifaceted benefits of intercropping. The objective of this study was to determine the benefits of intercropping in terms of energetic, economic and land-sparing potential through the framework of the stress-gradient hypothesis. We expected more intercropping benefits under stressful abiotic conditions. From 126 studies that were retrieved from the scientific literature, 939 intercropping observations were considered. When compared to the same area of land that was managed in monoculture, intercrops produced 38% more gross energy (mean relative land output of 1.38) and 33% more gross incomes (mean relative land output of 1.33) on average, whilst using 23% less land (mean land equivalent ratio of 1.30). Irrigation and the aridity index in non-irrigated intercrops did not affect land equivalent ratio, thereby indicating that intercropping remains beneficial, both under stressful and non-stressful contexts concerning moisture availability. Fertilisation and intercropping patterns (rows and strips *vs.* mixed) did not affect land equivalent ratio. Although intercropping offers a great opportunity for intensification of existing agricultural lands, many challenges need to be tackled by experts from multiple disciplines to ensure its feasible implementation.

1. Introduction

By the middle of the 21st century, the global human population is projected to exceed nine billion and will continue to grow (Gerland

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et al., 2014). To meet people's needs for calories and proteins, some have predicted that crop production will have to double (100–110%) relative to its 2005 level, or roughly triple (176–238%), if the entire population were to gain access to the same *per capita* consumption enjoyed by First World inhabitants (Tilman et al., 2011). Achieving this goal with limited environmental impacts offers an unprecedented challenge to humankind. Ideally, this challenge would be met through the sustainable intensification of agriculture, *i.e*., without harmful trade-offs between productivity and other ecosystem services (Millennium Ecosystem Assessment, 2005; Tilman et al., 2011; FAO, 2017). By increasing the yields of some cereals, the Green Revolution has so far permitted humans to cope with population growth (Khush, 2001; Pingali, 2012), and its new technologies are still central to ongoing reduction in the total number of undernourished people (FAO et al., 2015). However, improving the potential yields of staple crops is proving to be increasingly challenging in developed countries; closing yield gaps in developing countries, which are the differences between actual and potential yields, might be insufficient to ensure global food security in the future (Cassman et al., 2003). Here we argue that intercropping could push back forecasted yield ceilings in a sustainable way and may help solve the potential humanitarian crisis to come.

The yield improvement potential of intercropping has been repeatedly demonstrated (Ren et al., 2014; Aziz et al., 2015; Bedoussac et al., 2015; Yu et al., 2015, 2016; Himmelstein et al., 2017), although this response is often limited to cereal/legume intercropping systems, to their certain geographical scope, or to specific benefits, such as land sparing. Intercropping can also provide many ecosystem services, such as reducing the needs for chemical inputs to control insect pests (Letourneau et al., 2011; Iverson et al., 2014), weeds (Liebman and Dyck, 1993) and diseases (Boudreau, 2013), whilst diminishing greenhouse gas emissions that are linked to industrial N_2-fixation (Crews and Peoples, 2004). The presence of N_2-fixing legumes in intercrops could also solve the problem of N fertilisation asynchrony with crop demand, which is known to incur great losses through leaching (Crews and Peoples, 2005). This enhanced N-retention could even be accompanied by a greater potential for carbon sequestration in soils (*e.g*., Chapagain and Riseman, 2014; Cong et al., 2015). Furthermore, micronutrient malnutrition, also called the 'hidden hunger', is one of the failings of the Green Revolution (Pingali, 2012), a problem to which many regions of the world are still susceptible (FAO et al., 2015), particularly under ongoing atmospheric change (Loladze, 2002, 2014). Hence, natural biofortification of food products through the mobilisation of P, Fe and Zn by cereals in intercrops is another example where intercropping could be of great utility (Zuo and Zhang, 2009; Xue et al., 2016). All of this suggests multiple win-win trade-offs between productivity and ecosystems services (Iverson et al., 2014), but much effort is still required to determine which other services are improved by intercropping (Brooker et al., 2015).

Most of these ecosystem services are directly linked to the biomass-enhancing mechanisms that are in place within intercropping systems, *e.g*., dilution effects of host diversity for herbivory and disease, and facilitation effects for the acquisition of nutrients. The interactions between species that govern these mechanisms have been hypothesised to be mediated by the environment, with facilitation being more common under conditions of high physical stress relative to more benign abiotic conditions (Maestre et al., 2009). This is worth noticing, because the innovations of the Green Revolution have done well in fertile environments, but not so well in harsh ones where crop improvement programmes lag behind (Pingali, 2012). This means that positive interactions between species in intercropping systems could hypothetically exert a greater effect on marginal lands or in stressful environments.

Nevertheless, the most obvious ecological advantage of intercropping remains land sparing (Waggoner, 1996) which is the most common way to quantify intercropping benefits. Land sparing through intercropping is usually quantified by the land equivalent ratio (LER) (Willey and Osiru, 1972). The LER is the relative land area that is required under sole cropping to produce the yield that can be achieved under intercropping. A meta-analysis containing 100 different studies found a median LER of 1.17, meaning that 1 ha under intercropping produced, on average, as much as 1.17 ha under sole cropping (Yu et al., 2015). Even though LER offers the possibility to evaluate the potential for land sparing, this metric may be ill-adapted in other situations, *e.g*., when we are concerned about a given amount of agricultural land. The relative land output (RLO) has been used less frequently, but offers a good way to assess benefits in the latter situation. By converting harvested biomass of each intercropped species into a comparable value (*e.g*., harvested gross energy), it is possible to join their yields together. The RLO is then the comparison of total yield under intercropping with total yield under sole cropping for a given amount of land.

As promising as intercropping might seem for ecological reasons, farmers will require economic incentives for adopting this more complex practice. A meta-analysis in Africa found that intercropping benefits on yield were linked to benefits on gross incomes (Himmelstein et al., 2017). A greater independence from industrial N-fertilisers, the prices of which are highly sensitive to the energy market (Huang, 2007), is another reason why producers could consider intercropping.

In this study, our objective was to assess the benefits of intercropping in terms of harvested gross energy, farmer gross incomes, and land sparing potential. To do so, we carried out the first worldwide multifaceted assessment of intercropping benefits using available data on two intercropping species in the scientific literature. We hypothesised that intercropping was generally beneficial, whatever benefit is considered. We predicted that RLO would be larger than LER and more efficient at capturing all the benefits of intercropping. We also wanted to test the importance of the stress-gradient hypothesis (*i.e*., benefits should be greater under harsher conditions) for explaining variability in intercropping benefits (Maestre et al., 2009). More specifically, we predicted that intercrops in arid environment would have more positive interactions between their species than intercrops under wetter conditions. Also, following the stress-gradient hypothesis, we predicted that irrigated and fertilised agricultural lands would benefit less from intercropping than non-irrigated and non-fertilised lands. Given the well-known ability of leguminous species to fix nitrogen, we also verified if the presence of this taxonomic group affected the performance of intercropping systems through facilitative interactions. Finally, we tested the importance of intercropping patterns by comparing mixed intercropping to row/strip intercropping, because they potentially have consequences for the degree of interaction between the intercropped species.

2. Methods

2.1. Data collection

We searched the literature published between 1975 and 2014 using the following electronic databases: CAB Abstracts, Biological Abstract, Scopus and Google Scholar. Titles, abstracts and keywords were searched using these keywords: "intercropping," "intercrop," "mixture," "polyculture," "land equivalent ratio," and "relative yield." Intercropping data that were considered appropriate for analyses satisfied the following criteria: 1) intercrops contained only two species; 2) yields for both species in the intercrop were available, as well as yields in their sole crops; 3) yields were expressed in terms of the marketable part of crops, and not their whole biomass; and 4) intercrops and corresponding sole crops received the same agricultural treatments, *i.e*., irrigation, fertilisation and pest management. During this process, we estimated that in roughly 60% of all studies data did not include any sort of variance estimate (*i.e*., standard deviation, standard error or variance). We evaluated that removal of these studies would be more detrimental to the accuracy of our statistical estimates than the lack of a formal

Table 1
Formulas for all linear mixed models used in our meta-analysis. All models have a study random effect accounting for intra-study correlation. Models 1–6 are null models with different dependent variables. Model 7 is a meta-regression with five different moderators (independent variables) to explain variability in LER. Aridity index (AI) was the only continuous moderator and was tested for an interaction with irrigation (Yes/No). Intercropping pattern compared row and strip intercropping together *vs*. mixed intercropping. Presence of an interaction between a N-fixing legume and a non-leguminous species was tested for an interaction with fertilisation (Yes/No).

Model	Formula
1	ln(LER) ~ 1 + (1|Study)
2	$\ln(RLO_{gross\ energy})$ ~ 1 + (1|Study)
3	$\ln(RLO_{gross\ incomes})$ ~ 1 + (1|Study)
4	$\ln(LER/RLO_{gross\ energy})$ ~ 1 + (1|Study)
5	$\ln(LER/RLO_{gross\ incomes})$ ~ 1 + (1|Study)
6	$\ln(RLO_{gross\ energy}/RLO_{gross\ incomes})$ ~ 1 + (1|Study)
7	ln(LER) ~ 1 + AI ∗ Irrigation + Intercrop. Pattern + N-fixing legume ∗ Fertilisation + (1|Study)

variance weighting. Therefore, variance estimates were not extracted from the literature.

Location and time frame were used to insure that different studies were independent. Duplicated data were then removed. Observations in the same study were treated as unique if they differed in terms of growing year, experimental site, crop genotype, the spatial arrangement of plants, or the implementation of fertilisation and irrigation. For each unique observation, average yields for each species in intercrop and average yields in their corresponding sole crops were extracted, sometimes graphically, and compiled in a database. The number of blocks or replicates associated with each intercrop and sole crop were noted. For each intercrop, data on fertilisation and irrigation were reduced to binary variables. The presence of an interaction between a leguminous and a non-leguminous species and the intercropping pattern (rows and strips *vs* mixed) were also noted. The aridity index (AI) was defined as the ratio of mean annual precipitation over potential evapotranspiration and was extracted from the Global Aridity and PET Database using the locations for all experimental sites (Trabucco et al., 2008).

2.2. Metrics of intercropping benefits

Throughout the paper, yield is always meant in relative terms, *i.e*., production per unit area of land. The first metric described here, the land equivalent ratio (LER) (Willey and Osiru, 1972), is mathematically equivalent to the relative yield total (RYT) (De Wit and Van Den Bergh, 1965), which is widely used in ecology to measure positive interactions in a mixture. The LER is the most common way to quantify intercropping benefits in agriculture and is calculated using the following equation:

$$LER = \sum \frac{Y_i}{M_i} \tag{1}$$

where Y_i is the yield of species *i* in the intercrop based upon the entire area of the intercrop, and M_i is its yield in sole crop.

The second metric that we describe, the relative land output (RLO) (Jolliffe, 1997), was used in order to capture the full benefits of intercropping when considering a given amount of land. The RLO is obtained by dividing the observed yield (Y_T) of an intercrop by its expected value (E_T) derived from sole crop yields, as shown here:

$$RLO = \frac{Y_T}{E_T} = \frac{\sum Y_i}{\sum p_i M_i} \tag{2}$$

where Y_T is the total of all the species yields in the intercrop (Y_i; each based upon the entire area of the intercrop) and E_T is the total of all corresponding sole crop yields (M_i), weighted by the relative abundance of each species in the intercrop (p_i), *i.e*., the expected yield of the mixture if each component species produced the same as they do in sole crop (Loreau, 1998). For the summations in eq. (2) to hold, each crop had to be compared on an equal basis. First, yields in mass for each crops were transformed in terms of gross energy (MJ/ha) using crop-specific conversion factors that were available in the literature (Guzmán et al., 2014). Second, yields were converted to local currency units using the FAO data on producer prices from 2006 to 2015 that were specific to each country (FAO, 2009). Using inflation rate data from The World Bank (2017) we adjusted all of these producer prices to their corresponding 2015 values to avoid a bias when comparing two crops for which data were not available for the same years (see Appendix A). RLO were computed only with 50:50 ($p_i = 0.5$) intercrops to simplify calculations, and avoid controlling for differences of density between the crops in the intercrop and their corresponding sole crops.

2.3. Statistical analysis

Both metrics that were presented above have the same mathematical properties as the response ratio (or ratio of means), which is a useful effect size metric in meta-analyses when most primary studies fail to present variance estimates associated with the means of the different treatments or controls (Hedges et al., 1999; Lajeunesse, 2013). For the sake of clarity, we used the terms LER and RLO because they have two slightly different effect sizes. As does the response ratio, these metrics have a null hypothesis, *i.e*., no effect of intercropping on yield, centred on one. More plainly put, when LER and RLO are greater than one, the intercrop is considered beneficial, as it produces more than would sole

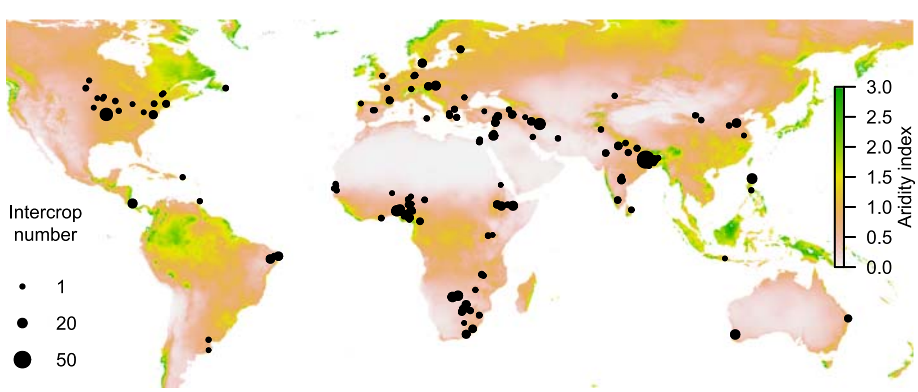

Fig. 1. Locations of all intercropping experiments that were retrieved from the literature, together with global aridity data in the background. Point size indicates the number of intercrops that were associated to each experimental site. The aridity index increases in humid environments, and decreases in arid environments. The experiments span the globe and include various climates.

crops of the same species over the same total area. As it is usually done for the response ratio in meta-analyses, their zero-bound distributions were normalised through log-transformation (natural logarithm was used for all transformations), which rescaled the null hypothesis to zero. To test whether these distributions differed from zero, null model intercepts were computed (see Models 1–3 in Table 1). These null models were mixed models including a random effect to control for intra-study correlation. Following the method proposed by Adams et al. (1997), observations were weighted by their sample sizes and bootstrapping was used to get 95% confidence interval for the models intercepts (Lajeunesse, 2013). This non-parametric bootstrapping consisted in 5000 random samples of the original dataset (with replacement). The differences between the distributions of LER and RLO was assessed using the same test, but with the quotients between LER and RLO as the independent variable of the models, thus obtaining response ratios between effect size metrics (see Models 4–6 in Table 1).

To test for the effect of aridity, a mixed model with the same random effect was fit to all intercrops, with LER as the dependent variable. Alongside the AI, the independent variables were intercropping pattern (rows and strips intercropping *vs*. mixed intercropping), presence of fertilisation, the presence of a legume/non-legume interaction, an interaction between these last two variables, presence of irrigation, and an interaction between irrigation and AI.

The absence of publication bias was assessed using two graphical tools, *i.e*., a funnel plot and a cumulative meta-analysis (see Appendix B). All analyses were performed using R version 3.1.3 (R Development Core Team, 2012) with package *raster* for AI data extraction (Hijmans, 2015), *nlme* for mixed model parameterisation (Pinheiro et al., 2015) and package *MuMIn* for mixed model R^2 calculations (Kamil, 2016).

3. Results

A total of 939 intercrop observations from 126 published studies that covered 41 countries were included in the meta-analysis (see Appendix C for a list of references). Indeed, these experiments spanned the globe, from arid (aridity index [AI] < 0.2) to humid environments (AI > 0.65; Fig. 1). The LER of these intercrops were on average greater than one ($N = 939$; 95% CI: [1.27, 1.32]), with an overall LER of 1.30 and a median LER of 1.28 (Fig. 2A). This means that half of the time, at least 22% of land could be spared through intercropping (LER^{-1}). The RLO that was based upon gross energy were also significantly greater than one ($N = 356$; 95% CI: [1.32, 1.41]), with an overall value of 1.38 and a median of 1.40 (Fig. 2B). This result meant that for a given area of land, intercropping increases gross energy production by 38%, on average, compared with sole cropping. The RLO that was based upon gross incomes were also significantly greater than one ($N = 245$; 95% CI: [1.28, 1.37]). The overall value for RLO was 1.33 and the median RLO was 1.35, which means a 33% increase in gross incomes using the same amount of land (Fig. 2C). Mean RLO that was based upon gross energy was greater than LER (Model 4; $N = 336$; intercept 95% CI: [−0.05, −0.02]) and RLO that was based upon gross incomes (Model 6; $N = 202$; intercept 95% CI: [0.02, 0.05]). The latter two values were equivalent (Model 5; $N = 245$; intercept 95% CI: [−0.02, 0.02]).

AI did not explain variation in LER in Model 7, nor did fertilisation, irrigation, presence of a legume/non-legume interaction (Fig. 3), or intercropping patterns ($P > 0.05$, full model conditional $R^2 = 0.02$). The random effect that was associated with intra-study correlation contributed the most to model fit (marginal $R^2 = 0.61$). This strong intra-study correlation is mainly due to the fact that most of the experiments tested only one or two combinations of species. This encouraged us to explore the role that was played by choices of crop combinations. In the 23 most common combinations (reported for more than ten occasions in our dataset), 18 had an LER greater than one, but one of them also had an LER significantly lower than one ($P < 0.002$; threshold corrected for multiple testing; Fig. 3). Although certain crop combinations seemed to offer greater advantages compared to others, when looking to the variability within the most abundant combinations, *i.e*., soybean/corn, cowpea/sorghum, cowpea/corn and common bean/corn intercropping systems (Fig. 3), it is clear that experimental settings also influence the outcomes of intercropping.

4. Discussion

Intercropping is an old one that has been used in many traditional agriculture settings, with prominent examples such as the 'three sisters' of pre-Columbian America, *viz*., corn, beans and squash (Mt. Pleasant and Burt, 2010). Using meta-analysis, we show that this practice is not merely a relic of the past, but a promising agricultural system that would improve yields all around the world. The benefits of intercropping are manifold. With increased yields comes the possibility of producing more energy (38% increase) and improving the incomes of

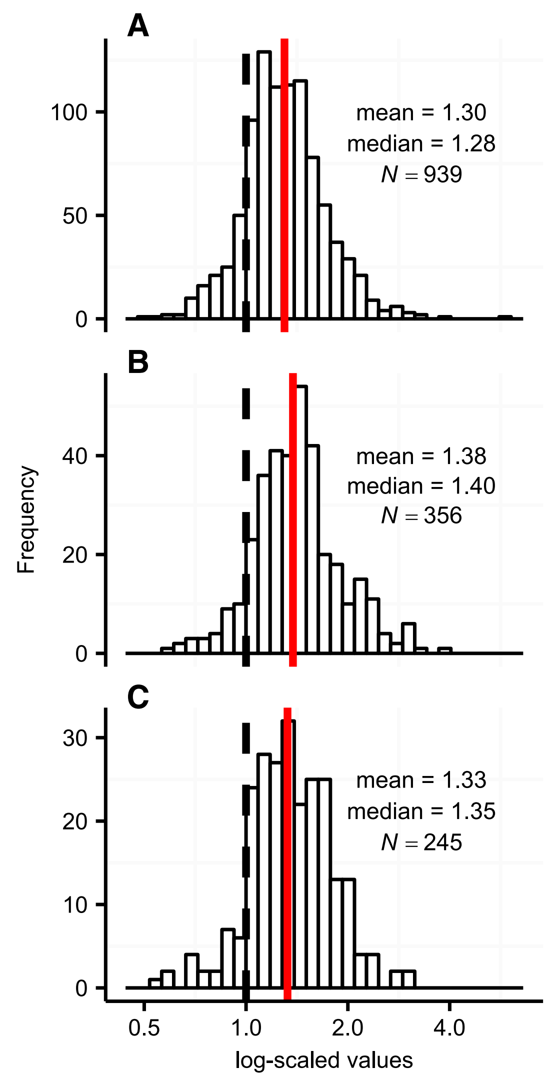

Fig. 2. Frequency distributions of three different metrics of intercropping benefits, *i.e*., land equivalent ratio (LER) (A), relative land output (RLO) based upon gross energy (B), and RLO based upon gross incomes (C). The medians values are red lines; the null hypothesis is represented by the dashed lines. Following null models that were controlled for intra-study correlation, the three distributions are significantly greater than one (LER 95% CI: [1.27, 1.32]; $RLO_{gross\ energy}$ 95% CI: [1.32, 1.41]; $RLO_{gross\ incomes}$ 95% CI: [1.28, 1.37]); RLO based upon gross energy is significantly greater than LER (95% CI: [−0.05, −0.02]), and RLO based upon gross incomes (95% CI: [0.02, 0.05]); and LER and RLO based upon gross incomes are equivalent (95% CI: [−0.02, 0.02]). Therefore, intercropping could help spare 23% of land, or produce 38% more energy and 33% more revenue for a given area of land. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

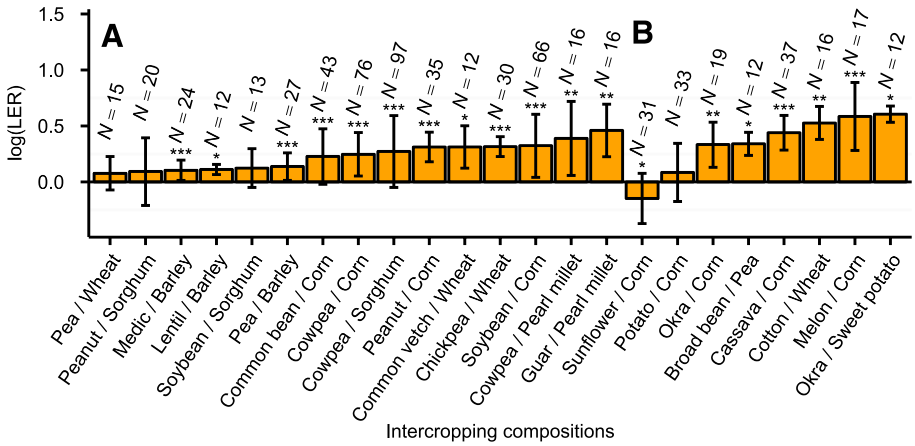

Fig. 3. Average land equivalent ratio (LER) for all distinct intercropping compositions with >10 occurrences in the dataset. A = legume/non legume; B = other intercropping compositions. LER is log-transformed, meaning that positive values represent beneficial intercrops. Even though there is great variability within- and between- compositions, most (18 of the 23) have a clear potential for land sparing. Presence of a legume/non-legume interaction does not seem to influence intercropping performance. Error bars are standard deviation. Above each column, the number of intercrops having each composition is indicated, as well as the result of a conservative Wilcoxon signed-rank test with Bonferroni correction of the significance thresholds. Significance levels are: * $P < 0.002$; ** $P < 0.00004$; *** $P < 0.000004$.

farmers (33% increase). It also results in a non-negligible potential for land sparing, *i.e.*, 23% less land is needed, or conversely, 30% more land is needed in sole cropping to achieve intercropping yields. Our median LER of 1.28 is greater than the median LER of 1.17 found in a previous global-scale meta-analysis of 100 studies (Yu et al., 2015). These two results can be considered fairly independent since only 26 out of our 126 studies were used in their meta-analysis (see Methods A6 in Yu et al., 2015). This narrow overlap, which is probably due to differences in the paper selection process, reinforces the unique character of the present meta-analysis.

We argue that intercropping can offer a solution to the conundrum of maximising both land sparing and sharing, with conventional agriculture considered to be best for land sparing and wildlife-friendly/organic farming the best for land sharing (Fischer et al., 2008; Phalan et al., 2011). In other words, intercropping could potentially be the sustainable intensification that is necessary to feed the expected nine billion people by 2050 with limited environmental impacts (Tilman et al., 2011). A full picture of greenhouse gas emissions is needed to help evaluate the impact of possibly having more intensive machinery work over the same area with intercropping, whilst being less dependent upon N-fertilisers at the same time (Crews and Peoples, 2004).

Important caveats regarding the metrics that were used in our meta-analysis must be stated. First, it is important to keep in mind that the calculation of LER implies that the exact same yield proportion that was obtained in the intercrop would represent the proportion desired by farmers, which is impractical for farmers (Mead and Willey, 1980). This also means that an intercrop where, for example, the leguminous species has enhanced yield relative to its sole crop, but where there is no effect on the cereal species production, can be equivalent to LER that is derived from the reverse situation, *i.e.*, where the leguminous species is unaffected and where the cereal species has enhanced yield. Therefore, LER does not take into account whether one of the crops is more valuable than the other. RLO did take into account which crop was more valuable, using gross energy and incomes to compare them. However, its calculation also assumes a desired proportion, which in this case is defined by the sown proportion and known sole crop yields. It is only pertinent in the case of the 50:50 intercrops, which were used here. For example, this means that when evaluating a soybean/corn intercrop using the RLO, a patch of land that produces soybean on half of its area and corn on the other half was envisioned, which again does not necessarily represent the needs of farmers.

We need to explore the interpretations of LER and RLO to understand why they differed. LER and the relative yield total (RYT) are equivalent in measuring diversity effects, and both capture the positive interaction between species in a mixture. In biodiversity and ecosystem functioning science, the result of these positive interactions has been described as the complementarity effect (or competition reduction), a metric that is directly proportional to RYT and which includes both facilitation and niche partitioning (Loreau and Hector, 2001). Yet, when quantifying the total benefits of an intercrop, which RLO does, another effect is then taken into account, which is referred to as the selection or dominance effect (Loreau and Hector, 2001; Fox, 2005). This dominance effect occurs when species relative yields in the intercrop are positively correlated with their yields under sole cropping conditions. In other words, it occurs when the most productive species in sole crop are also the ones gaining more from intercropping. This dominance effect should always be considered when modeling benefits for future intercrops. In this respect, we argue that RLO is better than LER at capturing the whole benefit of intercropping, *i.e.*, the net effect, and should be considered first when addressing farmers with a fixed area of land on this issue. From the difference between LER and RLO that is based upon gross energy, we can conclude that the most productive species in terms of harvested energy were the ones gaining more from intercropping. Since energy was not based upon total biomass, we can only suggest the role of the dominance effect in creating this difference. Previous meta-analyses have shown that cereals gain more from intercropping whilst legumes were unaffected, on average (Ren et al., 2014; Yu et al., 2016). Cereal/legume intercrops represented 68% of the 939 observations that were included in our meta-analysis. Hence, the competitive superiority of highly productive cereals is likely to have created a dominance effect that is beneficial for intercropping.

Irrigation and the aridity index (AI) in non-irrigated intercrops did not affect LER. These results suggest that intercropping remains beneficial, both under stressful and non-stressful contexts concerning moisture availability, and are supported by data from a previous meta-analysis (Ren et al., 2014). We found that fertilisation did not affect LER. This agrees with other meta-analyses, which found either inconsistent effects or no effect of fertilisation on LER (Ren et al., 2014; Yu et al., 2015; Himmelstein et al., 2017). Yet, fertilisation was found to be an important determinant of specific responses of cereals and legumes when intercropped (Yu et al., 2016). Moreover, LER in the 716 legume/non-legume intercrops out of the 939 observations, were not greater than LER in the other 223 intercrops (Fig. 3). This suggests that facilitation by N_2-fixation was not the only mechanism enhancing biomass in these intercrop systems.

Intercropping patterns in our meta-analysis did not exert a significant effect on LER. This result contrasts with a previous meta-analysis, which found a greater LER in strips than in mixed intercropping (Yu et al., 2015). A better performance of strip intercrops would improve the mechanical implementation of intercropping. Indeed, when strip width is sufficient, smaller combine harvesters, which already exist, could be used. Mechanical implementation is certainly one of the challenges ahead. Other challenges, such as the development of specialised varieties for intercropping, the education of farmers with regard to these new practices, economic incentives for the transition from current practices, the adaptation of the crop-processing chain, and improved knowledge regarding the underlying mechanisms will also need to be addressed (Bedoussac et al., 2015), as each could curb efforts to go forward with intercropping. Consequently, a multidisciplinary approach would be of great help for this potentially crucial component in the implementation of a new Green Revolution.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.10.024.

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