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REVIEW

COMPARING PERFORMANCE OF CROP SPECIES MIXTURES AND PURE STANDS

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KEYWORDS

intercropping, species mixtures, meta-analysis, metrics, indicators

HIGHLIGHTS

- The literature on intercropping comprises thousands of papers.
- Evidence synthesis is needed to develop general conclusions.
- Quantitative evidence synthesis requires meaningful comparative performance metrics.
- The background, meaning, and limitations of some performance metrics is explained.
- Future challenges are identified.

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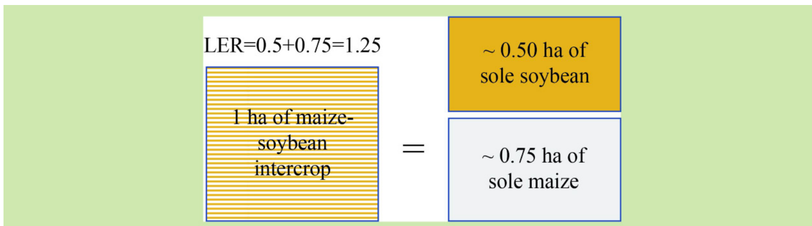
GRAPHICAL ABSTRACT



ABSTRACT

Intercropping is the planned cultivation of species mixtures on agricultural land. Intercropping has many attributes that make it attractive for developing a more sustainable agriculture, such as high yield, high resource use efficiency, lower input requirements, natural suppression of pests, pathogens and weeds, and building a soil with more organic carbon and nitrogen. Information is needed which species combinations perform best under different circumstances and which management is suitable to bring out the best from intercropping in a given production situation. The literature is replete with case studies on intercropping from across the globe, but evidence synthesis is needed to make this information accessible. Meta-analysis requires a careful choice of metric that is appropriate for answering the question at hand, and which lends itself for a robust meta-analysis. This paper reviews some metrics that may be used in the quantitative synthesis of literature data on intercropping.

1 INTRODUCTION

Comparing the performance of intercrops (i.e., species mixtures) and sole crops (i.e., pure stands) is critical to make a sound evaluation of the benefits of intercropping and assess interactions between species choice, intercrop design, intercrop management and factors related to the production situation and pedo-climatic context. Many indicators with subtly different meaning have been proposed in the literature for assessing the productivity and resource use efficiency, and the variety of indicators is bewildering to those new to the intercropping literature. Informative reviews of frequently used indicators are given by Weigelt and Jolliffe[1] and by Bedoussac and Justes[2]. While specific in depth calculations may be made according to the needs of a specific study, conducting meta-analyses requires the definition of simple general indicators that can be easily calculated from the data that are generally included in publications on intercropping[3]. Choice of metrics and interpretation of the values of metrics require careful consideration[4]. It is important to ascertain the exact meaning of an indicator, taking into account how it is calculated, defining clearly which question it answers, and giving close attention to the units of measurement. This paper reviews a few indicators that are considered useful in future literature-based analyses of the potential of intercropping to help fulfil the need for a productive, efficient and environmentally more benign agriculture[5,6].

2 LAND USE EFFICIENCY

The most widely used index for comparing productivity of intercrops and sole crops is the land equivalent ratio (LER). In general, the LER is defined as the sum of the relative yields of component species in the mixture compared to the pure stand:

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

where Y_i and M_i are the intercrop and sole crop yields of species i[7]. For the most common case of a two-species mixture, the LER is defined as:

$$\mathrm{LER} = \frac{Y_1}{M_1} + \frac{Y_2}{M_2} \tag{2}$$

Here, Y_1 is the yield of the first species in the mixed stand, expressed per unit of intercrop area, and M_1 is the yield of the first species in the pure stand, expressed per unit area of the sole crop. Y_2 and M_2 are the intercrop and sole crop yields of species 2. The ratios Y_1/M_1 and Y_2/M_2 are the relative yields of species 1 and 2, also referred to as RY_1 and RY_2 or as partial land equivalent ratios, pLER_1 and pLER_2. A dimension analysis shows the meaning of the LER.

$$[\mathrm{LER}] = \frac{\text{kg yield or biomass of species 1 per ha intercrop}}{\text{kg yield or biomass of species 1 per ha of sole crop 1}} + \frac{\text{kg yield or biomass of species 2 per ha intercrop}}{\text{kg yield or biomass of species 2 per ha of sole crop 2}} \tag{3}$$

Here, the square brackets around LER indicate that we define the units of the LER. On the right hand side, the units of yield in the two ratios cancel out, but the units of land area do not cancel out because a unit of intercropped land is different from a unit of land that is cultivated with a single species.

$$[\mathrm{LER}] = \frac{\text{ha of sole crop 1}}{\text{ha intercrop}} + \frac{\text{ha of sole crop 2}}{\text{ha intercrop}} = \frac{\text{total sole crop area}}{\text{intercrop area}} \tag{4}$$

The first component, $\frac{\text{ha of sole crop 1}}{\text{ha intercrop}}$, represents the land area of sole crop 1 that would be needed to produce the same yield of species 1 as the intercrop does, while the second component, $\frac{\text{ha of sole crop 2}}{\text{ha intercrop}}$, represents the land area of sole crop 2 that would be needed to produce the same yield of species 2 that the intercrop does. The LER as a whole is the sum of the two parts and represents the total sole crop area that would be needed to obtain the component crop yields produced on one unit area of the intercrop.

Take for example a sole maize yield of 12 $\mathrm{t \cdot ha^{-1}}$ and a soybean yield of 3 $\mathrm{t \cdot ha^{-1}}$. Now suppose an intercrop with 50% maize and 50% soybean has a maize yield of 9 $\mathrm{t \cdot ha^{-1}}$ maize and a soybean yield of 1.5 $\mathrm{t \cdot ha^{-1}}$. Then the LER is:

$$\mathrm{LER} = \frac{9}{12} + \frac{1.5}{3} = 0.75 + 0.50 = 1.25 \tag{5}$$

The concept of the LER in a mixture of these two species is illustrated in Fig. 1.

The land equivalent ratio is probably the most frequently used metric in intercropping research because it captures in a single number the area of land that might be saved by producing crops in mixtures instead of pure stands. The associated land savings are:

$$\text{land saving proportion} = \frac{\mathrm{LER} - 1}{\mathrm{LER}} = 1 - \frac{1}{\mathrm{LER}} \tag{6}$$

In the case of the example given above, the land savings would amount to 1−1/1.25 = 1−0.8 = 20%.

Meta-analyses in recent years have yielded several estimates of the land equivalent ratio in intercropping. Yu et al.[8] found an

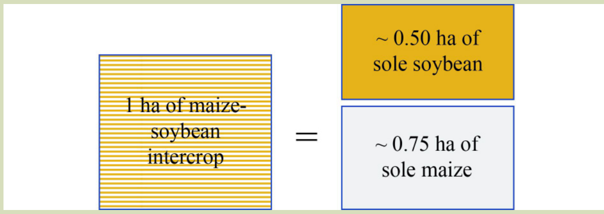


Fig. 1 Illustration of the land equivalent ratio (LER). A sole maize yield is presumed to be 12 $t \cdot ha^{-1}$ and a soybean yield to be 3 $t \cdot ha^{-1}$. Now suppose an intercrop with 50% maize and 50% soybean has a maize yield of 9 $t \cdot ha^{-1}$ maize and a soybean yield of 1.5 $t \cdot ha^{-1}$. Production of the same yields with sole crops would require 0.75 ha of maize and 0.5 ha of soybean. Hence, the land equivalent ratio is 1.25. Intercropping uses 20% less land than required for the same yield in sole crops.

average LER of 1.22 ± 0.02 based on analysis of a global data set based on 100 publications for a range of species combinations. Martin-Guay et al.[9] found an average LER of 1.30 ± 0.01 for a range of species combinations in an independent global data set extracted from 126 publications. Xu et al.[10] conducted an analysis specifically for maize-soybean intercropping, and they found an LER of 1.32 ± 0.02 based on 47 studies. Feng et al.[11] conducted an analysis for maize-peanut intercropping, based on 36 studies, and found an LER of 1.31 ± 0.03. Li et al.[12] found an average LER of 1.29 ± 0.02 for intercrops with maize and 1.16 ± 0.02 for intercrops without maize, based on a global data set of intercropping data extracted from 132 publications.

These global meta-analyses of the LER provide unequivocal evidence that intercropping saves land, in other words: it reduces the area of land required to obtain certain product quantities. It should, however, be kept in mind that the LER is a comparative metric. Its value is a ratio of land areas, based on yields of intercrops and sole crops under the same growing conditions, with the ratio of the component yields equal to those obtained in the intercrop. The LER sets an upper limit to the land savings that may be obtained by intercropping, because the ratio of yields in the intercrop might be different from that required by the market[13]. The LER provides no information on the absolute yield level, which is clearly evident from the units of measurement. The LER merely expresses the relative land areas needed under sole crops to obtain the intercrop yields under certain growing conditions.

Interpretation of the partial land equivalent ratios, $pLER_1$ and $pLER_2$, is the same as that for the LER; they represent the relative land areas of sole crops 1 and 2 needed to produce the yields obtained on a unit area of intercrop. $pLER_1$ and $pLER_2$ indicate which crop species is most responsible for the (efficient) land use in intercropping, but interpretation of the $pLER_1$ and $pLER_2$ is not straightforward because their values depend strongly on the species relative densities in the intercrop as compared to the sole crop. A species that is grown at a high density in the intercrop as compared to the sole crop will obtain a competitive advantage in the mixture, and tend to dominate and get a higher yield and pLER[8].

3 EFFECTS OF PLANT DENSITY

Plant density has profound effects on the yields obtained in intercropping. It is not meaningful to simply add plant densities of component species in intercrops because densities differ substantially between species in relation to individual plant size. For instance, density varies from up to ten plants m^{-2} in maize, several tens of plants m^{-2} in soybean to hundreds of plants m^{-2} in wheat. The component species densities in an intercrop may be scaled to make densities more comparable. Relative density is defined as the plant density of a species in the intercrop (expressed per unit of total intercrop area) divided by the plant density in the sole crop:

$$RD_1 = \frac{D_{1,IC}}{D_{1,SC}}$$

$$RD_2 = \frac{D_{2,IC}}{D_{2,SC}} \tag{7}$$

where $D_{1,IC}$ and $D_{1,SC}$ represent the density (plants m^{-2}) in the intercrop (per unit total intercrop area) and sole crop while $D_{2,IC}$ and $D_{2,SC}$ have the same meanings for species 2[8]. The effects of overall density in an intercrop can then be captured by calculating the relative density total:

$$RDT = RD_1 + RD_2 \tag{8}$$

Several meta-analyses have found that the LER in intercrops increases with the relative density total[8]. There are (at least) two alternative explanations for this phenomenon: (1) the reference sole crops are grown at too low a density, therefore sole crops do not reach full resource utilization and yield; (2) due to species complementarities (niche divergence), densities in intercropping can be increased as compared to the pure stands; hence a higher RDT than one reflects the complementarity between the species, and this opportunity is expressed in the study design. Attention should be paid to making sure that intercrop yields are compared to sole crop yields obtained at the optimal density. This point has been made early on[13] but does need continued scrutiny to leave no doubt about the validity of claims of overyielding in intercropping. Wang et al.[14] provide an example of an analysis in which the value of LER depended critically on plant density in the reference sole crop. In her case, maize-peanut intercropping, the intercropping context indeed allowed an increase in relative density beyond one. Under the conditions of the study, maize could not be grown at a high density in the sole crop because of the thinner stems at high density, resulting in an increased risk of stem lodging. However, in an intercrop with peanut, maize plants receive more light than in a pure maize stand, which increases stem thickness and reduces the risk of stem lodging. Hence, higher densities of maize within the row could be used in the intercrop without increased risk of stem lodging.

Plant competition models[15] may be used in the future to develop a predictive model for weed biomass in intercropping based on crop species densities in intercrops and sole crops and observed weed biomass in sole crops. Such competition models might also be used to develop new predictive equations for yield in intercropping that incorporate plant densities. They may also provide a basis to formulate new indices that take into account the characteristic nonlinearity of yield response to density in pure stands and mixtures.

4 THE COMPARISON OF OBSERVED AND EXPECTED YIELD

The value of the land equivalent ratio shows whether producing yields in mixtures saves land but it does not answer the question whether the component species in an intercrop have higher or lower yield than would be expected on the basis of the sole crop yields and the species proportions in the mixture. One way to answer this question is to calculate the net effect: the difference between observed yield in the mixture and the expected yield. For a species i in a mixture, this net effect is defined as:

$$\mathrm{NE}_i = Y_i - p_i M_i \qquad (9)$$

The net effect is also referred to as yield gain while a relative version of the net effect is referred to as relative yield gain[11]:

$$\Delta RY_i = \frac{Y_i}{M_i} - p_i \qquad (10)$$

The intercrop yield Y_i and the sole crop yield M_i have already been defined, but the expected yield proportion p_i (i.e., the expected relative yield) has not been defined yet. In biodiversity trials the expected yield proportion is $1/N$ where N is the number of species in a mixture because all species are grown at a fixed proportion of their pure stand density[16]. In intercropping trials, the expected yield proportion depends on species density, overall relative density, and, potentially, intercrop spatial configuration, e.g., in rows, strips or completely mixed[17]. In strip intercrops, strip width also influences the observed yield[18–20]. Li et al.[17] suggest pragmatic approaches to calculate the expected yield proportion in different situations. For a replacement intercrop, in which the relative density total (RDT) equals one by definition, the expected relative yield is simply the relative density.

$$p_i = RD_i \qquad (11)$$

This expectation assumes implicitly that the yield per plant is the same in the intercrop and the sole crop, i.e., a species experiences no difference in competitive effect if it is grown with neighbors of the same or the other species. However, if the relative density total is greater than one, it is expected that increased competition for resources would reduce the yield per plant below that in the sole crop. In this situation, Li et al.[17] suggest using as the expected relative yield:

$$p_i = \frac{RD_i}{RDT} \qquad (12)$$

i.e., dividing the relative density by the relative density total. This equation is in line with the “law of constant final yield”[21–23] which posits that for densities that are high enough to ensure the maximum possible resource capture, a species stand will obtain a constant final yield:

$$Y = \frac{D}{b_0 + b_1 D} \qquad (13)$$

where D is density of a species grown as a pure stand, Y is the pure stand yield at density D, b_0 is the inverse of the yield of a free standing plant that does not experience competition and b_1 is the rate at which the inverse of individual plant weight increases with plant density in a pure stand[23]. If density is high enough, the total yield is not sensitive to density because, if density increases by an arbitrary factor F, yield per plant changes by a factor $1/F$ such that yield per unit area remains the same.

The total net effect for the whole intercrop is the sum of the net effects for the component species:

$$\mathrm{NE} = \mathrm{NE}_1 + \mathrm{NE}_2 \qquad (14)$$

This total net effect is only meaningful if the units of yields for the mixed species can be summed without losing meaning. In biodiversity experiments, the NE is expressed as dry matter, which can be meaningfully summed across species because such biodiversity experiments focus on total aboveground biomass production. However, in intercropping, species may differ greatly in the proportion of biomass that is invested in yield, and not all yields are comparable; e.g., yield of grass (total biomass), maize (grain) and cotton (fiber) cannot be meaningfully summed. Therefore, when the net effect is used to assess intercrop productivity, the units of yield or production of the component species should be sufficiently comparable.

Li et al.[17] determined the average net effect of intercropping for cereal-legume mixtures, focusing on the total grain yield. For a data set on cereal-legume intercropping in China, Li et al.[17] found an average net effect of 2.1 ± 0.2 t·ha^{-1} grain. For a combined data set with global and Chinese data, Li et al.[12] found an average net effect of 1.5 ± 0.1 t·ha^{-1} grain, while the net effect was substantially larger in intercrops with maize (2.1 ± 0.1 t·ha^{-1}) than in intercrops without maize (0.5 ± 0.1 t·ha^{-1}). These results clearly show that, on average, species have greater yields in mixtures than in pure stands. Further work is needed to show which component crop species are responsible for overyielding, and elucidate the relative importance of factors affecting the intercropping yield gain, such as the species composition, the fertilizer input, the spatial configuration, the temporal niche difference (i.e., whether species were simultaneous or grown in relay, Yu et al.[8]), and the relative densities.

One caveat when focusing on the net effect is that is does not clarify to what extent the apparent yield gain (observed minus expected yield) is due to the more productive species dominating a less productive species or to a more balanced complementarity in which both component species benefit from growing together. Li et al.[17] show that the complementarity effect[16] is responsible for 90% of the yield gain in Chinese intercropping systems whereas the selection effect (suggesting species dominance effects) is responsible for only 10% of the net effect. This suggests that in many of the intercropping systems that are practiced and studied in China, both species can benefit from growing together. This does, however, require further analyses in which the yield gain is analyzed per each species in intercropping, and not only for the intercrop as a whole. In such studies, yield gains per species (NE_1 and NE_2) or relative yield gains per species (ΔRY_1 and ΔRY_2) can be considered[11]. Also, it will be important to analyze whether complementarity still exists if the yield is expressed in nutritionally relevant units such as calorie yield ha^{-1} or protein yield ha^{-1}.

5 TRANSGRESSIVE OVERYIELDING

Transgressive overyielding is the phenomenon that a mixture has greater total yield than the highest yielding component species[24]. Yu[25] proposed an index for transgressive overyielding:

$$\mathrm{TOI} = \frac{Y_1 + Y_2}{\max(M_1, M_2)} \tag{15}$$

A priori, it would seem challenging for a crop species mixture to obtain a greater yield than the highest yielding sole crop. Transgressive overyielding requires that by replacing some individuals of a species with high yield by individuals with a lower yield, the total yield is increased. This means that strong complementarity (yield increase) between species is required to offset the yield difference between the highest yielding species and the species that is added. Even in natural systems, in which strong negative plant–soil feedback may dramatically affect the performance of pure stands, transgressive overyielding is not common[26]. Berghuijs et al.[27] found by modeling that at intermediate nitrogen input levels, wheat-faba bean mixtures obtain a greater yield than either of the pure stands. At high nitrogen input, wheat was the highest yielding crop in terms of grain yield per ha, whereas at low nitrogen input, faba bean was the highest yielding crop. It is not known how frequently transgressive overyielding is obtained in intercropping trials, and and under which conditions it is most often found, e.g., for which species combinations, configuration, temporal niche difference, densities and management.

There are (at least) two caveats in the use of transgressive overyielding as a concept. First, the metric defines the highest yielding species as a reference after the fact. If species yields are highly variable between sites or years, this will increase the chance of a TOI smaller than one, but it does not really reflect badly on the mixture, because the highest yielding species can then not be predicted before the experiment is done. Second, agriculture produces a variety of crops for a reason. Societies and markets demand different crop products for different uses, e.g., food, nutrition, taste, or protein content. Nevertheless, transgressive overyielding can serve well as the ultimate test for the yield enhancing ability of intercropping. Particular challenges exist in the development of metrics for expressing productivity gains in multi-year or multi-season trials. It is unclear if multi-year metrics should be generalizations of LER, NE or TOI. Further work is needed to address this question.

6 RESOURCE USE EFFICIENCY

Crops grow by converting carbon dioxide, water and various chemical elements (N, P, K, S, Ca, Mg, and micro nutrients) into structural dry matter using solar energy to drive this biosynthesis. Different factors limit growth in different production situations[28]. When provisioning of soil resources such as water and nutrients is optimal, crop growth is determined foremost by radiation capture[29,30]. In intercropping systems, yield gains of mixtures compared to sole crops under such optimal conditions may be caused by either increased radiation capture, e.g., in relay intercrops, or by changes in light distribution that would facilitate a greater canopy photosynthesis at unchanged light capture. There is ample evidence for increased light capture in relay intercrops[31,32], but the evidence for improved radiation use efficiency is mixed[19,33].

When soil resources are limiting, complementarity between species can, however, be important. Under such conditions, it is pertinent to question whether intercropping saves resources. The water equivalent ratio[34] and the fertilizer equivalent ratio[10] were developed to answer this question. The water equivalent ratio represents the relative amount of water used in sole crops to obtain the yield obtained in a unit area of intercrop while the fertilizer equivalent ratio represents the relative amount of fertilizer used in sole crops to obtain the yield obtained in a unit area of intercrop.

The water equivalent ratio is defined as:

$$\begin{aligned}\mathrm{WER} &= \mathrm{pLER}_1\frac{\mathrm{WU}_1}{\mathrm{WU}_{\mathrm{IC}}}+\mathrm{pLER}_2\frac{\mathrm{WU}_2}{\mathrm{WU}_{\mathrm{IC}}}\\ &= \frac{1}{\mathrm{WU}_{\mathrm{IC}}}(\mathrm{pLER}_1\mathrm{WU}_1+\mathrm{pLER}_2\mathrm{WU}_2) \qquad (16)\end{aligned}$$

where WU_1, WU_2 and WU_{IC} are the water use (m^3 water per ha) in the sole crops 1 and 2 and in the intercrop, respectively.

Conceptually, the right hand side of the formula for the WER has the relative land areas required of the sole crops 1 and 2 ($pLER_1$ and $pLER_2$) to produce the component crop yields from a unit area of intercropping. Furthermore, it has the water uses (WU_1 and WU_2, per unit area) in sole crops 1 and 2. The water uses are multiplied by the relative land area, which gives the relative amounts of water that are used in sole crops to produce the same yields as a unit area of the intercrop. Finally, this water amount is divided by the amount of water (ha^{-1}) used in the intercrop (WU_{IC}).

Dimensionally, the left hand side of the equation has units of water used in sole crops per unit of water used in the intercrop, for the same yields. The product $pLER_1WU_1$ has units ha of sole crop 1 per ha intercrop times m^3 water per ha sole crop 1, so the units are m^3 water in sole crop 1 per ha intercrop, while the product $pLER_2WU_2$ has units m^3 water in sole crop 2 per ha intercrop. The units of WU_{IC} are m^3 water per ha intercrop, hence the right hand side of above equation has units m^3 water used in the two sole crops over m^3 water used in the intercrop, when producing the same yields.

Water use can be quantified as the total evapotranspiration by the crop system over a reference period. This reference period needs to be carefully chosen to be relevant to answer the question at hand. For instance, Evapotranspiration can be calculated over the cultivation periods of the sole crops and the intercrop (from sowing to harvest), acknowledging that these could be different in the case that the intercrop is a relay system, or they could also take a reference period of a whole growing season (e.g., the frost free period), depending on what is relevant given the contextualization of the question[35].

The water use in irrigated relay intercrops tends to be greater than that in each of the sole crops[36]. In such a case, the WER tends to be smaller than the LER. If the WER tends to unity while LER is larger than one, this indicates that an intercropping system saves land, but still requires the same amount of water per unit product because there is no improvement in the capture efficiency of water or the efficiency with which water use results in production. If there is some complementarity for water capture in the intercrop, the WER could be greater than one, even if the water use is greater in intercropping than in the sole crop. In dryland farming, there will usually not be a difference in the water use between the intercrop and the sole crop, and then the WER will have the same value as the LER. It means that water sparing is achieved as a result of land sparing. There are good examples of increased water use efficiency as a result of intercropping[34,37,38].

The fertilizer equivalent ratio is defined in the same way as the water equivalent ratio:

$$\begin{aligned}\mathrm{FER} &= \mathrm{pFER}_1\frac{\mathrm{FU}_1}{\mathrm{FU}_{\mathrm{IC}}}+\mathrm{pFER}_2\frac{\mathrm{FU}_2}{\mathrm{FU}_{\mathrm{IC}}}\\ &= \frac{1}{\mathrm{FU}_{\mathrm{IC}}}(\mathrm{pLER}_1\mathrm{FU}_1+\mathrm{pLER}_2\mathrm{FU}_2) \qquad (17)\end{aligned}$$

where FU_1, FU_2 and FU_{IC} are the fertilizer use (kg fertilizer per ha) in the sole crops 1 and 2 and in the intercrop.

Xu et al.[10] conducted a meta-analysis of LER and nitrogen FER (NFER) in maize/soybean intercropping and they found that the average nitrogen input was 111 ± 7.1 $kg \cdot ha^{-1}$ in the sole maize and 56 ± 4.3 $kg \cdot ha^{-1}$ in the sole soybean, and 79 ± 4.9 $kg \cdot ha^{-1}$ in the intercrop (4 $kg \cdot ha^{-1}$ less than the average of the sole crop N inputs). These input levels are tailored to the needs of the crop species according to the cropping system, the experience of the researchers, and the aims of the experiment, and they reflect meaningful agronomic practices that are likely also adopted by farmers. Maize/soybean intercropping gives a partial land equivalent ratio of 0.79 ± 0.02 for the maize and 0.56 ± 0.02 for the soybean, demonstrating that the intercropping system produces especially a high relative yield of the species that requires more nitrogen fertilizer (maize). If the N inputs differ between the sole crops and the intercrop, the NFER is usually not the same as the LER. Xu et al.[10] found that the LER was 1.32 ± 0.02 while the NFER was 1.44 ± 0.02. Thus intercropping gave a substantial improvement in land use efficiency (LER > 1) but it gave an even greater improvement in the nitrogen use efficiency (NFER > LER > 1).

The WER and (N)FER have the same limitation as the LER in that they are relative metrics that express the comparative use efficiency of water and fertilizer in intercrops to that in sole crops without providing information on the actual efficiencies. They are efficiency ratios and as such not easy to interpret. Water and fertilizer are resources that are in short supply in many regions of the globe, and further work is therefore needed to analyze use efficiencies of water and nutrients using metrics expressed in absolute terms. Furthermore, the WER and NFER are affected by input levels in sole crops and intercrops. This can affect conclusions. In maize/soybean intercropping, researchers mostly gave N inputs to the intercrop that were intermediate between the inputs given to maize and soybean[10] whereas in maize/peanut intercropping, researchers mostly gave N inputs to the intercrop that were similar to those given to maize, the species with the higher N input of the two[11]. Partly as a result of this difference in experimental design, maize/soybean intercropping resulted in high values of the NFER[10], whereas maize/peanut intercropping did not[11].

Metrics can be generalized by not focusing on yield, but, e.g., on nitrogen yield, or another yield component that is nutritionally relevant, e.g. protein content, fat content, etc. LER can be generalized by focusing on other resource inputs than land. Tang et al.[39] conducted a meta-analysis on the use efficiency of phosphorus in crop species mixtures using a suite of metrics: LER for yield, FER for P, NE_{grain}, and NE_P. Here, NE_{grain} is the net effect on grain yield, and NE_P is the net effect on P uptake in grain, i.e., the difference between observed and expected P yield. Furthermore, they analyzed the relationship between P capture in the biomass and the grain yield, which is an internal use efficiency. It will be quite interesting in the future to conduct meta-analyses on capture efficiencies and conversion efficiencies for applied fertilizer nutrients in intercropping, to better quantify how fertilizer use in agriculture can be reduced without yield loss and to assess to which extent overyielding in intercropping can be attributed to high harvest index and resource conversion on the one hand and to improved resource uptake on the other hand. Further development of concepts and metrics is needed to enable such meta-analyses.

Metrics need to fulfill several criteria to be suitable. Key criteria are: (1) relevant to the question based on a clear interpretation in the real world; (2) sufficiently homogeneous in value to enable a meaningful analysis across species compositions, crop management, configuration, and production situations. The latter criterion is needed because meta-analyses are only possible if a common effect size can be observed across studies. If different studies measure different attributes, overarching analyses becomes muddy. However, taking ratios or differences as shown can help to standardize, but the pitfalls of ratios and differences need to be acknowledged.

7 OVERYIELDING

The LER is frequently used as an indicator for overyielding, but as explained, the LER is not exactly an indicator for overyielding but for land use efficiency. Overyielding is best characterized by comparing observed and expected yield, where observed yield is directly observed in trials while expected yield is a theoretical construct based on sole crop yield and an expectation about the relative yield in the mixture. This expected relative yield is usually based on relative densities of the species (see above). When intercrops are not planted according to replacement principles, allowance should be made for the effect of density on yield. Net effect per species is a good indicator for overyielding, and can be used to analyze species performance in intercropping. Instead of the net effect, $NE_i = Y_i - p_i M_i$[16], a net effect ratio between observed and expected yield can also be used, $NER_i = \frac{Y_i}{p_i M_i}$[26], or the relative yield gain, $\Delta RY_i = \frac{Y_i}{M_i} - p_i$[11]. The advantage of the net effect is its real world meaning due to the units of of kg·ha^{-1}, whereas the advantage of the net effect ratio and the relative yield gain are the scaling as a proportion of the sole crop yield, which makes these relative metrics more robust to variation in yield between species and production situations. Therefore a ratio is likely more robust as a metric in meta-analyses, but it suffers from a difficulty in interpretation in real world terms. As metrics that are based on differences and those based on ratios both have advantages and disadvantages, it may be advantageous to analyze both types of metrics and build the interpretation on the basis of two rather than one analysis. This was done, for instance, by Tang et al.[39] and Li et al.[12].

8 COMPETITION

Plants in species mixtures compete for resources, and yield gains in one species often go to some extent at the expense of the other species. Complementarity exists if the relative yield gain for the competitively dominant species is greater than the relative yield loss for the competitively weaker species or when both species profit from the species interaction. Dominance is often dynamic, with one species taking over from the other in terms of dominance over time[40]. In strip intercrops of more than two rows per species, there are large differences in competitive context between plants in border rows of strips, which are on one side neighboring on allo-specific individuals, and plants in inner rows which are on both sides neighboring on conspecific individuals. The literature has suggested several metrics for competition within species mixtures such as the competitive ratio or aggressivity[1]. It could be informative to analyze intercrop performance using such competitive indices, but here it may be of concern that competition is density dependent, whereas many competitive indices ignore density and relative proportions of the component species in the mixture.

9 CONCLUSIONS

Intercropping has many attributes that make it an attractive proposition for developing a more sustainable agricultural system: more efficient use of land, nutrients and water, suppression of pests, pathogens and weeds, and building of organic carbon and nitrogen in soil. The literature on intercropping comprises thousands of papers, and a major effort is needed to synthesize results of different studies using metrics that are robust and meaningful. This short paper has reviewed some indices that are considered useful for future analyses, emphasizing the meaning and interpretation. Some pitfalls, open questions and possibilities for further research have also been highlighted.

Compliance with ethics guidelines

Wopke van der Werf, Lizhen Zhang, Chunjie Li, Ping Chen, Chen Feng, Zhan Xu, Chaochun Zhang, Chunfeng Gu, Lammert Bastiaans, David Makowski, and TjeerdJan Stomph declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any study with human or animal subjects performed by any of the authors.

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