REVIEW ARTICLE

Intercropping indices evaluation on grain legume-small grain cereals mixture: a critical meta-analysis review

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Abstract

Intercropping is a mature and well-known agronomic practice that began to attract interest from the scientific community in the mid-1900s and has known an exponential growth in research activity since the beginning of this century. Over the years, different intercropping indices have been developed to evaluate the performance of this crop production system in comparison to standard monoculture practices. Nowadays, more than 20 of these intercropping indices have been described in scientific literature. This review aims to review these indices and check their performance using a meta-dataset consisting of data points from various intercropping experiments that have been described in peer-reviewed publications. Our results show that different indices evaluate different aspects of intercropping trials and that commonly used indices generally do not capture the full performance of the system. More specifically, intercropping results are influenced by both the total sowing density and the crop ratio and indices differ in the way that these dependencies are accounted for. This study suggests creating a standard protocol for the intercropping trials and their evaluation as crucial elements to optimize intercropping research.

Keywords Intercropping · Grain legume · Small grain cereals · Intercropping indices

1 Introduction

In the last decades, conventional agriculture has become a source of debate due to its extensive use of resources and loss of biodiversity gradually masking its benefits in terms of food and feed production (Lithourgidis et al. 2011; Bybee-Finley and Ryan 2018). Climate change, increased world population, scarcity of resources, new governmental policies, and other socio-economic factors call for a new approach to food/feed production. "Ecological intensification", "agro-ecological intensification" and "sustainable intensification" (Wezel et al. 2015; Martin-Guay et al. 2018) are three recently developed concepts that describe the guidelines to which production systems should adhere to reach the common goal of high yield and low environmental impact. All three concepts

propose intercropping, the agronomic practice where two or more crops are cultivated on the same field (Dhima et al. 2014; Pankou et al. 2021b), as a possible way to achieve this purpose (Martin-Guay et al. 2018; Jensen et al. 2020; Pankou et al. 2021a).

Intercropping is an old practice commonly used in subsistence agriculture, forage production, and pastures (Fujita et al. 1992; Annicchiarico et al. 2019). However, the system has not been optimized for use in large-scale and mechanized agriculture. Nonetheless, research activities related to intercropping have increased exponentially since the beginning of the twenty-first century, which exemplifies the growing interest in this topic with applications in agronomy, forestry, environmental sciences, and ecology (Lv et al. 2021). The system can include different types of plant mixtures such as annual, perennial, or mixtures of both and different sowing arrangements are referred to as strip, row, relay, and mixed intercropping (Mousavi and Eskandari 2011; Homulle et al. 2021).

Most studies compare crop mixtures to sole crop systems to quantify production benefits, nitrogen (N) use, and other ecosystem services. As a general rule of thumb, intercropping showed the ability to increase yields by more than 20%

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on the same unit of land, compared to a low-input monoculture system according to different long-term experiments and essays (Jensen et al. 2020; Tilman 2020; Li et al. 2021; Shtaya et al. 2021). Additional benefits related to yield stability over the years (Lithourgidis et al. 2011; Mousavi and Eskandari 2011), increased soil conservation and soil fertility (Mousavi and Eskandari 2011; Pankou et al. 2021a), more efficient use of available resources and reduced pest, weeds and disease pressure (Mousavi and Eskandari 2011) are listed in the literature. These benefits are also explained by the theories of niche differentiation, facilitation, and competition (Homulle et al. 2021; Pankou et al. 2021a). The general idea is that the complementary use of the environment (e.g., above-ground space, below-ground space (Streit et al. 2019), and solar radiation (Lithourgidis et al. 2011)) by crop mixtures raises the system's net efficiency, resulting in a production increase.

Despite these benefits, intercropping introduces several challenges along the value chain of food/feed production (Mamine and Farès 2020) including (1) a higher installation cost for farmers due to the double sowing operation and larger seed quantity in case of an additive design; (2) limited opportunity for chemical control of weeds and pests as only a few active compounds are registered for use in mixed cropping systems; (3) increased post-harvest costs as separation of seeds requires additional machinery and labor; (4) increased complexity in supply chains due to instability of crop proportions at harvest; (5) limited applications for human food as a result of potential cross-contamination of the harvest by allergen components.

The aforementioned challenges explain why mixed cropping cannot compete with or substitute the large-scale monoculture that is today's standard cropping system (Li et al. 2013, 2014). Intercropping research and development efforts should therefore focus on new technologies for simultaneous sowing and harvesting, boosting industry and market demand for mixed grain harvests, and the efficiency of different crop husbandries used in mixed cropping cultivation (Li et al. 2013, 2014; Mamine and Farès 2020). Developing new value chains for intercropping harvests engages different stakeholders, each with its challenges and opportunities (Khanal et al. 2021). For example, farmers would more likely look at yield potential, protein yield per hectare (ha), and total revenue. At the same time, breeders and researchers could be more involved in species' and genotypes' performances and interactions, while food and feed producers are interested in quality, uniformity, and continuity of supply (Mamine and Farès 2020).

In agriculture, mathematics equations are commonly used because they facilitate the analysis of the results (Adah et al. 2015). As well, the scientific literature suggests a myriad of intercropping indices that allow quantifying the advantages of intercropping systems over traditional monocultures (Bedoussac and Justes 2011; Lithourgidis et al. 2011). These metrics provide a summary and interpretation of the interactions between the crops that are not directly perceptible from the raw observed data (Weigelt and Jolliffe 2003; van der Werf et al. 2021). The performances of intercropping over the pure stand can be calculated in two main forms: biological advantage and economic advantage (Brooker et al. 2015; Gitari et al. 2020). These two ways of evaluating intercropping advantage might not perform in the same way. Even if the total harvest per unit of area of mixed cropping is generally higher than pure stand, intercropping requires additional labor costs and its yield could have a lower market value (Bonnet et al. 2021) which can reduce the total revenue for the same land unit. The indices help researchers to study and optimize intercropping systems by evaluating influential factors such as species/variety combinations, sowing densities, and crop ratios. In this sense, intercropping indices are also useful instruments that can advise farmers concerning agronomic practices that increase efficiency and give a monetary return on intercrop implementations.

In 1960 the first characterization of intercropping indices for mixed crop cultivation was published by De Wit (1960). A more detailed explanation can be found in a subsequent book from the same author (De Wit and Van den Bergh 1965), where the first mention of the "Relative Yield" index (RY) is noted. Willey and Rao (1980) reconsidered the definition of this index and developed the "Land Equivalent Ratio" (LER) which is, in fact, mathematically equivalent to the RY. The LER expresses the area of land needed for a pure stand system to reach the same yield production as the intercropping system under study. The LER is widely used and appreciated for its simplicity of calculation and interpretation (van der Werf et al. 2021) and numerous research efforts have used this index to evaluate and compare the advantages of intercropping trials (Bedoussac et al. 2015). However, the LER does not allow the assessment of the efficiency of the individual species in the mixture (Khanal et al. 2021). Other metrics have been introduced in an attempt to capture all aspects of intercropping systems, leading up to the more than 20 different indices that exist today. Most of these indices have multiple acronyms and source citations, substantially increasing the apparent number of intercrop indices that appear in scientific literature.

This study analyses annual, binary mixtures of small grain cereals and grain legumes in a mixed- or row-intercropping arrangement that are suitable for cultivation in the various pedoclimatic zones of Europe. This analysis mostly considers underutilized protein crops that could reduce Europe's dependency on imported soybeans and that could increase the diversification of the regional agroecosystem. The performance (grain or biomass yield and protein yield) of these crops and their mixtures are analyzed by means of the intercropping indices that are found in scientific literature. The research roadmap, represented in Fig. 1, targets the following
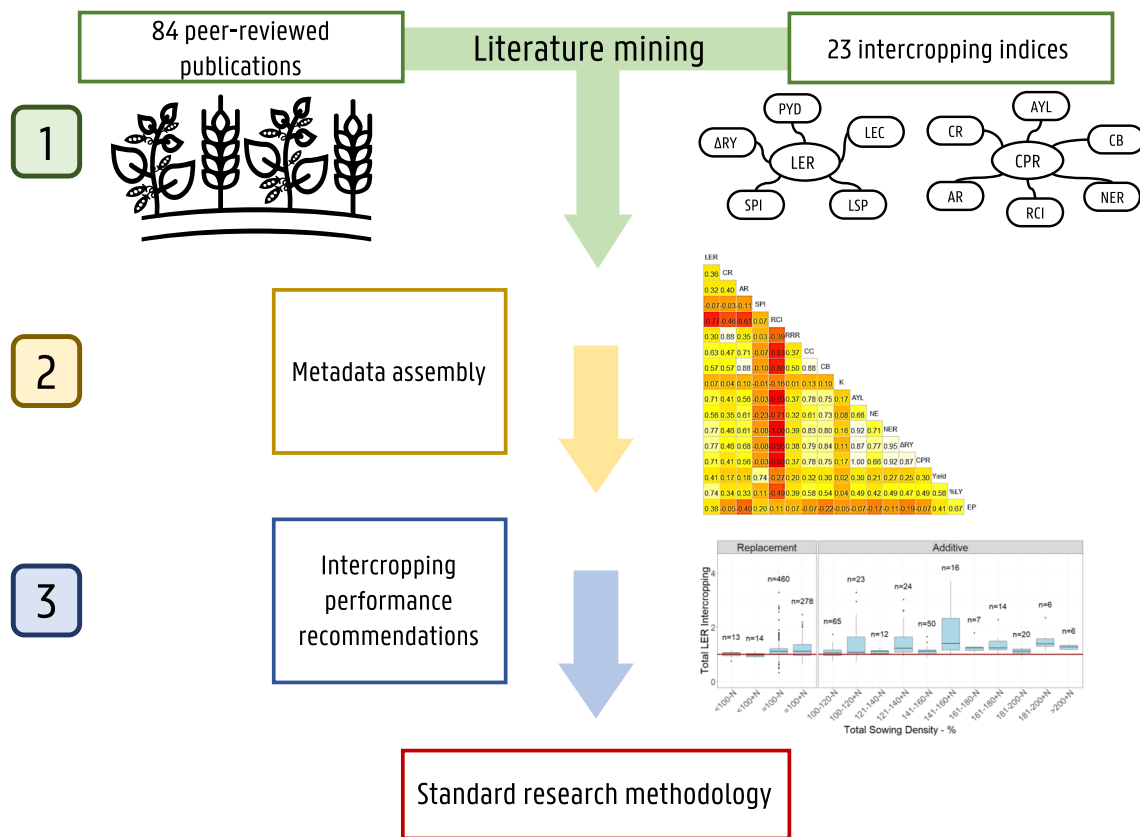
Fig. 1 The research roadmap is divided into three main layers: (1) Literature mining to collect experimental data on intercropping and the existing intercropping indices; (2) Computation of the intercropping indices based on a standard procedure; (3) Evaluation of the crop mixtures performances based on different crop husbandry measures.

goals: (1) to provide insight into the crop management factors that affect intercropping yields such as crop species, sowing ratio, and N fertilization; (2) to identify the factor levels that maximize the advantage of intercropping over the pure stand; (3) to demonstrate alternative aspects of mixed cropping evaluation; (4) to present the interconnections and differences between intercropping indices; (5) to establish guidelines and method standardization for the comparison of intercropping research.

2 Materials and methods

2.1 Literature study

A peer-reviewed literature search was performed on March 28th 2022, in both the Web of Science (WoS) and SCOPUS databases. The search query included underutilized annual crops of small grain cereals and grain legumes and one major crop (wheat and pea) for each of these groups. Differential spelling and synonyms were considered to ensure that all relevant publications were found. This study excluded major summer crops (i.e., maize and soybean) and forage crops

(i.e., clover and alfalfa) which are frequent objects of study in an intercropping context. The query also excluded papers in the field of agroforestry. This resulted in the following search string that was applied to match the title, abstract, and keywords of the papers in WoS and SCOPUS:

(triticale OR oat* OR barley OR wheat OR rye) AND ("faba bean*"OR "field bean*"OR "broad bean*" OR "fava bean*" OR lupin* OR pea* OR chickpea* OR "chick-pea*" OR lentil* OR "common bean*") AND (intercrop* OR "mixed crop*" OR "multi-crop*" OR "mixed stand*" OR "mixed intercrop*") NOT (agroforest* OR forest*) NOT (maize OR corn OR rice) NOT (soybean* OR clover* OR oilseed*)

This search resulted in 944 papers (445 from WoS and 499 from SCOPUS), from which 526 papers remained after removing duplicates, errata, and papers that were not written in English.

A first screening of the papers was performed by reading the title and the abstract to identify publications that relate to intercropping experiments that were performed in open-field conditions, excluding experiments in pot, greenhouse, and semi-field conditions. After this selection, the dataset contained about 300 papers. The full text of the open access papers in this selection was subsequently analyzed and papers

were selected based on their reporting of the following three parameters: (1) dry matter (DM) yields data of both pure stand crops; (2) partial DM yields of the two components in the mixture, or data to retrieve them such as the percentage composition of the final harvest; (3) sowing ratio and sowing density of the two components inside the mixture. Articles were discarded if the type of intercropping was different from mixed or row intercropping. These two types of intercropping share similar properties and crop management practices, justifying their inclusion in a common meta-dataset. The complete selection process resulted in a dataset containing 84 papers.

Yield data were, if possible, directly copied from the papers or extracted from visualizations (such as bar plots) using WebPlotDigitazer (Rohatgi 2022). Additionally, the meta-dataset included geographical information, weather data, and additional crop husbandry measurements such as fertilization, irrigation, and crop species.

2.2 Intercropping indices

An analysis of the selected papers and their references allowed the collection of numerous intercropping performance metrics (i.e., intercropping indices). Other papers reviewing intercrop indices were also explored but perceived as incomplete as they only cover the "commonly used indices" (Williams and McCarthy 2001; Khanal et al. 2021), reported on different subsets of these indices and were largely based on simulated data. In total, 23 different indices relating to intercrop performance have been collected for this study, not including duplicates or cosmetic updates. As an example of the latter, our analysis did not include metrics that only differ from other indices by a scaling factor (e.g., transformation in percentage). The analysis also did not consider the temporal differentiation indices used for relay intercropping, the economic metrics to assess production value, and the equivalent ratio indices for water and fertilizer use (van der Werf et al. 2021) which are based on LER, but require additional information that is mostly not available for the individual components of the meta-dataset. Also, the indices based on factors rarely present in open-field studies such as the yield of a single plant (no competition) or the yield of the pure stand at half of the optimal sowing density such as the "Interspecific interaction index" and the "Intraspecific interaction index" (Weigelt and Jolliffe 2003; Bedoussac and Justes 2011) have not been included.

2.3 Data analysis

The intercropping experiments are classified into one of two design types according to their total sowing density, using the simplified definition from Snaydon (1991) and Rodriguez et al. (2020):

- Replacement: when the sum of the sowing densities of the cereal and the legume is smaller than or equal to 100%;
- Additive: when the sum of the sowing densities of the cereal and the legume is greater than 100%.

Where 100% represents the optimal sowing density for the pure stand of the corresponding sole crop. The sowing density of each component is reported as a percentage of the optimal sowing density of the corresponding pure stand.

The dataset contains a diverse set of experiments so a few assumptions were made to allow for statistical analysis. Furthermore, all intercropping indices were calculated and not extracted from the papers' results. Indices that include terms in their equation that refer to the pure stand were assumed to relate to the DM yield of the pure stand at optimal sowing density without N fertilization as suggested by Bulson et al. (1997). The sowing densities of intercropping were grouped into 8 classes and each of these was split into two classes to separate non-N-fertilized (-N) experiments from N-fertilized (+N) experiments. To the best of our knowledge, no other review has evaluated a large collection of intercropping metrics on a comprehensive meta-dataset of real experimental results, as is presented in this paper.

The analysis was performed using RStudio (version 4.1.2 (2021-11-01)) (R Core Team 2021) and the graphical representation of the results was performed with the R package "ggplot2" (Wickham 2016).

3 Results

3.1 Literature study distribution

The literature review covers more than 30 years of experiments. The oldest article found is dated 1987 (Harris et al. 1987) and the most recent articles were dated 2021, while the yield data ranged from 1980 to 2019. However, the distribution of the publication years is severely left-skewed as most papers have been published between 2010 and 2020, which is in accordance with the trend described by Lv et al. (2021) on intercropping research.

Three-quarters of the experiments are located in Europe, and the remaining ones are equally distributed between Asia, Africa, and North America. The country with the highest amount of published studies is Greece with 11 papers about intercropping, followed by Denmark (10) and Germany (9).

The soil texture type most represented is sandy loam which is recorded in 20% of the experiments. In total there are 13 different texture types of soil (12 types according to USDA classification and one gravel soil), some of them recorded only once. Around 10% of the collected manuscripts do not report any information about the soil texture.

Seven different species of legumes (peas [*Pisum* spp.], faba beans [*Vicia faba*], lupines [*Lupinus* spp.], grass-peas [*Lathyrus* spp.], lentils [*Lens culinaris*], chickpeas [*Cicer arietinum*], and common beans [*Phaseolus vulgaris*]) are represented in the dataset. Peas are used in more than half of the experiments which is twice as frequent as the faba bean, the second most frequent legume species. Together, they represent 85% of the dataset. Six cereal species (barley [*Hordeum vulgare*], common wheat [*Triticum aestivum*], oat [*Avena sativa*], triticale [*xTriticosecale*], durum wheat [*Triticum turgidum* spp. *durum*], and rye [*Secale cereale*]) are recorded and their distribution is more uniform compared to the legumes. Barley, common wheat, and oats appear at comparable frequencies and account for two-thirds of the total dataset. Triticale is present in only half of the experiments compared to wheat, while rye was used in only two experiments. As a result, the types of crop mixtures that have been studied most frequently were barley-pea (20%), wheat-pea (15%), and oats-pea (13%).

The resulting meta-dataset contains 1984 rows, with each row reflecting trait observations that were made on a single experimental unit, referring to either a sole crop or a mixture. The number of dataset entries originating from a single paper varies between 3 (two pure stands and one mixture) and 180. Two-thirds of the dataset consists of measurements that were made in experimental fields that did not receive any N fertilization while the remaining experiments were treated with varying levels of N input ranging from 10 kg N ha^{-1} to 210 kg N ha^{-1}. 41 papers report information on crude protein or N content of the harvest, resulting in 700 dataset entries. 33 of these papers, equivalent to 303 dataset entries, report these traits for the two crops in the mixture and pure stand and therefore allow an evaluation of the various intercropping indices for protein yield.

In terms of experimental design, the replacement system is most frequently used, representing three-quarters of the examined papers. Additionally, there are more than 30 different combinations of crop sowing proportions in the meta-dataset where the 50:50 type of mixture accounts for more than half of all data points.

3.2 Intercropping indices

3.2.1 Summary of intercropping indices

The different intercropping indices that have been gathered from the scientific literature are listed in Table 1. Some of these indices, such as the Land Equivalent Ratio (LER) and the Relative Crowding Coefficient (K), are frequently used in papers, while others, such as the Percentage Yield Difference (PYD) and the Land Equivalent Coefficient (LEC) only appear sparingly. As a general rule of thumb, each equation in Table 1 is linked to the name of the corresponding index as it appeared for the first time in scientific literature. However, in the past, slightly different formulas have been used for the same index, or the same equation was used with two distinct names. A few modifications were required when one of the following situations occurred:

- the metric name currently used is different from the first appearance;
- the equation was updated to include the sowing ratios both in replacement and additive design;
- identical equations were found under diverse names;
- identical index name was used for contrasting equations.

For example, in Williams and McCarthy (2001) various equations are written with the same name RY (Relative Yield), and in Khanal et al. (2021) one equation is named both CPR (Crop Performance Ratio) and YR (Yield Ratio).

The following paragraph provides a short description of each index, detailing the agronomic performance metrics that are targeted in their evaluation:

- LER (Land Equivalent Ratio): the most commonly used index, defines the amount of land needed for a pure stand system to produce the same yield quantity as the intercropping system. When this value is above 1, intercropping has an advantage over the sole crop. LER derives from the sum of the partial LER of each mixture's component. In literature, this value can also be found as RYT — Relative Yield Total (or RY — Relative Yield) (Mead and Willey 1980; Willey 1985; van der Werf et al. 2021). LER (or RYT) is not a good indication of the yield performance when the crop ratio in the mixture is not similar between the two components (van der Werf et al. 2021);
- LEC (Land Equivalent Coefficient): the index measures the yield balance after the interaction of one species with the other crop. For a binary system, the lowest value to be considered advantageous is 0.25 deriving from the theoretical mixture yield proportion of 50:50 (Adetiloye et al. 1983). As this index was developed under the assumption of a 50:50 sowing density proportion, the index may not support a meaningful interpretation when applied to results from other sowing ratios;
- LSP (Land Saving Proportions): this value gives the percentage of the land saved when cultivating a mixture of crops instead of a pure stand (van der Werf et al. 2021);
- PYD (Percentage Yield Difference): has been developed recently and is defined as the difference between the

Table 1 Equation of the different agronomic indices found in the scientific literature.

Intercropping indices	Equations	References
LER (Land Equivalent Ratio)	$\text{LER} = \text{LER}^c + \text{LER}^c \quad \text{LER}^c = y^{ci}/y^c$ $\text{LER}^l = y^{li}/y^l$	De Wit and Van den Bergh (1965) Rao and Willey (1980)
LEC (Land Equivalent Coefficient)	$\text{LEC} = \text{LER}^c \text{LER}^l$	Adetiloye et al. (1983)
LSP (Land Saving Proportion)	$\text{LSP} = (\text{LER} - 1)/\text{LER}$	van der Werf et al. (2021)
PYD (Percentage Yield Difference)	$\text{PYD} = 100 - [((y^c - y^{ci})/y^c) + ((y^l - y^{li})/y^l))100]$	Afe et al. (2015) Gitari et al. (2020)
SPI (System Productivity Index)	$\text{SPI}^c = y^{ci} + (y^c/y^l)y^{li} \quad \text{SPI}^l = y^{li} + (y^l/y^c)y^{ci}$	Odo (1991)
ΔRY (Relative Yield gain)	$\Delta\text{RY} = \Delta\text{RY}^c + \Delta\text{RY}^l \quad \Delta\text{RY}^c = (y^{ci}/y^c) - p^c$ $\Delta\text{RY}^l = (y^{li}/y^l) - p^l$	van der Werf et al. (2021)
CPR[1] (Crop Performance Ratio)	$\text{CPR} = \text{CPR}^c + \text{CPR}^l \quad \text{CPR}^c = y^{ci}/(y^c z^{ci})$ $\text{CPR}^l = y^{li}/(y^l z^{li})$	Harris et al. (1987) Khanal et al. (2021)
AR (Aggressivity Ratio)	$\text{AR}^c = y^{ci}/(y^c z^{ci}) - y^{li}/(y^l z^{li})$ $\text{AR}^l = y^{li}/(y^l z^{li}) - y^{ci}/(y^c z^{ci})$	Willey and Rao (1980)
CR (Competitive Ratio)	$\text{CR}^c = [y^{ci}/(y^c z^{ci})]/[y^{li}/(y^l z^{li})]$ $\text{CR}^l = [y^{li}/(y^l z^{li})]/[y^{ci}/(y^c z^{ci})]$	Willey and Rao (1980)
AYL (Actual Yield Loss)	$\text{AYL} = \text{AYL}^c + \text{AYL}^c \quad \text{AYL}^l = [y^{ci}/y^c z^{ci}) - 1]$ $\text{AYL}^l = [y^{li}/(y^l z^{li}) - 1]$	Banik (1996)
NER (Net Effect Ratio)	$\text{NER} = \text{NER}^c + \text{NER}^l \quad \text{NER}^c = y^{ci}/(p^c y^c)$ $\text{NER}^l = y^{li}/(p^l y^l)$	van der Werf et al. (2021)
K (Crowding Coefficient)	$\text{K} = \text{K}^c \text{K}^l \quad \text{K}^c = [y^{ci}/(y^c - y^{ci})](z^{li}/z^{ci})$ $\text{K}^l = [y^{li}/(y^l - y^{li})](z^{ci}/z^{li})$	De Wit and Van den Bergh (1965) Willey and Rao (1980)
YR (Yield Ratio)	$\text{YR} = (y^{ci} + y^{li})/(y^c z^{ci} + y^l z^{li})$	Khanal et al. (2021)
TOI (Transgressive Overyielding)	$\text{TOI} = (y^{ci} + y^{li})/[\max(y^c, y^l)]$	Yu (2016)
NE (Net Effect)	$\text{NE} = \text{NE}^c + \text{NE}^l = \text{SE} + \text{CE} \quad \text{NE}^c = y^{ci} - p^c y^c$ $\text{NE}^l = y^{li} - p^l y^l$	van der Werf et al. (2021)
RRR[2] (Relative Replacement Rate)	$\text{RRR}^c = (y^{ci}/z^{ci})/(y^{li}/z^{li})$ $\text{RRR}^c = (y^{li}/z^{li})/(y^{ci}/z^{ci})$	Dekker et al. (1983) Williams and McCarthy (2001)
CI (Competition Intensity)	$\text{CI} = (p^c y^c + p^l y^l)/(y^{ci} + y^{li}) - 1$	Wilson (1988) Williams and McCarthy (2001)
CC (Change in Contribution)	$\text{CC}^c = [y^{ci}/(y^{ci} + y^{li})]/[(p^c y^c)/(p^c y^c + p^l y^l)] - 1$ $\text{CC}^l = [y^{li}/(y^{ci} + y^{li})]/[(p^l y^l)/(p^c y^c + p^l y^l)] - 1$	Williams and McCarthy (2001)
CB[2] (Competitive Balance)	$\text{CB}^c = \ln[(z^{li} y^{ci})/(z^{ci} y^{li})]/(y^c/y^l)$ $\text{CB}^l = \ln[(z^{ci} y^{li})/(z^{li} y^{ci})]/(y^l/y^c)$	modified from Wilson (1988) Williams and McCarthy (2001)
EP[3] (Expected harvested Proportion)	$\text{EP}^c = (z^{ci} y^c)/(z^{ci} y^c + z^{li} y^l)$ $\text{EP}^l = (z^{li} y^l)/(z^{ci} y^c + z^{li} y^l)$	Snaydon and Satorre (1989)
RCI (Relative Competitive Intensity)	$\text{RCI}^c = (p^c y^c - y^{ci})/(p^c y^c)$ $\text{RCI}^l = (p^l y^l - y^{li})/(p^l y^l)$	modified from Grace (1995) Williams and McCarthy (2001)
SE (Selection Effect)	$\text{SE} = \text{N}(\text{cov}[\Delta\text{RY}; y]) \quad$ for a binary system $\text{SE} = \frac{1}{2}(\Delta\text{RY}^c - \Delta\text{RY}^l)(y^c - y^l)$	Loreau and Hector (2001) Li et al. (2020)
CE (Complementarity Effect)	$\text{CE} = \text{N}(\overline{\Delta\text{RY}})(\overline{y})$ for a binary system $\quad \text{CE} = (\text{LER} - 1)(\overline{y})$	Loreau and Hector (2001) Li et al. (2020)
p (relative proportion of the crop)	$p^c = z^{ci}/z^{tot} \quad p^l = z^{li}/z^{tot} \quad p^c + p^l = 1$	Williams and McCarthy (2001) van der Werf et al. (2021)

superscript "l" concerns the partial index refers to the legume; superscript "c" concerns the partial index refers to the cereal; No superscript means that the index concern the whole mixture; N = the number of species present inside the mixture; $\overline{y}$ = the average between the yield in the pure stand of the two mixed cropping components; y^l = yield of the legume in the pure stand; y^c = yield of the cereal in the pure stand; y^{li} = yield of the legume in the mixed stand; y^{ci} = yield of the cereal in the mixed stand; z^{li} = absolute sowing proportion of legume as a percentage of optimal sowing density for the pure stand; z^{ci} = absolute sowing proportion of cereal as a percentage of optimal sowing density for the pure stand; z^{tot} = sum of the absolute sowing proportions of cereal and legume in the mixture, as a percentage of optimal sowing density for the pure stand; p^l = relative sowing proportion of legume in the mixture; p^c = relative sowing proportion of cereal in the mixture; p = sum of the relative sowing proportion of cereal and legume in the mixture; it is also called "land share".

[1] Modified from Harris et al. (1987). [2] Simplified from the original equation. The original equation uses p but the term z^{tot} cancels out. [3] The acronym was modified from the original (p (Snaydon and Satorre 1989)); The expected harvested proportion was calculated only for legume yield.

sole crop at full population (100%) and the intercrop expressed as a percentage (Afe et al. 2015);

- SPI (System Productivity Index): standardizes the yield of the second crop in terms of the primary one (Odo 1991; Khanal et al. 2021). Intercropping is considered advantageous when the SPI of one component is greater than the respective sole crop yield. Thus, SPI can be seen as the yield that the sole crop should achieve to be as productive as the intercropping system. The SPI can have an equivocal interpretation because it is not always clear which is the primary crop in the mixture, hence, in this paper, the SPI was calculated for both legumes and cereals;

- ΔRY (Relative Yield gain): this index evaluates the deviation from the expected yield and quantifies the contribution of each crop to the final yield (Loreau and Hector 2001; Feng et al. 2021). There is an advantage when the relative yield is greater than the relative sowing proportion p (van der Werf et al. 2021). This index is related to NE and NER so Table 1 also includes the sum of the partial ΔRY;

- CPR (Crop Performance Ratio): an index that expresses the measured partial yields in the mixture relative to its expected yield, given the absolute sowing proportion of the component. A partial CPR value that is greater than 1 implies that the mixed crop exceeds its expectation (Harris et al. 1987). In this study, we introduced the total CPR as the sum of the partial CPR values so a value of 2 or more is desirable for an intercropping system;

- AR (Aggressivity Ratio): index representing the competition between the two crops of the mixture. In the absence of competition, this value should be equal to zero while a value above zero indicates the aggressor component and a value below zero indicates the suppressed species (Willey and Rao 1980). The greater the absolute value, the greater the competition between the two crops. The values resulting from the two components are each other's opposite ($AR^c + AR^l = 0$);

- CR (Competitive Ratio): this index uses the same arguments as the AR formula but uses a ratio instead of a difference to quantify the level of competition between the crops (Willey and Rao 1980). For example, a value of 2 means that one crop is twice as competitive as the second crop (see also relative crowding coefficient in (Snaydon 1991)). The values of the two components are reciprocal ($CR^cCR^l = 1$);

- AYL (Actual Yield Loss): it measures the amount of yield difference between the expected yield and the actual yield of the crop in the mixture. The sum of the partial AYL values gives the final result. There is a yield gain when the value is above zero and there is a yield loss when the value is below zero (Banik 1996);

- NER (Net Effect Ratio): this index evaluates the overyielding potential of the intercropping system relative to the pure stand (van der Werf et al. 2021). This metric is related to NE and Δ RY so Table 1 also includes the sum of the partial NER;

- K (Crowding Coefficient): is one of the oldest intercropping indices used in ecology studies by De Wit and Van den Bergh (1965) that was later refined by Willey and Rao (1980) and Firbank and Watkinson (1985). For each crop, this index could be less than, equal to, or greater than 1. The value of 1 equals the absence of competition;

- YR (Yield Ratio): this index compares the total yield of the mixture with the sum of the expected yield of the components. Different versions of this index appear in literature as initially it was only used for 50:50 type of mixtures (Wilson 1988). In this paper, we use the version that takes into account the sowing proportion of each crop (Williams and McCarthy 2001; Khanal et al. 2021). As mentioned earlier, the same equation was also found in Harris et al. (1987) under a different name (total CPR), and a similar equation was found in Martin-Guay et al. (2018) under the name Relative Land Output (RLO);

- TOI (Transgressive Overyielding): describes the complementarity effect when plants are grown in a mixture. The transgressive overyielding index is calculated as the ratio of total intercropping yield over the highest sole crop yield. A value of TOI >1 means that intercropping is more productive than either of the sole crops. LER is always greater than or equal to TOI (Yu 2016);

- NE (Net Effect): the net effect quantifies the overyielding potential of intercropping based on the relative sowing proportion of the mixture p. The result is a value with kg ha^{-1} as a measurement unit which makes it easy to evaluate the actual application in the field (van der Werf et al. 2021). Nevertheless, this index is not a ratio and thus it is less suitable to compare intercropping experiments that use different crop species with uneven yield potentials;

- RRR (Relative Replacement Rate): is the product of two ratios, the terms inside each ratio are the yield of the crops in the mixture and its sowing proportion in absolute terms. A value equal to 1 indicates the formation of a stable community between the two crops (Dekker et al. 1983). A value above 1 means that one crop tends to replace the other. The values for each crop in the mixture are reciprocal ($RRR^cRRR^l = 1$);

- CI (Competition Intensity): This index was created for additive mixtures by Wilson (1988), later modified by Williams and McCarthy (2001) to adapt it for all sowing ratios. If there is no change in the performance of either species in the mixture, compared to the expected yield of the pure stand, the value is equal to zero and no competition is detectable. Otherwise, if the mixture produces

more biomass compared to the expected pure stand, the value is below zero since the intercropping yield is placed at the denominator of the equation. Vice-versa, when the value is above zero the mixture produces less biomass than the expected (Williams and McCarthy 2001);

- CC (Change in Contribution): this index represents a ratio of the proportional biomass or grain yield reached by one crop over the expected proportion. When the value is positive, the species produces more biomass than expected and a negative value implies that the species suffers from a yield loss (Williams and McCarthy 2001);
- CB (Competitive Balance): This index is the only logarithmic metric found among the other intercropping indices and was also created for an additive mixture by Wilson (1988), later modified by Williams and McCarthy (2001), to adapt it for different sowing ratios. If there is no competition, the value is equal to zero and no yield reduction is noticeable. Otherwise, a value different from zero means that one species is more competitive than the other (Wilson 1988). The values resulting from the two components are each other's opposite ($CB^c + CB^l = 0$);
- EP (Expected harvested Proportion): compares the competitive ability using the harvest proportion of one crop, its sowing proportion, and the yield in pure stand. This formula assumes that there is no competition between crops. When the expected harvest proportion is different from the measured value, it means that one crop suppresses the other (Snaydon and Satorre 1989);
- RCI (Relative Competitive Intensity): this equation measures the effect of intercropping yield compared to the expected yield. A negative value means that the crop produces more biomass in the mixture and a positive value implies that the crop in the mixture produces less than expected (Grace 1995; Williams and McCarthy 2001);
- SE (Selection Effect): this index measures the changes in relative yield between the mixed crop and the sole crop. Species selection is measured by the Price equation of evolutionary genetics (Price et al. 1970) which has an expected value of zero when changes are nonrandomly related to their traits (yields) in pure stand. SE under an effect of biodiversity can result in a negative value when the lowest yielding species in the sole crop has a higher ΔRY in the mixed intercropping. The value of SE is positive when the highest-yielding species in the sole crop has also the highest ΔRY in intercropping (Loreau and Hector 2001; Li et al. 2020);
- CE (Complementarity Effect): this index measures the change as the average gain (or loss) in the relative yield. The expected value is zero when there is no effect of biodiversity, while a positive value infers resource facilitation between the mixture components and a negative value describes a competitive interaction between species (Loreau and Hector 2001; Li et al. 2020). The sum of CE

and SE gives the net biodiversity effect (or net effect — NE) which can have a positive, negative, or null value.

Each of these indices can be used with any yield-related traits such as grain yield, biomass yield, protein yield, total nitrogen, and root biomass (Streit et al. 2019; van der Werf et al. 2021). Also, the metrics can be used to focus on other resource inputs such as water or fertilizer and can be used for quantifying nutritional values of the mixed crop harvest (van der Werf et al. 2021).

3.2.2 Classification of intercropping indices

Most of the indices are connected to two major indices, the LER and the CPR. Several intercropping indices admit to a mathematical simplification which is shown in Table 2, in addition, the indices are grouped according to their affinity with LER or CPR. Mathematical proof of these simplifications is provided in the Appendix.

3.2.3 Pearson correlation between intercropping indices

This study combines a large dataset of experimental yield observations and a large number of intercropping indices as a basis for one correlation analysis. The goal is to check the similarity between the indices and their relationship with (inter)crop yield. The plots in Fig. 2 represent the pairwise Pearson correlation between the various partial indices for legumes and cereals and between the indices that relate to the complete intercropping system.

Index pairs show different correlation values when comparing cereals with legumes but they have the same sign, with %LY (measured percentage of legume in the final yield) and EP (Expected harvest Proportion of legume) being the exception. These two indices (%LY and EP) are calculated only on legume yield thus they show a positive correlation with legume-related indices and a negative correlation with cereal-related indices. The partial LER displays a weak but significant correlation with many of the indices and showed a stronger correlation with NER, ΔRY, and %LY. A positive correlation exists between LER and CPR, being stronger in the legume and weaker in the cereal, the values for these two indices are equal when the absolute sowing proportion of the crop in the additive design equals 100%.

The legume proportion at harvest shows a positive correlation with the partial yield of the legumes and a negative correlation with the partial yield of the cereal and the total yield of the mixture. In addition, the index EP has a positive correlation with %LY, so EP could be used as a prediction of the harvest composition. Figure 2C demonstrates that the indices which have a similar equation structure (e.g., LER-TOI, AYL-NER, and CPR-YR) show a strong positive correlation.

Table 2 Simplified equations of several agronomic indices found in the scientific literature.

Group	Eq. name	Equation
LER	LEC	$LEC = LER^c LER^l$
	LSP	$LSP = 1 - \frac{1}{LER}$
	PYD	$PYD = 100(LER - 1)$
	SPI	$SPI^c = y^{ci} + y^c LER^l \quad SPI^l = y^{li} + y^l LER^c$
	ΔRY	$\Delta RY = LER - 1 \quad \Delta RY^c = LER^c - p^c \quad \Delta RY^l = LER^l - p^l$
CPR	AR	$AR^c = CPR^c - CPR^l \quad AR^l = CRP^l - CPR^c$
	CR	$CR^c = \frac{CPR^c}{CPR^l} \quad CR^l = \frac{CPR^l}{CPR^c}$
	AYL	$AYL^c = CPR^c - 1 \quad AYL^l = CPR^l - 1$
	NER	$NER = CPR z^{tot} \quad NER^c = CPR^c z^{tot} \quad NER^l = CPR^l z^{tot}$
	RCI	$RCI^c = 1 - CPR^c z^{tot} = 1 - NER^c \quad RCI^l = 1 - CPR^l z^{tot} = 1 - NER^l$
	CC	$CC^c = \frac{CPR^c}{YR} - 1 \quad CC^l = \frac{CPR^l}{YR} - 1$
	CB	$CB^c = \ln \frac{CPR^c}{CPR^l} = \ln CR^c \quad CB^l = \ln \frac{CPR^l}{CPR^c} = \ln CR^l$
	CI	$CI = \frac{z^{tot}}{YR} - 1$

The intercropping indices NE, TOI, K, YR, RRR, SE, CE, and EP do not admit to an obvious simplification of their equations. superscript "l" concerns the partial index refers to the legume; superscript "c" concerns the partial index refers to the cereal; No superscript means that the index concern the whole mixture; z^{tot} = sum of the absolute sowing proportions of cereal and legume in the mixture as a percentage of optimal sowing density for the pure stand; p^l = relative sowing proportion of legume in the mixture;p^c = relative sowing proportion of cereal in the mixture; p = sum of the relative sowing proportion of cereal and legume in the mixture, it is also called "land share".

3.3 Agronomic performance of intercropping

3.3.1 Yield: effect of total sowing density

Most studies on intercropping use the LER to estimate the advantage of this cropping system. According to LER values, the various species explored in this study show a difference in the mean performance but the diverse number of available data for each species and the dissimilarity in the execution of the experiments (e.g., the N fertilization) might have affected the results. Analogous results are also found when the LER data were analyzed by soil texture
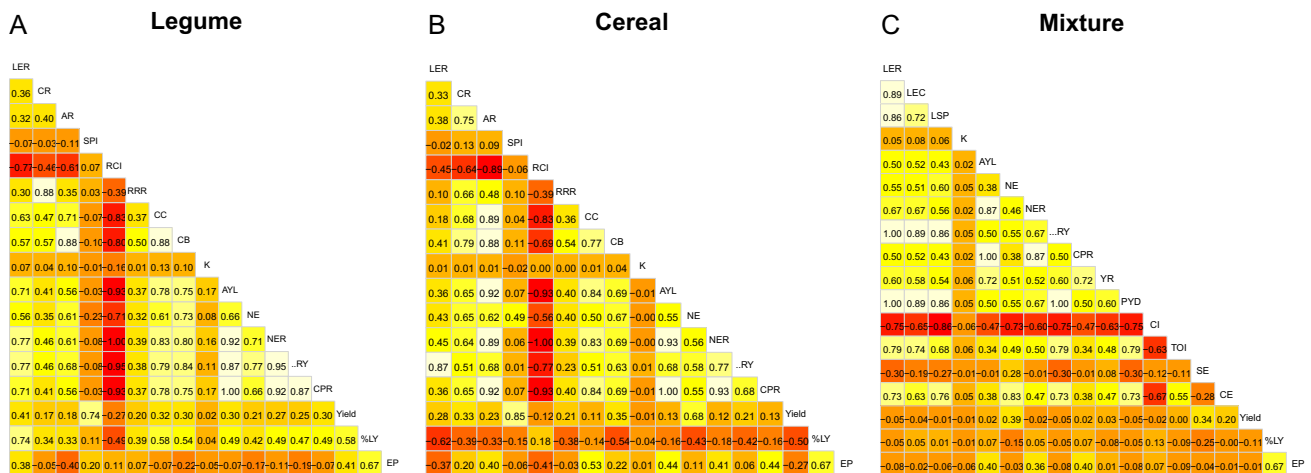

Fig. 2 Correlation plot between the intercropping indices, yield, and legume proportion at sowing and harvest. LER = Land Equivalent ratio; LEC = Land Equivalent Coefficient; LSP = Land Saving Proportion; CR = Competitive Ratio; AR = Aggressivity Ratio; SPI = System Productivity Index; RCI = Relative Competition Index; RRR = Relative Replacement Rate; CC = Change in Contribution; CB = Competitive Balance; K = Relative Crowding Coefficient; AYL = Actual Yield Loss; NE = Net Effect; NER = Net effect Ratio; ΔRY = Relative Yield gain; CPR = Crop Performance Ratio; YR = Yield ratio; PYD= Percentage Yield Difference; CI = Competitive Intensity; TOI = Transgressive Overyielding; SE = Selection Effect; CE = Complementarity Effect; Yield = Crop yield in kg (partial yield in Fig. 2A and B and total yield in Fig. 2C); %LY = measured percentage of legume in the final yield; EP = Expected harvest Proportion of the legume.

type and country of cultivation while no differences in mean LER value results from the comparison of the sowing season (winter-sown versus spring-sown), and the harvest type (whole crop biomass yield versus grain yield). On the contrary, an introductory analysis of the cereals and legumes cultivars utilized in comparable mixed intercropping experiments (similar growing conditions) displays that a difference in the mean performance between cultivars might exist. The analysis was performed with the values from the two main indices LER and CPR (data not shown). However, cultivar frequency showed extensive variation in the dataset with several cultivars appearing only once, therefore preventing strong conclusions with respect to the impact of this factor.

A Kruskal-Wallis rank-based test was performed to assess the impact of the total sowing density on the LER, CPR, and NER index values, explicitly separating additive from replacement designs. These three indices have a similar equation structure but identify the different uses of the crop sowing proportion in the calculation. The average LER value over the whole dataset is 1.18, demonstrating a general advantage of intercropping over the pure stand, in accordance with the results of most intercropping studies. The lowest observed LER value is 0.33 while the highest is 3.71. The average LER for the replacement design (1.16) was slightly lower compared to the additive design (1.24). Moreover, the average LER of non-fertilized experiments (1.14) was lower than the average LER of the fertilized experiments (1.26), though the range was around 3 for both groups. It should be noted that in this study, the various intercropping indices have not been calculated using the pure stand reference of the cereal at optimal fertilization and sowing density as this information was not available for the majority of the experiments. Using a fertilized pure stand as a reference is expected to lower the mean value of the indices, possibly revealing a less optimistic view of the competitiveness of intercropping compared to pure stands.

The partial LER values of legumes and cereals and the total LER value of these intercropping systems are presented in Fig. 3. The LER value depends on the total sowing density

in the mixture which explains why the lowest values are observed at sub-optimal densities ($< 100\%$) and the LER value increases as the total sowing density increases. N fertilization also impacts the LER as the partial LER values of legumes tend to be higher where no N fertilization is applied and the sowing density is low ($< 120\%$) as can be seen in Fig. 3A. The cereals reveal an opposite trend where N fertilization increases the partial LER. The total LER in Fig. 3C follows the same trend as the partial LER of the cereals as this is the main productive component of the mixture. In addition, N fertilization allows increasing the maximum sowing density ($180–200\%$) without causing a decrease in LER.

The CPR from which several other indices have been derived is shown in Fig. 4 as an alternative to the LER. In general, this index seems to be more influenced by the sowing density of each component compared to LER, while N fertilization seems to have little impact. From Fig. 4A and B, it is clear that legumes and cereals demonstrate a similar behavior where the performance of each plant decreases with an increase in sowing density. This trend is, however, more pronounced for cereals. Furthermore, cereals sown at low sowing densities surpass the expected yield while legumes generally remain below the threshold of 1. The total CPR (Fig. 4C) has a set threshold of 2 (sum of the two partial CPR) to estimate the advantages of intercropping and, similar to the partial CPR of the cereal, this threshold is exceeded at lower sowing density.

The distribution of the NER index is shown in Fig. 5 and is similar to that of the NE and ΔRY indices. The NER index uses the relative sowing proportion to estimate the expected response of a crop component while CPR makes use of the absolute sowing proportion. The NER generally results in values that exceed the threshold (i.e., 1 for the partial NER values and 2 for the total NER) and these values increase as the sowing density increases. The NER has a similar interpretation to LER where most of the data are above the threshold. Nevertheless, this index flattens all sowing densities to 100%, and in the end, no substantial differences arise.
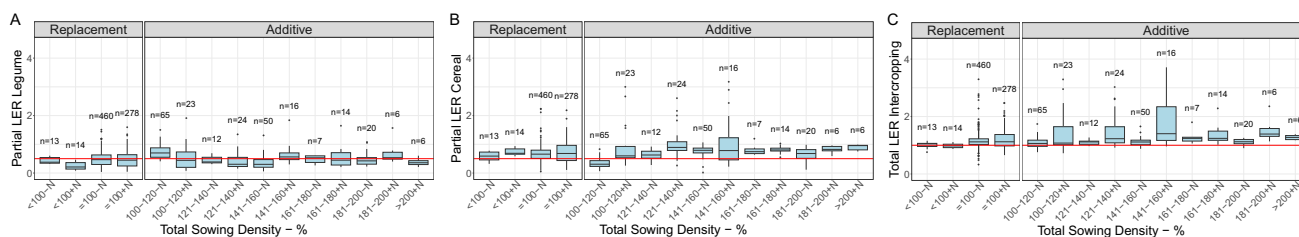

Fig. 3 Effect of total sowing density on the partial and the total LER. **A** Partial LER legume; **B** Partial LER cereal; **C** Total LER of the mixture. The horizontal axis represents the eight ranges of sowing densities where the optimal sowing density of the pure stand represents a value of 100; "n=" represents the number of the data points in each group; the red line indicates the theoretical threshold above which intercropping is considered to be advantageous; each range of sowing densities is divided in fertilized (+N) and not-fertilized (-N).
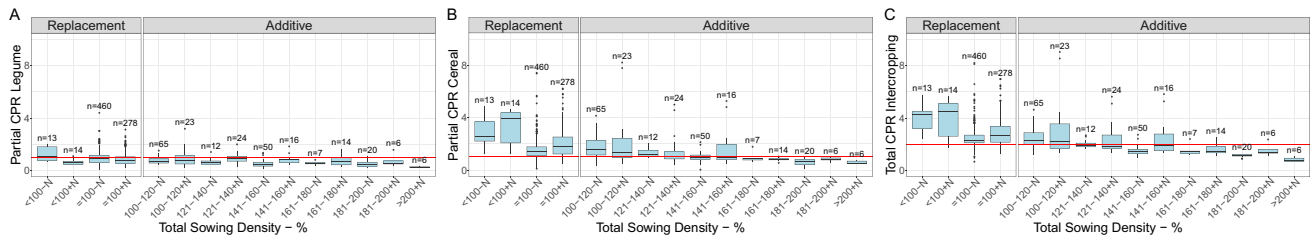
Fig. 4 Effect of total sowing density on the partial and the total CPR. **A** Partial CPR legume; **B** Partial CPR cereal; **C** Total CPR of the mixture. The horizontal axis represents the eight ranges of sowing densities where the optimal sowing density of the pure stand represents a value of 100; "n=" represents the number of the data points in each group; the red line indicates the theoretical threshold above which intercropping is considered to be advantageous; each range of sowing density is divided in fertilized (+N) and not-fertilized (-N).

3.3.2 Yield of replacement design

The replacement design is the most popular type of intercropping study and is therefore examined more closely. The total sowing density is fixed at 100% and the evaluation of the performance is based on the legume sowing proportion in the mixture (%L), while the respective cereal percentage is 100%–%L. The distributions of both the LER (Fig. 6) and the CPR (Fig. 7) values are presented. As expected, the partial LER of the legume increases with an increased proportion in the mixture and reaches a plateau value close to 70%. The LER of the cereal shows the inverse pattern as this value decreases with an increase of the legume proportion in the mixture (Fig. 6B) and shows the highest values when the legume sowing proportion exceeds 50%. However, the total LER of the intercropping system seems less affected by a change in the sowing proportion of the two components, showing only a slight decrease when the legume proportion is very high (90%) (Fig. 6C). The CPR presents a different view on these sowing proportions as can be seen in Fig. 7. The performance of the cereal in Fig. 7B is high at low cereal sowing densities and decreases as the proportion of cereals in the mixture increases. By contrast, legumes do not show any particular plasticity and the performances are more or less constant at all sowing densities (Fig. 7A), implying that the total CPR is mostly determined by the cereal component.

3.3.3 Protein yield production

Legume species differ in their yield potential (Preissel et al. 2015) but also demonstrate a large variation in seed composition (Sinclair and Vadez 2012). Protein content can be as low as 22–24% for peas and up to 45% for some lupin species (Watson et al. 2017). This range creates challenges when comparing different cropping systems as plant-based protein sources for feed and food purposes. This issue is even more pronounced for intercropping systems where crop interactions add further complication. Despite its importance, protein yield per unit of land is often not considered in intercropping studies, explaining the limited number of data points (303) available to study this trait. The average LER for crude protein yield (CP LER), as shown in Fig. 8C, is 1.24. This value demonstrates that intercropping also has the potential to improve protein production per unit of land. The average LER for grain or biomass yield for the same set of data is 1.16 (Fig. 8F). The two indices, CP LER and LER, follow the same trend where a higher median is found at higher sowing densities. This is to be expected as yield and protein yield show a positive correlation. The available data do not allow for determining the potential impact of N fertilization on protein yield and associated CP-LER values. The average CPR value for protein yield (CP CPR) is 2.83 and is shown in Fig. 9C. This value is higher compared to the average CPR
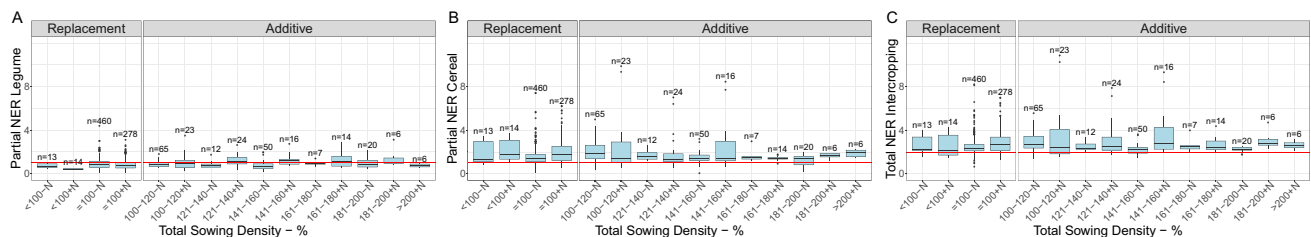

Fig. 5 Effect of total sowing density on the partial and the total NER. **A** Partial NER legume; **B** Partial NER cereal; **C** Total NER of the mixture. The horizontal axis represents the eight ranges of sowing densities where the optimal sowing density of the pure stand represents a value of 100; "n=" represents the number of the data points in each group; the red line indicates the theoretical threshold above which intercropping is considered to be advantageous; each range of sowing density is divided in fertilized (+N) and not-fertilized (-N).
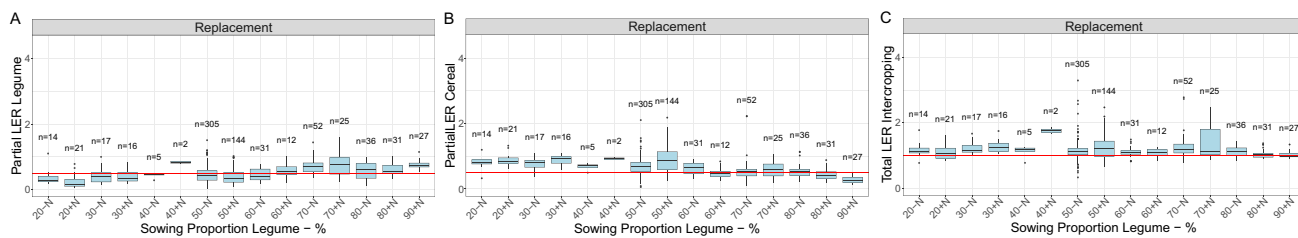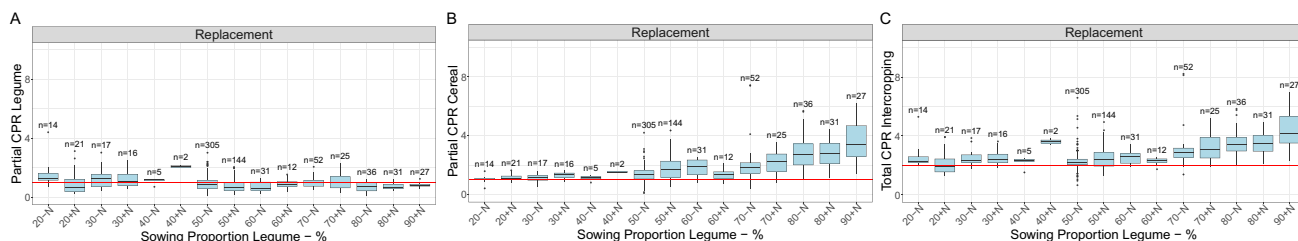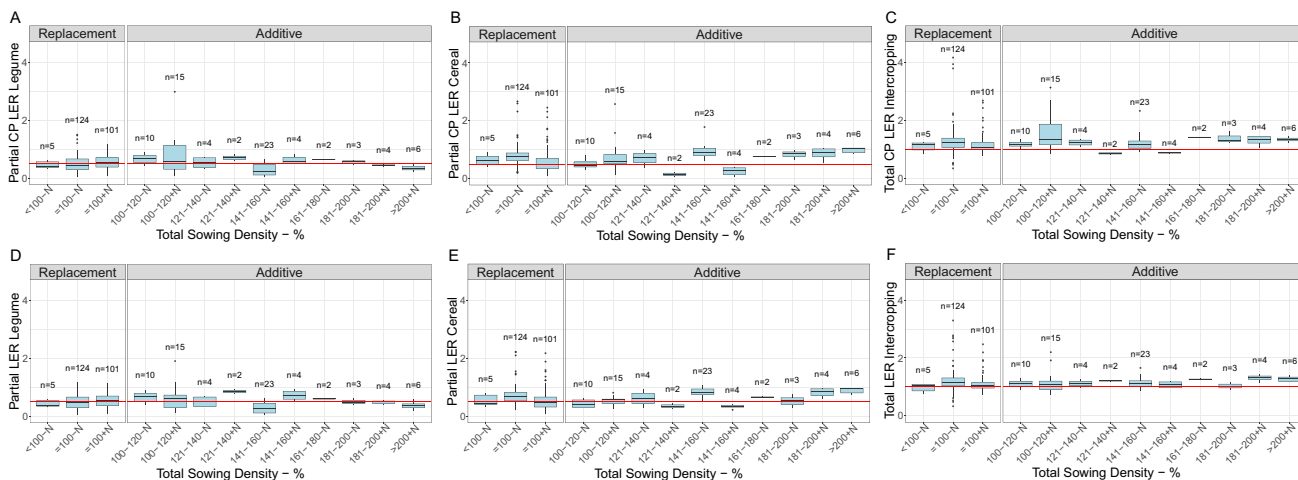
Fig. 6 Effect of legume sowing proportion (%L) in the intercropping replacement design on LER. **A** Partial LER legume; **B** Partial LER cereal; **C** Total LER of the mixture. The horizontal axis represents the percentages of sowing density of the legume; "n=" represents the num-ber of the data points in each group; the red line indicates the theoretical threshold above which intercropping is considered to be advantageous; each range of sowing density is divided in fertilized (+N) and not-fertilized (-N).
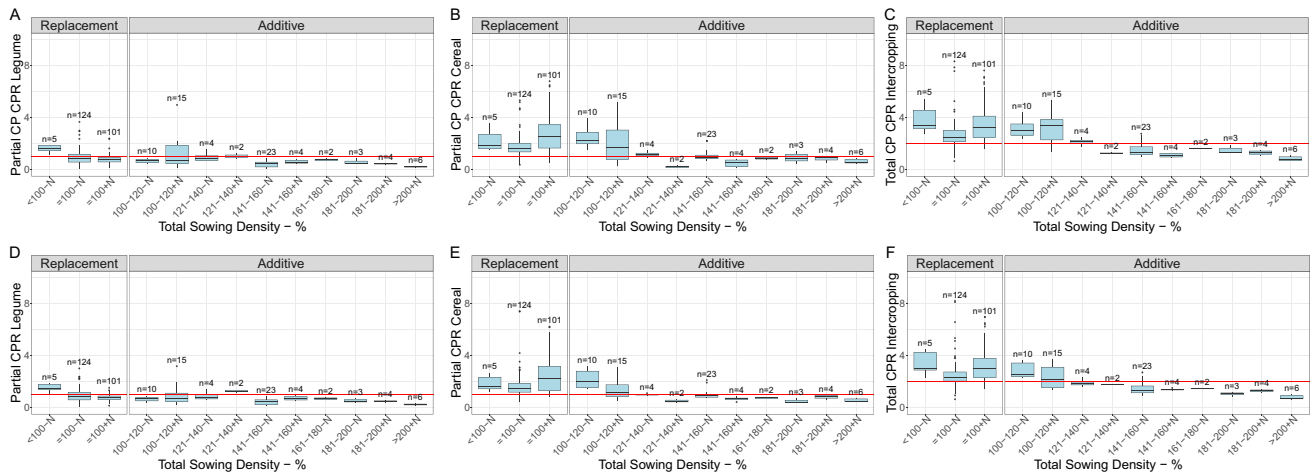

Fig. 7 Effect of legume sowing proportion (%L) in the intercropping replacement design on CPR. **A** Partial CPR legume; **B** Partial CPR cereal; **C** Total CPR of the mixture. The horizontal axis represents the percentages of sowing density of the legume; "n=" represents the num-ber of the data points in each group; the red line indicates the theoretical threshold above which intercropping is considered to be advantageous; each range of sowing density is divided in fertilized (+N) and not-fertilized (-N).

Fig. 8 Effect of total sowing density on the partial and the total LER using a reduced dataset containing only entries that report protein yields. **A** Partial CP LER legume; **B** Partial CP LER cereal; **C** Total CP LER of the mixture (CP = Crude Protein); **D** Partial LER legume; **E** Partial LER cereal; **F** Total LER of the mixture. The horizontal axis represents the eight ranges of sowing densities where the optimal sowing density of the pure stand represents a value of 100; "n=" represents the number of the data points in each group; the red line indicates the theoretical threshold above which intercropping is considered to be advantageous; each range of sowing density is divided in fertilized (+N) and not-fertilized (-N).

Fig. 9 Effect of total sowing density on the partial and the total CPR using a reduced dataset containing only entries that report protein yields. **A** Partial CP CPR legume; **B** Partial CP CPR cereal; **C** Total CP CPR of the mixture (CP = Crude Protein); **D** Partial CPR legume; **E** Partial CPR cereal; **F** Total CPR of the mixture. The horizontal axis represents the eight ranges of sowing densities where the optimal sowing density of the pure stand represents a value of 100; "n=" represents the number of the data points in each group; the red line indicates the theoretical threshold above which intercropping is considered to be advantageous; each range of sowing density is divided in fertilized (+N) and not-fertilized (-N).

calculated for yield (2.63) on the same set of data (Fig. 9F) but both traits show a similar CPR distribution over the studied range of sowing densities. The average values for the cereal are higher at lower sowing densities where the competition for mineral N between individual plants is reduced and partly due to an over-correction of the index compared to the pure stand.

4 Discussion

4.1 Literature study

This study highlights some of the challenges that one encounters when analyzing intercropping data collected from the scientific literature. Our query string retrieved over 500 papers but only 16% of these were considered relevant for evaluating intercropping indices. Many articles lack data on the partial yield of mixture components or the yield of the pure stand, precluding the calculation of intercropping indices and comparison between experiments. Missing data on the sowing proportion or sowing density of the crops in the mixture was another reason for paper exclusion as this information is essential for the classification of experimental designs as replacement or additive and the computation of several intercropping indices. Besides these prerequisites, other properties are useful for the interpretation of the results of mixed cropping experiments. For instance, information on N fertilization and water availability (precipitation and irrigation) during the growing season is generally relevant as

these parameters can influence the interaction between cereals and legumes. These metadata can, for example, be used to examine the efficiency of mixed crop systems under optimal or limiting conditions (van der Werf et al. 2021) and across different seasons and climates.

4.2 Intercropping indices

Intercropping indices are valuable tools that allow evaluating the performance of intercrop systems as compared to the performance of sole crop implementations. However, due to the many indices that are used and their regular updates over time, the comparison between intercropping results is not a trivial matter. Future research efforts in intercropping should use a common set of suitable metrics to facilitate the evaluation and comparison of research results.

The crowding coefficient (K) shows a unique correlation pattern, both for the partial (Fig. 2A and B) and the total (Fig. 2C) index specification. This index is one of the most frequently used indices in the scientific literature but shows no correlation with other indices or crop yield both the partial and combined variants. K values are generally in the range between zero and one but, in some cases, they show spikes that exceed values of one hundred and more. The highest K value in our dataset is 1651 where the yield of the cereal component in the mixture is very close to the yield of the respective pure stand. The lowest observed K value is -193 where the yield of the component in the mixture exceeds the yield of the respective pure stand. Another index with a similar trend is the SPI which only shows a significant

correlation with the partial yield in both crops. Interestingly, the total yield itself (Fig. 2C) does not admit to a strong correlation with any of the indices, including the ones which are computed on the combined yield of the mixture (i.e., TOI, YR, PYD, CI, and LEC). NE does, however, show a weak positive correlation with total yield, possibly because it is the only index that is not based on a ratio.

The legume yield percentage in the total harvest admits to a weak, negative correlation with total yield as a result of the lower yield potential of the legume that can decrease the total yield of the mixture when present at a high percentage (Agegnehu et al. 2006). On the other hand, the partial yield of the intercropping components shows a weak, but significant, correlation with many indices which indicates that in this setting, it is more appropriate to evaluate the performance of each individual crop component rather than considering the mixture as a single production unit. The index PYD raises a few concerns about its equation and meaning. Afe et al. (2015) states that the lower the value of PYD the higher the efficiency of the system because the index is inversely proportional to yield advantage (LER>1 (Li et al. 2001)). This review disagrees with the statement since it found that the index PYD is a linear function of the LER, implying a perfect positive correlation of 1. It means that the index PYD is directly proportional to yield advantage (LER) and the higher the value the higher the efficiency of the system.

The use of a single index is not sufficient to grasp all performance aspects of intercropping interaction, so the general advice is to use at least two different indices (Yu 2016; van der Werf et al. 2021). The indices should be able to describe the 4C (competition, cooperation, compensation, and complementarity) which represents the ecological processes developing during the cultivation of mixed crops (Justes et al. 2021).

- Competition stands for the ability of one species to use limiting resources better than the other one in mixed intercropping;
- Complementarity stands for the difference in resource requirements that the species in the mixture need;
- Cooperation (or facilitation) stands for the ability of one species to benefit from the other;
- Compensation stands for the ability of one species to cover the failure of the other species.

Each of these abilities does not exclude the others and is likely to be present at the same time in different proportions (Justes et al. 2021; Bedoussac et al. 2015).

The intercropping indices can describe the different advantages of the aforementioned 4C (Bedoussac et al. 2015). In particular, LER and CPR together explain the whole interactions present in the mixture and when taken separately,

quantify the singular abilities. LER, which does not take into account the sowing proportion, pictures the total effect of competition and complementarity effect, while the CPR visualizes the compensation and cooperation ability of the species inside the mixture. Thus, the recommendation is to use the partial indices (one for legumes and one for cereals) of LER and CPR as the primary source of evaluation for the experiments. The values resulting from the partial indices of legume and cereal can be plotted together to unravel the total effect of the interactions in mixed intercropping (Williams and McCarthy 2001; Bedoussac and Justes 2011; Justes et al. 2021). Evaluating a mixed crop using only the LER or one of its related indices allows for assessment of the global performance of the intercrop but does not provide insight into the plasticity of the involved plant species to adapt to changes in the cultivation system. This capacity for adaptation is key for realizing yield stability of the intercrop, even when growing conditions are less than favorable. Stable performance of other traits such as protein yield is likely just as important.

The total sowing density is an important agronomic management factor that predetermines a possible advantage or disadvantage of an intercrop system as it relates to the levels of inter- and intra-competition between and within the species of the mixture. The results of this study indicate that the density affects the yielding potential of the intercrop per unit of land and the yielding potential of each individual plant, which was also established in other studies (Eskandari and Ghanbari 2010; Barker and Dennett 2013). Consequently, the relative sowing density (or land share) and its related indices (i.e., NE, NER, and ΔRY) do not seem appropriate for evaluating mixed cropping systems. These metrics consider each intercropping system as a replacement design, removing the total sowing density from the equation and therefore ignoring an essential factor that determines the competition between crop components (Ren et al. 2016).

It should be noted that there are other intercrop performance indicators that were not included in this study. Informative traits such as yield, yield stability (as defined by Raseduzzaman and Jensen (2017)), and harvest ratio of the two components are equally valuable (Hauggaard-Nielsen et al. 2006). The information provided by these performance indicators and derived intercropping indices allow for describing the adaptability of certain crops or varieties to different intercropping combinations, enhancing our understanding of genotype×genotype×environment interactions and general and specific mixing abilities (Moutier et al. 2022).

4.3 Agronomic performance of intercropping

The evaluation of different indices has shown that both the total sowing density and N fertilization level are major factors

that affect intercropping yield (Pelzer et al. 2014; Rodriguez et al. 2020). The LER shows a trend to increase as sowing density increases while the CPR tends to decrease under the same conditions. Assuming a fixed total sowing density, a change in the cereal-legume proportions only has a limited effect on the final outcome of the intercropping system while there is a substantial effect on the partial performance of the component crops. Inside the mixture, one component nearly always dominates the other as shown in Fig. 6, implying one low and one high partial LER regardless of the cereal-legume proportion. As a consequence, the total LER does not identify the mixture components that perform well or poorly (van der Werf et al. 2021).

The CPR shows a different behavior where the proportion of cereal in the mixture does effectively change the final outcome of the intercrop (Fig. 7). While the legume counterpart often yields as expected by its sowing proportion, possibly due to low space for development and minor ability to compensate with additional branches from the higher competition level, additional studies are needed to evaluate this theory (Bedoussac et al. 2015). Cereals, in general, show exceptionally high values at low sowing proportions. This phenomenon is partly due to cereals' higher trait plasticity in different environments and growing conditions (Ajal et al. 2021, 2022). In intercropping, the cereals show elevated trait values (i.e., tillering and canopy) (Demie et al. 2022; Ajal et al. 2022) and these factors are normally associated with yield advantage (Ajal et al. 2021). However, the CPR can be misleading for small cereals as the reference yield is scaled linearly according to the sowing density, ignoring the crop's compensating behavior in the sole crop while accounting for it in the mixture. This results in overly optimistic and pessimistic CPR values at respectively, low and high sowing densities of the cereal in the mixture. The LER, on the other hand, does not correct for sowing density and therefore demonstrates the exact opposite behavior when estimated for a crop component that has the ability to compensate for sowing density. The combined evaluation of both the LER and CPR seems key for identifying the optimal cereal proportion that reaches a complementarity-competition balance and sufficient yield level in low-input settings (Monti et al. 2016).

Most intercropping systems include a protein crop so the evaluation of performance should also consider the protein production per unit of land. This characteristic is often not considered a crop production trait but it is often included in crop quality. Additionally, the protein content measurements require additional time, costs, and labor but with the advent of new technology for faster and easier evaluation (e.g., NIR) and collaboration between the scientific community, this obstacle could be overcome. Lastly, the yield as one agronomic trait and protein content as a quality trait is often split in different publications (e.g., Baxevanos et al. (2017) and Tsialtas et al. (2018)). This study shows LER and

CPR values for protein yield exceeding those for biomass and grain yield. This increase is mainly driven by the presence of the legume in the harvest but some studies show that also the cereal has a higher N content, both in the grain and in the straw, when grown in combination with a legume crop (Bedoussac and Justes 2008; Monti et al. 2016). Several reasons explain the increased protein content of the cereal component. The cereal benefits from increased availability of N per plant as a result of the limited competition of the legume for mineral N and the reduced cereal sowing density (Gooding et al. 2007). Other studies suggest that the ability of legumes to fixate nitrogen can affect the neighboring cereal crop by releasing some of this nutrient in the soil (Paynel et al. 2008; Chapagain and Riseman 2015), and few papers suggest that nitrogen could be transferred through mycorrhizal hyphal networks from legume to cereal (Selosse et al. 2006; Van Der Heijden and Horton 2009; Homulle et al. 2021). The variation of the LER and CPR indices for grain or biomass yield and crude protein yield are displayed in Fig. 8 and Fig. 9, respectively. Crop mixtures can show different abilities in terms of yield and protein yield, there is the possibility that a mixture performs well in terms of both grain or biomass yield and protein yield or that the mixture performs well only for one of the two characteristics. This behavior not only depends on the sowing density or N fertilization but also on the specific crop combination in the mixture (Baxevanos et al. 2017). Therefore, future intercropping research efforts should also focus on indices for protein yield to evaluate the system's performance under study.

The data available for this study did not allow for a comprehensive assessment of the effect of the chosen species and varieties on the intercropping performance. Other studies provide a more comprehensive evaluation of these design factors (Hauggaard-Nielsen and Jensen 2001; Annicchiarico et al. 2017; Streit et al. 2019; Demie et al. 2022) but generally rely exclusively on LER values. Complementing the LER with the CPR index allows the evaluation of land use and crop plasticity which can identify the suitable genotypes for different crop species combinations, crop ratios inside the mixture, and N fertilization input levels (Haug et al. 2021). The combined analysis of LER and CPR indices allows the quantification of the complementarity of two genotypes or species in an intercropping system and could help to identify which phenotypic traits (e.g., growing habits, root structure, nutrient requirements, and pest susceptibility) impact the total intercropping efficiency (Duc et al. 2015; Demie et al. 2022).

The reliability of future meta-analyses and experiment comparison would increase if a uniform procedure is used, beginning with the setup of the intercropping trial and ending with the indices used to evaluate the mixture. The inclusion of standard treatments in all intercropping trials allows for a straightforward evaluation of the different factors involved.

The trial setup should contain at least (1) a low-fertilized pure stand reference at optimal sowing density, both for the legume and the cereal, to evaluate the performance of the intercrop in a setting relating to organic and low-input agriculture; (2) a pure stand reference of the cereal at optimal fertilization and sowing density relating to conventional agronomic practices. Furthermore, there is evidence suggesting that plant biomass production could increase significantly, even with low levels of fertilization (Sobkowicz and Śniady 2004), so it could be argued if the low-fertilized pure stand reference should be equal to 0 or should match a low fertilization level around 25–30 kg N ha^{-1}. More research is needed to identify the most suitable practice of N fertilization that allows for a fair comparison between mixed cropping and pure stand. In terms of intercropping indices, the combination of the LER and CPR should be considered the gold standard which does not preclude the inclusion of other metrics for substantiating specific research claims. The intercropping indices should evaluate both the grain or biomass yield and the protein yield and they should be calculated for each replicate as suggested by Oyejola and Mead (1982) to capture the variation within the field. Finally, the interpretation of the terms in the equations of the various indices should be standardized among the scientific and public community. At first, the nomenclature for the indices and the terms should be similar, if not identical. Secondly, a common way of calculating the equation should be approached in a way that all results are easily comparable at first encounter. Thus, this research laid the basis for common nomenclature and suggests that it should be appropriate to use the yield of the pure stand at the optimal sowing density as a reference value as was described by Bulson et al. (1997) but one should provide the estimation of this value under both low and optimal fertilization levels.

4.4 Advantages and disadvantages of intercropping indices

All intercropping indices have strong and weak points in the involved parameters and calculation, which means that none of them fully describes the consequences of plant interactions happening in the field. The indices can be equally used for any yield-related trait or measure (e.g., grain yield, biomass yield, protein yield, and oil/fat yield), and each of these measures could bring a different point of view on intercropping (van der Werf et al. 2021). Resource use efficiency is more difficult to target with the aforementioned indices, without any additional measurement, since an intercrop in a low input system uses a greater amount of soil-derived nitrogen, ranging from 25 to 39% (Rodriguez et al. 2020). The equivalent ratio indices for water and fertilizer are equal to LER or to zero when the treatments receive respectively the same

amount of resource or when they do not receive any supply (Xu et al. 2020). The calculation of any resource use efficiency should be derived from a balance of resources in the environment [Input − Output − Soil Changes] (Sainju 2017), such as total nitrogen balance, the seasonally available water, ET (evapotranspiration) potential, and precipitation distribution (Morris and Garrity 1993). Only then, the results could be associated with the production trait or other intercropping indices.

The subsequent paragraph provides a summary of the main advantages and disadvantages of each intercropping index, taking into account the discussed results in this paper. [4C = which ecological process is described by the index (Justes et al. 2021); A = Advantage(s); D = Disadvantage(s)].

- LER (Land Equivalent Ratio): 4C — Competition and complementarity effects, A — Indication of unit of land saved and it is easy to calculate and understand for everyone, D — Does not consider plant interaction and sowing densities;
- LEC (Land Equivalent Coefficient): 4C — Competition, cooperation, and complementarity effects, A — Simulates plant interaction, D — The reference value needs to be adjusted to every sowing density;
- LSP (Land Saving Proportion): 4C — Competition and complementarity effects, A — Gives the exact percentage of the land saved with intercropping, D — Is commonly accepted to use LER as a unit of the land saved by using intercropping;
- PYD (Percentage Yield Difference): 4C — Competition and complementarity effects, A — Values are on a scale based on 100 which makes the values easy to plot, D — Is equal to LER, with no added information and it has a difficult equation at first;
- SPI (System Productivity Index) 4C — Competition and complementarity effects, A — Indication of species productivity in intercropping, D — Unrealistic values when the yield gap between species is large;
- ΔRY (Relative Yield gain): 4C — Competition and complementarity effects, A — Reference to expected yield; Easy to understand, D — Does not differentiate between additive or replacement designs;
- CPR (Crop Performance Ratio): 4C — Compensation and cooperation effects, A — Consider the actual sowing proportion and give a reference to the expected yield, D — Does not account for the tillering ability of cereals;
- AR (Aggressivity Ratio): 4C — Competition and cooperation effects, A — Insight on the dominant crop, D — Not a direct value on intercropping production;
- CR (Competitive Ratio): 4C — Competition, compensation, and cooperation effects, A — Insight on the dominance level of one crop, D — Not a direct value on intercropping production;

- AYL (Actual Yield Loss): 4C — Compensation and cooperation effects, A — Value on overyielding based on crop proportions, D — Equal to CPR with no additional information;
- NER (Net Effect Ratio): 4C — Competition and complementarity effects, A — Expressing the overyielding in an easy-to-compare way with CPR and LER, D — Does not differentiate between additive or replacement designs;
- K (Crowding Coefficient): 4C — Competition effects, A — Could have a positive use in ecological studies with complex species mixtures, D — Has a complex equation and its results are rarely significant;
- YR (Yield Ratio): 4C — Compensation and complementarity effects, A — Fast evaluation of intercropping based on the crop proportions, D — Does not consider single species performance;
- TOI (Transgressive Overyielding): 4C — Compensation, competition, and complementarity effects, A — Fast evaluation of intercropping overyielding, D — Does not consider single species performance;
- NE (Net Effect): 4C — Compensation and complementarity effects, A — The only index with a measurement unit that makes the application of intercropping easy to understand, D — Does not differentiate between additive or replacement designs; Value can have difficult evaluation due to high yield gap between species;
- RRR (Relative Replacement Rate): 4C — Compensation and competition effects, A — Valuable in complex and permanent mixtures to evaluate the mixtures over time, D — Looses meaning in the annual binary mixtures and cereal yield compensation can bias the result;
- CI (Competition Intensity): 4C — Competition effects, A — A theoretical value ranging between -1 and 1 which makes it easy to understand the overall production of intercropping D — No single species evaluation, Opposite results interpretation compared to the other indices (below zero is good for intercropping over the sole crop);
- CC (Change in Contribution): 4C — Competition, compensation, and complementarity effects, A — Explains plant interactions and deviations from the expected yield, D — Complex model for evaluation and interpretation of results compared to other indices;
- CB (Competitive Balance): 4C — Competition effects, A — Magnitude of crop competitive ability, D — Not a direct value on intercropping production;
- EP (Expected harvested Proportion): 4C — Compensation, competition, and complementarity effects, A — Predicts harvest proportions with good accuracy, D — Cannot distinguish if the obtained value derives from good or bad performance of the species;
- RCI (Relative Competitive Intensity): 4C — Competition and complementarity effects, A — Value of overyielding over the expected yield, D — Is not intuitive being the reverse value of NER and does not differentiate between additive or replacement designs;
- SE (Selection Effect): 4C — Competition and complementarity effects, A — Indicates the interaction between components as a portion of the overyielding, D — Does not differentiate between additive or replacement designs;
- CE (Complementarity Effect): 4C — Cooperation and complementarity effects, A — Indicates the facilitation between components as a portion of the overyielding, D — Does not differentiate between additive or replacement design.

5 Conclusions

The main point of interest relates to the impact of various crop husbandry practices on intercropping performance. An additive design, inherently associated with a higher sowing density, generally appears to be more advantageous in terms of LER values when compared to a replacement design. However, in this design, each crop component suffers more from competition effects which decrease the crop efficiency, resulting in a lower CPR value. Inside a replacement design, the proportion of cereal has little impact on the final value of LER, while it does impact the total CPR. Nevertheless, both indices are required to suggest the best practices in order to achieve a high-yield outcome (LER) and reduce the competition between crops (CPR).

The mixed intercropping system is not yet largely adopted due to the limited know-how of the best practices to maximize yield and revenue. Mixed intercropping relies on the balance of competition, cooperation, compensation, and complementarity which adjust differently with changes in cropping conditions. Nitrogen fertilization has an impact on the intercropping yield, it increases the total outcome but also increases the cereal competitiveness. On the other hand, the crop proportion in the mixed cropping system does not largely affect the LER but it could determine the higher or lower protein yield per unit of land.

Furthermore, an intercropping system generally includes a protein crop in the mixture, enabling the estimation of performance metrics for both grain or biomass and protein yield. The advantage of intercropping is generally more pronounced when only considering protein yield and crop combinations do not necessarily perform well for both traits. Nevertheless, future intercropping studies should evaluate performance metrics for both grain or biomass and protein yield.

A large number of intercropping indices can be found in the scientific literature, but one index alone is not capable of evaluating all the advantages of intercropping, implying that results should include at least two different/contrasting

indices to gain a broader knowledge of crop performances. This research points out that most of these indices can be rewritten as functions of the LER or CPR indices, and that single-crop performance is favorable over total intercropping performance. So, together with the yield results, the review advises using the LER index as an indicator of land use and total yield production in combination with the CPR index to reflect the plasticity and performance potential of the cropping system. Combining these indices together with a standardized experimental protocol will facilitate the optimization of agronomic practices that maximize mixed cropping performance.

The number of studies on intercropping is growing both in terms of published papers and in the diversity of experiments. Until now, the replacement design is the most commonly used in intercropping experiments, with a particular focus on the 50:50 ratio, representing half of the data points in the assembled meta-dataset. This study lays the foundations for a standardized protocol to set up and evaluate intercropping trials that enable cross-experiment comparison of results. Our study suggests using a uniform trial setup that includes both a non-fertilized pure stand of both crops and a pure stand of the cereal with optimal fertilization. This approach allows the evaluation of an intercropping system in both low-input and conventional agricultural settings.

Appendix: Mathematical proof

Here are listed the mathematical proofs of the simplifications in Table 2 of PYD, CI, NER, RCI, CB, and CC.
The simplification is done only for one of the two partial indices.
The formula of PYD

$$PYD = 100 - [(\frac{y^c - y^{ci}}{y^c} + \frac{y^c - y^{li}}{y^c})100]$$

$$= 100 - [(\frac{y^c}{y^c} - \frac{y^{ci}}{y^c} + \frac{y^c}{y^c} - \frac{y^{li}}{y^c})100]$$

$$= 100 - [(1 - LER^c + 1 - LER^c)100]$$

$$= 100 - [(2 - LER)100]$$

$$= 100 - [200 - 100LER]$$

$$= 100 - 200 + 100LER$$

$$= 100(LER - 1)$$

The formula of CI

$$CI = \frac{p^c y^c + p^c y^c}{y^{ci} + y^{li}} - 1$$

$$= \frac{(z^{ci}/z^{tot})y^c + (z^{li}/z^{tot})y^c}{y^{ci} + y^{li}} - 1$$

$$= z^{tot}\frac{z^{ci}y^c + z^{li}y^c}{y^{ci} + y^{li}} - 1$$

$$= z^{tot}\frac{1}{YR} - 1$$

$$= \frac{z^{tot}}{YR} - 1$$

The formula of NER is

$$NER^c = \frac{y^{ci}}{p^c y^c}$$

$$= \frac{y^{ci}}{\frac{z^{ci}}{z^{tot}} y^c}$$

$$= \frac{y^{ci}}{z^{ci} y^c} z^{tot}$$

$$= CPR^c z^{tot}$$

The formula of RCI is

$$RCI^c = \frac{p^c y^c - y^{ci}}{p^c y^c}$$

$$= \frac{p^c y^c}{p^c y^c} - \frac{y^{ci}}{p^c y^c}$$

$$= 1 - \frac{y^{ci}}{\frac{z^{ci}}{z^{tot}} y^c}$$

$$= 1 - \frac{y^{ci}}{z^{ci} y^c} z^{tot}$$

$$= 1 - CPR^c z^{tot}$$

$$= 1 - NER^c$$

The formula of CB is

$$CB^c = \ln\frac{(z^{li}y^{ci})/(z^{ci}y^{li})}{y^c/y^c}$$

$$= \ln(\frac{z^{li}y^{ci}}{z^{ci}y^{li}}/\frac{y^c}{y^c})$$

$$= \ln(\frac{z^{li}y^{ci}}{z^{ci}y^{li}}\frac{y^c}{y^c})$$

$$= \ln(\frac{z^{li}y^l y^{ci}}{z^{ci}y^c y^{li}})$$

$$= \ln(CPR^c \frac{1}{CPR^c})$$

$$= \ln\frac{CPR^c}{CPR^c}$$

The formula of CC is

$$CC^c = (\frac{y^{ci}}{y^{ci} + y^{li}}/\frac{p^c y^c}{p^c y^c + p^l y^l}) - 1$$

$$= \left(\frac{y^{ci}}{y^{ci} + y^{li}} \Big/ \frac{\frac{z^{ci}}{z^{tot}} y^c}{\frac{z^{ci}}{z^{tot}} y^c + \frac{z^{li}}{z^{tot}} y^c} \right) - 1$$

$$= \left(\frac{y^{ci}}{y^{ci} + y^{li}} \frac{\frac{1}{z^{tot}}(z^{ci} y^c + z^{li} y^c)}{\frac{1}{z^{tot}}(z^{ci} y^c)} \right) - 1$$

$$= \left(y^{ci} \frac{1}{y^{ci} + y^{li}} (z^{ci} y^c + z^{li} y^c) \frac{1}{(z^{ci} y^c)} \right) - 1$$

$$= \left(\frac{y^{ci}}{z^{ci} y^c} \frac{z^{ci} y^c + z^{li} y^c}{y^{ci} + y^{li}} \right) - 1$$

$$= \left(CPR^c \frac{1}{YR} \right) - 1$$

$$= \left(\frac{CPR^c}{YR} \right) - 1$$

Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

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