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Finding guidelines for cabbage intercropping systems design as a first step in a meta-analysis relay for vegetables

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ABSTRACT

Modern agriculture has been focused on optimizing production, neglecting supporting and regulating ecosystem services. Meta-analyses have demonstrated the potential of intercropping to deliver multiple ecosystem services. However, guidelines for the design and management of such systems remain unclear, especially for the under-studied vegetable-based intercropping systems. Given the diversity of vegetable crops, we propose a 'relay' of classical crop-specific meta-analyses to capitalize on vegetable intercropping research. Each 'leg' in the relay analyzes the effects of companion crops on a focal crop, and over the course of subsequent legs, the network of interactions among the different crops is built. In this study we start what we aspire to be the meta-analysis relay, focusing on cabbage (*Brassica oleracea* ssp.) and the delivery of the provisioning services Productivity, Product Quality (grade and pest injury in cabbage products), and Yield Stability across different companion species, spatio-temporal configurations, and management practices. We identified 76 studies from all inhabited continents across 81 field sites, comprising 892 data records, of which 689 remained after cleaning. We show that intercropping reduced cabbage productivity (−7% on average, $P < 0.05$) but also pest injury (−48%, $P < 0.001$) relative to sole cabbage systems. Cabbage grade on the contrary was not significantly improved by intercropping (+1%, $P = 0.71$). Effects on yield stability varied widely as only few data records were available from trials conducted over more than two years, pointing to the need for longer-term experimentation. Greater productivity was associated with companion species with a low growth habit or types sown at or after planting of the cabbage crop thus limiting competition with cabbage at early development stages. The decrease in pest injuries was associated with intercropping patterns involving strong inter-plant interactions (i.e., mixed, row, and additive) and companion species that supported biodiversity such as living mulches. Overall, beneficial effects of intercropping tended to be more evident in organic production systems, possibly because synthetic inputs may have hidden regulating effects. Cabbage growers and agricultural advisors can use these guidelines when designing intercrop systems specific to their needs. Applying the approach to other crops and agro-ecosystem services as part of the proposed meta-analysis relay will foster comprehensive understanding of vegetable intercropping systems interactions.

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1. Introduction

Agricultural intensification through the homogenization of crops and reliance on external inputs (i.e., irrigation water, pesticides and fertilizers) has led to an unprecedented biodiversity loss (Raven and Wagner, 2021) and has been detrimental to ecological regulation of water, soil fertility, and pests and diseases (Campbell et al., 2017; Foley et al., 2005). Agricultural transformation towards systems that are productive and replace external inputs by harnessing ecosystem services will be crucial to restoring global sustainability (Bommarco et al., 2013). In this respect, growing evidence is showing that crop diversification practices (e.g., rotations, agroforestry, or cultivar mixtures) can support multiple ecosystem services while maintaining or even increasing provisioning services (i.e., food, fuel or fiber production) compared with mainstream monocropping (Beillouin et al., 2021). The increase of crop diversity in time (e.g., crop rotations) and/or space (e.g., alley cropping) can enhance pollination, soil conservation, water and nutrient use efficiency, or landscape aesthetic services and provide more resilient production under climate extremes (Beillouin et al., 2019; Tamburini et al., 2020). Within crop diversification, intercropping – the practice of growing two or more species simultaneously in the same field for the whole or a part of their growing periods – has been demonstrated to be particularly beneficial in terms of production, yield stability, associated biodiversity and pest and disease control per unit of land (Beillouin et al., 2021; Iverson et al., 2014; Raseduzzaman and Jensen, 2017; Tamburini et al., 2020; Zhang et al., 2019). Attaining such benefits involves leveraging space, water, nutrients and light using the ecological principles of niche complementarity and facilitation (Brooker et al., 2015). Niche complementarity is achieved by selecting species that do not overlap in their resource acquisition traits, such as temporal differences in peak resource demands or different rooting patterns (i.e., deep versus shallow), resulting in reduced competitive interplant interactions. Facilitation arises when one species provides a limiting resource for or improves the microenvironment of another species (Brooker et al., 2016; Shanmugam et al., 2021). Examples are N transfer from nitrogen-fixing legumes to companion species or greater nutrient availability to the entire plant community through secretion of root exudates (Brooker et al., 2016; Li et al., 2014). Increasing plant species diversity can have cascading effects for other trophic groups in the farmland such as increased diversity and abundance of pollinators, natural pest enemies or beneficial soil microbes (Duchene et al., 2017; Wan et al., 2020).

Despite their demonstrated potential, intercropping systems are underrepresented in modern agriculture and largely confined to traditional smallholder farming in Latin America, Africa and China and some types of animal feed production in Europe (Brooker et al., 2015). Farmers face a number of socio-technical lock-ins, from production to market as a consequence of wide-spread specialization and maximization of short-term profits (Morel et al., 2020). Morel et al. (2020) found the greater number of barriers at the production level, revealing practical challenges and knowledge gaps that discouraged farmers from trying out intercropping in the first place. Transitioning from monocropping to the simultaneous cultivation of multiple crops with different production requirements can be (scientifically and practically) knowledge-intensive as it entails a greater understanding of agroecological processes and rethinking how the field is managed to navigate trade-offs (Ditzler et al., 2021a; Duru et al., 2015; Himanen et al., 2016). Which crop combinations, what temporal differences between the intercrop components, and how they should be spatially arranged (e.g., in rows or mixed) to make intercropping most effective for the intended goals are pivotal questions in intercropping design. In this respect, research can contribute by providing design principles that facilitate farmers' decision-making and advance intercropping uptake (Duru et al., 2015; Himanen et al., 2016; Juventia et al., 2022).

Conceptually, systems design for crop diversification involves choices regarding the genetic, spatial and temporal dimensions of diversity (Ditzler et al., 2021a) as well as field management. The choice of a focal crop (the genetic dimension of crop diversification) is likely driven by market demands as it is grown to sell for profit, i.e., to act as a cash crop. The choice of the companion species can serve different objectives such as supporting the cash crop by improving pest suppression, pollination, or nutrient availability; supporting the revenue of the system; or improving soil health (Hatt et al., 2018; Schipanski et al., 2014). From an ecological perspective, an ideal companion species maximizes positive interactions (niche complementarities and facilitation) and minimizes negative competition with the focal crop (competition relaxation) while maintaining reasonable growth and survival (Bedoussac et al., 2015; Brooker et al., 2015). Plant-plant interactions are context-dependent so that intercropping design cannot be addressed without taking into account the spatial arrangement of the intercropped species, i.e., the spatial dimension, and the time they coexist, i.e., the temporal dimension (Brooker et al., 2008; Ditzler et al., 2021a). Moreover, system inputs, together representing field management can exert a strong influence on the intercropping outcome (Li et al., 2020) and, thus, must be considered as part of systems design (Stomph et al., 2020). Different choices in these genetic, spatial, temporal and management aspects will result in different degrees of agro-ecosystem services delivery. The vast majority of empirical studies have examined how a limited number of these aspects influenced ecosystem services individually. Synthesizing current intercropping knowledge on the relationships between intercropping system aspects and agro-ecosystem services delivery would contribute a basis for intercropping design.

Meta-analysis has proved to be a useful tool to synthesize the scientific literature and to identify generalisable patterns across contexts and site-specific field study results. This allows to draw more rigorous scientific conclusions and to provide guidelines during context-specific cropping systems design by farmers and advisors (Gurevitch et al., 2018; Juventia et al., 2022). Examples of such guidelines for intercrop design drawn from meta-analyses include that replacement designs more consistently enhance yield stability of intercrops than additive designs, that temporal differentiation between maize and its companion species enhances land productivity in high-input systems, and that the inclusion of legumes at high planting densities can benefit both production and biocontrol services (Iverson et al., 2014; Raseduzzaman and Jensen, 2017; Yu et al., 2016). Much of the intercropping meta-analysis literature, however, is built on the predominant experimentation with cereal/legume intercropping systems (Ditzler et al., 2021b). Here we aim for guidelines when vegetables are the focal components of the intercropping system.

A major query from farmers practising vegetable-based intercropping is which species are good companions (Hondebrink et al., 2019). The large number of vegetables and non-vegetables that may be combined makes the task of identifying good companions cumbersome. Drawing on a metaphor from athletics, we propose a 'relay' of meta-analyses, in which the focal crop species in a particular meta-analysis serves as a 'baton' by being a companion species in the next meta-analysis. Over the course of the various meta-analyses, knowledge is thus built for a network of focal and companion species. Each meta-analysis, or, each 'leg' in the relay, may be carried out independently and adds to the knowledge base on vegetable-based intercropping. This way of working has the advantage of combining the scientific rigour of meta-analyses with a pragmatic sharing of workload within the scientific community. To kick off the proposed relay of meta-analyses in vegetable production systems, we carried out a meta-analysis with cabbages as the focal species as the first 'leg'.

Cabbages are the fourth most-produced vegetable in the world, reaching an annual global production of over 70 million tonnes (FAOSTAT, 2021), and are cultivated worldwide due to their nutritional value and adaptability to diverse agro-climatic conditions (Ahuja et al., 2011). Cabbage cultivars encompass a wide variety of cash-crop vegetables mainly represented by head cabbage, cauliflower, broccoli, kale, and Brussels sprouts. In addition to yield, profitability of cabbage products largely depends on their quality as they are commonly sold per unit rather than in bulk (Ahuja et al., 2011; Juventia et al., 2021). Adequate size, shape, firmness and absence of anomalies (here referred to as grade), and the absence of pest injuries (hereafter referred to as injury-free product) determine the quality of cabbage products (European Parliament, 2013).

In this study, we aimed to analyze the effects of the diversity dimensions and field management (Ditzler et al., 2021a) on agro-ecosystem services delivery in intercropped cabbage systems to derive guidelines for vegetable-based intercropping design and ultimately facilitate adoption by farmers. We focused on the effect of intercropping on provisioning services, which due to their relation with profitability influence the adoption of diversified systems (Kleijn et al., 2019). We first quantify the intercropping effect on the performance of cabbages in terms of productivity, product quality, and yield stability, and explore the relations among them. We then examine the modifying effect of genetic, spatial and temporal dimensions and of field management in terms of fertilizer and pesticide use to identify promoters and limiting factors for the delivery of each provisioning service. We end with a discussion of implications in terms of the three dimensions of diversity and the management practices for cabbages, and next steps in meta-analysis contributions to vegetable-based cropping systems design.

2. Material and methods

2.1. Sources of data, inclusion criteria, and data organisation

A literature search was carried out in 'Scopus' on 23 May 2022 using two term clauses. The first clause targeted any literature related to intercropping, and the second clause further delimited literature to cabbage systems: TITLE-ABS-KEY ("intercrop*" OR "mixed crop*" OR "crop mixture" OR "mixed cultivation" OR "coculture" OR "strip-crop*" OR "stripcrop*" OR "crop combin*" OR "crop divers*" OR "mixed farming" OR "co-culture" OR "poly-culture" OR "polyculture" OR "multiple crop" OR "inter crop*" OR "inter-crop*" OR "strip crop*" OR "living mulch*" OR "relay crop*" OR "relay-crop*" OR "relaycrop*" OR "undersow*") AND TITLE-ABS-KEY ("cabbage" OR "brussels sprout" OR "cauliflower" OR "Brassica oleracea" OR "b. oleracea" OR "kale" OR "collard" OR "broccoli"). This search resulted in a total of 414 studies. A first screening of these studies was performed by an analyst at title and abstract level to exclude studies that did not address intercropping or field studies (e.g., reviews, simulation modelling or greenhouse experiments). This resulted in removal of 177 studies from the database (Fig. S1).

The remaining 237 articles were screened at full-text level for relevance adhering to the following criteria. Cabbage-based intercropping was defined as the cultivation of *Brassica oleracea* species concurrently with other species (companion species) in space (i.e., the same field; lab or greenhouse experiments were excluded) and in time (i.e., relay intercropping designs were included, but not crop rotations). The studies had to have a cabbage sole crop control under equivalent management and growing conditions as the intercrop treatments. Companion species included both harvested crops and non-harvested plant species (e.g., cover crops, flower strips and living mulch). The studies had to quantify at least one of the provisioning services: Productivity, Product Quality, and Yield Stability.

Productivity data records consisted of measurements of biomass of the plant part for which the crop was grown (e.g., head for white cabbage, curd for cauliflower, leaves for kale and collards). Product quality data records encompassed metrics related to market quality requirements and general appearance of the cabbage product (e.g., size indicators, quality grades, or pest injury scores). Yield Stability was a subset of productivity data records consisting of data records of experiments that had been repeated over at least three seasons or three locations, thus providing an indication of the robustness of effects. Data records within provisioning services were further organised into sub-categories (hereafter 'response variables') according to the metric type (Table S1). The mean value, a measure of variability (e.g., standard deviation, coefficient of variance or least significance differences), and the number of replicates in the sole cabbage and intercrop cabbage system were recorded for each metric of interest. Mean and measure of variability values presented in published graphs were extracted taking a snapshot of the figure and scaling the axes with WebPlotDigitizer (Rohatgi, 2019). In addition to data retrieved from published studies, we collated data from yet unpublished studies belonging to the SureVeg (https://projects.au.dk/coreorganiccofund/core-organic-cofund-projects/sureveg/), DiverIMPACTS (https://www.diverimpacts.net/index.html), and the PPS Beter Bodembeheer (https://www.beterbodembeheer.nl/nl/beterbodembeheer.htm) research networks.

Each of the articles was read in full by one analyst and, if it complied with the inclusion criteria detailed in Fig. S1, relevant data was extracted. Each paper that had been found to contain data for the meta-analysis was then read by a second analyst and all the data extracted was checked by another analyst. Decisions about interpretation were discussed within the team of three analysts. Table 1.

We identified 86 published studies fitting the criteria which, together with the unpublished studies ($n = 6$), gave a total of 92 valid studies for meta-analysis (Fig. S1, Table S2). Within the studies, 146 experiments, i.e., combinations of site and year were distinguished from which 892 data records were extracted.

2.2. Explanatory variables (moderators)

Along with the response variables, several characteristics of the intercropping system (hereafter: 'moderator variables') were recorded for use as explanatory variables in the analysis (Table 2; for a full overview of all the recorded moderators and detailed descriptions see Table S3). These moderator variables characterised genetic, spatial and temporal dimensions of the intercrop configuration as well as its nutrient and pest management. The provisioning service response variables and the aspect moderator variables were integrated into a database reported in the Supplementary Materials. In this way they will be re-usable in other legs of the meta-analysis relay.

2.3. Effect size calculation

For the metrics describing productivity and product quality the intercropping effect relative to the sole crop was quantified using the natural log-ratio (ln$R$), later referred to as effect-size, which approximates ratios to normality (Hedges and Gurevitch, 1999):

Table 1
Types of provisioning services, response variables, and their definitions.

Provisioning service	Response variable	Definition
Productivity	Harvested biomass	Total biomass of the plant tissue for which the crop is grown before cleaning and/or screening for non-marketable sizes
	Saleable biomass	Biomass of the edible (marketable) part after trimming outer (injured) leaves and removing non-marketable sizes
Product Quality	Grade	All metrics commonly used to determine the marketability of the product such as size or quality class
	Injury-free product	The complement of any metric used to quantify injuries caused by pests on the edible part of the plant
Yield Stability	Relative yield stability	Relative variability of harvested or saleable biomass in experiments conducted for a minimum of three years or at a minimum of three locations. The relative variability was calculated as variability per unit yield.

Table 2
Aspects of the intercrop systems, moderator variables, and their levels distinguished in the 87 studies. Detailed explanation of the levels of moderators can be found in Table S3.

Aspect	Moderator variable	Levels within the moderator
Genetic	Companion species taxonomic order	Alismatales, apiales, asparagales, asterales, brassicales, caryophyllales, cucurbitales, fabales, lamiales, poales, rosales, solanales, Not available (NA)
	Companion species agronomic class	Bulbs, cereals, harvested legumes, herbs and flowers, living mulches, other brassicas, root and tubers, vegetables, NA
Temporal	Relative sowing date	Number of days between companion species sowing/transplanting date and focal crop transplanting date. Negative when sowing/transplanting of companion species took place earlier than the focal crop and positive when later
	Relative harvest date	Number of days between companion species harvest date and focal crop harvest date. Negative when harvest of companion species took place earlier than the focal crop and positive when later
Spatial	Intercropping design	Row, strip, mixed, NA
	Density design	Replacement, augmented, additive, NA
Management	Type of fertilizer	Synthetic, (certified) organic, mixed, no fertilizer, NA
	Type of pesticide	Synthetic, (certified) organic, no pesticide, NA

$$\ln R = \ln\left(\frac{\overline{X}_{ic}}{\overline{X}_{sc}}\right)$$

where $\overline{X}_{ic}$ and $\overline{X}_{sc}$ are the intercrop (ic) and sole crop (sc) means for the metric X, respectively. When the data record described a negative effect on the crop (e.g., percentage of cabbage heads injured by pests), we changed the sign of the effect size to simplify interpretation of the analysis. Thus, positive effect sizes always express an increase and negative effect sizes express a decrease of the provisioning service in intercropping relative to the sole crop.

The variance of the $\ln R$ was calculated as:

$$V_{\ln R} = \frac{(sd_{ic})^2}{n_{ic}(\overline{X}_{ic})^2} + \frac{(sd_{sc})^2}{n_{sc}(\overline{X}_{sc})^2}$$

where sd_{ic} and sd_{sc} are standard deviation and n_{ic} and n_{sc} are the number of replicates for intercrop and sole crop, respectively, for each metric. All recorded measures of variability were transformed to standard deviation (Methods S1) prior to $V_{\ln R}$ calculation. Given that a measure of variability was missing from almost 50% of the data records (442 out of 892 data records), we imputed missing variance with the upper quartile of the known variances for each dataset (Kambach et al., 2020). Although conservative, this approach provided consistent results for productivity and product quality datasets compared to complete-case only or unweighted analyses (Fig. S2).

For Yield Stability, the data records of a given treatment, i.e., the unique combination of moderator variables within one study, were pooled together using the mean and the standard deviation of the productivity over the different years and locations. The effect sizes of relative yield stability were estimated using (Knapp and van der Heijden, 2018):

$$\ln(relative\ stability\ ratio) = \ln\left(\frac{CV_{sc}}{CV_{ic}}\right)$$

where $CV_{sc} = \frac{sd_{sc}}{\overline{X}_{sc}}$ and $CV_{ic} = \frac{sd_{ic}}{\overline{X}_{ic}}$, representing the respective yield stability estimates for sole cropping and intercropping, respectively.

The respective variances were calculated as (adapted from Knapp and van der Heijden 2018):

$$\mathrm{var}(\ln(relative\quad stability\quad ratio)) = \frac{(sd_{ic})^2}{n(\overline{X}_{ic})^2} + \frac{(sd_{sc})^2}{n(\overline{X}_{sc})^2} + \frac{1}{n-1}$$

where n is the number of data records pooled together for the given treatment.

2.4. Data cleaning and standardisation

In order to avoid redundant data records within datasets, data records from the same treatment and experiment describing metrics that, in our expert opinion, would be correlated (e.g., leaf length and leaf width) were merged by averaging their $\ln R$ and $V_{\ln R}$ (Methods S2). Following the same reasoning, the response variables 'Saleable biomass' and 'Harvested biomass', initially meant to be analysed separately, were merged into the response variable Productivity because of their strong correlation. This reduced the number of data records from 892 to 689. Since data records with $V_{\ln R}$ equal to zero cannot be processed, the $V_{\ln R}$ of such data records were replaced by the smallest non-zero $V_{\ln R}$ in the corresponding dataset ($n = 3$).

Data records for which mean values equalled zero were considered a sign of crop or experimental failure and were excluded (n = 17). This resulted in the exclusion of all the data records extracted from Pfeiffer et al. (2016).

2.4.1. Productivity dataset

When productivity was expressed per unit land area, treatments in which the plant density in the intercrop differed from that of the sole crops were adjusted to the equivalent plant density (Methods S3).

2.4.2. Product quality dataset

Remaining data records for which mean values equalled zero were assessed individually. When both the intercrop and sole crop means were equal to zero for the metric of interest, we gave the value of zero to the effect size (i.e., no difference between intercrop and sole crop) ($n = 1$). For other situations, we added the lowest non-zero value in the study for the given metric to both the intercrop and sole crop mean values ($n = 4$).

2.5. Data analysis

To determine the relation between productivity and product quality, Spearman rank correlation coefficients were calculated for pairs of effect sizes of productivity and grade and pairs of productivity and pest injury from the same treatments and experiments. The relationship between the pairs of effect-sizes coming from the same study was taken into account by including a random effect in the model at the study level.

Meta-analytical mixed-effects models were fitted using individual $\ln R$ of each response variable and weighted by the inverse of their $V_{\ln R}$. Analyses were performed in R version 4.0.2 (R Development Core Team, 2016) using the *rma.mv* function from the *metafor* package, which allows specification of fixed (moderator variables) and random effects (Viechtbauer, 2010). Study and experiment (sites × years) within study were included as nested random effects to account for the hierarchical structure of the data. The choice of random effects structure was based on the model with the lowest Bayesian Information Criterion (BIC) value for the Productivity dataset, then the same model structure was applied to the other two response variables, i.e., Grade and Injury-free product (Table S4). The model structure was validated by checking whether all variance components were identifiable in profile-likelihood plots (Fig. S3). A null model, i.e., without moderator variables, was used for the estimation of the overall effect for each response variable.

To further investigate the effects of the intercrop characteristics, we separately tested each moderator variable by including it in the null model. The significance of a moderator variable on each of the response variables, i.e., the heterogeneity explained by the moderators, was determined using an F test ($p \leq 0.05$) (Viechtbauer, 2010). We considered levels within moderators to be significantly different from one another when their 95% confidence intervals (CI) did not overlap. Outcomes of the statistical models are presented after back-transformation of effect sizes to percentages.

2.6. Publication bias and sensitivity analysis

The publication rate of studies varies with significance or direction of the results (Dickersin, 1990). This bias is often referred to as publication bias. Even though it cannot be identified with certitude, some methods exist to detect a possible publication bias. In this meta-analysis, we performed a graphical analysis through a funnel plot (a graph representing the effect sizes of each study on the x-axis, and the associated standard errors on the y-axis), and a statistical analysis using Egger's method (Egger et al., 1997) for each null model. An asymmetry in the funnel plot and an intercept of the regression significantly different from zero in Egger's method was used as an indication of a possible publication bias (Makowski et al., 2019).

Additionally, a "leave-one-out analysis" was performed to identify studies statistically influencing the outcome of the meta-analysis on their own. The influence of a given study on the outcome of the meta-analysis was obtained by comparing the outcome of the global model, to the outcome of the same model run after the removal of the data records from the said study (Viechtbauer and Cheung, 2010). A study was considered significantly influencial if the "leave-one-out" model's mean effect size did not overlap with the overall model's confidence interval.

3. Results

3.1. Overview of the dataset

The database included 689 data records from experiments conducted from 1977 to 2021 across 82 locations under a wide variety of climates around the world (Fig. S4). The most common spatio-temporal configuration was based on row intercropping in additive design where both *Brassica oleracea* and companion species were sown simultaneously (approx. 20% of the data records). There were 109 different companion species or mixtures. Broccoli, white cabbage and cauliflower were the most frequent main crops (26%, 24% and 17% of the data records, respectively), and onion and white clover were the most common companion species (9% and 7% of the data records, respectively) (Fig. S5). Productivity was by far the most recorded provisioning service (88 studies). Only three studies reported data across at least three years or locations qualifying for evaluation of Yield Stability.

Some overlap existed between levels of companion species taxonomic order and companion species agronomic class. About 80% of the data records in the poales group were cereals. Asparagales data records were identical to the data records in the bulbs group. Approximately three quarters of the fabales group consisted of living mulches data records and one quarter were harvested legumes. Additive density designs consisted of about 80% row intercrop patterns.

3.2. Productivity, Product Quality and Yield Stability overall means

We found that the overall Productivity of cabbages in intercropping was 7% lower than those grown as sole crops (CI = [−12%; −2%], $P = 0.011$; Fig. 1). However, 142 (29%) individual effect sizes, which are the comparison between intercropping and sole cropping, did not significantly differ from zero, and 137 (28%) were significantly positive indicating that maintain or increase in Productivity relative to the sole crop were also frequent. The funnel plot (Fig. S6) was symmetric and the intercept was not significantly different from zero in Egger's method ($P = 0.343$), hence publication bias was unlikely to be present in the dataset. The leave-one-out sensitivity analysis did not reveal any study significantly affecting the magnitude of the effect size.

Regarding Product Quality, no differences in Grade were found between cabbages grown in intercropping relative to sole cropping (1%, CI = [−5%; 7%], $P = 0.715$). On the other hand, the effect size of Injury-free product, although variable (CI = [18%; 86%]), was markedly positive (48%, $P < 0.001$), meaning that cabbage products consistently exhibited fewer pest injuries when intercropped than when grown as a sole crop. No evidence of publication bias was found in the Grade dataset or in the Injury-free product dataset (Fig. S6b and Fig. S6c). No influential study was revealed in this dataset.

Analysis of Yield Stability resulted in a widely variable estimate (−35%, CI = [−68%; 33%], $P = 0.21$) due to the low number of studies contributing to this overall effect size ($n = 3$). Publication bias and influence of the studies were not tested on the Yield Stability dataset because of the too small number of studies.

3.3. Relation between provisioning services

We further examined the relation between Productivity and each of the Product Quality responses using studies in which both provisioning services were reported jointly. We found 22 studies analysing Productivity-Grade and 15 studies for Productivity-Injury-free product combinations. A moderate positive correlation was found between Productivity and Grade effect sizes ($r = 0.43$, $P < 0.001$) where

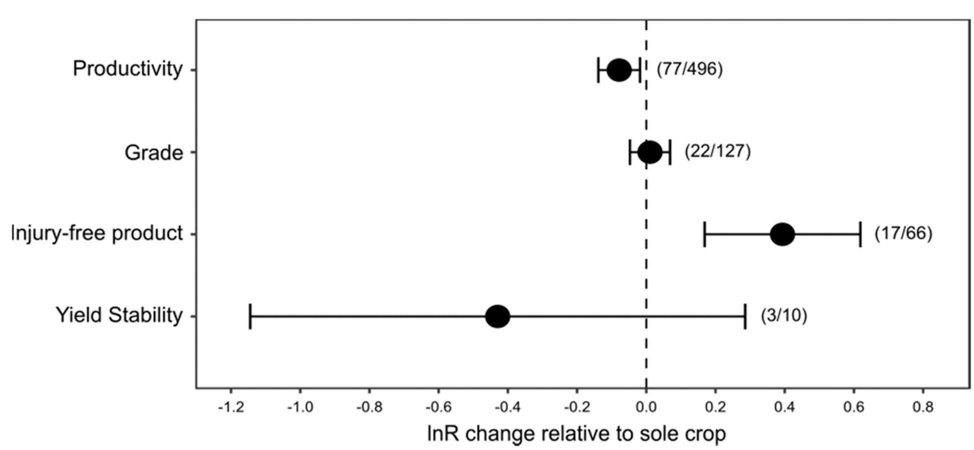

Fig. 1. Overall effects of intercropping cabbages for each response variable relative to sole cropping. Error bars represent 95% confidence intervals. Confidence intervals overlapping zero indicate no significant differences with the sole crop. Numbers between parentheses indicate the number of studies and the number of data records, respectively.

significant “lose-lose” situations between Productivity and Grade were the most frequent, that is, lower yield and smaller size of cabbages in intercropping compared to sole cropping (Fig. 2a). Productivity and Injury-free product did not show to be correlated ($r = 0.13$ $P = 0.298$) but “win-win” situations were the only significant results found in intercropping compared to sole cropping (Fig. 2b).

Productivity of intercropping relative to sole cropping was significantly affected by management, spatial, genetic, and temporal variables suggesting a high degree of context-dependency (Table 3). The most significant moderators were the type of fertilizer and the relative sowing date (RSD) followed by the agronomic class of the companion species and the intercropping design. In contrast, Injury-free product was most significantly associated by spatial arrangement (intercrop and density design) and, to a lesser degree, by management (type of fertilizer and pesticide). Grade was only significantly affected by RSD. Moderator analyses for Yield Stability were not performed due to the low number of data records.

3.4. *Influence of intercropping configuration and management*

Intercropping cabbages with species of the taxonomic order fabales and brassicales resulted in significantly negative Productivity effect sizes (−10%, CI = [−16%; −2%], $P = 0.010$ and −12%, CI = [−22%; −1%], $P = 0.041$, respectively). Agronomically, the fabales, which occurred as harvested legumes had a non-significant effect on cabbage Productivity (−4%, CI = [−15%; 9%], $P = 0.524$), while living mulches (mostly represented by clover species) were associated with significantly lowered cabbage Productivity (−17%, CI = [−24%; −9%], $P < 0.001$). However, both fabales and living mulches increased Injury-free product (103%, CI = [25%; 231%], $P = 0.005$% and 80%, CI = [17%; 177%], $P = 0.008$, respectively).

Planting or sowing of the companion species before transplanting the cabbages decreased cabbage Productivity by 0.11% d^{-1} (CI = [0.06%; 0.16%], $P < 0.001$) but increased their Grade by 0.06% d^{-1} (CI = [−0.10%; −0.01%], $P = 0.016$) (Fig. 4a, b). Earlier or simultaneous transplantation/sowing of companion species with cabbages had no effect on Injury-free product ($P = 0.266$, Fig. 4c). The effect of transplanting/sowing companion species after cabbages could not be inferred due to the lack of data records. Harvesting companion species earlier or later than cabbages had no significant effect on both Productivity and Product quality (Table 3).

Spatial configuration significantly reduced Productivity effect sizes for row, strip and additive designs (−8%, CI = [−14%; −2%], $P = 0.014$; −11%, CI = [−20%; 0%], $P = 0.045$; and −8%, CI = [−14%; −2%], $P = 0.010$, respectively) (Fig. 5). Significant positive effects on Injury-free product were apparent when intercrops were arranged in row and mixed patterns (59%, CI = [17%; 116%], $P = 0.004$% and 62%, CI = [2%; 160%], $P = 0.043$ respectively), and followed by additive designs (72%, CI = [25%; 138%], $P = 0.001$). In other words, spatial arrangements that involved close interspecific plant interactions (i.e., mixed, row, additive or augmented) increased the amount of Injury-free product compared to monoculture, whereas wider configurations (i.e., strip, replacement) did not significantly influence Injury-free product.

The effect of the type of fertilizer on Productivity in intercropping compared to monocropping systems was − 17% (CI = [−24%; −10%], $P < 0.001$) for synthetic fertilization and 3% (CI = [−6%; 13%], $P = 0.516$) for organic fertilisation (Fig. 6a). Intercropping under organic fertilization yielded a significantly greater Injury-free product (61%, CI = [16%; 124%], $P = 0.006$) than the sole crop reference under the same fertilizer type but did not affect Grade (−2%, CI = [−10%; 6%], $P = 0.614$) (Fig. 6b, c). The Grade of intercropped cabbages was enhanced in systems using organic pesticides (20%, CI = [3%; 39%], $P = 0.019$) compared to monoculture systems using the same organic pesticides, but the Injury-free product was not (29%, CI = [−12%; 90%], $P = 0.185$), and Productivity even decreased in these systems (−15%, CI = [−27%; −1%], $P = 0.041$). When no pesticides were applied, cabbages in intercropping systems exhibited significantly fewer injuries (33%, CI = [1%; 74%], $P = 0.041$) compared to sole cropping.

4. Discussion

4.1. *Cabbage provisioning services are not compromised in intercropping*

Overall, intercropping tended to generate losses in productivity of cabbage as the main crop (estimated at −7% on average, $P<0.05$) compared to sole crop systems, even though in 48% of cases we found overyielding. This result is comparable to results found for intercropped legume species, for which also no to slightly negative effects on productivity were found, when compared to the legume monoculture, but is different from cereal species, which often overyield when grown in association (Iverson et al., 2014; Yu et al., 2016). When Productivity was reduced, Grade was also lower. This is not surprising as many of the grade parameters, such as those related to size, are associated with weight. Both weight and size of cabbages are linked to plant biomass so that the prevalence of “lose-lose” situations (Fig. 2a) may reflect the dominance of growth suppression over complementarity (Bybee-Finley and Ryan, 2018). This result questions whether competition control strategies such as root pruning are being exploited to their full potential

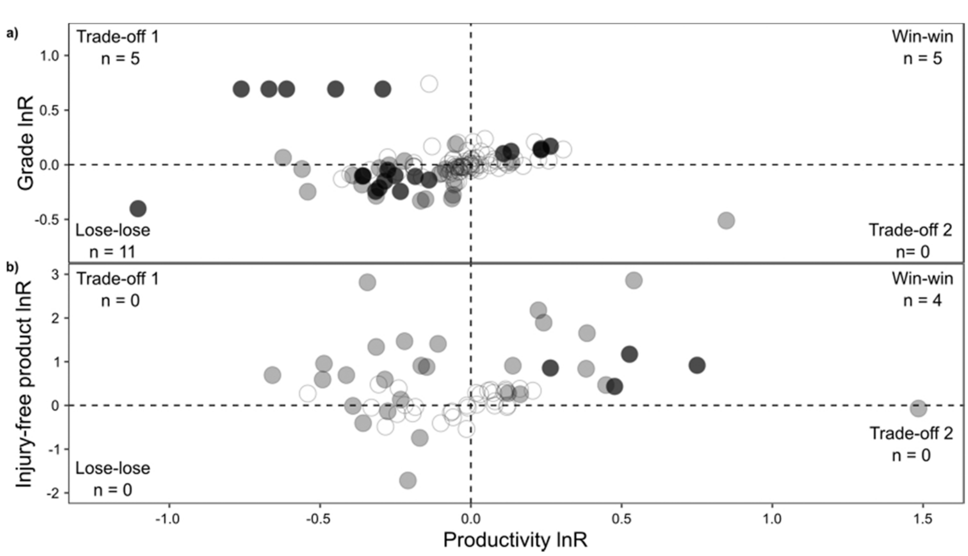

Fig. 2. Relation between Productivity and (a) Grade or (b) Injury-free product. Points represent individual effect sizes (lnR) of Productivity (x axis) and one of the Product Quality response variables (y axis). Effect-sizes significantly different from 0 for both response variables are shown with black circles, effect-sizes significantly different from 0 for only one response variable are shown with grey circles, and effect-sizes not significantly different from zero for both response variables are shown with empty circles. The numbers indicated in the figure only take into account effect sizes significantly different from 0 for both response variables.

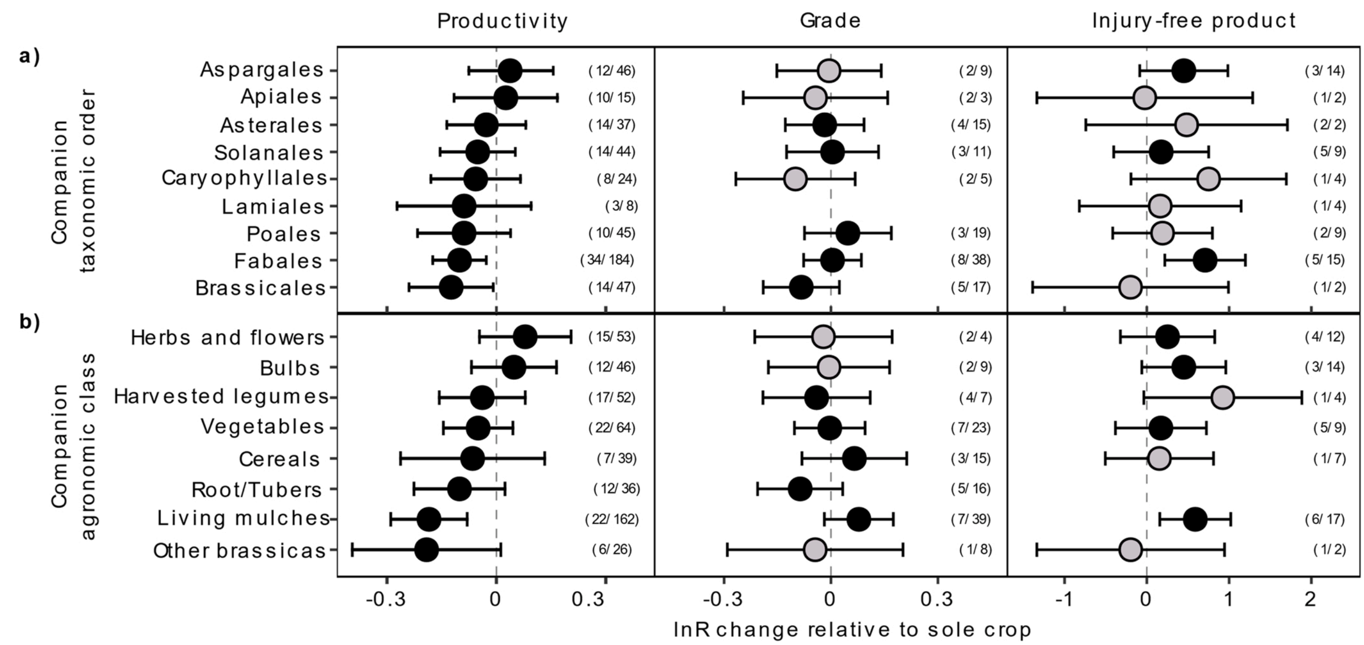

Fig. 3. Effect of (a) companion species taxonomic order and (b) companion species agronomic class on effect sizes of Productivity, Grade and Injury-free product. Error bars represent 95% confidence intervals around the mean effect size. Numbers in parenthesis indicate the number of studies and the number of data records, respectively. Effect sizes based on fewer than three studies are shown with grey symbols.

Table 3
Effect of moderator variables on the response variables Productivity, Grade and Injury-free product. Numbers represent significance (*P*-values). Significant effects ($P < 0.05$) are highlighted in bold.

Aspect	Moderator	Productivity	Grade	Injury-free product
Genetic	Order	0.092	0.825	0.119
	Agronomic class	**0.001**	0.641	**0.031**
Temporal	Relative sowing date	**< 0.001**	**0.016**	0.266
	Relative harvest date	0.262	0.260	0.142
Spatial	Intercropping design	**0.035**	0.782	**0.006**
	Density design	0.099	0.895	**0.002**
Management	Type of fertilizer	**< 0.001**	0.159	**0.044**
	Type of pesticide	0.309	0.129	0.093

in intercropped cabbages (Båth et al., 2008). On the other hand, our results show substantial reductions in pest injuries on cabbage products in intercropping (48% less on average than for cabbages grown as a sole crop), which are in line with pest control benefits (averaging from 34% to 66% relative to monoculture references) identified in non crop-specific meta-analyses (Beillouin et al., 2021; Iverson et al., 2014). Productivity versus Injury-free product commonly resulted in "win-win" situations, especially for mixed cropping designs (10 out of 12 data-points; data not shown), revealing that reduced pest-injury resulted in greater yield. Effects on Yield Stability were highly variable due to the low number of studies: trials were rarely conducted for more than two years or covered more than two locations in any year.

The Productivity and Grading datasets did not show signs of publication bias as the effect sizes were spread symmetrically in the funnel plots. The slight asymmetry in the Injury-free product funnel plot and the data points outside the funnels could be publication bias, or it could be caused by differences in experimental layouts, which would lead to (slight) differences in true effect sizes, also called heterogeneity (Sterne et al., 2011).

4.2. *Crop choice: cabbage sensitivity to interspecific competition and trade-offs with mulches*

Crop complementarity (competition relaxation and facilitation), which would have been reflected by positive lnR values for the companion groups (Fig. 3a), was not significant in this study. Whilst this may be a logical outcome in additive designs where the main crop is subjected to a greater inter- and intra-specific competition, replacement designs did not show signs of competition relaxation either (Fig. 5b). Our results indicate that cabbages can be considered weak competitors compared with arable crops (i.e., cereals, tubers, and harvested legumes) as interspecific competition was frequently more costly than intraspecific competition for cabbages (Fig. 1). Competitiveness of cabbages in intercropping systems may be further explored as part of breeding strategies (Bourke et al., 2021; Litrico and Violle, 2015) as observations by breeders suggest that, in early growth stages, early-maturing cabbages tended to be more competitive than late maturing cabbages (Bram Weijland, Bejo Seeds, personal communication, Dec. 2021). Positive effects on both productivity and pest injury were identified when cabbages were intercropped with bulbs (mostly onion), herbs and flowers (particularly marigold) but effect sizes lacked statistical significance. Their compact growth habit and shallow rooting relative to cabbages, and their deterrent effects on various cabbage pests may cause facilitation in combination with low competition (Mrnka et al., 2020; Mutiga et al., 2010). Further work is needed to explore the potential of these agronomic classes.

Intercropping cabbages with living mulches revealed a trade-off between Productivity and Injury-free product. Whilst Injury-free product increased, Productivity was significantly hampered (Fig. 3b). The former effect has been associated with reduced colonization by pests, fundamentally lepidopteran caterpillars and aphids. The actual mechanism (i.e., bottom-up or top-down) is highly variable depending on the arthropod species involved (Altieri et al., 1985; Brandsæter et al., 1998; Depalo et al., 2017; Hooks and Johnson, 2003). The decrease in productivity can be ascribed to below-ground competition for nutrients and water. Competition of living mulches for N with the cash crop have often been identified as a main cause of yield loss (e.g., Tempesta et al., 2019; Xie and Kristensen, 2016). Therefore, the companion mulch species

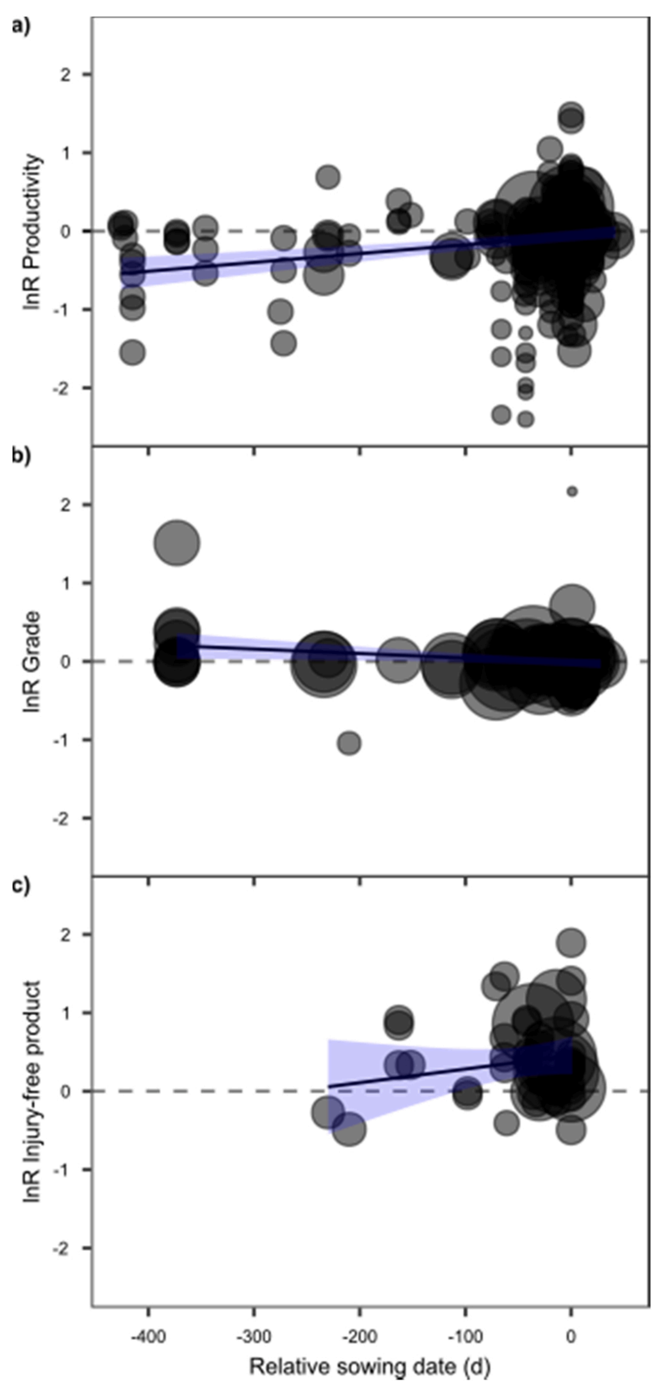

Fig. 4. Effect of relative sowing date (RSD) on effect sizes of (a) Productivity, (b) Grade and (c) Injury-free product of cabbages for each of the data records included in the meta-analysis. Each bubble represents a data record. Solid lines represent the weighted model regression lines, and shadows represent 95% confident intervals. Bubble size represents the weight of each study in the regression.

must be carefully selected based on traits such as vigour and maturing timing and its ecological benefits (e.g., attraction of natural enemies and nutrient retention capacity). Båth et al. (2008) showed that root pruning reduces the competition by the mulch and resulted in a higher above ground biomass of cabbage.

4.3. The optimal spatio-temporal configuration depends on the targeted provisioning service

When high cabbage yield is the main target, temporal diversification was found to be more effective than spatial diversification. Our analysis showed that sowing/transplanting the companion species simultaneously with cabbage neutralized potential yield penalties. Variation in the timing of companion species harvest (which can be understood as interspecific competition during later stages of the cabbage growing season) showed no effect. Early-season competition may be more influential on the final yield than competition occurring later in the cabbage cropping period as, once established, cabbages produce a deep rooting system that allows exploitation of nutrients and water contained in deeper soil layers (Båth et al., 2008; Tempesta et al., 2019; Thorup-Kristensen, 2001). Surprisingly, productivity was lower in strip and row designs and not different in mixed designs compared to monoculture, which contrasts with the findings in meta-analyses covering multiple focal crops where higher land equivalent ratios were found in strip designs compared to mixed designs (Yu et al., 2016). This may be caused by the comparison across ranges of crops versus a focus on cabbage in this study and by measuring Productivity as land equivalent ratio rather than single-crop yield. However, our findings are similar to the results of Iverson et al. (2014) who showed a higher yield in replacement designs compared to additive designs.

We applied a yield correction in those cases where an augmentative density design had been implemented. For these cases, Productivity effect sizes were not significantly different from zero, while Injury-free effect sizes were significantly greater than zero (Fig. 5). This means that while cabbage yields of augmentative designs per cabbage area may be less than those of the monocrops, Injury-free product and thus price per unit cabbage may be higher. This hypothesis could not be checked due to lack of data on Grade for augmentative designs. It will depend on local prices to which extent this trade-off is beneficial to revenue.

Reduction of pest injury in the product was found to be affected by modifications in the spatial distribution of the intercropped species. Spatial arrangements involving closer interspecific plant interactions (i.e., mixed, row and additive) showed consistent reductions in injury relative to sole cropping, whilst these effects were non-significant in wider configurations (i.e., strip, replacement). Closer arrangements entail both greater total plant density and greater companion species relative frequency, suggesting physical and chemical barriers (dilution or confounding of host volatiles) to restrict the movement of and recognition by pests as the predominant biocontrol mechanisms (Finch and Collier, 2012; Hambäck et al., 2010). The timing of companion species establishment appears less important when it comes to protecting cabbage products from pest injuries, as earlier planting of the companion species did not necessarily increase pest-injury control. Therefore, from both Productivity and Injury-free perspectives (Fig. 4a, c) a delayed inclusion of the companion species may be preferred over an early inclusion to ensure well-established cabbages, as early-season competition is generally more constraining than the pests' repercussions (Hooks and Johnson, 2003). However, the extent to which companion establishment may be delayed while still preserving biocontrol benefits at the end of the season could not be estimated in our analysis due to the lack of experiments in which the companion species was sown after the cabbages (Fig. 4c).

4.4. The influence of management: system inputs

Our study shows that benefits of intercropping, both for productivity and product quality, were more consistently attained under organic management or in low-input systems. This was best illustrated for Productivity and Type of fertilizers, exhibiting a dichotomic response to synthetic (strongly negative) and organic fertilization (not significant) (Fig. 6a). As previously argued, cabbages are sensitive to interspecific competition especially at early growth stages, so that the readily

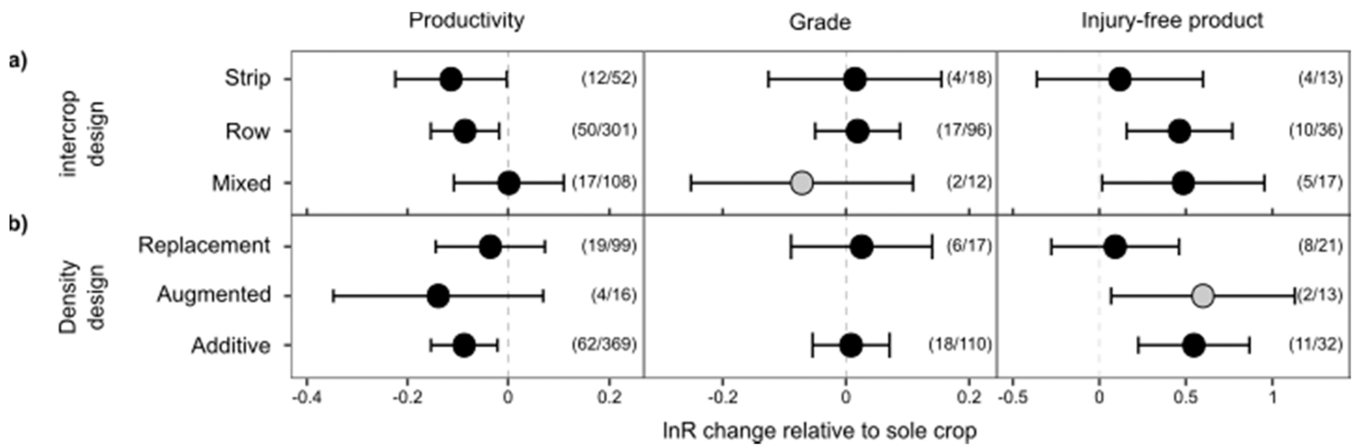

Fig. 5. Effect of intercrop design (a) and density design (b) on effect sizes of Productivity, Grade and Injury-free product. Error bars represent 95% confidence intervals around the mean effect size. Numbers in parentheses indicate the number of studies and data records, respectively. Effect sizes based on fewer than three studies are shown with grey symbols.

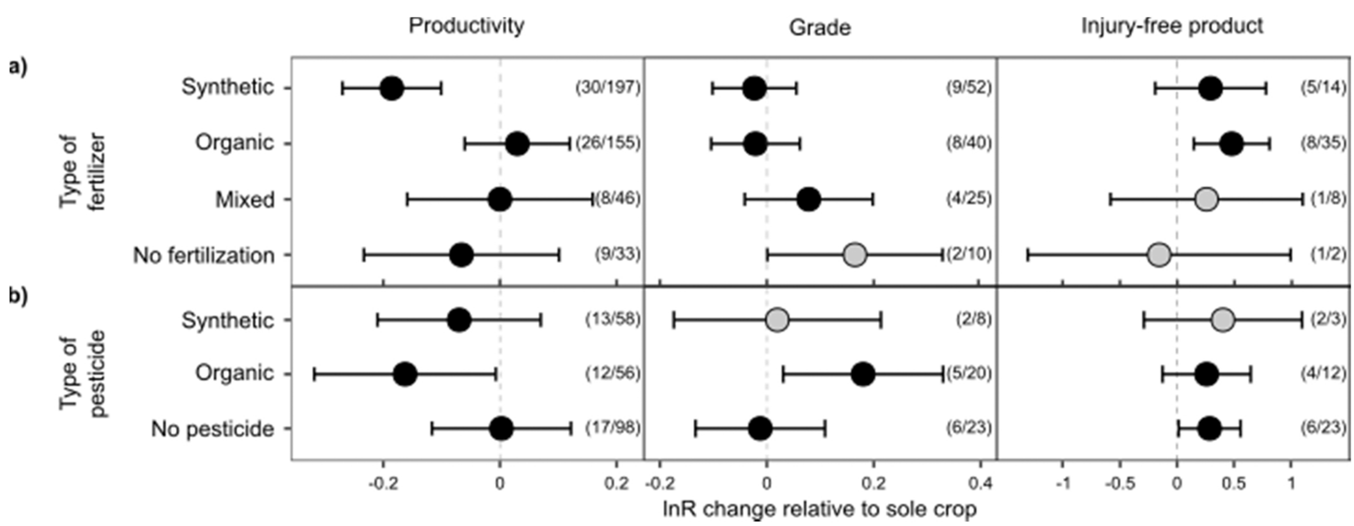

Fig. 6. Effect of (a) type of fertilizer and (b) type of pesticide on effect sizes of Productivity, Grade and Injury-free product. Error bars represent 95% confidence intervals around the mean effect size. Numbers in parentheses indicate the number of studies and data records, respectively. Effect sizes based on fewer than three studies are shown with grey symbols.

available inorganic fertilizers may exacerbate differences in dominance when intercropped with more vigorous species such as arable crops and mulches (Andersen et al., 2005; Tempesta et al., 2019). The slow release of nutrients from organic fertilizers may create a more stressful environment, favoring the expression of complementarity traits e.g., resulting in spatially different root systems or nitrogen fixation by companion legume species (Bedoussac et al., 2015; Brooker et al., 2008). Moreover, conventional management can mask the effect of regulating services provided by biodiversity such as those of biological pest control and nutrient supply through soil microbial community (Gagic et al., 2017; Sutter et al., 2018). Thus, intercropping cabbages can be best applied in production systems where no insecticides are used as enhanced biocontrol can compensate the use of pesticides (Fig. 6b).

4.5. Implications and future research needs

This study highlights that finding good companion species for intercropping cabbages goes beyond the identification of trait complementarity. We found the influence of the spatio-temporal and management aspects to be often greater than the influence exerted by the nature of the companion species (the genetic component), confirming results of (Brooker et al., 2015). In fact, companion species was only relevant for Productivity in this study (Table 3). This can be explained by the stress gradient hypothesis, which postulates that the expression of the interacting traits (e.g., rooting depth, vegetative architecture, and growth rhythms) of the intercropped species is ultimately modulated by the environmental conditions (Brooker et al., 2008; Litrico and Violle, 2015) within the genetic boundaries. Thus, the recommendation of particular companion species or complementary traits is of limited use without further details about the context. Nevertheless, structuring data by aspects (i.e., the three dimensions of diversity and the management practices) proved to be useful for unravelling which context elements must be mobilized for optimal delivery of each agro-ecosystem service. For the next 'leg' in the relay we suggest herbs and flowers, bulbs or aspargales, which offer opportunities for adjusting spatio-temporal management beyond those in the experiments in our database and increase provisioning services of both themselves and the cabbages. The database structure developed for this purpose is available for implementation with other focal crops and agro-ecosystem services.

4.6. Limitations

The variability and lack of standardization of the metadata reported in intercropping literature represented a major limitation for their use in a meta-analysis. This severe shortcoming in data quality was also highlighted by Young et al. (2021) in their meta-analysis of agronomic measures on crop, soil and environment variables. To leverage the information available in the primary studies, we considered a broad range of moderator variables (Table S3). Although the general recommendation is to select a limited number of moderator variables prior to data gathering (Koricheva and Gurevitch, 2014), we opted for a long-list because it was unknown which moderators would be more consistently available and which of them would best capture changes in the genetic, spatial and temporal dimensions and management beforehand. Information about moderator variables was not always reported in the primary studies resulting in incomplete datasets. This impeded the use of multivariate analyses, and the effects of moderators on response variables were instead analysed in a univariate fashion. Although including a single moderator at a time does not control for the other moderator variables, single moderator analysis allows that studies providing information on a particular moderator variable can be used, thus reducing potential bias due to missing information. To better harness experimental intercropping research, we strongly encourage researchers to report methods, practices and field conditions in as much detail as possible in shared data.

We set out to analyze effects of companion species on Yield Stability of cabbages but found only 3 relevant studies. As yield stability is a growing concern also in relation to weather extremes (Reckling et al., 2021) our findings point to a lack of multi-year and multi-location experiments.

5. Conclusions

In this paper we showed that the quality of cabbages was not compromised by intercropping, but also that productivity was lower in such systems. The question is to which extent increases in companion species yields or other ecosystem services offset cabbage losses. The clearest benefit of intercropping was in reducing pest injury in cabbage products, suggesting increased biocontrol ecosystem regulation. Cabbages are commonly sold per unit rather than by weight so that enhanced quality can give access to premium prices. Future research should include regulating and supporting services to identify synergistic interactions among ecosystem services. This would allow mechanistic understanding of ecological processes at work in intercropping and the design of multi-service systems. The database structure developed for this study can be adapted for such purpose by selecting suitable metrics for each ecosystem service of study.

The provisioning services were positively associated to each other to some extent, however, maximization of productivity or product quality requires fine-tuning different elements of the intercrop configuration. When high productivity is the main objective, plants of compact growth habit, shallow rooting relative to cabbages, and deterrent effects on cabbage pests, such as alliums or marigold sown at or after the cabbage crop are advisable because of the limited competitiveness of cabbages at early stages. When high-quality product is the goal, intercrop patterns involving closer inter-plant interactions (i.e., mixed, row and additive) and companion species that support insect biodiversity such as mulches are preferred. In general, non-detrimental or beneficial effects of intercropping tended to be more evident in systems with organic fertilizer as synthetic inputs possibly override potential regulating effects and/or promote imbalance between the intercropped species. These guidelines can be used by researchers, advisors and farmers as part of context-specific cropping systems design, using methods such as proposed by Juventia et al. (2022).

This first 'leg' of the proposed relay of meta-analyses proved useful in elucidating the performance and particularities of cabbages in intercropping. Similar meta-analyses for other vegetable crops that are connected to the knowledge base compiled for cabbages are now needed to enable expanding a network of scientific information on what constitutes good companion crops in diversified vegetable production systems.

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CRediT authorship contribution statement

JCR: Conceptualization, Methodology, Validation, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Supervision. **TLN**: Conceptualization, Methodology, Validation, Software, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. **DvA**: Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **AW**: Conceptualization, Methodology, Investigation. **SS**: Formal analysis, Investigation, Data curation, Writing – review & editing. **HLK**: Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **SDJ:** Investigation, Data curation, Writing – review & editing. **MH, SJH, PK, LL, SD**: Investigation, Data curation. **W*R***: Conceptualization, Validation, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Javier Carrillo-Reche reports financial support was provided by CORE Organic. Dirk F. van Apeldoorn reports financial support was provided by CORE Organic. Annet Westhoek reports financial support was provided by CORE Organic. Sindhuja Shanmugam reports financial support was provided by CORE Organic. Hanne L. Kristensen reports financial support was provided by CORE Organic. Merel Hondebrink reports financial support was provided by CORE Organic. Sari J. Himanen reports financial support was provided by CORE Organic. Pirjo Kivijarvi reports financial support was provided by CORE Organic. Liga Lepse reports financial support was provided by CORE Organic. Sandra Dane reports financial support was provided by CORE Organic. Walter A.H. Rossing reports financial support was provided by CORE Organic. Titouan Le Noc reports financial support was provided by Serdis Beheer B.V. Dirk F. van Apeldoorn reports financial support was provided by Serdis Beheer B.V. Dirk F. van Apeldoorn reports financial support was provided by TKI Agri & Food.

Data availability

The datasets generated during the current study are available in the Data Station Physical and Technical Sciences of the Dutch national center of expertise and repository for research data (DANS) https://doi.org/10.17026/dans-z3s-wezp and on Zenodo https://zenodo.org/record/7928052#.ZF3ir85BxPY.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108564.

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