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ANALYSIS

Financial profitability of diversified farming systems: A global meta-analysis

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ABSTRACT

Diversified farming systems are promoted as a pathway to more sustainable agricultural production. Yet wide-scale adoption may be slow because of uncertainty about the viability of farmer livelihoods on diversified farms and entrenched perceptions that monocultures are key to making farming profitable. Here, a global meta-analysis of 3192 effect sizes from 119 peer-reviewed articles provides evidence that diversified farming systems are at least as profitable as simplified farming systems. Our study showed that, on average, total costs, gross income and profits (net income, or gross margin) were higher in diversified systems relative to simplified ones, while the benefit-cost ratio was equivalent. These results held in developed and developing countries and across geographic regions. From a subset of 43 articles reporting labour inputs, we found that labour costs increased in diversified farming systems, but so did gross incomes leading to farm profits equivalent to those in simplified systems and dispelling myths that higher labour requirements undermine the viability of diversification. Our global meta-analysis provides compelling evidence that diversified farming systems are not only viable but actually economically preferable to simplified systems in the wide range of contexts represented in this study. Policies, markets, investments, and value chains need to align with this evidence and promote diversified farming systems for the benefit of farmers and rural economies.

1. Introduction

Agricultural systems around the world have become increasingly simplified across time and space over the last 150 years as a strategy to meet food production demands of growing populations, while increasing economic profits and reducing physical and financial risks in the short-term (Barrett, 2020; Pretty, 2008; Ramankutty et al., 2018). Now, more farms than ever before are characterized by high-yielding monocultures, heavy use of chemical fertilizers and pesticides, and a dependence on irrigation and fossil-fuels (Hendrickson, 2015). Transnational agribusinesses and food supply chains tend to favour large-scale producers specialized in certain crops and livestock, making it hard for smallholders and diversified farms to compete and secure viable incomes (Harris, 2019; Stringer et al., 2020). At the same time, large-scale specialized farms are now experiencing economic constraints because they are not resilient to climate change (Nelson and Phillips, 2018; Ray et al., 2015) or global supply chain shocks (like Covid-19– Altieri and Nicholls, 2020; Clapp and Moseley, 2020; FIAN International, 2020). Scientists have flagged the dangers of high-input simplified production systems for failing to meet human nutritional needs (Snapp, 2020), eroding soil health (Kopittke et al., 2019), and contributing to widespread biodiversity decline (Allen and Hof, 2019; Benton et al., 2021; Brühl and Zaller, 2019; Carmona et al., 2020) sometimes with substantial negative consequences not only for farm yields and economic returns (Pérez-Méndez et al., 2020) but also society as a whole (IPES-Food, 2020). Simplified, intensive agricultural systems need shifting to deliver on the Sustainable Development Goal (SDG) ambition to double income for small-scale producers by 2030 (SDG 2.3), while ensuring sustainable food systems (SDG 2.4) that provide more than just food (Barrett, 2020; Wezel et al., 2020).

Diversifying farming systems may be part of the solution. Diversified systems incorporate different species and/or varieties of plants, fish, and/or livestock at multiple temporal and/or spatial scales (Kremen et al., 2012). Multiple reviews show that, compared to simplified farming systems, diversification of fields and farms improves biodiversity and ecosystem services including pollination, soil nutrients, and

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water regulation (Beillouin et al., 2021; Rosa-Schleich et al., 2019; Sánchez et al., 2022; Tamburini et al., 2020) improving outcomes for people and nature. However, the effects of these diversified systems on costs and profits are unclear. While Beillouin et al. (2018) and Rosa-Schleich et al. (2019), provide evidence that farming system diversification can improve economic outcomes, these reviews also show outcomes are highly variable.

In theory, diversified farming may provide better financial outcomes than the simplified ones by reducing the risk of profit losses that arise from yield, price, input, or output market risks (Bowman and Zilberman, 2013). For example, risks can be lowered by selecting crop combinations with uncorrelated price risks (i.e., variability in prices do not follow the same market trends, reducing price risks), or that have different input constraints (e.g., different dry spell and frost tolerance levels, reducing yield risks), or different input requirements (e.g., planted or harvested at different times, reducing labour risks) (Bowman and Zilberman, 2013). Yield risks can also be lowered by enhancing ecological processes through diversity-based practices, such as crop rotations to control the spread of pests and diseases, or fallow periods and use of cover crops to restore soil nutrients and minimize yield losses caused by adverse weather conditions (Power, 2010; Rosa-Schleich et al., 2019; Swinton et al., 2007).

In practice, several large-scale reviews have compared financial outcomes of diversified versus simplified farming systems including in low and middle-income countries (Castle et al., 2021) but provide conflicting evidence on the profitability of diversification. Some reviews show that, relative to simplified systems, diversification can lead to higher gross incomes (Himmelstein et al., 2017) and lower direct production costs (Rosa-Schleich et al., 2019; Sanderson et al., 2013). Others show diversification leads to comparable incomes, e.g., agroforestry (Castle et al., 2021), and still others show diversification leads to lower profits, e.g., in North America (Roesch-McNally et al., 2018) and Europe (Gawęda et al., 2020). This variability is unsurprising, since farm system profitability is affected by many factors including crop choices (e.g., timing of peak management requirements, perishability, complementarity), use of technology (e.g., precision farming to minimize and target fertilizer and water applications, in-situ rainwater harvesting with basins, ridges or terraces, and digital tools facilitating market access), input conditions (e.g., labour availability, water constraints), farm size (larger farms benefiting from economies of scale), and output market conditions (e.g., prices and price stability, transportation and processing costs, trade policies) (Bowman and Zilberman, 2013). These factors play a role and may drive differences in the profitability between simplified and diversified farming systems. For example, previous reviews have shown that intercropping in Africa has a more positive effect on gross incomes when herbicides are applied helping suppress weeds (Himmelstein et al., 2017). Another example is agroforestry, which research in Zambia shows can be more profitable when compared to monocultures grown without fertilizer applications, but less profitable when compared to fertilized monocultures – though the latter is likely due to government fertilizer subsidies reducing the true costs of production (Ajayi et al., 2009). On the other hand, Himmelstein et al. (2017), found that in Africa, the gross returns of intercropping systems relative to monocultures did not depend on the inclusion of legumes, tillage practices, pesticides (i.e., fungicides, insecticides, nematicides, fumigants) or fertilizers.

This conflicting evidence and the remaining knowledge gaps about the profitability of diversified farming systems are understandably off-putting to farmers and investors. Consistent concerns of agricultural research donors about investing in diversified agricultural practices include uncertainties about profitability and scalability (Anderson et al., 2020). It is highly likely that knowledge gaps are slowing down uptake of diversified practices even in places where these are profitable, since lack of information about costs and benefits deters farmers from shifting to a new practice (Arslan et al., 2020). Stronger evidence is needed to provide clear messages about what circumstances make diversified farming profitable, versus situations that lead to higher production costs or a loss of income and support may be needed to enable diversification. No global review to date has sought to identify the agronomic and socio-economic conditions in which diversified farming is economically viable and yet this is arguably the primary concern for farmers and policymakers.

Here, we conduct a global meta-analysis to help close evidence gaps on the economic costs and benefits of diversified farming systems, relative to simplified farming systems. We compare five economic outcomes: benefit-cost ratio, gross income, total cost, gross margin and net income, in diversified and simplified farming systems. We address the question: In what situations are financial outcomes more favourable in diversified relative to simplified farming systems, and where can financial losses be expected? To answer this question, we compare economic outcomes of diversified and simplified farming systems across situations that vary in terms of crop type (woodiness, life cycle) and commodity group, diversification practice, agrochemical management, geographic region, country development level, and year of assessment.

2. Methods

2.1. Literature search

The literature search strategy aimed to identify studies comparing the financial performance of diversified and simplified farming systems. First, we searched for relevant, peer-reviewed studies in two online databases: Scopus (https://www.scopus.com/) and Web of Science (https://apps.webofknowledge.com/), placing no restrictions on the publication year or geographic focus of the study (Table A.1). Second, we expanded the article search by extracting the list of primary studies included in 6 meta-analyses and 15 reviews on related topics (Table A.2). In total, 10,396 articles with the potential to be included in the meta-analysis were identified (Appendix B: Dataset_1; Fig. A.1).

2.2. Studies selection

2.2.1. Inclusion criteria

All articles were screened and excluded if they did not satisfy our inclusion criteria. The inclusion criteria were based on the five PICOC components (Population, Intervention, Comparator, Outcomes, Context) (Mengist et al., 2020) (Table 1).

2.2.2. Screening process

Article screening was accomplished in two different stages. First, two reviewers classified each article as "relevant", "irrelevant" or "borderline" (i.e., uncertainty about whether or not the article should be included), through reading the title and abstract in the software Abstrackr (Wallace et al., 2012). All articles classified as "relevant" and "borderline" were assigned a unique numerical ID (Article_ID). Secondly, all accessible articles that passed the first screening stage were downloaded in PDF format, and two reviewers read the full article to ensure they satisfied our inclusion criteria. After the screening process, a total of 119 articles were retained (Fig. A.1 and Table A.3). The excluded articles were coded with an exclusion reason (Appendix B: Dataset_1).

2.3. Data extraction

We extracted qualitative (e.g., financial outcome, diversified and simplified systems; application of inputs – such as fertilizers, pesticides – and agricultural practices – such as soil management, irrigation), and quantitative (e.g., financial mean, variance values, sample sizes) data from the articles that fulfilled all inclusion criteria (Appendix B: Dataset_2). Qualitative and quantitative data were extracted directly from publication text, tables, figures, or supplementary information. Data from figures were extracted using WebPlotDigitizer v4.2. Where data values or units were unclear or not provided, corresponding authors

Table 1
Description of the article inclusion criteria arranged by Population, Intervention, Comparator, Outcome and Context (PICOC) component. Comparator farming systems are taken from Table 2 in Sánchez et al. (2021), with permission.

PICOC's components	Description
a) Eligible Populations	Articles analysing the financial performance of agricultural systems at the farm level worldwide, with full-text available in English.
b) Eligible Interventions	Articles reporting outcomes in diversified farming systems. We defined diversified farming as agricultural systems that cultivate different plant species or varieties together at multiple temporal and/or spatial scales (e.g., crop rotations, intercropping, agroforestry), that embed natural habitat into fields and farms (e.g., hedgerows, flower strips, set aside), or that integrate livestock or fish production with crop production (e.g., aquaculture, integrated crop-livestock systems).
Agroforestry	Satisfies three conditions: (i) at least two plant species interact biologically, (ii) at least one of the plant species is a woody perennial, and (iii) at least one of the plant species is managed for forage, annual or perennial crop production. Includes alley cropping with trees, shade monoculture, silvo-pasture (Beillouin et al., 2019).
Associated plant species	Plants grow in addition to the main crop for agronomic purposes, e.g., to manage soil erosion, pests, soil fertility or soil quality. The associated plant could be harvested or not, perennial or not (e.g., cover crops) (Beillouin et al., 2019).
Combined practices	Includes the combinations of single practices, such as crop rotation and cover crops used in unison, and integrated crop-livestock systems.
Crop rotation	Recurrent succession of a set of selected crops grown on a particular agricultural land each season or each year according to a definite plan (Beillouin et al., 2019).
Embedded natural	Land on-farm not used for farming and where non-crop plants are sown or regenerated naturally to benefit biodiversity or for other environmental purposes. Includes fallow (regular, >6 months), fallow (regular, >1 yr), hedgerows.
Intercropping	The simultaneous cultivation in the same field of two or more crop species, varieties, or cultivars, for all or part of their growth cycle. All crops are harvested (adapted from Beillouin et al., 2019).
c) Eligible Comparators	Articles reporting outcomes in relatively simplified farming systems. We defined simplified farming systems as agricultural plots with a single crop species or variety (e.g., monocultures), or with comparatively far fewer plant species or varieties than a paired diversified system (e.g., an agroforestry system grown with a single tree species versus agroforestry with multi-strata mixed tree species), or with no embedded natural habitat when compared to a system with embedded natural habitat (e.g. field with no hedgerows versus field with hedgerows), or that do not integrate livestock or fish with crop production compared to an integrated crop-livestock or crop-fish system. We included articles comparing a diversified system against a simplified system irrespective of whether the latter was a monoculture, because the simplified system can still have a severe lack of diversity and the difference in diversity between the two systems can still be very large. We excluded comparisons where there was no major difference in diversity between the two systems.
Monoculture	The cultivation of a single crop species or variety in the same plot at the same time or continually in different seasons.
Simplified other	Relatively low diversity (usually only 2 species) agroforestry, cover crop, crop rotation or intercropping, for studies comparing these against the same cropping system planted with relatively high diversity (usually ≥3 species); or cropped areas with no embedded natural features (e.g., hedgerows, vegetation strips) when compared against cropped areas with these embedded natural natures.
d) Eligible Outcomes	Articles reporting quantitative assessments of the effect of the intervention and comparator farming systems on financial outcomes (benefit-cost ratio, gross income, gross margin, net income, and total costs). Suitable metrics for financial outcomes included monetary values (any currency) for interventions and comparators. Articles reporting location data (e.g., country), financial outcome means (or medians), sample sizes, and variance measures (e.g., SD, SE, IQR, CI) or provided enough information to calculate variance measures (i.e., financial outcome means for each year of study) for intervention and comparator systems assessed. The same or similar sampling approaches were used to collect economic outcomes for the intervention and comparator systems, i.e., data collected at the same or very similar points in time, using the same or very similar sampling methods.
Benefit-cost ratio	Relationship between the gross income and total costs or partial cost $\left(\frac{Gross\ income}{Total\ cost}\right)$ or $\left(\frac{Gross\ income}{Partial\ cost}\right)$
Gross income	Crop/s production value, calculated by multiplying the crop/s yield by the market price ($Crop\ yield \times Price$)
Gross margin	Gross income minus the direct production costs, such as labour, supplies (e.g., fertilizers, seeds, pesticides), irrigation, machinery ($Gross\ income - Direct\ cost$)
Net income	Gross income of a farming system minus the total cost of production ($Gross\ income - Total\ cost$)
Total cost	Includes all costs directly and/or indirectly related to the production.
e) Eligible Context	Articles reporting outcomes from primary field-based studies, and surveys. We excluded articles reporting experiments carried out in laboratories or greenhouses and reporting results from secondary data (i.e., data from another study, reviews or meta-analysis).

were contacted by email. When the authors did not respond, the article was excluded. More details about the coding strategy are available in Appendix A: Coding Strategy).

2.4. *Effect size calculation*

We calculated effect sizes to compare the impact of diversified relative to simplified farming systems on five financial outcomes using the *escalc* function of the R-4.0.0 package *metafor* (Viechtbauer, 2010). For the benefit-cost ratio, gross income, and total cost, the effect size was calculated as the weighted log-response ratio (log-RR) (Hedges et al., 1999). For the gross margin and net income, some comparisons presented negative mean values meaning log-RR could not be calculated. For these two outcomes, the effect size was calculated as the standardized mean difference (SMD) (Borenstein et al., 2009).

Both effect size metrics were calculated in such a manner that a positive value meant diversification had a positive effect on the financial outcome, while a negative value meant the financial outcome was better in simplified systems. We reported the average and confidence intervals for the log-RR as percentages ($100 \times (exp(logRR) - 1)$) to aid interpretation of the results (Pustejovsky, 2018).

In total, our meta-data included 3192 effect sizes from 119 articles that compared financial performance between diversified and simplified systems (Fig. A.1). We performed an internal validity assessment to account for the possibility of effect sizes being biased (CEE, 2013), classifying the effect sizes as having a High (score 0–4), or Low (score 5–7) risk of bias based on seven quality criteria (Table A.4).

2.5. *Meta-analysis*

We applied three-level meta-analytical models to calculate the average effect of diversified (relative to simplified) farming systems on the financial outcomes using the *rma.mv* function of the *metafor* R package (Viechtbauer, 2010). In contrast to two-level meta-analytical models, three-level models consider the statistical dependency within effect sizes coming from the same article (López-López et al., 2018). Effect sizes in this analysis were potentially statistically dependent in cases where articles provided multiple effect sizes corresponding to: the same agricultural controls or treatments (i.e., articles reporting financial outcomes for multiple treatments compared against the same control); multiple time or location points (i.e., articles reporting financial outcomes for multiple study sites, or over multiple years), or; multiple outcomes (i.e., articles reporting multiple financial outcomes for the same comparator-intervention system).

We controlled for possible dependencies between effect sizes by adding the following random effects to the meta-analytical model: sampling variance as the random effect at the first level of the model, effect size ID as the second level, and article ID as the third level (van den Noortgate et al., 2013). The t-distribution was used to calculate the 95% confidence intervals around average effect sizes (Knapp and Hartung, 2003). Overall effect sizes were estimated using the Restricted Maximum-Likelihood (REML) as this method is more efficient and less biased when calculating heterogeneity (Viechtbauer, 2005).

First, we applied meta-analytical models to estimate the overall mean effect of simplified and diversified farming systems on each of the five evaluated financial outcomes. We ran two separate one-sided log-likelihood-ratio tests for the variances at the second (within studies) and third (between studies) levels to test the suitability of conducting the three-level comparing to the two-level meta-analysis (Assink and Wibbelink, 2016). The three-level model is justified when variance at the second and third levels significantly deviate from zero (Cheung, 2014). We quantified the proportion of the observed variance (I^2) accounted for by each of the three levels (Cheung, 2014). The application of meta-regression models is justified when the I^2 at the first level is close to zero, compared to the total variance (Borenstein et al., 2009).

Second, we applied univariate meta-regression models to examine whether the following variables moderated the overall effect of farming system diversification on each financial outcome: FAO commodity groups, crop life cycle, crop woodiness, diversification practice, agrochemical (chemical fertilizer and/or pesticide) inputs, chemical fertilizer inputs, pesticide inputs, irrigation inputs, tillage practice, UN country development status, UN geographic sub-region, year of assessment, and labour inputs difference of diversified compared to simplified farming systems (Table A.5). The moderating effect of each assessed variable was tested based on a F-distribution (Viechtbauer, 2010).

Third, multivariate meta-regressions were used to examine whether each variable continued to have a moderating effect when controlling for effects of other significant variables (Ho, 2006) (see further details in Appendix A: Multivariate meta-regressions results).

2.6. Publication bias

We tested for the presence of publication bias in our database using statistical and visual approaches. The statistical approach involved conducting Egger's regression test with the inverse of the standard error of the effect sizes as a moderator (Kunc and Schmidt, 2019; Tamburini et al., 2020). An intercept significantly different from zero means there is evidence of publication bias (Egger et al., 1998). Funnel plots were used to visually detect whether the effect sizes were asymmetrically distributed, which can also indicate publication bias (Borenstein et al., 2009).

2.7. Sensitivity analysis

We conducted a sensitivity analysis to establish whether the direction and significance of our overall results were robust to the exclusion of effect size outliers, potentially biased effect sizes (Aguinis et al., 2013), and effect sizes involving a non-monoculture control (i.e., simplified other). We classified as outliers those effect sizes with a Cook's distance greater than $\frac{4}{n-p}$ (Bollen and Jackman, 1985), where n refers to the number of effect sizes and p refers to the number of model coefficients, or those with comparatively large Cook's distance values based on visual inspection (Viechtbauer and Cheung, 2010). We considered effect sizes to have a high risk of bias if they were assigned a bias score ≤ 4 (see Section 2.3). The R code used to run all the analyses presented in this paper is available in Appendix C.

3. Results

3.1. Data distribution

The 3192 included effect sizes (119 articles) span 39 countries covering six continents and ten UN sub-regions (Fig. A.2a). Most of these effect sizes represented net income (1265 effect sizes) from experiments in North America (74%) and Southern Asia (9%) (Fig. A.2b). Effect sizes for gross margin (800 effect sizes) were mainly from experiments in Western Europe (67%), Southern Asia (14%) and Sub-Saharan Africa (12%). The majority of effect sizes that represented gross income (534 effect sizes) or total cost (503 effect sizes) came from studies performed in North America (46% and 50%, respectively), Sub-Saharan Africa (25% and 21%, respectively), and Southern Asia (20% and 15%, respectively). Relatively few effect sizes represented benefit-cost ratios (90 effect sizes), and most of these were collected from farming systems in Southern Asia (59%). Overall, the financial data were dominated by articles analysing diversified farming systems combining annual crops (e.g., cereals, cereals-vegetables, cereals-pulses) (Fig. A.3) in crop rotation systems (Fig. A.4) in North America and Southern Asia (Fig. A.5–6), under various agrochemical, soil, and water management practices (Fig. A.7–8).

3.2. Overall results

The overall mean gross income, gross margin, net income and total cost were significantly higher in diversified farming systems compared to simplified ones (Fig. 1). The mean benefit-cost ratio tended to be positively affected by farming system diversification but effects were not significant. The heterogeneity analyses supported the application of three-level meta-analysis and moderator analyses for each of the studied financial outcomes (Table A.6).

3.3. Meta-regression results

All variables considered in our analysis moderated the effects of diversification on at least one financial metric (Table A.7). The financial metrics assessed here can be grouped into three types: i) metrics that assess profits, which include benefit-cost ratio, gross margin, and net returns, ii) metrics that assess gross income, and iii) metrics that assess total costs. We discuss the results across these three metric groups, for each of the moderators assessed.

3.3.1. Crop selection and arrangements

Among FAO commodity groups and relative to simplified farming systems, net income was higher in diversified systems combining cereals and pulses (0.96 SMD [0.5, 1.4], e.g., rice with lentils), cereals with –'others' - which includes fibres and/or roots and/or tubers and/or fruits (0.4 SMD [0.1, 0.7], e.g., cereals with cotton or potato) and in diversified systems containing fruits (1.23 SMD [0.14, 2.3], e.g., apple, pear) (Fig. 2). Gross margins were higher in diversified systems with cereal-pulse crop combinations (0.9 SMD [0.01, 1.8]) and those with cereals and oil-bearing crops (1.03 SMD [0.1, 1.9]). For diversified systems with cereals and pulses, total costs were positive but not significantly different to those in simplified systems, which may explain why profits can still be higher than in simplified systems despite significantly lower gross income (−28% [−47, −3]). Profits were variable when systems with other commodity groups were diversified, with the magnitude and significance of the response varying across the three metrics. The average benefit-cost ratio and gross margin were higher in diversified vegetable systems (e.g., eggplant, onion, spinach) relative to simplified systems (327% [169, 579]; and 1.5 SMD [0.2, 2.8]; respectively), despite higher costs (101% [59, 154]). In diversified vegetable

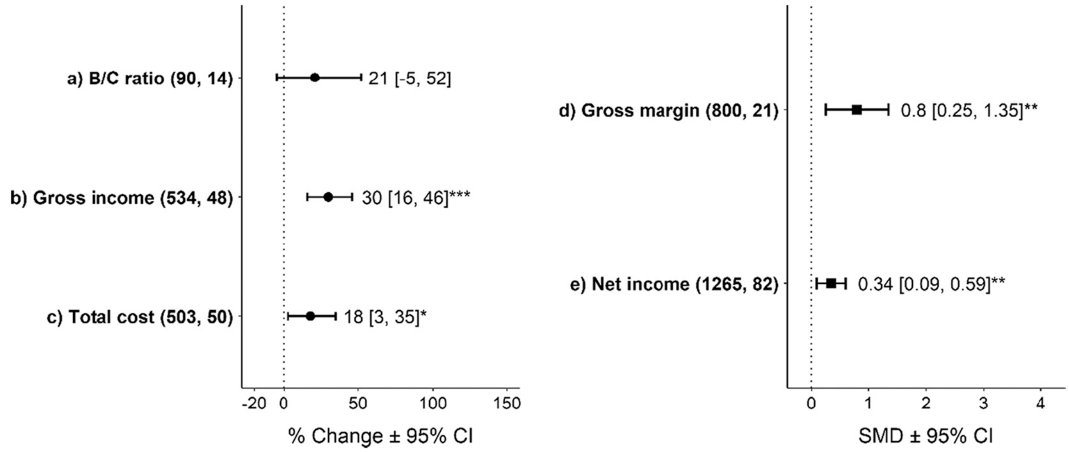

Fig. 1. Overall mean effect of farming system diversification on a) benefit-cost ratio, b) gross income, c) total cost, d) gross margin, and e) net income. Labels on the plot represent the mean effect sizes [±95% CI] and statistical significance: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$. Labels in parentheses on the y-axis represent the number of effect sizes followed by the number of articles.

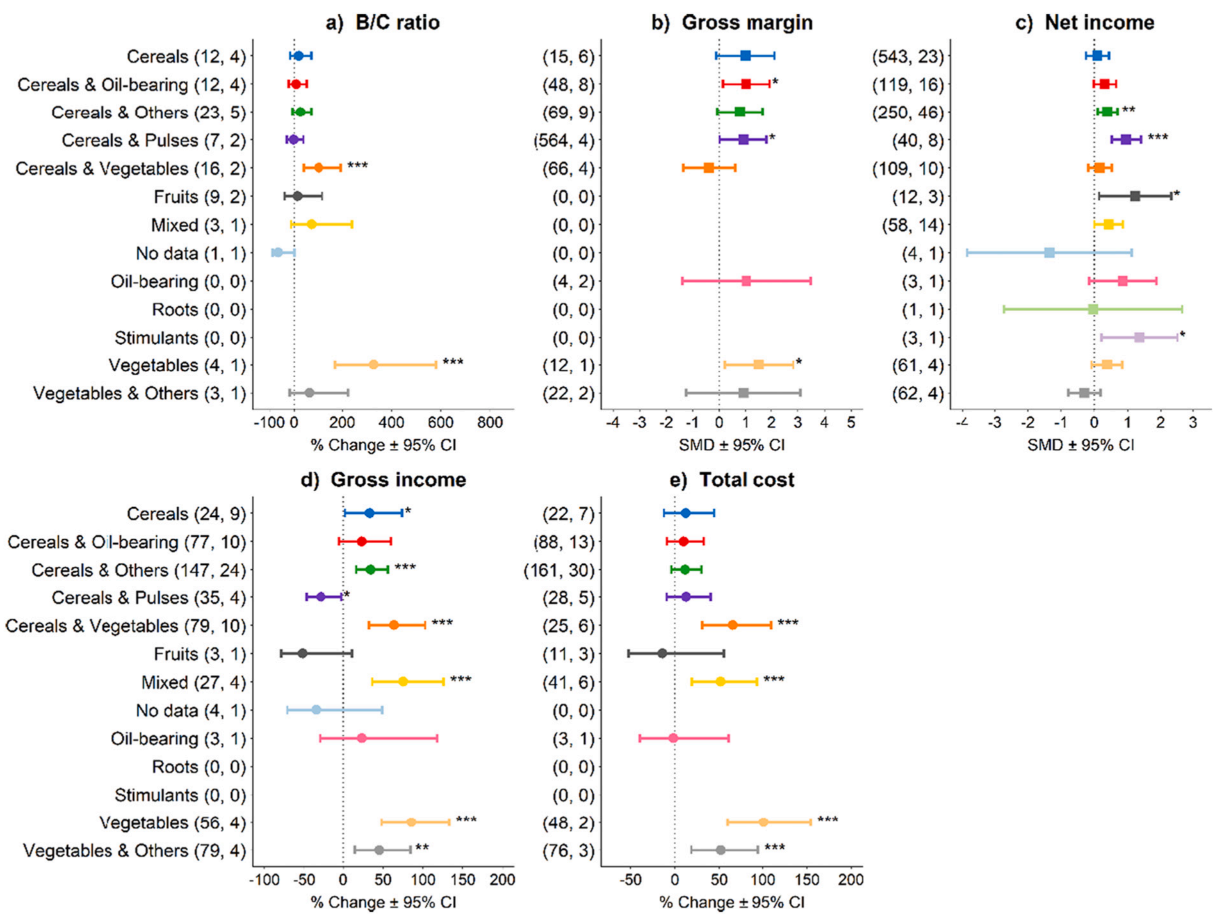

Fig. 2. Mean effect of farming system diversification on a) benefit-cost ratio, b) gross margin, c) net income, d) gross income, and e) total cost, across FAO commodities for crops growing in the diversified systems. The absence of points on the forest plot means no data were available for that variable. Note the difference in scale of the x-axes when comparing the figures. Labels on the figures show the statistical significance of the average effect size: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$. Labels in parentheses on the y-axis represent the number of effect sizes followed by the number of articles.

systems, gross income was also higher (86% [48, 133]) and net income tended to be positive but was not significantly different to net income in simplified systems. Of note, net income was higher in diversified stimulant systems (i.e., coffee), relative to simplified systems (1.36 SMD [0.2, 2.5]). No studies in our database assessed gross income or total costs in stimulant systems.

Crop life cycle and woodiness altered the effect of diversification on profits and costs (Table A.7). Profits, in terms of net income and gross margins, were higher in diversified annual, compared to simplified cropping systems (0.5 SMD [0.2,0.8] and 1.1 SMD [0.5, 1.6], respectively), despite higher costs (28% [11, 49]) (Fig. A.9). Linked to this (since annual crops are often herbaceous), net income and gross margins were higher in diversified herbaceous, relative to simplified cropping systems (0.5 SMD [0.2, 0.7.] and 0.9 SMD [0.4, 1.4], respectively), while gross income and total costs were also higher (40% [24, 57] and 29% [14, 48], respectively) (Fig. A.10). In contrast, diversification of perennial, or mixed annual and perennial, crops presented similar profitability and total costs as simplified systems. Of interest, we found that diversified tree cropping systems were less costly than simplified systems (−63% [−81, −29]), while gross income and profits were comparable.

Diversification practice moderated the impact of farming system diversification on gross income, total cost, gross margin and net income (Table A.7). Combining practices, crop rotations, and embedding natural habitat, had a positive effect on net incomes relative to simplified farming systems (1 SMD [0.5, 1.5], 0.5 SMD [0.2, 0.8], and 0.5 SMD [0.07, 0.9], respectively), and gross incomes were also higher in systems with combined practices or crop rotations (72% [32,122] and 54% [28, 85], respectively) (Fig. 3). The total production costs of diversified and simplified farming systems were similar across all diversification practices, except in the case of crop rotation which was 34% [9, 64] more costly. The benefit-cost ratio was higher in diversified systems using agroforestry (87% [18, 196]), while differences were not significant when other diversification strategies were used.

3.3.2. Agrochemical, water and labour inputs

Agrochemical inputs moderated the effect of farming systems on gross income, total cost and net income (Table A.7). Net income, gross margin and gross income were higher in diversified farms when agrochemicals (synthetic fertilizers or pesticides) were applied in both the simplified and diversified systems (0.4 SMD [0.1, 0.6], 0.7 SMD [0.1, 1.3] and 29% [15, 45], respectively), while the benefit-cost ratio was positive but not significantly different (Fig. A.11). When agrochemicals were applied in the diversified system and only organic inputs in the simplified system, net income was higher (1 SMD [0.6, 1.5]) but gross margin was not (no data on benefit-cost ratio), while gross income and total costs were also higher (109% [71, 157], and 67% [40, 106], respectively). Crop diversification significantly improved gross income on organic farms. The unique disaggregated effects of synthetic fertilizers and pesticides on financial outcomes are shown in Fig. A.12. and Fig. A.13.

Irrigated and rainfed diversified farming systems both presented higher net incomes (0.7 SMD [0.06, 1.4] and 0.32 SMD [0.04,0.6], respectively) than rainfed simplified systems (Fig. A.14). When comparing rainfed-only farms, diversification resulted in higher gross margins (0.9 SMD [0.3, 1.6]), while the benefit-cost ratio was not significantly different. Implementing irrigated or rainfed diversified systems was more costly than non-irrigated simplified systems, while irrigated simplified and diversified systems presented similar total costs. However, gross income was higher in diversified irrigated (139% [56, 266]) and diversified rainfed (36% [18, 58]) systems compared to their simplified equivalents, which may explain the higher profitability of these diversified systems despite their higher costs.

Profits in terms of benefit-cost ratio and net income, and total costs, were not significantly different across diversified and simplified systems under different tillage practices. However, profits in terms of gross margin were higher in diversified systems under conventional tillage than in conventional or no-till simplified systems (1.2 SMD [0.34, 2] and 1.4 SMD [0.3, 2.4], respectively). Gross incomes were higher in diversified systems when tillage practices were applied in the diversified and

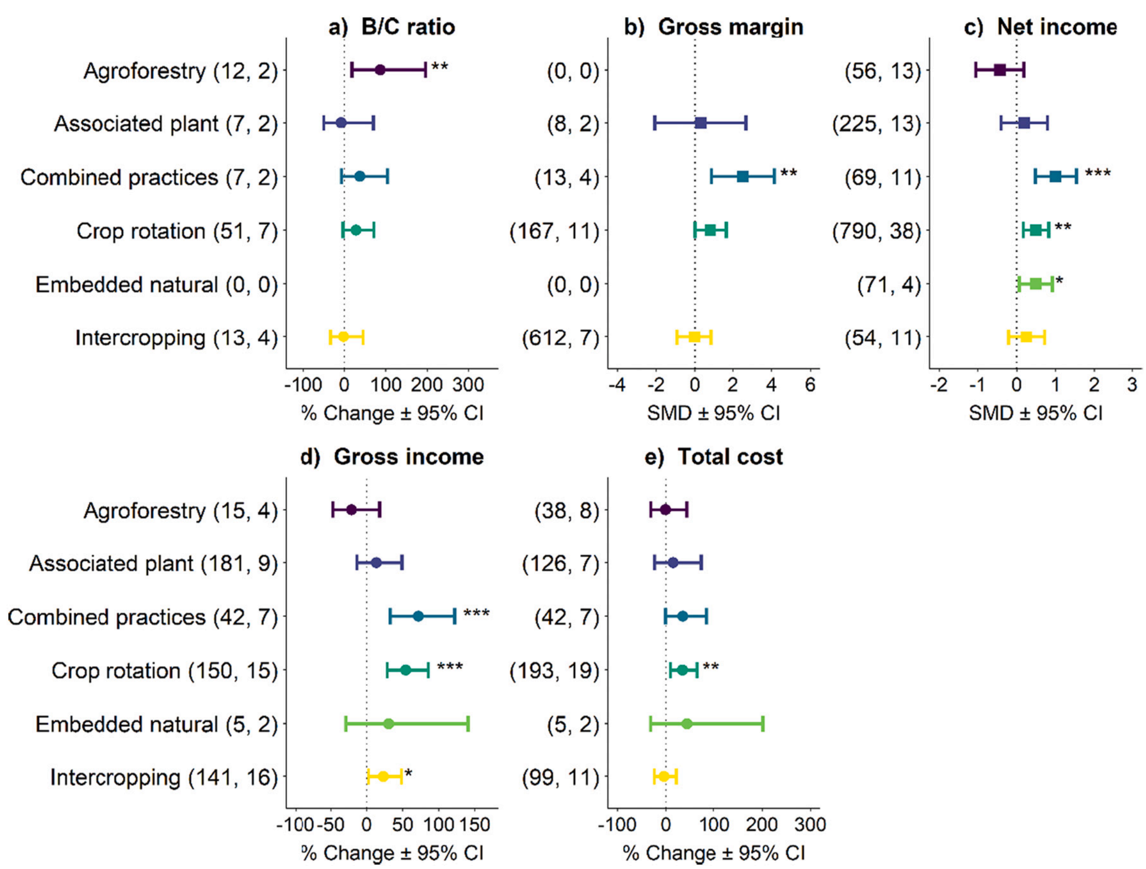

Fig. 3. Mean effect of farming system diversification on a) benefit-cost ratio, b) gross margin, c) net income, d) gross income, and e) total cost for the diversified practices. The absence of points on the forest plot means no data were available for that variable. Note the difference in scale of the x-axes when comparing the figures. Labels on the figures show the statistical significance of the average effect size: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$. Labels in parentheses on the y-axis represent the number of effect sizes followed by the number of articles.

not in the simplified system, but also in the reverse case (no till in the diversified and conventional till in the simplified system) suggesting that tillage practices have variable effects on gross incomes (Fig. A.15).

Labour input moderated the effect of farming system diversification on benefit-cost ratio, gross income and total cost, but not net income or gross margin (Table A.7). Gross incomes in diversified farming systems increased by 0.5% [0.4, 0.6] with every 1% increment in the labour input in the diversified system relative to the simplified system (Fig. A.16). At the same time, total costs of implementing diversified systems increased by 0.45% [0.37, 0.5] with every 1% increment in labour input. However, diversified and simplified systems were equally profitable in terms of gross margin and net income, despite higher costs associated with increased labour requirements in diversified systems.

3.3.3. Geographic and economic context

UN sub-regions moderated the effect of farming systems on benefit-cost ratio and gross income (Table A.7). Farming system diversification in south-eastern Asia led to large increases in net incomes (1.4 SMD [0.24, 2.6]), gross incomes (119% [29, 274]) and gross margins (3.4 SMD [0.8, 6.1]), but also a significant increase in total costs (106% [5, 303]) (Fig. 4). Diversification also led to large increases in net income in southern Asia (0.8 SMD [0.1, 1.5]). In sub-Saharan Africa, there were large increases in the benefit-cost ratio (320% [99, 787]), gross margin (1.2 SMD [0.2, 2.2]) and gross income (55% [26, 90]) in diversified systems, relative to simplified, while total costs were not significantly different.

UN development country status moderated the effect of farming systems on gross income, gross margin and net income (Table A.7). Diversified farming systems were more profitable in developing countries, leading to higher net incomes (0.6 SMD [0.3, 1]), gross margins (1.1 SMD [0.4, 2]), benefit-cost ratios (33% [3, 70]) and gross incomes (38% [21, 58]) relative to simplified systems (Fig. A.17). Importantly, in developing countries, total costs were 21% [2, 43] higher in diversified compared to simplified farming systems.

Inter-annual fluctuations in market prices and economic contexts may explain why the year of assessment moderated the effect of farming system diversification on gross and net income (Table A.7). Diversification led to significantly higher gross and net incomes between 2000 and 2010 (55% [31, 82]; 0.7 SMD [0.3, 1.2]; respectively), but also higher costs (34% [6, 68]) (Fig. A.18). There were no significant differences in financial outcomes in diversified and simplified systems in other decades.

3.4. Multivariate meta-regression results

The results from the multivariate meta-regression models applied by adding the non-collinear variables that had a significant moderating effect on the assessed financial outcomes are described in the Appendix A (Section: Multivariate meta-regression results).

3.5. Publication bias

For the benefit-cost ratio, adapted Egger's regression tests (t_{88} = 0.81, $p \sim 0.42$) (Table A.8) and visual inspection of the funnel plot (Fig. A.19) revealed no evidence of publication bias. However, the intercept from the Egger's regression test was significantly different from zero for gross income ($t_{532} = 5.19, p < 0.001$), total cost ($t_{501} = 2.6$, $p \sim 0.0106$), gross margin ($t_{7988} = 3.2, p \sim 0.001$) and net income ($t_{1263}$ = 13, $p < 0.001$), and the funnel plots showed clear asymmetry, suggesting evidence of publication bias. This may reflect that, articles reporting non-significant or negative effects are not well represented in our database, because research on economic performance of farming

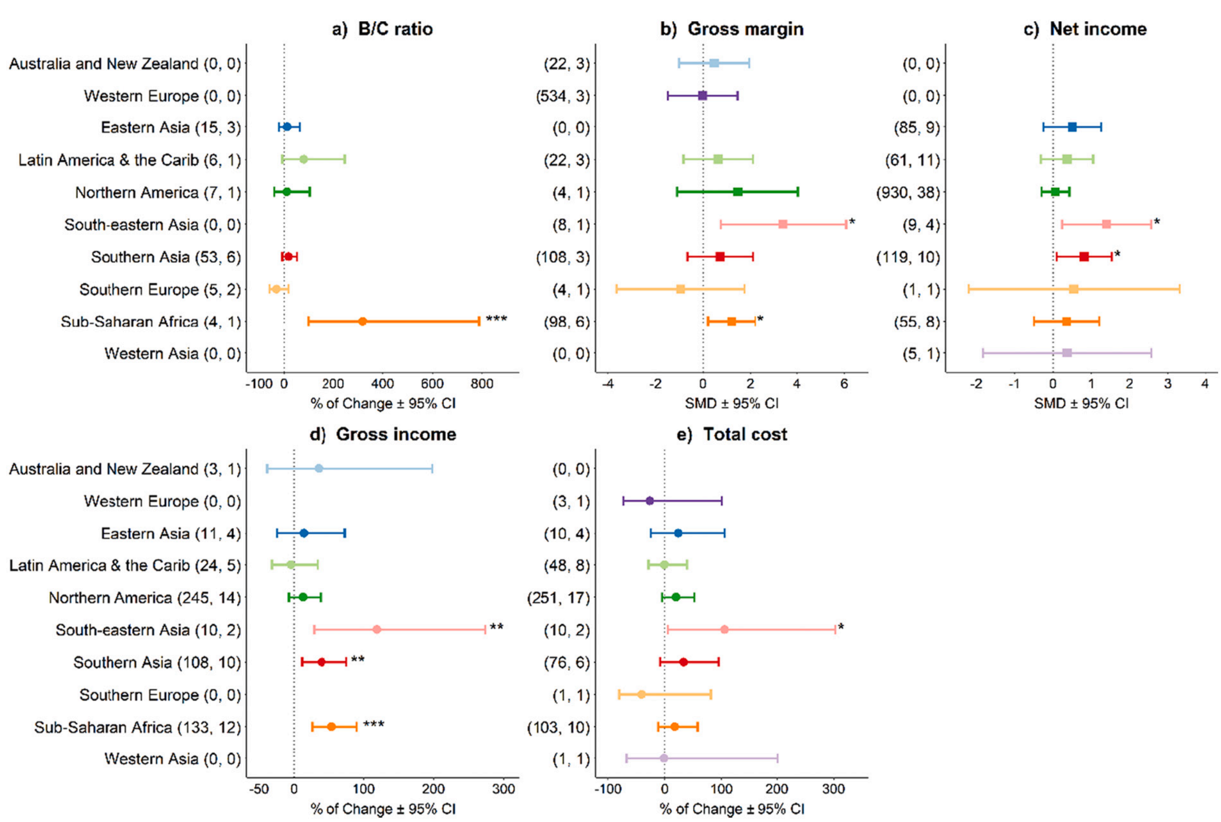

Fig. 4. Mean effect of farming system diversification on a) benefit-cost ratio, b) gross margin, c) net income, d) gross income, and e) total cost for each the UN sub-regions. The absence of points on the forest plot means no data were available for that variable. Note the difference in scale of the x-axes when comparing the figures. Labels on the figures show the statistical significance of the average effect size: *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$. Labels in parentheses on the y-axis represent the number of effect sizes followed by the number of articles.

system diversification has not yet peaked.

3.6. Sensitivity analysis

We identified statistical outliers (based on Cook's distance values) in effect sizes representing benefit-cost ratios (1 effect size), gross margins (12 effect sizes), net income (17 effect sizes), gross income (4 effect sizes), and total costs (12 effect sizes) (Fig. A.20). A number of effect sizes were found to have a high risk of selection or performance bias, including those representing net income (10 effect sizes), gross income (50 effect sizes), and total costs (31 effect sizes) (Fig. A.21).

The exclusion of effect sizes with high risk of bias, effect sizes outliers and effect sizes involving a non-monoculture control, did not affect the direction or significance of the overall mean effect of diversification on gross income, total costs, gross margin or net income. (Fig. A.22). However, the mean positive effect of diversification on the benefit-cost ratio switched from not significant to significant (27% [4, 57], p = 0.023) after excluding effect size outliers.

4. Discussion

Providing evidence of situations where diversified farming systems are economically viable could have major implications for donors, policymakers and farmers who recognise the unsustainability of the simplified systems that dominate the world's agricultural land. This study presents the most comprehensive meta-analysis to date on the total costs, gross income, and profitability of diversified farming systems relative to simplified ones. The results show that average profits are higher in diversified systems compared to simplified ones, particularly in developing countries. However, average total costs are also higher in diversified farming systems compared to simplified systems. The benefits and costs of diversification are driven in part by crop commodity and arrangement, agrochemical and water management, geographic region and economic context. Considering these factors will help determine the range of affordable and profitable diversification strategies in a specific farming context.

4.1. Diversified farming systems make economic sense

Our results show that gross margins and net income are, on average, higher in diversified farming systems. This is consistent with several reviews showing the economic benefits of diversification (Beillouin et al., 2021; Rosa-Schleich et al., 2019). Our study revealed several situations where diversified farming has particularly favourable economic outcomes.

First, we found that diversification of systems with high-value crops such as mixed cereal-vegetables (e.g., maize with radish, or sorghum with peas), fruits (e.g., pear, apple) and stimulants (i.e., coffee) were more profitable than simplified systems. Incorporating high value crops typically improves the overall profitability of a farming system and previous research indicates this result holds even when yields of the original crop are negatively impacted. For example, a previous meta-analysis (Jezeer et al., 2017) found the lower production costs and higher prices of cocoa or coffee growing in diversified systems improved their financial profitability despite their lower yields. High-value fruit and vegetables may be particularly effective crops to include in profitable diversified systems because of their nutritional benefits. A growing body of literature is demonstrating that fruit and vegetable production can generate higher farm incomes and more rural employment than other commodities (Basu, 2014; Birthal et al., 2008; Feliciano, 2019; Joshi et al., 2006), promoting food and nutritional security (Ebert, 2020; Feliciano, 2019; Schreinemachers et al., 2018). However, the implementation of diversified systems with high-value crops usually requires capital to purchase specific inputs (e.g., fertilizers, seeds) and train employees/farmers to ensure good management (de Roest et al., 2018). Perennial high-value crops (e.g., fruit trees, coffee) have longer gestation periods than annual commodities, which often make them inaccessible to poor farmers in developing countries (Basu and Gallardo, 2021; Birthal et al., 2015; Do et al., 2020). Moreover, input-intensive crops are not biophysically viable to grow everywhere and effort and investment will be needed to prioritise and develop profitable value chains for locally adapted fruits and vegetables (Abraham and Pingali, 2020; de Roest et al., 2018).

Second, our results revealed that diversified annual cropping systems were more costly but also much more profitable than simplified cropping systems. Diversified systems combining annual crops may generate more regular and higher seasonal returns, being an attractive alternative for poor farmers (Feliciano, 2019). The higher production costs of diversifying annual crop systems may be compensated at medium or long-term by enhancing ecological benefits and optimizing resource use (Rosa-Schleich et al., 2019).

Third, based on our data, combined practices, crop rotation, embedding natural habitat, and agroforestry, each lead to significantly higher profits in terms of net income, or benefit-cost ratio in the case of agroforestry. Previous reviews have similarly suggested that crop rotation usually results in higher income and fewer production risks, particularly for low-income smallholder farmers (Feliciano, 2019; Shah et al., 2021). However, the adoption of diversified rotation systems may be negatively influenced by the higher investment (e.g., inputs, machinery, labour) needed to integrate and manage extra crops compared to simpler rotations (Feliciano, 2019), which may explain the higher costs for crop rotations found in our study. On the other hand, our results showed that total production costs are comparable to those in simplified farming systems for combined practices, embedded natural infrastructures and agroforestry systems. Combined practices were also highlighted by Beillouin et al. (2021) and Rosa-Schleich et al. (2019) as among the most promising strategies for boosting economic outcomes, while providing multiple co-benefits. Meanwhile, embedding natural habitat is gaining global attention as a strategy to maintain biodiversity and ecosystem function in agricultural landscapes (Garibaldi et al., 2020). Our results support previous literature showing that maintaining semi-natural habitat on-farm and other practices that boost biotic services supporting agricultural production may enhance crop yield and quality (Ricketts, 2004), with no significant variation in monetary returns compared to simplified farming systems (Pywell et al., 2015). In contrast, previous research indicates the financial performance of agroforestry is highly variable. Jezeer et al. (2017), indicated that cacao and coffee systems under shade trees present a better financial performance with greater cost-efficiency and lower total production costs than unshaded sun plantations. Contrarily, Niether et al. (2020), found that although cocoa agroforestry systems present higher productivity, their profitability and total costs are the same as those in monoculture systems when prorated. Moreover, Do et al. (2020) revealed agroforestry systems yield higher net profits than monocultures, yet the time-lag these diversified systems need to compensate for the initial investment depends exclusively on the crop combination. Given the scarcity of evidence in our database about financial performance of embedded natural systems (<5 articles), our results for these practices should be interpreted with caution and additional primary studies are needed to confirm the relative economic costs and benefits accruing from these practices.

Fourth, our results suggest that synthetic inputs amplify the economic benefits of diversification. The use of agrochemicals (i.e., fertilizer or pesticides) in diversified systems generated higher gross and net profits compared to simplified systems applying organic or chemical inputs for soil fertility and pest control. This is consistent with previous syntheses (Harris and Orr, 2014; Himmelstein et al., 2017; Jezeer et al., 2017; Niether et al., 2020) where the mean effect of farming systems on the economic outcomes assessed depended on the agricultural management applied in those systems. Contrarily to results in Crowder and Reganold (2015), we found that the use of agrochemical inputs (specifically chemical fertilizers) in diversified farming systems was associated with higher total costs compared to simplified organic systems, but also higher gross and net incomes. These findings suggest that the additional investment cost of applying chemical fertilizers in diversified systems can be compensated by the higher quality (and associated price premiums) and/or quantity of agricultural outputs (Tey and Brindal, 2014) resulting in higher net profits.

Fifth, our results indicate that the economic benefits of diversification are minimally affected by water inputs and tillage management. Diversified systems were more profitable than rainfed simplified systems, regardless of whether or not they were irrigated. Conversely, profits from diversified rainfed systems were not significantly different to those from irrigated simplified systems, suggesting that diversification can be an effective strategy to close profit gaps in irrigation-limited areas (Harris and Orr, 2014). Water scarcity is already a pressing issue in many agricultural landscapes and predicted to intensify under climate change (Rosa et al., 2020), meaning that strategies like diversification will be increasingly important to maintain productive and profitable rainfed and water-limited farming systems (Wezel et al., 2014).

Regarding tillage management, net profits and total costs were similar across diversified and simplified systems under all tillage treatments (i.e., conventional/reduced/no-tillage) where data on tillage practices were reported. Our results provide an added incentive to reduce the application of costly soil tillage practices, since diversification in no-till or reduced tillage systems leads to profits that are comparable with conventionally tilled simplified systems. Wezel et al. (2014) suggested that the application of agroecological practices such as minimum tillage increase soil fertility by promoting soil biota activity, and reduce herbicide use by limiting weed growth. Moreover, diversified systems in themselves have been found to provide a natural mechanism for controlling the dynamics and propagation of weeds through competition of available resources (Weisberger et al., 2019), maintaining soil health, and improving water efficiency (Kremen et al., 2012), that will be particularly beneficial in systems with low or no access to soil management technologies, agrochemicals and irrigation inputs.

4.2. More employment with no loss of income

Diversified farming systems have previously been shown to be labour intensive at all levels (land preparation, planting, management and harvesting) and, in addition to other costs related to inputs and seedlings, are associated with much higher costs than simplified systems (Iles and Marsh, 2012). Yet, our results show that higher labour requirements do not translate to lower profits. This result might be explained by both agronomic and economic factors. For example, inclusion of cover crops or shade plants eventually reduces labour requirements associated with weed management (Joshi et al., 2006; van Zonneveld et al., 2020). On a larger scale, increasing employment stimulates rural economies, allowing markets to grow and farmers to sell more produce, boosting the standard of living for everyone (Rodríguez-Pose and Hardy, 2015). The lower labour requirements of industrialized, simplified systems are much more likely to create problems for rural economies (de Roest et al., 2018). Improving working conditions for farmers and farm labourers worldwide is essential, through the use of technology and local networks that reduce difficult and back-breaking tasks (FAO, AUC, 2018; Visser and Ferrer, 2015), as well as regulation, support, and education to elevate the farming profession to a respected, attractive livelihood, particularly for youth (Eissler and Brennan, 2015). While labour costs can be higher, there are ways to offset these costs in both the short and long run.

A primary concern with the adoption of diversified farming systems is that it can drive up labour and investment costs, undermining farm profits (Bowman and Zilberman, 2013; Iles and Marsh, 2012). Focusing on production costs is probably creating unnecessary hesitancy in switching away from less profitable industrialized farming systems. We found that diversified systems promote more employment opportunities with no loss of profits when compared to simplified systems. The higher gross income and comparable profits in diversified systems in our study may be explained by higher productivity associated with increases in farm work and crop diversification (Branca et al., 2021; Durham and Mizik, 2021; Tey and Brindal, 2014). Improving data collection on labour inputs would help strengthen the evidence base. Although almost all articles in our study included labour in their total cost or profit analyses, only 36% of them reported labour requirements as separate data and these were reported in many different formats (e.g., hours/ha, USD/day), a weakness already highlighted in previous studies (Garibaldi et al., 2016; Harris and Orr, 2014; Jezeer et al., 2017).

4.3. Policy implications

Overall, we found no situations where diversified farming systems incur significant losses, as measured by net income, gross margins, or benefit-cost ratios. However, we did find several situations where total costs were significantly higher in diversified farms. In these cases, as with the onset of any transition to new practices, subsidies and investments are likely to be needed to incentivise farmers and ensure inclusivity and realization of economic benefits for the poorest (Ding et al., 2021). Despite growing evidence of their environmental, social, and economic advantages, the implementation of diversified systems is mostly restricted to small areas in low- and middle-income countries (Herrero et al., 2017). Our results showed diversified farming systems in developing countries presented higher gross and net financial benefits compared to simplified systems, especially for farms in Sub-Saharan Africa, south-eastern and southern Asia, with higher total costs only in diversified systems in south-eastern Asia. This is consistent with many other studies that have concluded that crop diversification leads to gross income gains in smallholder farming systems across African and Asian countries, simultaneously increasing their climate change adaptation capacity and food security status (Himmelstein et al., 2017; Makate et al., 2016; Pellegrini and Tasciotti, 2014). On the other hand, our study found that diversified farming systems in developed countries tended to be as profitable and costly as simplified systems. The adoption and spread of farm diversification in both low and high-income countries may be obstructed by reinforcing economic and political incentives to industrialize agriculture, the erosion of agroecological knowledge to implement these systems, and supply-chain constraints (Iles and Marsh, 2012). Farmers already implementing or considering shifting to diversified practices need strong policy support (Ding et al., 2021), market incentives (Swensson et al., 2021; Valencia et al., 2019) and access to cost and labour-saving social and technological knowledge and resources (Jones et al., 2022), to maintain and scale diversified farming systems.

We note that the reasons why diversification leads to more profitable farming systems may depend on several factors not directly considered in our study. For example, according to Lancaster and Torres (2019), crop diversification helps farmers in the US sell their fruits and vegetables in high-value local markets, which is reflected in higher profitability through access to premium prices. However, not all markets are adapted to charging premium prices for food produced from diversified farms and moreover this makes food from diversified farms unaffordable or economically unattractive to many consumers (IPES-Food, 2020). Particularly in developing countries, diversified horticultural systems may enhance smallholders' profits through other means, such as by increasing farm economic returns per unit land area (Joshi et al., 2006) and reducing market and climate risks (Ahmed and Stepp, 2016; Ali, 2015). This may in part explain the highly favourable economic outcomes in developing countries found in our study, helping dispel the notion that diversification is a dead end for poverty alleviation (Mugwanya, 2019). In fact, our results show that simplified systems are more likely to leave farmers in poverty.

Our meta-analysis contributes to the scientific evidence promoting the implementation of diversified farming systems as economically viable food systems in the context of global environmental and market changes. The spread of diversified systems is, however, challenged by the lack of market support, and dominant policies supporting simplified agricultural systems. Policies promoting paddy monoculture in countries from South-eastern Asia (Nguyen, 2017), and fertilizer subsidies encouraging maize monoculture in Zambia (Ding et al., 2021) are just examples of strategies that need to be redesigned and adjusted to improve farmers' livelihood while ensuring food security and agroecosystem resilience. In contrast, public food procurement programs in Brazil (Valencia et al., 2019) and Denmark (Holmbeck, 2020) are successful model examples of how the public sector can support the transition to more diversified food systems. Policy interventions must account for the true cost of production, including the cost of negative externalities and the benefits of the positive ones (TEEB, 2015). Moreover, market structures and value chains for diversified farms produces are needed for farmers to thrive when diversifying their production systems (IPES-Food, 2020).

4.4. Limitations and future research priorities

Future field experiments should include closing knowledge gaps for poorly studied commodities, regions and practices. For example, across FAO commodity groups, cereals and vegetable crops were relatively well represented in our database (2412 and 355 effect sizes, respectively), yet fruits, nuts, pulses, roots, stimulants, livestock and dairy products, and some staple food crops (e.g., cassava, sweet potatoes), were poorly represented despite their nutritional and economic importance in global food systems. As with many other reviews, a disproportionate number of effect sizes in our database are from experiments in North America, while experiments in Africa and South and Central America together represent only 17% of the effect sizes. Another notable gap is on certain diversification strategies with lesser-known agronomic benefits but high potential to benefit biodiversity conservation, climate mitigation, and other sustainability objectives. For example, while crop rotations, intercropping and cover crops were widely studied, embedded natural habitat and agroforestry systems were not, despite being among the most beneficial strategies for enhancing ecosystem services and climate resilience on-farm.

Moreover, primary studies need to be more consistent in how they collect and report information on financial outcomes (e.g., report gross and net income, and costs per production factor) and agronomic characteristics at the study sites, to enable robust predictions of the costs and benefits of diversification in different contexts. For example, many studies fail to report the amount and type of fertilizers and pesticides applied, tillage practices, and crop species and arrangements, limiting whether and how comprehensively these factors can be considered in synthesis studies.

5. Conclusion

This global meta-analysis provides evidence that, on average, diversified farming systems are at least as profitable as simplified ones. In developing countries, diversification results in significantly higher gross and net financial returns and total costs relative to simplified systems, while in developed countries, profits, gross income, and costs are comparable. Further, our results show that diversified farming systems provide more employment opportunities with no loss of profits. The findings suggest that promoting diversification is a promising strategy for providing sustainable livelihoods for farmers and nutritious diets for households and society alongside contributing to biodiversity conservation and climate mitigation.

Authors' contributions

All authors read and approved the final version of the manuscript. A.C.S. and S.K.J. conceived of the study. All authors contributed to the article search, screening, data entry and validation. A.C.S. designed the methodology, and conducted the analysis. A.C.S. and S.K.J. wrote the first draft of the manuscript. H.N·K and F.G. reviewed and edited the manuscript.

Ethical approval

Not applicable.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107595.

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