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Farming for the future: Understanding factors enabling the adoption of diversified farming systems

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ABSTRACT

Diversified farming practices offer a promising pathway to sustainable food production by providing economic, environmental, and social benefits to farmers and society. However, the factors influencing their adoption are poorly understood, hindering the development of effective promotion strategies.

This study presents a comprehensive global meta-analysis of 154 peer-reviewed studies analysing factors influencing adoption. We examined the effects of 71 factors across nine key categories—biophysical context, farm management characteristics, farmers' attitudes, political and institutional context (access to knowledge, land tenure, financial risk management), and five forms of capital (financial, human, natural, physical, and social)—on the adoption of ten diversified practices in 42 countries across five UN regions.

Our results reveal that access to knowledge, social capital, and farmers' attitudes are key enablers of adoption, surpassing financial, physical, human, and natural capital. Specifically, access to extension services, strong social networks, and perceived environmental benefits significantly correlate with adoption. Land ownership, household income, literacy levels, and shallow soils have smaller positive effects. The influence of these factors varies across practices and geographic contexts, highlighting the complex and multifaceted nature of adoption.

These findings emphasize the need for holistic agricultural initiatives and policies to promote the adoption of sustainable practices. Strategies that build technical knowledge and social capital and that are tailored to local contexts, sociocultural norms, and market structures, considering farmers' perceptions and attitudes through codesign processes, are more likely to succeed. Adaptive and context-specific strategies are crucial for fostering the widespread adoption of diversified farming practices and a more sustainable agricultural future.

1. Introduction

Achieving food security, alleviating rural poverty, mitigating climate change and biodiversity loss require the adoption of agricultural practices that are productive, efficient, and resilient in the long term (Convention on Biological Diversity, 2022; FAO et al., 2023; Mbow, C et al., 2019). Diversified farming systems incorporate a set of agricultural practices that can make it possible to produce food more sustainably by providing economic, environmental, and social benefits to farmers and rural and urban communities (Beillouin et al., 2021; Jones et al., 2023; Sánchez et al., 2022a, 2022b; Tamburini et al., 2020). These diversified systems encompass various agricultural practices that integrate functional biodiversity by growing different species and/or varieties of plants and/or animals at multiple temporal and/or spatial scales, such as agroforestry systems, crop rotations, or integrated crop−livestock systems (Kremen et al., 2012; Rosa-Schleich et al., 2019; Tamburini et al., 2020). Despite the potential of diversified practices to play a key role in the shift to sustainable food production (Dwivedi et al., 2017; Rosa-Schleich et al., 2019), the factors determining their adoption are poorly understood, and non-diversified farming systems still dominate in many agricultural landscapes (Ramankutty et al., 2018).

Efforts to promote the adoption of diversified farming

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practices—defined as the initial uptake, implementation, or continued use of these practices by individuals or groups of farmers—have often relied on standardized rural development strategies involving policies, incentives, or market regulations (European Commission, 2018; Heumesser and Kray, 2019; Leshan et al., 2018). However, the success of such initiatives tends to be hindered by the narrow assumption that farmers' decisions are motivated solely by economic and production benefits, without adequately considering alignment with local contexts and farmers' specific goals (Bell et al., 2023; Brown et al., 2021; Costanza et al., 2017; Guerra et al., 2017).

The adoption of diversified farming practices is influenced by a combination of farmer-specific characteristics and contextual factors, such as sociodemographic, perceptions, land tenure security, market access, and social networks (Bowman and Zilberman, 2013; Chapman et al., 2022; Pannell et al., 2006; Pretty et al., 2020). For example, while social networks and secure land tenure often correlate positively with adoption rates (Blesh et al., 2023; Chapman et al., 2022; Cooreman et al., 2018; Pretty et al., 2020), factors such as credit constraints and labour shortages may act as barriers (Bowman and Zilberman, 2013; Tittonell, 2023). Existing evidence highlights the multifaceted nature of farmer decision-making but often overlooks the complex interplay of these factors, focusing instead on isolated aspects such as political and institutional factors (Piñeiro et al., 2020); socioeconomic, natural, and physical factors (Ruzzante et al., 2021); or behavioural factors (Dessart et al., 2019; Swart et al., 2023). Hence, a comprehensive understanding of these diverse factors is critical for promoting more effective strategies to support and accelerate the adoption of diversified farming practices.

The adoption of diversified farming practices is influenced by factors that vary across geographical regions and types of practices. However, most available reviews are region specific (Arslan et al., 2022; Baumgart-Getz et al., 2012; Ruzzante et al., 2021; Swart et al., 2023), failing to provide a comprehensive understanding of these differences across the globe. Although global reviews exist (Knowler and Bradshaw, 2007; Liu et al., 2018; Sok et al., 2020; Tacconi et al., 2022), they often overlook regional contexts because of their reliance on narrative reviews or vote-counting methods, which lack the statistical power of meta-analyses. Moreover, global reviews often limit their focus to a small subset of diversified farming practices, such as agroforestry, crop rotations, or intercropping, while neglecting systems that integrate animals such as rotational grazing or integrated crop−livestock systems. There is a need for comprehensive statistical syntheses that consider the full range of diversified farming practices and account for regional variations to better understand and promote their adoption.

This study addresses these limitations by conducting a global assessment of 71 factors across nine key categories: biophysical context, farm management characteristics, farmers' attitudes, political and institutional context (access to knowledge, land tenure, financial risk management), and five forms of capital (financial, human, natural, physical, and social) that influence the adoption of diversified practices. Our comprehensive meta-analysis included 154 primary studies reporting factors that influence the adoption of 10 diversified practices (Table 1) across 42 countries in five UN regions. We aimed to (*1*) identify the most important factors that enable or hinder the adoption of diversified farming practices, and (2) understand how the strength of factor−adoption relationships varies across different diversified practices, geographical contexts, farm attributes, farmer demographics, and methodological approaches.

2. Methods

2.1. Literature search

Following the ROSES guidelines for systematic reviews (Haddaway et al., 2017), we conducted a systematic search for peer-reviewed studies published in English that analysed factors that influence the adoption of diversified farming practices. The literature search was guided by the key components of our research questions, using the PIDOC framework (Population, Independent variables (factors), Dependent variables, Outcome, and Context) (Table A.1).

We developed our search strings through an iterative process (see Appendix A: Section A.1). Initially, we compiled relevant search terms of three related systematic reviews (Arslan et al., 2022; Sánchez et al., 2022b; Tacconi et al., 2022), and supplemented this list with additional relevant terms. We then refined the string using a text mining method proposed by Grames et al. (2019) to ensure the inclusion of synonyms and other relevant terms in the final string. At this stage, we manually refined the search string to accommodate variable spellings of some terms (see search strings in Table A.2). The search was conducted in two scientific databases: Scopus (https://www.scopus.com/) and Web of Science (https://apps.webofknowledge.com/), and was last updated on December 6, 2023. No restrictions were set on the year of publication or geographical location of the studies.

Additionally, we systematically extracted a list of 1307 unique studies included in 18 syntheses on related topics (see Table A.3). We identified a total of 12,945 unique potentially relevant studies (Figure A.1; Appendix B: studies_list).

Table 1
Description of the 10 diversified farming practices considered in the analysis.

Diversified practices	Description
Agro-aquaculture	Farming systems including aquatic organisms (e.g., fish, crustaceans) produced together with crops on the same plot of agricultural land (Hasimuna et al., 2023).
Agroforestry	Farming systems that combine woody perennial plant species with annual or perennial crop production on the same plot of agricultural land (Beillouin et al., 2019).
Agro-silvopasture	Farming systems that intentionally combine livestock with woody perennial species, and forage crops, or food crops on the same plot of agricultural land at the same time or in succession (Burgess et al., 2022).
Combined systems	Farming systems that combine individual diversified farming practices such as crop rotation and intercropping, agroforestry and fallow, crop rotation and cover crops.
Cover crops	Farming system where crops are sown in fallow periods to maintain soil moisture, recycle nutrients, control weeds, and reduce soil erosion, but it is not harvested at the end of the growing season (FAO, 2021).
Crop rotation	Farming systems where a set of selected crops grow in recurrent succession in a particular agricultural plot each season or each year according to a definite plan, with all crops being harvested at the end of the growing season (Beillouin et al., 2019).
Embedded natural	Farming systems where crops or non-crop plants are sown or regenerate naturally on land that is not used for farming, aiming to enhance biodiversity, control soil erosion, or improving soil fertility (Sánchez et al., 2022a).
Fallow	Farming systems where the previously cultivated land is left uncultivated for one or more seasons to permit natural vegetation to grow (FAO, 2021).
Intercropping	Farming systems where two or more nonwoody crop species are cultivated simultaneously in the same plot of agricultural land for all or part of their growth cycle. All crops are harvested (adapted from Beillouin et al., 2019).
Rotational grazing	Farming systems where livestock is moved from one field to another to permit forages to regrowth, renew carbohydrate stores, and improve yield and persistency.

2.2. Screening and selection of studies

Screening was conducted in a two-step process (see Section A.2). First, we screened the titles and abstracts of the identified studies through search strings, selecting 908 studies that met our inclusion criteria. In the second step, we reviewed the full texts of these studies, as well as those identified through related syntheses. We included only studies that met the following inclusion criteria: i) reported empirical results based on data from primary or secondary field-based studies (e.g., panel country data or regional databases); ii) analysed the relationship between factors and the adoption of diversified farming practices using binary multivariable regression models (i.e., 1 = adoption, 0 = non-adoption) with at least two factors considered simultaneously; and iii) reported regression coefficients, significance statistics (e.g., standard error, *p*-value, *t*-value), and sample sizes from multivariable regression models (see selection criteria in Table A.4).

In this meta-analysis, '*adoption*' refers to the process by which farmers initially take up, implement, or choose to maintain diversified farming practices over time. *Diversified farming practices* are agricultural management practices that intentionally incorporate functional biodiversity by growing different species and/or varieties of plants and/or animals at multiple temporal and/or spatial scales (Kremen et al., 2012; Rosa-Schleich et al., 2019; Tamburini et al., 2020). We categorized the identified diversified practices into 10 broad categories, as outlined in Table 1. While most practices fit naturally into these categories, some assumptions were made due to limited information. For example, we classified home gardens and alley cropping as agroforestry practices, despite their variability in design and tree−crop integration. We also acknowledge that practices such as crop rotation can vary greatly in intensity—ranging from two to several crops—but such details were often not provided in the primary studies.

We excluded studies focused on the adoption of on-farm crop diversification that did not specify specific temporal, horizontal, or vertical arrangements (e.g., Skarbø, 2014); those analysing livelihood strategy diversification (e.g., Nguyen et al., 2020); and those that did not clearly define the practice assessed. After the screening and selection processes, a total of 154 studies satisfied all the inclusion criteria (Fig. A.1; Table A.5).

2.3. Data extraction and reclassification

We extracted qualitative and quantitative data from the texts, tables, figures, or supplementary information of the studies that met our inclusion criteria (see Section A.2 for more details). When studies reported results from separate models for the adoption of different diversified farming practices, time points, and/or locations, we extracted data from all models and assigned each one a unique identifier (model_id). For each model, we extracted data on the diversified farming practices analysed, the type of multivariable model used (e.g., probit, logit, other), the sampling method, the number of samples, the number of factors, and the location of assessment (i.e., village, country). In total, we extracted data from 245 models.

The included models examined the effect of a wide range of factors on adoption, often using nonstandard unit metrics. For each factor, we recorded its definition, unit metric, regression coefficient, and significance statistic (e.g., *p*-values, *t*-values) (see Appendix B: meta_data). After data extraction, we reclassified the factors and standardized their definitions and unit metrics through conversions and adjustments (see Section A.3). Following this process, only the most frequently studied factors with comparable units were retained for synthesis, as a sufficient number of observations was required for the meta-analysis. The final database used for analysis included information on the effects of 71 factors (see Table A.6), with each model analysing between 1 and 22 of the retained factors. These factors were grouped into nine key categories based on the sustainable livelihood framework (Tambe, 2022; UNDP, 2017) and behaviour theories (Dessart et al., 2019).

2.4. Effect size calculation

We chose the partial correlation coefficient (r_p) as the effect size because it enables comparisons across studies using different regression models (e.g., probit, logit, other) and different metrics to analyse factors (e.g., farm size in hectares or in logarithmic hectares). The partial correlation coefficient is a unitless effect size that quantifies the magnitude and direction of the association between two variables, controlling for the effects of other variables (Stanley and Doucouliagos, 2012).

We calculated the partial correlation coefficient and its corresponding standard error using the "PCOR" measure in the *escalc* function of the *metafor* R package (Viechtbauer, 2010) (see Section A.4). This function requires the *t*-values, number of samples, and number of factors included in the model as inputs. When *t*-values were not directly reported by the studies, we derived them from the available data (see Appendix C: R code). Meta-analysis on r_p can introduce bias due to violations of the assumption of normality in the distribution of effect sizes (Van Aert, 2023). This bias can be reduced by converting r_p values to Fisher's z values prior to analysis (Van Aert, 2023). We therefore transformed the effect sizes from r_p to Fisher's z using the equations in Section A.4, meta-analysed the Fisher's z effect sizes, and then transformed the results back to r_p (Van Aert, 2023). A partial correlation coefficient ranges from −1 to 1, where values greater than zero suggest that the analysed factor had a positive influence on adoption, whereas values lower than zero indicate a negative influence. Following Doucouliagos's (2011)suggestion, we considered partial correlations of 0.07, 0.17, and 0.33 to represent small, moderate, and large effects, respectively.

2.5. Meta-analyses

We ran meta-analytical models to estimate the effect of each factor (i.e., the 71 factors retained) on the adoption (relative to non-adoption) of diversified farming practices. The general form of the models was as follows:

$$Y_{ij} = \mu + B_1 X_{ij} + b_i + \varphi_{ij} + \varepsilon_{ij} \quad \text{(Eq. 1)}$$

with $b_i \sim N(0, \tau^2),\ \varphi_{ij} \sim N(0, \upsilon^2)$, and $\varepsilon_{ij} \sim N(0, \sigma_{ij}{}^2)$

where $\boldsymbol{Y_{ij}}$ is the *j*th effect size of the *i*th study, $\boldsymbol{\mu}$ is the estimated overall mean effect size, $\boldsymbol{\beta_1}$ is the slope coefficient for moderator $\boldsymbol{X_{ij}}$, $\boldsymbol{X_{ij}}$ is the moderator at study *i*th for the *j*th effect size, $\mathbf{b_i}$ is the random study effect, $\boldsymbol{\varphi_{ij}}$ is the random effect size within the *i*th study, $\boldsymbol{\varepsilon_{ij}}$ is the random estimation error associated with the *j*th effect size of the *i*th study (i.e., the sampling error), $\boldsymbol{\tau^2}$ is the between-study variance, $\boldsymbol{\nu^2}$ is the between effect size variance and $\boldsymbol{\sigma_{ij}}^2$ is the variance of the *j*th effect size estimated effect size of the ith meta-study.

First, we determined the optimal random structure of each model by comparing three-level (Eq. 1) and two-level (Eq. 1 without the within-study random effect - φ_{ij}) **models.** The three-level meta-analytical model considers the potential statistical dependence across effect sizes from the same study (López-López et al., 2018). In contrast, the two-level model treats each effect size as independent, ignoring these possible dependencies. **The best model was selected based on** the Akaike Information Criteria (AIC) and Likelihood Ratio Test (LRT). The two-level model showed a better fit for 59 factors, whereas the three-level structure was favourable for the remaining 12 factors (see Table A.7). Optimal models were then used to estimate the mean overall effect of each factor on the adoption of diversified farming practices. No moderators (i.e., $\boldsymbol{\beta 1\, Xij}$ term) were included for these comparisons.

The models were fitted using the functions *rma. mv* from the R package *metafor* with the restricted maximum-likelihood (REML) method (Viechtbauer, 2010). For the two-level models, we applied *the "knha"* method (Knapp and Hartung, 2003) to calculate 95% confidence intervals, whereas the *t*-distribution was used for the three-level models.

We checked the normality assumption of the effect size residuals (Wang and Bushman, 1998). The heterogeneity (i.e., the amount of variability - I^2) was detailed at the sampling ($I^2_{(1)}$) and non-sampling ($I^2_{(2,\ 3)}$) levels of variance for the two-level models, and at the sampling ($I^2_{(1)}$), within studies ($I^2_{(2)}$) and between studies ($I^2_{(3)}$) levels of variance for the three-level models (Table A.8) (Cheung, 2014).

We applied single meta-regression models (i.e., models with moderator effects, i.e., **β1 Xij**) to examine whether the following 11 variables moderated the overall effect of factors on adoption: diversified practices, geographic regions and subregions according to the United Nations (UN, 1998), farmers' years of formal education, farm size (ha), and methodological characteristics of the included studies (i.e., number of factors included in the model, year of assessment, sampling unit, sampling methods, data source, and model type) (Table A.9). The meta-regression models were applied only to factors with at least 10 effect sizes and more than 75% unexplained variation at the non-sampling variability level ($I^2_{(2,\ 3)}$) (see Table A.8) (Borenstein, 2009). The importance of moderators in explaining the variance in overall effects was assessed using omnibus tests based on the *F*-distribution.

2.6. Publication bias and sensitivity analysis

We used funnel plots to detect publication bias, indicated by asymmetry in the distribution of effect sizes (Borenstein, 2009). To statistically test for funnel plot asymmetry, we applied an adapted version of Egger's regression test, using the inverse of the standard error of effect sizes as a moderator (Habeck and Schultz, 2015). A significant deviation of the intercept from zero in Egger's regression suggests the potential presence of publication bias (Egger et al., 1998). Additionally, we performed a trim and fill analysis when possible, as the *metafor* R package only supports this method for two-level models (Viechtbauer, 2010). We therefore applied the trim-and-fill method to factors showing signs of publication bias in the two-level models. This method estimates an overall effect '*without*' publication bias by imputing missing effect sizes to correct funnel asymmetry (Duval and Tweedie, 2000).

We compared the mean overall effects using the partial correlation coefficient (r_p) and log-odds ratio (log-OR) effect sizes as part of a sensitivity analysis. The log-odds ratio effect size can only be calculated for regression coefficients from studies using logit or probit multivariable models with consistent definitions of dependent variables and factors (1709 effect sizes from 151 studies) (see Fig. A.1 and Table A.6). We calculated log-OR effect sizes (see Section A.4), performed a meta-analysis of the log-ORs, and then transformed the results into odds ratios (ORs) (Borenstein, 2009).

3. Results and discussion

3.1. Data distribution

Our meta-database includes 2106 effect sizes from 154 peer-reviewed studies conducted in 42 countries across 5 regions (Fig. 1a). Most effect sizes were from Africa (64%), followed by Asia (18%) and North America (13%), whereas Europe (3%) and Latin America (2%) were the least represented regions (Fig. 1b). The most studied factor categories were human capital (34%), political and institutional context (18%) and financial capital (11%), whereas physical capital (5%) and farm management characteristics (1.3%) were the least studied (Fig. 1b). The representation of diversified farming practices in our meta-database was dominated by agroforestry (26%) and crop rotation (25%), followed by intercropping (14%). The least studied practices were fallow (3%), rotational grazing (1%), and integrated agro-aquaculture systems (0.7%) (Fig. 1b).

3.2. Overall determinants of the adoption of diversified farming practices

Of the 71 factors analysed (see Table A.6 for factor descriptions), 14 significantly influenced the overall adoption of diversified farming practices at the 95% confidence level (Figs. 2–4). Factors related to access to knowledge, social capital, and farmers' attitudes were the most important determinants, whereas factors related to physical capital, farm management characteristics, and financial risk management had no significant impact. These results were robust against publication bias and sensitivity analyses (Section A.5).

3.2.1. Embracing knowledge access, social networks, and attitudes for adoption

Access to technical knowledge was positively correlated with the adoption of diversified farming practices, with three out of four factors showing significant effects despite wide confidence intervals (Fig. 2a). The frequency of extension service occurrence ($rp = 0.3$; 95% CI [0.03–0.52]; $p = 0.03$) emerged as the main driver of adoption. Access to extension services ($rp = 0.09$; [0.01–0.17]; $p = 0.03$) and training programs ($rp = 0.06$; [0.02–0.1]; $p = 0.004$) also contributed positively, although with smaller effects.

Social interactions and networking had a positive influence on adoption through multiple pathways. Membership in collective structures ($r_p = 0.1$; [0.01–0.2]; $p = 0.02$), communication among farmers ($r_p = 0.07$; [0.02–0.11]; $p = 0.005$) and having more relatives and friends living nearby ($r_p = 0.02$; [0.001–0.03]; $p = 0.03$) were all positively associated with the adoption of diversified farming practices (see Fig. 2b).

These findings highlight the importance of access to technical knowledge and strong social networks in driving the adoption of diversified farming practices. Extension services and training programs are pivotal in disseminating agricultural knowledge, directly benefitting participants and generating positive spillover effects within rural communities through social networks (Yang and Ou, 2022). However, many countries face challenges in providing extension services due to reductions in public service funding (Yang and Ou, 2022). Modernizing extension and training strategies to allow digital reach (e.g., video calls, chat groups) may provide an affordable solution (Fabregas et al., 2019; Norton and Alwang, 2020), but further research is needed to confirm their effectiveness alongside face-to-face interactions. Moreover, communication among farmers fosters knowledge cocreation and enhances the adoption and diffusion of sustainable agricultural practices through sharing experiences and learning (Cooreman et al., 2018). Connected and cohesive social networks can facilitate adoption by enabling capacity-building, resource exchange, cooperation and trust among farmers and rural communities (Niles et al., 2021).

Finally, farmers' attitudes played a significant role in adoption despite being understudied (<10 studies per factor) (Fig. 2c). Productivist attitudes toward agriculture had a negative effect on adoption ($rp = -0.03$; [−0.04–0.023]; $p = 0.0008$), whereas environmental attitudes had a positive but not significant effect ($rp = 0.12$; [−0.13–0.35]; $p = 0.3$). Farmers who perceived environmental benefits from sustainable practices presented significantly greater adoption rates ($rp = 0.07$; [0.02–0.11]; $p = 0.01$), whereas risk-averse attitudes slightly hindered adoption ($rp = -0.05$; [−0.09–0.01]; $p = 0.01$). Our findings highlight and confirm the importance of better understanding farmers' perceptions and preferences when fostering adoption (Coe and Coe, 2023; Swart et al., 2023; Thompson et al., 2023). This better understanding of the local context can help tailor education, knowledge sharing, advertising, and rewards to help reverse negative attitudes by emphasizing the productivity and resilience benefits that diversified practices can offer (Bowman and Zilberman, 2013; Rosa-Schleich et al., 2019). Tailoring information is a relatively low-cost and potentially high-impact strategy to accelerate sustainable farming transitions (Dessart et al., 2019).

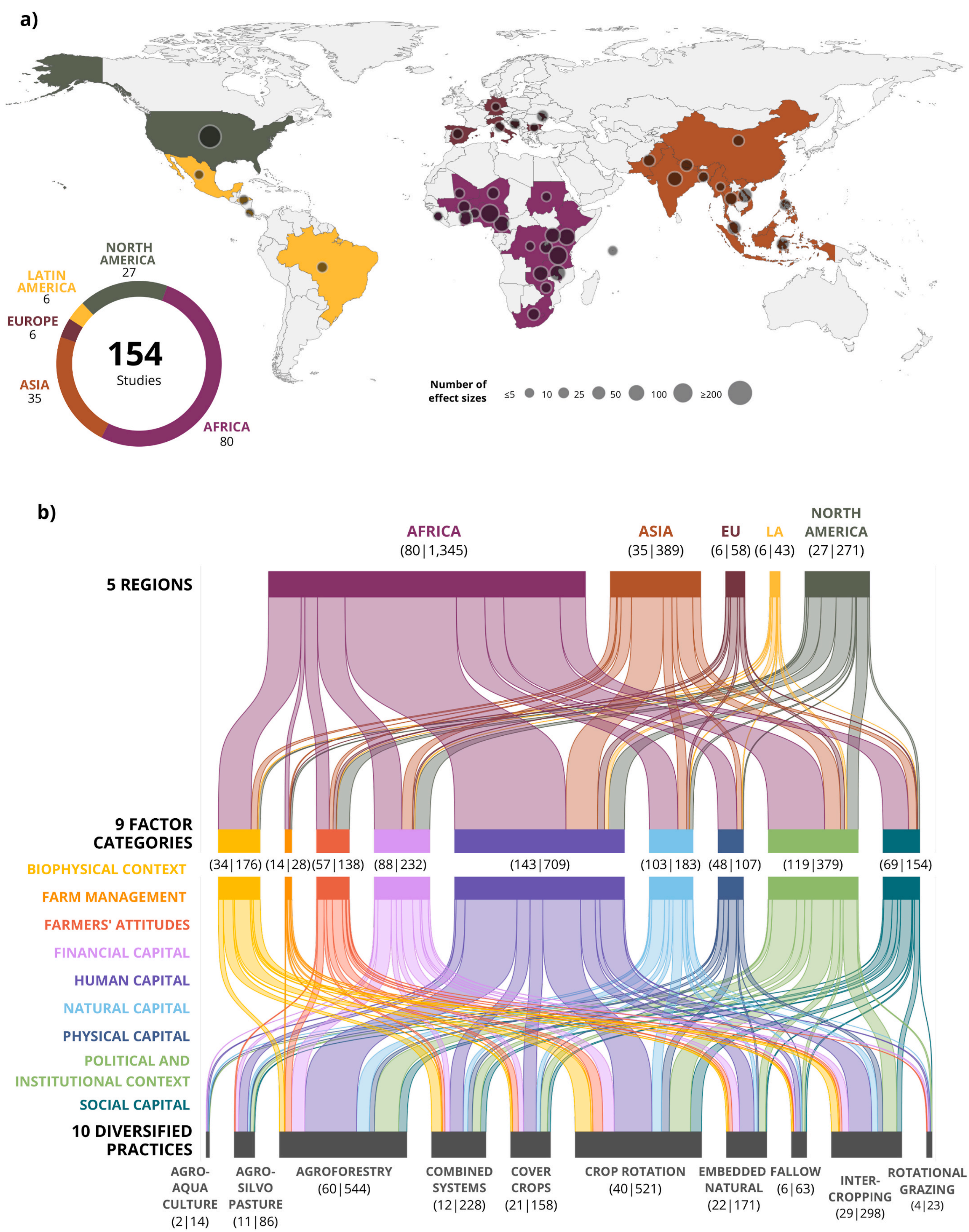

Fig. 1. Data distribution of included studies and effect sizes a) across 42 countries and 5 regions, and b) across 5 regions, 9 factor categories, and 10 diversified farming practices. The numbers in parentheses represent the number of studies | effect sizes.

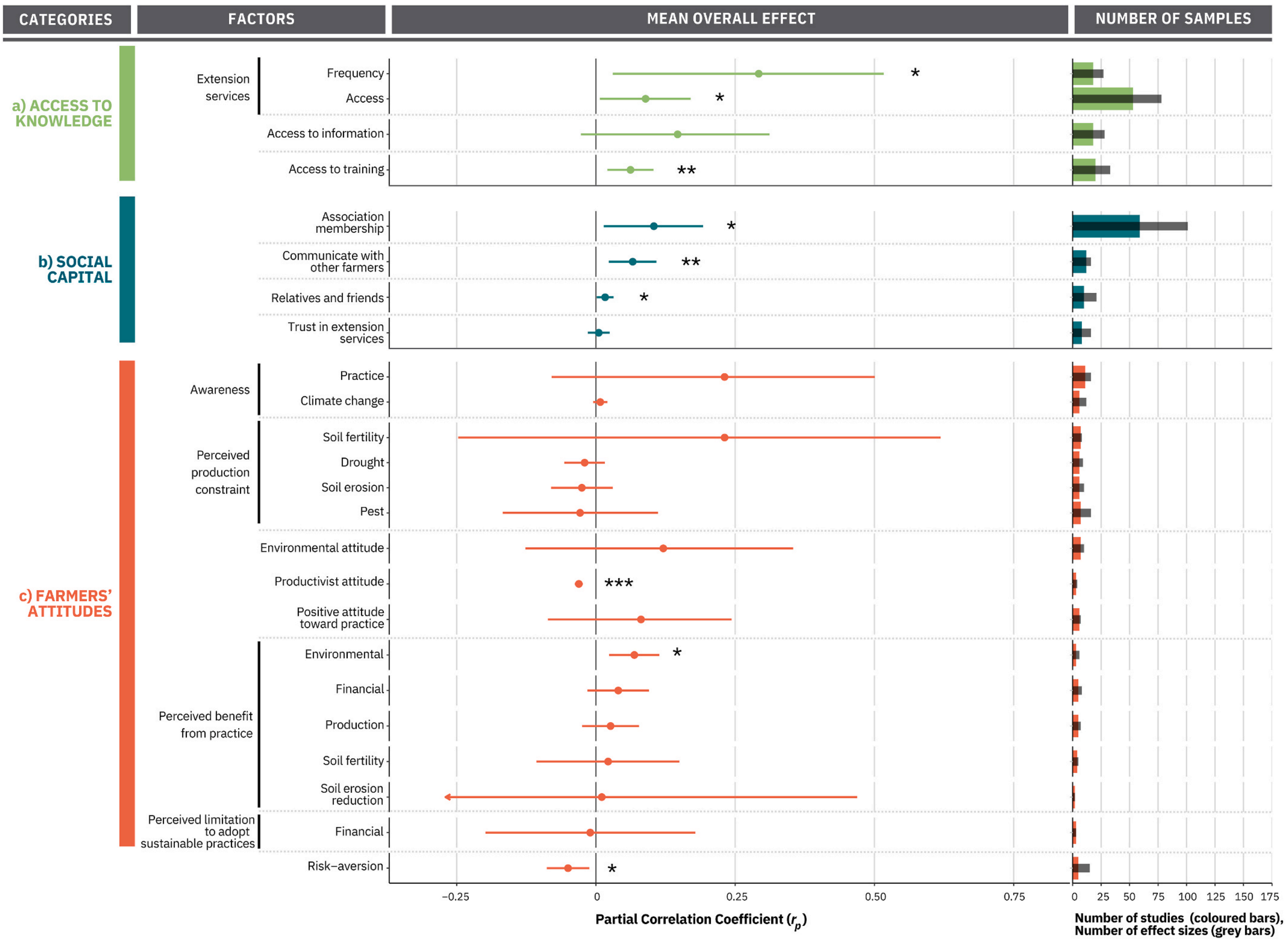

Fig. 2. Mean overall effect of factors related to a) access to knowledge, b) social capital, and c) farmers' attitudes on the adoption of diversified farming practices. Points and lines in the main plot represent the mean effect size and 95% confidence intervals, respectively. The effect sizes are expressed as partial correlation coefficients (r_p). Thus, the positive influences on adoption are denoted by $r_p > 0$, while the negative influences are denoted by $r_p < 0$. The statistical significance of the mean overall effects is denoted as $***p \leq 0.001$; $**p \leq 0.01$; and $*p \leq 0.05$. The bar plots on the right side of the main plot represent the number of primary studies for each factor (coloured bars) and the number of effect sizes included in the model (grey bars). The colours of points, lines and bars represent the category of each factor. Some factors included in the farmers' attitudes category may have limitations due to analytical approaches and data availability (see Table A.6 for details).

3.2.2. Land tenure and certain biophysical, natural, human and financial capital factors also matter

Farmers with secure land tenure had a large but non-significant positive correlation with the adoption of diversified farming practices ($rp = 0.6$; $[-0.01–0.086]$; $p = 0.054$) (Fig. 3a). A small yet significant positive effect was observed among farmers with more owned land ($rp = 0.05$; $[0.03–0.08]$; $p = 0.0003$), whereas land ownership status had a small non-significant positive effect ($rp = 0.1$; $[-0.03–0.22]$; $p = 0.1$). Conversely, rented land status ($rp = -0.02$; $[-0.05–0.01]$; $p = 0.2$) and area of rented land ($rp = 0.02$; $[-0.03–0.07]$; $p = 0.4$) had minimal and non-significant effects.

These results emphasize the importance of land ownership size in incentivizing sustainable agricultural land management (Arslan et al., 2022; Chapman et al., 2022; Ruzzante et al., 2021). The included studies focused mainly on the effect of land ownership or rented land on adoption, flagging large knowledge gaps concerning other land tenure types (e.g., customary rights, freeholds, etc.). Considering the widespread lack of clarity in tenure arrangements worldwide and the negative effects of land tenure formalization on communities and land degradation in certain contexts (Meyfroidt et al., 2022), careful attention is needed when developing policies to foster adoption through clarified tenure rights. Policies, therefore, should account for traditional and local stakeholders' needs, safeguard traditional landholders' rights, and ensure equitable access to land and resources (Lokhandwala, 2022; Putzel et al., 2015).

Other factor categories, such as biophysical context, and natural capital, had only a few factors significantly associated with adoption. For instance, biophysical factors like relatively shallow soils ($r_p = 0.04$; $[0.01–0.06]$; $p = 0.01$) might foster adoption (Fig. 3b), potentially in view of protecting or restoring ecosystem functions and services (Kremen et al., 2012; Rosa-Schleich et al., 2019). In contrast, farmers managing more plots tended to adopt less frequently diversified farming practices ($r_p = -0.04$; $[-0.08–0.005]$; $p = 0.03$) (Fig. 3c). Implementing and monitoring complex and diversified agricultural practices may indeed be challenging when managing multiple plots (Merot and Wery, 2017).

Our synthesis indicated a small positive effect of farmers' literacy ($r_p = 0.05$; $[0.003–0.09]$; $p = 0.04$) on adoption (Fig. 4a). These results emphasize the importance of comprehensive rural policies and initiatives that prioritize access to formal education to accelerate the transition to sustainable agriculture and empower rural households (OECD, 2022; Quisumbing et al., 2021). Similarly, total household income had a

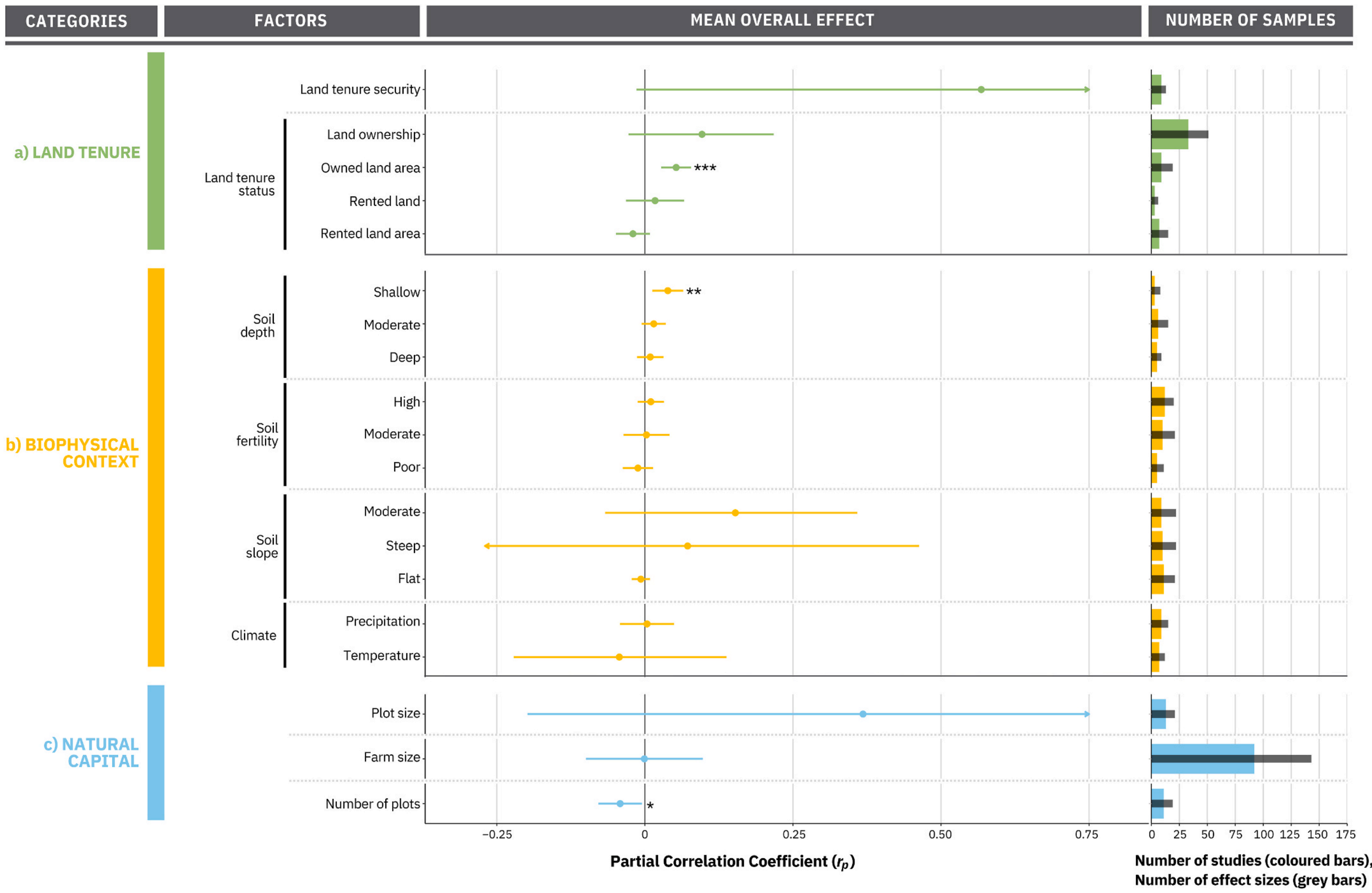

Fig. 3. Mean overall effect of factors related to a) land tenure, b) biophysical context, and c) natural capital on the adoption of diversified farming practices. Points and lines in the main plot represent the mean effect size and 95% confidence intervals, respectively. The effect sizes are expressed as partial correlation coefficients (r_p). Thus, the positive influences on adoption are denoted by $r_p > 0$, while the negative influences are denoted by $r_p < 0$. The statistical significance of the mean overall effects is denoted as $***p \leq 0.001$; $**p \leq 0.01$; and $*p \leq 0.05$. The bar plots on the right side of the main plot represent the number of primary studies for each factor (coloured bars) and the number of effect sizes included in the model (grey bars). The colours of points, lines and bars represent the category of each factor. Some factors included in the land tenure status and biophysical context categories may have limitations due to analytical approaches and data availability (see Table A.6 for details).

small positive influence on adoption ($r_p = 0.04$; [0.02–0.07]; $p = 0.001$) (Fig. 4b), highlighting the importance of higher and more stable incomes for supporting the adoption of sustainable agricultural systems (Arslan et al., 2022; Liu et al., 2018).

3.2.3. Factors not significantly associated with the overall adoption of diversified farming practices

Financial instruments, such as access to credit ($r_p = -0.05$; [−0.18–0.09]; $p = 0.5$) and receiving incentives for conservation ($r_p = 0.05$; [−0.03–0.13]; $p = 0.2$), had a non-significant effect on adoption (Fig. 4c). However, these strategies are frequently targeted by donors and projects for promoting sustainable agriculture (e.g., GIZ, 2023, IKI, 2024; Porras and Asquith, 2018). There are success stories from around the world regarding the use of financial incentives for promoting sustainable agricultural practices (Drucker and Ramirez, 2020; Nath et al., 2023; Wunder et al., 2008), so these interventions can work under the right conditions. Hence, it is essential to carefully consider the interests of farmers, their attitudes, and the social, natural, and physical contexts when codesigning financial strategies for promoting behavioural change (Brown et al., 2021; Piñeiro et al., 2020). As our study indicates, the effect of these financial risk-management factors on the adoption of diversified practices requires further investigation to fully understand their impact across sociopolitical and ecological contexts. The limited studies on incentives in our database may reflect a broader reliance on qualitative methods over multivariable regression models to analyse their impact on the adoption of diversified farming practices.

Diversified farming systems are potentially central to climate change adaptation and mitigation (Heumesser and Kray, 2019; Tittonell, 2023), yet we found weak evidence of climatic conditions (e.g., temperature, precipitation–Fig. 3b) driving adoption. The studies included in our synthesis assessed climatic factors in different ways, using methods such as farmers' perceptions, actual climate data, or agroecological zone classification. In addition, only a few studies in our database considered adoption in response to actual or modelled extreme event exposure. Implementing standardized methods for characterizing climatic conditions in adoption research would greatly enhance understanding of the role of present and projected climatic conditions in the adoption of diversified farming practices.

Demographic characteristics, such as age, gender, household size, and marital status, showed no significant effect on diversified practices adoption (Fig. 4a), aligning with previous research (Liu et al., 2018; Ruzzante et al., 2021; Tacconi et al., 2022; Thompson et al., 2021). These non-significant effects may be due to the oversimplification in studies that often analyse the relationship between demographic characteristics and adoption considering only their linear relationships (Burton, 2014). Investigating the mechanisms through which demographic factors influence behaviours towards the adoption of agricultural practices would greatly contribute to developing sustainable agricultural strategies that are inclusive for women, less-educated farmers, and marginalized groups.

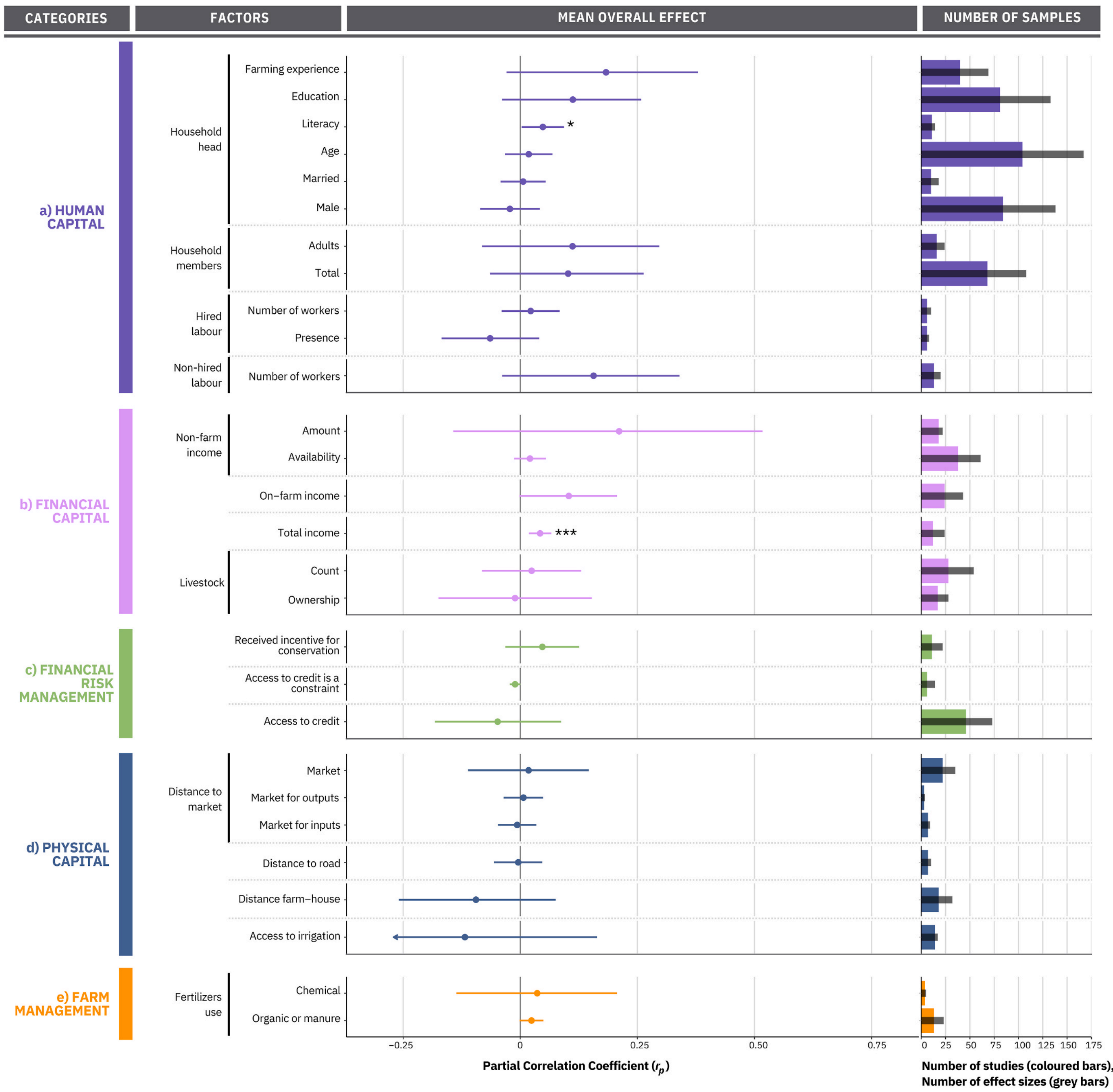

Fig. 4. Mean overall mean effect of factors related to a) human capital, b) financial capital, and c) financial risk management, d) physical capital, and e) farm management characteristics on the adoption of diversified farming practices. Points and lines in the main plot represent the mean effect size and 95% confidence intervals, respectively. The effect sizes are expressed as partial correlation coefficients (r_p). Thus, the positive influences on adoption are denoted by $r_p > 0$, while the negative influences are denoted by $r_p < 0$. The statistical significance of the mean overall effects is denoted as $***p \leq 0.001$; $**p \leq 0.01$; and $*p \leq 0.05$. The bar plots on the right side of the main plot represent the number of primary studies for each factor (coloured bars) and the number of effect sizes included in the model (grey bars). The colours of points, lines and bars represent the category of each factor. Some factors included in human and physical capital may have limitations due to analytical approaches and data availability (see Table A.6 for details).

Finally, none of the physical capital factors (e.g., distance to market or to farm-household–Fig. 4d) and farm management characteristics (i.e., the use of chemical or organic fertilizers–Fig. 4e) were significantly associated with the adoption of diversified farming practices.

3.3. Important moderators in the factor-adoption relationship

We investigated the moderating effect of 11 variables on the intensity and direction of factor-adoption relationships for a subset of 38 factors (see Section 2.5). Diversified practices (Section 3.3.1) and geographic subregions (Section 3.3.2) were the most important variables, moderating the effects of 26% (10 out of 38) and 29% (11 out of 38) of the factors, respectively (Fig. A.4). Methodological characteristics of the studies (e.g., number of predictors, use of primary data, year of assessment), farm size, and years of formal education were the least important, moderating the effects of only one to six factors (Fig. A.4 and A.5). This underscores the robustness of our overall results against variations in study methodology, farmers with different education levels, and those operating on farms with different sizes.

3.3.1. Factors driving adoption vary across diversified practices

Factors influencing adoption varied across diversified practices (Fig. A.6), with the adoption of some practices driven by factors that were not identified as influential when practices were considered together (Section 3.2).

Access to knowledge significantly promoted the adoption of 5 out of the 10 practices (Fig. 5). Extension services positively influenced the adoption of cover crops (access and frequency), agroforestry (access), and embedded natural systems (frequency). Access to training supported the adoption of agroforestry and combined practices, while access to information facilitated intercropping adoption. Social capital factors positively influenced adoption, particularly for agroforestry (association membership, communication with other farmers) and crop rotation (relatives and friends). However, the effects of farmers' attitudes varied by practice, with perceiving pests as a production constraint negatively impacting intercropping adoption, and increased practice awareness positively influencing crop rotation adoption.

In contrast to the overall results, financial capital, particularly non-farm income, facilitated the adoption of cover crops (amount), and fallow systems (amount), whereas on-farm income and livestock count supported embedded natural systems. Human capital factors positively impacted the adoption of cover crops (total number of household members, farming experience, number of non-hired workers), agroforestry (education), and crop rotation (adult household members). In contrast, access to credit hindered cover crop adoption, whereas factors related to the biophysical context (temperature, moderate soil fertility, moderate soil slope), natural capital (farm size, plot size), and physical capital (distance from farm to house, distance to market) had varied effects across different practices.

None of the analysed factors significantly influenced the adoption of diversified practices integrating animals (i.e., agro-aquaculture, agrosilvopasture, and rotational integration) (Fig. A.6).

3.3.2. Factors driving adoption vary across geographic contexts

Our meta-regression analyses revealed variations in factors influencing the adoption of diversified farming practices across geographic regions and subregions. Among the 38 factors, 10 consistently had a non-significant effect across the five UN regions (Fig. A.7) and 14 subregions (Fig. A.8), regardless of the number of effect sizes.

Access to knowledge significantly promoted adoption in Latin America, Africa and Asia, with regional variations in the specific drivers. (Fig. 6). In Latin America, access to extension services and land tenure security were critical, with additional positive effects from higher soil slopes, non-hired labour availability, and farmer age. In Africa, frequent extension services, access to training, and social networks (communication with other farmers, relatives and friends) positively influenced adoption. In Asia, adoption was positively influenced by access to information and moderate soil slopes.

In Europe, awareness of practices emerged as a primary driver, emphasizing the importance of properly communicating their benefits to overcome perception biases and promote adoption (Dessart et al., 2019). Conversely, none of the studied factors significantly influenced adoption in North America (Fig. A.7). Previous reviews identified financial capital, social capital, and perceived benefits, as key influences on adoption in the USA (Baumgart-Getz et al., 2012; Prokopy et al., 2019; Smith et al., 2021), but these findings were not supported by our results at the regional or sub-regional levels. Prokopy et al. (2019) and Smith et al. (2021) relied on vote-counting methods, while Baumgart-Getz et al. (2012) reviewed a broader range of practices than our study did, which may explain some differences in the results. Regardless, further localized research is needed to understand adoption in the USA, where political–economic structures may heavily influence farmers' decisions to diversify (Blesh et al., 2023).

Subregional analyses highlighted consistent positive associations between human capital factors and adoption in Western Africa (total household members, education, and farming experience), Central America (farmer age, non-hired workers), Southern Asia (adult household members), and Eastern Asia (non-hired workers) (Fig. A.8). In Western Africa, adoption was also positively associated with non-farm income and land ownership, whereas natural capital (farm size, plot size) and physical capital (distance from farm to house, access to irrigation) showed mixed effects. These findings underscore the importance of investing in human capital, enhancing skills, knowledge and capabilities to support the transition to diversified farming practices in these regions (Arslan et al., 2022; Ruzzante et al., 2021).

Environmental attitudes positively influenced adoption in Eastern Europe and North America but had a negative effect on adoption in Southern Europe. Previous research has similarly demonstrated that positive environmental attitudes can serve as a strong motivator for the adoption of diversified practices in certain regions (Brown et al., 2021; Ranjan et al., 2019). In Southern Europe, the lower adoption rates despite environmental attitudes may reflect conflicting local priorities with respect to farming system benefits, such as a preference for farming practices with lower labour requirements, or market demands favouring the mass purchase of single commodities (Papadopoulos, 2015). Additionally, conservation incentives had a positive effect on adoption in Southern Europe but a negative impact in Southern Asia. This last finding emphasizes the importance of considering contextual geographical differences when assessing the effectiveness of financial support strategies for promoting sustainable agriculture (Piñeiro et al., 2020).

Finally, the regional and subregional results from Latin America, Europe, and North America are constrained by a limited number of studies, highlighting the need for quantitative research to deepen our understanding of the factors driving adoption in these contexts. These gaps may be partially closed in future research that expands our search to non-English literature, e.g., to include studies in Spanish and Portuguese from Latin America.

4. Conclusion

Policymakers, businesses, and communities are becoming increasingly aware of the importance of transitioning to and maintaining existing sustainable farming practices. Understanding the factors that drive farmers to move toward or away from these practices is key to designing effective incentives and enabling their adoption. This study represents the most comprehensive global meta-analysis to date of the factors influencing the adoption of ten diversified farming practices, incorporating 2106 effect sizes from 154 studies. Three main messages emerge.

First, our results demonstrate the critical role of access to technical knowledge, strong social networks, and farmers' attitudes in driving adoption, while highlight the limited effectiveness of finance-based mechanisms in certain regions. Effective strategies for scaling up adoption should prioritize the dissemination of agricultural knowledge and provide support through tailoring extension services and training. Leveraging social networks to facilitate farmer-to-farmer learning, trust, and capacity building, along with positive, locally meaningful communication strategies, can ease scepticism and promote the acceptance of diversified practices.

Second, we found that farmers' decisions to adopt diversified farming practices were weakly linked to land ownership, household income capacity, farmers' literacy, and marginal soils. These first three factors create structural barriers that must be dismantled to allow farmer willingness, knowledge, and human capital to lead to increased adoption. Hence, progress towards sustainable farming requires investments in education to equip farmers with the skills and knowledge needed to adopt diversified practices. This could empower them to break poverty cycles, diversify income sources, and gain self-confidence to contribute to local governance and decision-making processes. These initiatives are

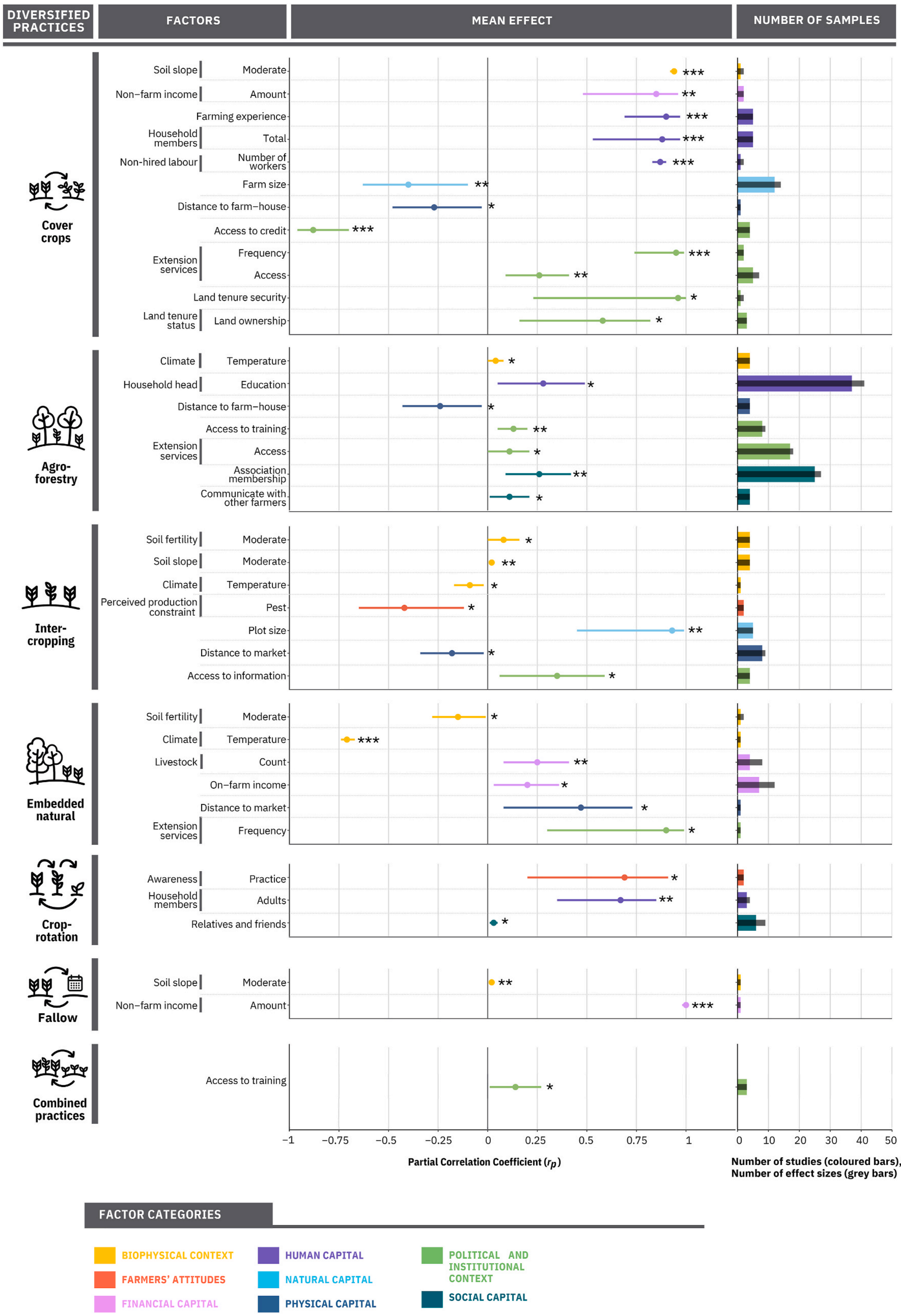

Fig. 5. Mean effect of factors significantly influencing adoption across diversified practices. Points and lines on the main plot represent the mean effect size and 95% confidence intervals, respectively. Effect sizes are calculated as partial correlation coefficients (r_p); hence, the positive effects of factors on adoption are denoted by $r_p > 0$, while the negative effects are denoted by $r_p < 0$. The statistical significance of the effects is denoted as $^{***}p \leq 0.001$; $^{**}p \leq 0.01$; and $^{*}p \leq 0.05$. The bar plots on the right side of the main plot represent the number of primary studies for each factor for that diversified practice (coloured bars) and the number of effect sizes included in the model (grey bars). The colours of points, lines and bars represent the category of each factor. Agro-aquaculture, agro-silvopasture, and

rotational grazing were excluded from this figure since none of the analysed factors significantly influenced their adoption; see the results for those practices in Fig. A.6.

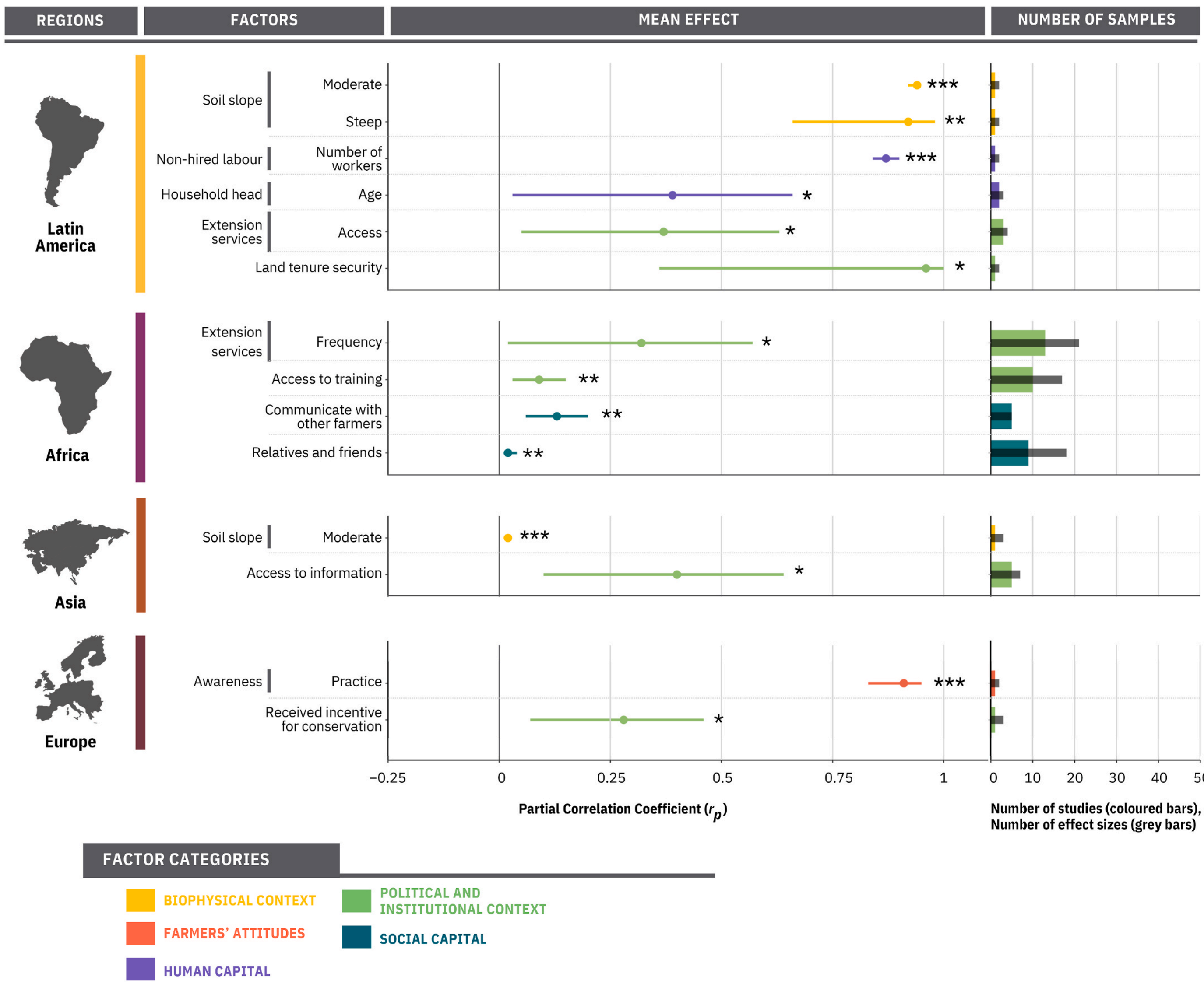

Fig. 6. Mean effect of factors significantly influencing adoption across geographical regions. Points and lines of the main plot represent the mean effect size and 95% confidence intervals, respectively. Effect sizes are calculated as partial correlation coefficients (r_p); hence, the positive effects of factors on adoption are denoted by $r_p > 0$, while the negative effects are denoted by $r_p < 0$. The statistical significance of the effects is denoted as $***p \leq 0.001$; $**p \leq 0.01$; and $*p \leq 0.05$. The bar plots on the right side of the main plot represent the number of primary studies for each factor for that diversified practice (coloured bars) and the number of effect sizes included in the model (grey bars). The colours of points, lines and bars represent the category of each factor. North America was excluded from this figure since none of the analysed factors significantly influenced adoption in this region; see the results for this regions in Fig. A.7.

particularly important for women and other marginalized groups. The influence of soil characteristics on adoption suggests that diversified practices may gain greater acceptance in areas with less productive land; therefore, these areas could be targeted to accelerate uptake.

Third, the variable influence of factors on adoption across practices and regions highlights the need for locally tailored adoption incentives that consider the complex interplay of local biophysical conditions, policies, farmer values, and resources. Co-designing adoption incentives with local farmers and land managers will help address local concerns and priorities, improving the chances of success. However, the uneven distribution of studies highlights critical knowledge gaps in some regions (notably Europe, Latin America, and North America), as well as for some diversified practices (particularly fallow, agro-aquaculture, and rotational grazing) and factor categories (such as farmers' attitudes, physical capital, farm management characteristics, and political and institutional context). These gaps mean that our findings should be interpreted with caution in poorly represented contexts. Closing these knowledge gaps in data-sparse contexts is central to supporting the design of effective incentives or policies that enable sustainable food system transitions.

Finally, our meta-analysis provides a robust quantitative assessment of the factors influencing the adoption of diversified farming practices. Future in-depth qualitative research can help to disentangle farmers' views, preferences, needs and bottle necks for adopting sustainable practices. Integrating qualitative and quantitative evidence can advance adoption theory while uncovering contextualized and complex factor-interactions which are often difficult to capture in large-scale meta-analyses but needed to accelerate sustainable transitions in agriculture.

CRediT authorship contribution statement

Andrea Cecilia Sánchez Bogado: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Natalia Estrada-Carmona:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization. **Damien Beillouin:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization. **Cecile Chéron-Bessou:** Writing – review & editing, Supervision, Conceptualization. **Bruno Rapidel:** Writing – review & editing, Supervision, Methodology. **Sarah K. Jones:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2024.100820.

Data availability

The meta-data and R code are provided as supplementary materials.

Global database of factors influencing the adoption of diversified farming practices (Reference data) ()

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