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REVIEW

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Response of cereals to intercropping with non-food crops in tropical and subtropical regions: A meta-analysis

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Abstract

Intercropping cereals with non-food intercrops (NFICs) provides a means to enhance cereal productivity while providing additional benefits such as improved soil health or forage production. We conducted a meta-analysis to investigate the effect of NFICs on cereal yields, cereal nitrogen uptake, and striga (*Striga* spp.) infestation, using 874 observations from 97 peer-reviewed studies across tropical and subtropical regions. Results showed that maize (*Zea mays* L.) grain yield increased by 7% and decreased by 10% when intercropped with Fabaceae and Poaceae, respectively, compared to sole cropping. Sorghum (*Sorghum bicolor* (L.) Moench.) grain yield was significantly reduced by an average of 47% under intercropping with Fabaceae NFICs (mostly perennial woody species) compared with sole cropping, likely due to competition for nutrients, light, and particularly water, as most sorghum trials included in this review were conducted under semi-arid climatic conditions. In general, higher rainfall and higher soil organic matter content increased the performance of intercropping relative to sole cropping. Performing intercropping for multiple consecutive years favored positive yield responses. NFICs had limited effect on nitrogen content in cereal biomass. *Striga* density in maize fields was significantly reduced (−130%) under intercropping with *Desmodium* spp. compared to sole cropping. Overall, intercropping maize with Fabaceae NFICs emerges as a promising strategy for enhancing maize yields in tropical and subtropical regions, though its effectiveness depends on factors such as NFIC category and climate. While caution is warranted when intercropping sorghum with perennial Fabaceae NFICs in semi-arid climates, the limited number of published studies on sorghum intercropping with annual Fabaceae NFICs suggests that further investigation is warranted.

Abbreviations: CGY, cereal grain yield; ES, effect size; NFIC, non-food intercrop; SOM, soil organic matter.

Plain Language Summary

Intercropping cereals with non-food intercrops can provide multiple benefits in terms of food or feed supply or soil health improvement. This meta-analysis examines the yield, cereal nitrogen nutrition, and pest control benefits of such intercropping systems based on 97 studies from 17 countries in tropical and subtropical regions. Results showed that intercropping with non-food intercrops can be beneficial for maize yields depending on the non-food intercrop family, rainfall, initial soil quality, or length of experimentation. On the contrary, sorghum yields are, on average, negatively affected by intercropping, likely due to competition for water as sorghum is mainly cultivated in drier areas. *Striga* density was significantly reduced in maize fields intercropped with *Desmodium* spp. These findings highlight the benefits of intercropping maize with non-food Fabaceae intercrops for improving yields and managing pests in tropical and subtropical regions.

1 | INTRODUCTION

Land degradation is one of several barriers to achieving long-term global food security in agriculture (Beddington et al., 2012; Godfray et al., 2010). Tropical and subtropical regions are particularly affected because they include a high proportion of low- and middle-income countries, where limited access to financial resources, technical capacity, extension services, and agricultural inputs often restricts the adoption of effective soil conservation and sustainable land management practices, thereby increasing vulnerability to land degradation (AbdelRahman, 2023). Loss of soil organic matter (SOM), nutrient mining, soil acidification, and soil erosion by wind and water are among the major causes of soil degradation in these regions (Lal, 2005), thereby significantly impairing the productive capacity of tropical and subtropical soils (Brown et al., 1994; Lal, 2015).

Various approaches have been promoted to reduce land degradation and increase the sustainability of crop production (Rodriguez et al., 2020), including diversification of cropping systems, which encompasses intercropping practices (Kremen & Miles, 2012; Shennan, 2008). Intercropping is defined as the cultivation of at least two or more crop species simultaneously in the same field for the whole or a part of their growing period (R. W. Willey, 1990). In the tropics, smallholder farmers often intercrop due to the multiple nutritional, agronomic, and environmental benefits that intercropping provides (Lithourgidis et al., 2011; Matusso et al., 2014). The diversification of crops in an intercropping system increased resilience against pests and diseases, as well as better yield stability in the face of climate variability (Brooker et al., 2015; Lithourgidis et al., 2011; Stomph et al., 2020). It has also been shown that intercropping systems increase soil carbon stocks (Chapagain & Riseman, 2014; W. Cong, Hoffland, Li, et al., 2015; W. F. Cong, Hoffland, Li, Janssen, et al., 2015; Dyer et al., 2012; Oelbermann et al., 2015), reduce runoff and soil erosion (Ijaz et al., 2007; E. A. R. Pinheiro et al., 2013; N. K. Sharma et al., 2017), improve soil microbial diversity (Maitra & Ray, 2019), and enhance nutrient availability to crops (Lai et al., 2022; Meena et al., 2020; R. C. Sharma & Banik, 2015; Tittonell, 2023; Y. Wang & Lambers, 2020; R. Willey, 1979).

One of the most common intercropping systems is the combination of cereals with food legumes such as cowpea (*Vigna unguiculata* (L.) Walp.) or soybean (*Glycine max* (L.) Merr.). Besides the abovementioned advantages, such associations enhance soil fertility through restitution of biologically fixed nitrogen, thereby reducing the need for synthetic fertilizers (Fustec et al., 2010; Giller, 2001). These benefits are particularly significant for smallholder farmers in tropical and subtropical regions, where access to external inputs is often limited (Snapp et al., 2010). These cereal–food legume intercropping systems have been extensively investigated in the literature. There is a large corpus of primary studies, as well as systematic reviews and meta-analyses, that have synthesized the impacts of cereal–food legume intercropping systems on cereal yield (e.g., C. Li et al., 2020; Mudare et al., 2022; Raseduzzaman & Jensen, 2017; Yu et al., 2016; Zhu et al., 2023), nutrient use efficiency (e.g., Jensen et al., 2020; Tang et al., 2021; Xu et al., 2020), land use efficiency (e.g., Feng et al., 2021; Xu et al., 2020), and weed suppression (e.g., Gu et al., 2021). This body of literature highlights the relevance and effectiveness of cereal–food legume intercropping systems in sustainable agriculture, particularly in the tropics.

In tropical and subtropical regions, non-food (i.e., not primarily grown for direct human consumption) intercrop legumes, particularly annual forage species, can be grown by smallholder farmers as a pasture in monocropping, but when intercropped with cereals, they may also serve as a green manure and provide biomass for soil cover and/or serve as animal feed (Ceccon et al., 2013; Crusciol et al., 2015; Manoj et al., 2021; Naudin et al., 2012; Pereira, 2016; Tittonell et al., 2015). In maize (*Zea mays* L.)- or sorghum (*Sorghum bicolor* (L.) Moench.)-based systems, these annual forages are typically sown simultaneously with the cereal or relay-planted shortly after cereal establishment, and their biomass is grazed or cut after cereal harvest, ensuring that the main food crop is not compromised (Sarto et al., 2021). In addition to annual fodder crops, tree legumes (also generally non-food intercrops [NFICs]) have been intercropped with cereals in agroforestry systems, where their high biomass production makes them an important source of green manure and mulch (Jose, 2009; Nair, 2012).

However, NFICs are not restricted to legumes. Several non-leguminous species, mainly grasses from the Poaceae family (e.g., *Brachiaria brizantha*), are also commonly intercropped with cereals in tropical and subtropical regions to improve soil health and provide dry-season fodder (Mateus et al., 2020; Sarto et al., 2021; L. F. N. Souza et al., 2023). Whether leguminous or not, NFICs supply a suite of ecosystem services highly relevant to low-input smallholder systems, including reducing water and wind erosion, enhancing soil physical, chemical, and biological functioning, increasing soil organic carbon, facilitating nutrient cycling, suppressing weeds, and contributing to yield stability—especially in regions with marked rainfall seasonality or high precipitation (Baligar & Fageria, 2007; Poeplau & Don, 2015; Quintarelli et al., 2022). Furthermore, intercropping cereals like maize and sorghum with specific species of NFICs (e.g., *Brachiaria brizantha* and *Desmodium intortum*) has been shown to reduce pests such as stem borers (*Chilo partellus* and *Busseola fusca*) and the parasitic weed striga (mainly *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze) (Khan et al., 2000, 2002, 2010; Midega et al., 2015). These multiple benefits help explain the interest in cereal–NFIC systems in tropical and subtropical smallholder agriculture.

Primary studies on cereal–NFIC systems have focused on assessing their effects on cereal grain yield (CGY) (Baldé et al., 2020; Borges et al., 2022; de Queiroz et al., 2016; Dzvene et al., 2022; Rodriguez et al., 2021), forage production (Borghi et al., 2013; Kichel et al., 2019; Santos et al., 2020), nitrogen accumulation in the associated cereal plants (Ahmed et al., 2020; Canisares et al., 2021; Deienno et al., 2021; S. S. D. Souza et al., 2022; Zhao et al., 2020), microbial biomass and nutrient cycling (Coser et al., 2016; Oliveira et al., 2019), as well as on weed, striga (*Striga* spp.), and other pest control (Araújo et al., 2021; Asmare et al., 2022; D'Amico-Damião et al., 2020; Midega et al., 2010, 2013, 2014; Pokharel et al., 2023). However, despite this apparent abundance of primary research, outcomes reported across studies often remain inconsistent, particularly regarding yield responses and nitrogen benefits under contrasting management practices and environmental conditions (Daryanto et al., 2020; Rusinamhodzi et al., 2012). These inconsistencies, combined with persistent uncertainty about potential trade-offs between cereal yield, nitrogen-use efficiency, and biological control of striga, highlight the need for a quantitative synthesis that jointly captures the agronomic and ecological effects of cereal–NFIC systems.

Core Ideas

- Maize grain yield increases when associated with non-food Fabaceae intercrops but decreases with Poaceae intercrops.
- Sorghum yield is negatively affected by intercropping with non-food Fabaceae and Poaceae.
- Maize and sorghum yield response to intercropping is strongly dependent on climatic conditions.
- Positive maize yield responses to intercropping emerge only after three or more consecutive years of implementation.
- *Striga* density in maize fields is reduced under intercropping with *Desmodium* spp.

To our knowledge, no previous meta-analysis has jointly quantified the effects of cereal–NFIC systems on cereal yield, nitrogen accumulation, and striga suppression across tropical and subtropical regions (Dossa et al., 2023; Lai et al., 2022). Addressing this gap is essential because a consolidated evidence base could strengthen decision-making for sustainable intensification, optimization of nitrogen inputs, and improved weed and parasitic plant management in resource-constrained farming systems. Accordingly, this study aims to provide a quantitative synthesis of the effects of NFICs on cereal yields, nitrogen content in cereal biomass, and striga infestation in cereal–NFIC intercropping systems in tropical and subtropical regions and to assess how these effects are mediated by management and environmental factors. We considered two main research questions: (i) What are the effects of NFIC family, period of NFIC sowing, type of intercropping system, climate, soil texture, tillage method, and fertilization rate on cereal yield and cereal nitrogen content in cereal–NFIC systems compared to sole cropping of cereals? (ii) Do cereal–NFIC systems reduce striga infestation? *Striga* infestation was specifically addressed in this study because it remains one of the most serious biotic constraints to cereal production in the tropics (Sibhatu, 2016; Teka, 2014).

2 | MATERIALS AND METHODS

2.1 | Literature search and selection criteria

The present study focused on the following three rainfed cereal crops: maize (*Zea mays* L.), sorghum (*Sorghum* *bicolor* (L.) Moench.), and millet (*Pennisetum glaucum* (L.) R.Br.). The PRISMA (preferred reporting items for systematic reviews and meta-analyses) methodology for systematic reviews was used to select articles. A literature search of peer-reviewed articles (last updated on November 26, 2024) was performed using the Scopus database. The research was limited to the agricultural and environmental sciences subject area and articles published in English. No restriction was applied to the publication year. Two search queries were applied to the title, abstract, and keyword fields. The following search terms were used to identify studies on cereal–NFICs:

(maize OR corn OR sorghum OR millet) AND …
(intercrop* OR associa* OR push-pull OR companion) AND …
(cover*crop* OR "cover crop" OR *crotalaria**OR *mucuna* OR *canavalia* OR *stylosanthes** OR *centrosema* OR *desmodium** OR *pueraria* OR *macroptilium* OR *tephrosia** OR *lablab* OR *clitoria* OR *aeschynomene* OR *calopogonium* OR *trifolium* OR *pennisetum** OR *panicum** OR *chrysopogon* OR *brachiaria** OR *cenchrus* OR *setaria* OR *andropogon* OR *chloris* OR *digitaria* OR *imperata* OR *urochloa** OR *melinis*).

After applying these first search terms, we observed that several woody legume species commonly used in cereal-based intercropping systems were not adequately captured. Therefore, an additional search term was used to specifically include woody species:

(maize OR corn OR sorghum OR millet) AND …
(agroforestry OR alley* OR *albizia** OR *chamaecytisus* OR *cratylia* OR *gliricidia* OR *leucaena* OR *sesbania** OR *indigofera** OR *flemingia* OR *atylosia** OR *faidherbia* OR *calliandra* OR *prosopis** OR *acacia** OR *moringa* OR *tephrosia* AND *vogelii* OR pigeonpea OR *cajanus**)

This meta-analysis focuses on NFICs. The term "non-food intercrop" is used here to refer to species whose main purpose is generally not human nutrition when grown as intercrops but rather to serve as animal feed, to supply nitrogen (legumes), to mitigate soil degradation processes, to improve soil health, or to control pest and disease. Food production may, however, be a co-benefit of some of these crops. Even though pigeon pea (*Cajanus cajan*) is widely consumed as a grain legume when grown in monoculture under management practices optimized for seed yield (Saxena, 2008), it was intentionally included in the present meta-analysis based on its functional role rather than its food status when grown as intercrop. Indeed, its use in cereal-based intercropping systems in tropical and subtropical regions is primarily agroecological, where it functions as a cover or alley crop providing ecosystem services and minor food production (Akchaya et al., 2025; Akinnifesi et al., 2010; Chamkhi et al., 2022; Garland et al., 2017). In such systems, pigeon pea is typically managed for high biomass production and biological nitrogen fixation, with a relatively low harvest index (0.17) compared to sole cropping, making grain production secondary or negligible (Chamkhi et al., 2022; Kuyah et al., 2022). Therefore, the inclusion of *Cajanus cajan* in this meta-analysis is consistent with a functional definition of cover crops, aligned with the agroecological literature that classifies intercrops according to their role in the system rather than their potential food use in other production contexts (Quintarelli et al., 2022; Snapp et al., 2005).

A total of 2652 articles were identified from the database for both equations. After screening article titles, abstracts, and full texts, 97, 10, and 7 articles were retained with 764, 40, and 70 observations for CGY, nitrogen content in cereal total biomass, and striga infestation in cereal plots, respectively. Cereal nitrogen content was used in the meta-analysis rather than total nitrogen uptake, because the latter is highly correlated with (biomass) yield. Nitrogen content in aboveground cereal biomass is expected to be a better indicator of the nitrogen nutrition benefits derived from associations with NFICs. Nitrogen content (kg of nitrogen per kg of biomass) was calculated as the ratio of reported nitrogen uptake (kg of nitrogen per ha) to aboveground biomass (kg ha^{-1}). An article was selected when meeting the following selection criteria: (1) the study was performed in tropical and subtropical regions (between latitude 40° N and 40° S; Corlett, 2013); (2) the results are from experiments on maize, sorghum, or millet crops; (3) the latter crops were intercropped with an NFIC; (4) data are provided with (treatment) and without (control) an intercropped NFIC; (5) the same rates of nitrogen, phosphorus, and potassium fertilizers are applied to the control and the treatment; and (6) the sowing density of the cereal crop is the same in the control and the treatment. Equal density is essential for two reasons. From a methodological perspective, the calculation of effect sizes (ESs) in meta-analyses (see further, Equation 4) requires equal baseline conditions. This ensures that observed effects can be attributed to NFICs rather than to confounding differences in cereal planting density. Furthermore, although NFICs in tropical and subtropical smallholder farming systems may provide benefits such as livestock feed or minor food products, maintaining cereal plant density remains a priority for farmers, as cereal yield is their primary production objective (food provisioning). Articles that reported data from pot and glasshouse experiments were excluded from this review.

2.2 | Data collection

2.2.1 | Data extraction and processing

Statistical measures (mean, standard deviation [SD], standard error (SE), standard error of the difference, coefficient of variation (CV), and *p*-value) were extracted from the tables and figures of the selected articles. When data were presented in a figure format, we used Engauge Digitizer software version 12.1 (Informer Technologies, Inc. https://engauge-digitizer.software.informer.com/) to extract the data. When the SD was not provided in an article, it was computed from the SE (Equation 1) or from the CV (Equation 2) if provided in the articles.

$$SD = \frac{SE}{\sqrt{\frac{1}{n_c} + \frac{1}{n_t}}} \tag{1}$$

where n_c and n_t are the number of replicates of the control and treatment, respectively.

$$SD = CV \times \bar{X} \tag{2}$$

where $\bar{X}$ is the mean.

In some articles, no measure of variability was reported. In such cases, we estimated the missing SDs using Equation (3) (Lajeunesse et al., 2013).

$$SD_j = \bar{X}_j \left(\frac{\sum_{i=1}^{k} SD_i}{\sum_{i=1}^{k} \bar{X}_i} \right) \tag{3}$$

where SD_j and $\bar{X}_j$ are the SD and mean, respectively, of observation j with missing SD; SD_i and $\bar{X}_i$ are the SD and mean, respectively, of the k observations with complete information. Among the 764 and 40 observations considered for grain yield and nitrogen content, SD had to be estimated for 263 and 19 observations, respectively. All observations related to striga infestation provided SD.

The following moderator variables were encoded because they are likely to affect the response variables and are either provided in most articles or can be estimated via alternate data sources: (a) cereal type, (b) soil texture, (c) climate, (d) tillage method, (e) NFIC in association, (f) period of intercrop sowing, (g) intercropping system, AND (h) fertilization rates (nitrogen, phosphorus, and potassium).

2.2.2 | Cereal type, NFIC category, and sowing period

Cereal type refers to maize, sorghum, and millet. NFICs intercropped with cereals were grouped into two families: Fabaceae and Poaceae. No other families were reported in the selected studies. Fabaceae were split into different categories depending on whether they are annual or perennial and herbaceous or woody intercrops. All Poaceae species were perennial herbaceous. We also considered three classes for the timing of NFIC sowing: before the main crop was sown (with growth extending into the main crop's growing season), at the same time as the main crop, or after the main crop was sown (but during the main crop's growing season).

2.2.3 | Intercropping system, NFIC sowing density, and number of intercropping years

Two intercropping systems were distinguished for this study: alley intercropping and row intercropping. Alley intercropping consists in sowing the main crop in-between hedgerows of perennial NFICs (often leguminous trees and shrubs). Row intercropping consists of sowing NFICs either in-between rows of the main crop or in the same row in-between plants of the main crop. No distinction could be made between the latter two systems due to insufficient data. Also, there was no indication of a difference between these two types of intercropping systems based on available data. NFIC sowing densities were directly extracted from articles, with corrections applied for viable seeds in the case of Poaceae provided in the articles. The number of consecutive years of intercropping at the same site was also retrieved from the articles.

2.2.4 | Climate and rainfall

When provided, climate was harmonized according to the Köppen–Geiger climate classification (Geiger, 1961). When climate was not reported in an article, the information was extracted from the Köppen–Geiger climate classification maps at 1 km resolution (Beck et al., 2018; Spinoni et al., 2015), respectively. The selected studies encompassed the following climate classes: tropical rainforest (Af), tropical monsoon (Am), tropical wet and dry (Aw), tropical semi-arid hot (BSh) and cold (BSk), subtropical monsoon (Cwa), subtropical humid (Cfa), subtropical highland (Cwb), and warm Summer Mediterranean (Csb). These were grouped into three classes: A, tropical moist (Af, Am, and Aw); B, semi-arid tropical (BSh and BSk); and C, subtropical (Cwa, Cfa, Cwb, and Csb). Annual precipitation from the WorldClim database (https://worldclim.org/data/monthlywth.html) at the spatial resolution of 2.5 min (~21 km at the equator) was used for the linear regressions. The rainfall amount during the experimental years of each study was then considered.

2.2.5 | Soil characteristics

Soil texture was extracted either directly from the selected articles or from the online SoilGrids250m 2.0 website (https://soilgrids.org/). Soil textures were grouped into three classes, based on the USDA textural soil classification (Allakonon et al., 2022; Ouedraogo et al., 2020; Tonitto & Ricker-Gilbert, 2016): light soils (sandy, sandy loam, loamy sand, and sandy clay loam), medium soils (loamy, silt loam, and sandy clay), and heavy soils (clay, clay loam, silt, silt clay, and silt clay loam). SOM content was retrieved from the articles when reported.

2.2.6 | Fertilizer type

We attempted to analyze the effect of fertilizer type (nitrogen, phosphorus, potassium, nitrogen + phosphorus, and nitrogen + phosphorus + potassium) and rate of application. However, given that the studies included in this review were conducted across a wide range of tropical and subtropical climatic conditions and a wide range of soil types, with fertilizer application rates specific to each area, it proved impossible to draw definitive conclusions about the effects of fertilizer composition or rates on cereal yields. These results are therefore not presented.

2.3 | Statistical analyses

2.3.1 | Variables, ESs, and variances

Three response variables were considered in this meta-analysis: CGY expressed in tonne per hectare, nitrogen content in cereal total aboveground biomass (including leaves, stems, and grains) expressed in kg of nitrogen per kg of total biomass and striga pest infestation (expressed as the density of striga plants per ha). The ESs were estimated as the natural logarithm of the ratio of a given response variable in the cereal intercropping treatment over the same response variable in the corresponding cereal monocropping treatment (Equation 4).

$$\text{ES} = \ln\left(\frac{\bar{X}_t}{\bar{X}_c}\right) \quad (4)$$

where $\bar{X}_t$ is the mean value of the response variable for the intercropping treatment and $\bar{X}_c$ is the mean value of the response variable of the control. ES can be greater, equal, or smaller than 0 depending on whether $\bar{X}_t$ is greater, equal, or smaller than $\bar{X}_c$.

Finally, the sampling variances (σ^2(ES)) were estimated using Equation (5) as described in Benítez-López et al. (2017).

$$\sigma^2\,(\text{ES}) = \frac{\text{SD}_t^2}{n_t \bar{X}_t^2} + \frac{\text{SD}_c^2}{n_C \bar{X}_c^2} \quad (5)$$

2.3.2 | Meta-analysis

The statistical analysis of this meta-analysis was computed using the "metafor" package (Viechtbauer, 2010) in R Version 4.2.3. A random-effects model was used to merge the studies' ESs, to compute the pooled ESs, and to assess the effect of moderator variables on the yield, nitrogen content, and striga infestation. This choice was made a priori, assuming that true ESs differ across studies because they were conducted in diverse agroecological contexts, cropping systems, and management conditions. The objective was therefore to estimate the mean of a distribution of effects rather than a single common effect. This approach was further supported by the observation of statistically significant between-study heterogeneity. We quantified the between-study heterogeneity of true ESs by means of the p-value associated with the heterogeneity test (Cochran Q; $p < 0.05$ indicates significant heterogeneity of ESs among studies or groups of studies) and using Higgins and Thompson's I^2 values (Higgins & Thompson, 2002). I^2 values are between 0% and 100%. A value of $I^2 > 50\%$ indicates between-study heterogeneity of ESs (Borenstein et al., 2009).

We used forest plots in this meta-analysis to synthesize the pooled studies' outcomes (Borenstein et al., 2009). Forest plots sub-meta-analysis was performed for each moderator variable level. We present each ES with a diamond whose bounds correspond to the 95% confidence interval (CI). The vertical discontinuous line (ES = 0) represents the line of no effect, that is, the response of intercropping treatments equals that of the control treatments. The ES for a given factor is considered significant whenever the 95% CI of the ES does not cross the line of no effect.

2.3.3 | Linear regression analysis

Linear regression with mixed-effects model (function lme in the nlme package; J. Pinheiro et al., 2012) was performed with a CI of 95% in R software. We used the ES of CGY as a response variable to evaluate the relationship with NFIC density, duration of intercropping experiment at the same site, annual rainfall (at the experiment years), and SOM content. The homogeneity of variances and normal distribution of the residuals were checked using a Q–Q plot of residuals in R (function qqnorm.gls {nlme}). Regression diagnostics (leave-one-out deletion) were performed with the cooks.distance function to assess the influence of individual points (Cook's distance > 0.5) on each linear model.

2.3.4 | Publication bias

Rosenthal's test was used to assess for a possible publication bias (Benítez-López et al., 2017; Pittelkow et al., 2015). Rosenthal's fail-safe number (Nfs) indicates the number of (missing) studies (observations) with mean null result that would be required to "nullify the mean ES," that is, a mean ES not significantly different from 0 (Adu et al., 2018; Egger et al., 1997). Publication bias results were also assessed using funnel plots (Figure S1). Publication bias in CGY, nitrogen content, and striga infestation were first evaluated through visual analysis of the distribution of the ES (symmetric or asymmetric distribution within the inverted funnel plot). However, as the funnel plots showed asymmetry, suggesting the possible presence of publication bias (Figure S1; Doleman et al., 2020), we used an improved method of testing the significance of the intercept using Egger's regression test (Egger et al., 1997).

The results of Egger's regression test show that the estimate of the intercept of the regression model for nitrogen content and striga infestation was not significantly different from zero ($p > 0.05$), indicating a symmetric distribution of these ESs. However, Egger's regression test indicates an asymmetric distribution of ESs for CGY ($p < 0.05$). As the occurrence of publication bias is not the only possible cause of an asymmetric distribution (Callot & Paldam, 2011), we calculated Rosenthal's fail-safe numbers (Nfs). Based on this, no publication bias was found for CGY and striga infestation, as the Nfs were statistically significant ($p < 0.05$). In fact, the calculated Nfs of the two ESs far exceeded the corresponding threshold ($5 \times n + 10$) required to consider the mean ES as robust (Table S1).

3 | RESULTS

3.1 | General characteristics of the dataset

The 874 cereal–NFIC observations that form the basis for the present study spanned across South America, Africa, and Asia. However, 75% of these observations came from just three countries: Brazil ($n = 269$), Kenya ($n = 188$), and India ($n = 118$) (Figure 1).

The majority of the 70 articles focused on maize–NFIC systems, with 547, 33, and 64 observations recorded for yield, nitrogen content, and striga infestation, respectively (Table S2; Figure 2). Sorghum–NFIC data were derived from 29 articles, contributing 217, 7, and 6 observations for yield, nitrogen content, and striga infestation, respectively. Only one article (with four observations) reported millet–NFIC systems. As a result, millet–NFIC systems will not be further discussed.

In maize cropping systems, the most frequently reported NFIC genus (n = number of observations) was *Brachiaria* [$n = 99$; three species (*ruziziensis*, *brizantha*, and *humidicola*)], followed by *Desmodium* [$n = 75$; four species (*intortum*, *uncinatum*, *pringlei*, and *sandwicense*)], *Lablab* [$n = 67$; one species (*purpureus*)], *Cajanus* [$n = 64$; one species (*cajan*)], *Crotalaria* [$n = 61$; three species (*juncea*, *spectabilis*, and *ochroleuca*)], *Gliricidia* [$n = 54$; one species (*sepium*)], and *Leucaena* [$n = 35$; one species (*leucocephala*)] (Table S2). For sorghum, *Leucaena* [$n = 87$; one species (*leucocephala*)] was the most common NFIC genus, followed by *Brachiaria* [$n = 37$; three species (*ruziziensis*, *brizantha*, and *decumbens*)], *Cajanus* [$n = 28$; one species (*cajan*)], *Gliricidia* [$n = 14$; one species (*sepium*)], and *Albizia* [$n = 10$; one species (*lebbeck*)] (Table S2). For both maize and sorghum, the studies encompassed species from the nitrogen-fixing Fabaceae family as well as species from the Poaceae family (Table S2). In the Fabaceae family, annual herbaceous, perennial herbaceous, and perennial woody species have been used in cereal–NFIC systems. In the Poaceae family, all species were of the perennial herbaceous type (Table S2).

3.2 | Effect of cereal crop type and NFIC category

On average, the grain yield of maize was not significantly affected by intercropping with NFIC compared to sole cropping, while the grain yield of sorghum was significantly lower (−39%) in intercropping compared to sole cropping (Figure 2A). Because of the large and significant difference in ES between maize and sorghum, these two crops are hereafter analyzed separately.

For maize, grain yield decreased by 10% with Poaceae NFICs but increased by 7% with Fabaceae NFICs compared to sole cropping (Figure 2A). The contrast is even starker when comparing the Poaceae (all of which are herbaceous perennial) with herbaceous perennial Fabaceae, which increased yield by 42% compared to sole cropping. Within the Fabaceae family, maize yield decreased by 15% for annual species but increased by 18% when intercropped with perennial species. For the perennial Fabaceae, the ES was significantly larger for herbaceous species (+42%) compared to woody species (+10%).

In the case of sorghum, yield reductions were observed for both NFIC families on average, although the negative impact on yield was strongest with Fabaceae (Figure 2A). Sorghum yield decreased by 15% on average when intercropped with Poaceae, yet by 47% when associated with Fabaceae. The majority of Fabaceae species intercropped with sorghum were woody (155 observations; 91%), *Leucaena leucocephala* (87 obs.), *Cajanus cajan* (28 obs.), *Gliricidia sepium* (14 obs.),

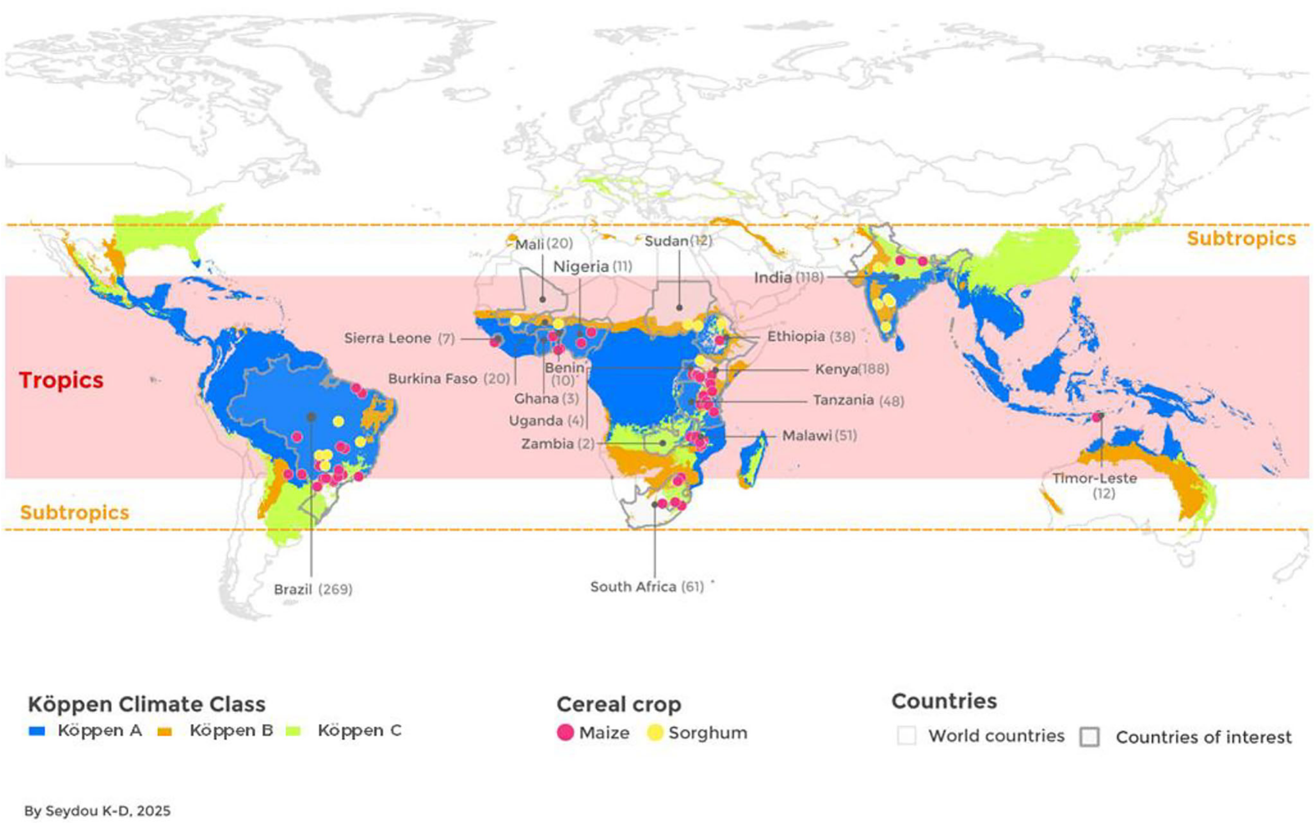

FIGURE 1 The geographical distribution of the experimental sites included in the meta-analysis. Only studies located in the tropics and subtropics between latitude 40° N and 40° S were considered. The numbers associated with each country are the total number of recorded observations. "Countries of interest" refers to countries where studies on non-food intercrops (NFICs) were reported. Köppen climate classes are also indicated. Köppen A = Af, Am, and Aw; Köppen B = BSh and BSk; Köppen C = Cwa, Cfa, Cwb, and Csb.

and *Albizia lebbeck* (10 obs.) being the most frequent. Very few studies addressed the association of sorghum with herbaceous Fabaceae NFICs. Only one article (six observations) addressed the association of sorghum with annual Fabaceae, and only two articles (nine observations) reported on perennial herbaceous Fabaceae NFICs. This was deemed too low to draw robust conclusions.

Nitrogen content in aboveground cereal biomass was generally not significantly affected by NFICs (Figure 2B). The only exception pertains to sorghum intercropped with woody Fabaceae, which resulted in a significant increase in cereal nitrogen content by 17% compared to sole cropping (Figure 2B). However, the number of studies and observations reporting nitrogen content in sorghum are low ($n = 7$, from two studies) and hence this result should be interpreted with great caution.

Intercropping with perennial Fabaceae led to a significant reduction in *Striga* density, by 119% in maize plots and by 287% in sorghum plots (Figure 2C). In 97% of the striga-related observations, the associated NFIC was *Desmodium spp*. Results regarding sorghum should, however, be interpreted with great caution since the number of studies is low ($n = 6$, from two studies).

3.3 | Effect of NFIC sowing period, intercropping system, and tillage type

Results showed that the timing of NFIC sowing had no significant effect on maize grain yield compared to sole cropping (Figure 3A). For sorghum, sowing NFICs before or at the same time as the main crop caused a strong reduction in yield ES, whereas delayed sowing of NFICs resulted in yields similar to those of sole cropping. However, the latter result is based on only 5 observations and therefore lacks robustness. There was no significant difference in yield ES when NFICs are sown before or at the same time as the main crop. For both maize and sorghum, alley intercropping did not differ significantly from row intercropping (Figure 3A). For both aboveground nitrogen content and striga infestation, the reported observations did not allow comparisons between different sowing dates or intercropping systems, whether for

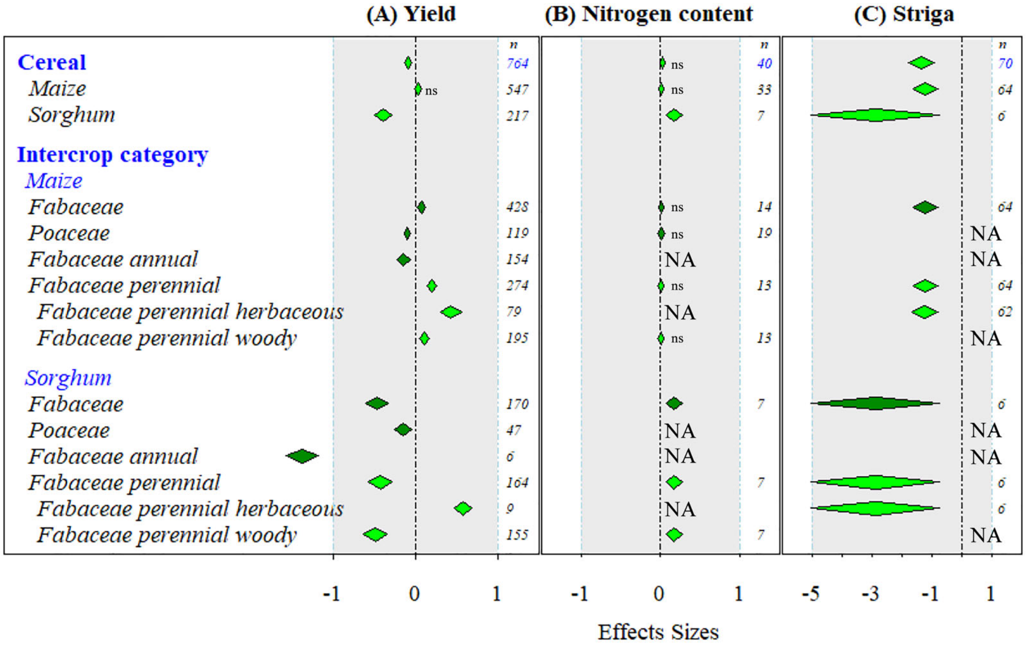

FIGURE 2 Effects sizes of maize and sorghum grain yield (A), nitrogen content (B), and striga infestation (C), as affected by cereal crop type and non-food intercrop category. The width of the symbols is equal to the 95% confidence interval of the effect size. NA indicates effect sizes for which the number of observations (n) was <5, which was deemed insufficiently reliable; ns, non-significant. The vertical discontinuous line (ES = 0) represents the line of no effect, that is, the response of cereal intercropping treatments equals that of the cereal control treatments. The effect size for a given factor is considered significant when the 95% confidence interval of the effect size does not cross the line of no effect.

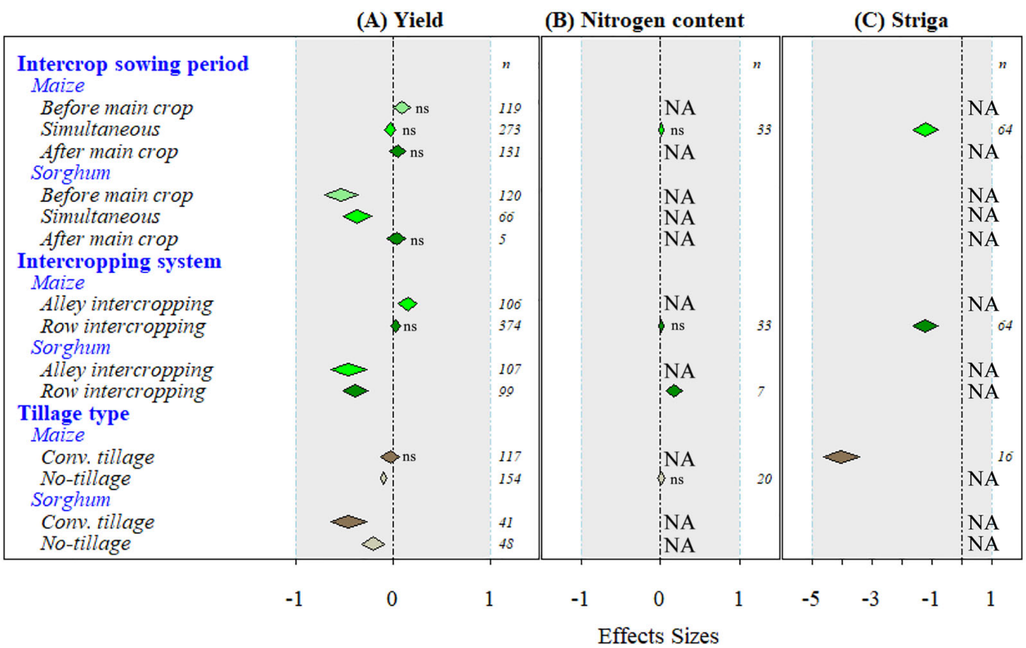

FIGURE 3 Effects sizes of maize and sorghum grain yield (A), nitrogen content (B), and striga infestation (C), as affected by period of non-food intercrop sowing, intercropping system, and tillage type. NA indicates effect sizes for which the number of observations (n) was <5, which are deemed insufficiently reliable; ns = non-significant.

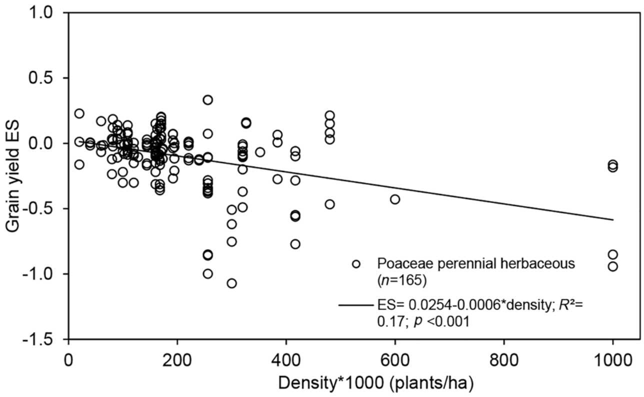

FIGURE 4 Relationship between effect size of cereal (maize and sorghum) grain yield and the sowing density of Poaceae non-food intercrops (corrected for viable seeds). ES, effect size.

maize or sorghum. The type of tillage system (conventional vs. no-tillage) had no significant effect on yield ES of maize and sorghum (Figure 3A).

3.4 | Effect of NFIC sowing density and numbers of intercropping years

For NFICs from the Poaceae family, CGY in intercropping relative to sole cropping systems significantly decreased with increasing NFIC sowing density ($p < 0.001$; Figure 4). At sowing densities <42 × 10^3 plants per hectare, intercropping with Poaceae had a neutral to positive effect on cereal yields, whereas at higher sowing densities, cereal yields were depressed. No significant relationship could be established for Fabaceae, whether annual or perennial.

The number of consecutive years of intercropping with annual herbaceous Fabaceae or woody Fabaceae significantly affected maize yield in intercropping compared to sole cropping (Figure 5). Specifically, while a slightly depressive effect is observed on average for both NFIC categories (annual herbaceous and perennial woody) in the first 2 years, the ES of maize grain yield becomes positive thereafter, ranging from 0.08 after three consecutive years to 0.56 after 6 years for annual herbaceous Fabaceae, and from 0.12 after three consecutive years to 1.08 after 14 years for perennial woody Fabaceae. As opposed to maize, the number of years sorghum was intercropped with perennial Fabaceae did not significantly affect sorghum grain yield over time ($p > 0.05$). Contrary to Fabaceae NFICs, the number of years of cereal (maize and sorghum) intercropping with Poaceae NFICs had no significant effect on CGY ($p > 0.05$; not shown).

3.5 | Effects of climate and annual rainfall

While maize intercropping trials covered a broad range of climatic zones, sorghum intercropping trials were mostly performed under tropical (Köppen A) and semi-arid (Köppen B) climatic conditions (Figures 1 and 5). Intercropping with NFICs led to a 17% increase in maize yields under tropical climatic conditions, whereas it resulted in a 23% decrease under semi-arid conditions. There is no significant effect of intercropping on maize yields under subtropical climatic conditions (Köppen C) (Figure 6A).

Sorghum trials mostly cover tropical and semi-arid climatic areas (Figure 6A). Under tropical conditions, sorghum yields in intercropping systems did not differ from sole cropping systems. On the contrary, under semi-arid conditions, yield response to intercropping was strongly negative (−61%). This is also observed under subtropical conditions (−49%), but since all the observations ($n = 13$) stem from only three articles, this result is deemed insufficiently robust.

Nitrogen content in maize did not differ between intercropping and sole cropping systems in the subtropical and semi-arid climatic zones. The only significant effect was observed under tropical climate (+10%), but the number of observations is too small to draw any meaningful conclusion (Figure 6B). For sorghum, lack of data does not allow comparison between climatic zones. In intercropping systems, striga infestation in maize under tropical conditions was strongly reduced (−119%) compared to sole cropping.

A positive relationship was found between cereal (maize and sorghum) yield ES and annual rainfall when intercropped with annual herbaceous Fabaceae ($p < 0.01$; Figure 7A), woody Fabaceae ($p < 0.001$; Figure 7B), perennial herbaceous species (both families, Fabaceae and Poaceae) ($p < 0.001$; Figure 7C), and perennial herbaceous Poaceae NFICs ($p < 0.001$; Figure 7D). At low annual rainfall levels, ESs were negative, becoming positive as rainfall increased. Specifically, yields in intercropping systems exceeded yields in sole cropping systems at rainfall thresholds of 1707 mm for intercropping with annual herbaceous Fabaceae, 1311 mm for woody Fabaceae, 1338 mm for perennial herbaceous (both families, Fabaceae and Poaceae), and 1448 mm for perennial herbaceous Poaceae NFICs.

3.6 | Effects of soil characteristics

Compared to sole cropping, maize yield response to intercropping was non-significant on light-textured soils but positive on heavy-textured (+6%) and particularly on medium-textured (+22%) soils. Light soils differ significantly from medium soils with intermediate values of ES for clay soils. For sorghum, texture did not affect the yield ES (Figure 8A). Soil texture had no significant effect on maize nitrogen content. The effect of texture on sorghum nitrogen content could not be evaluated for lack of diversity in the dataset. *Striga* control in maize plots by intercropping appeared to be more effective on heavy-textured soils than on medium-

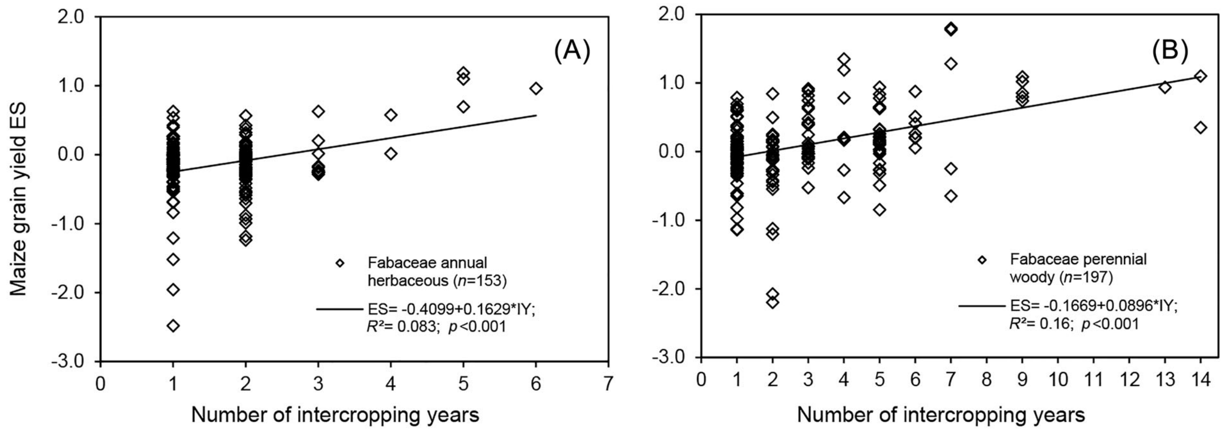

FIGURE 5 Relationship between effect size of maize grain yield and the number of consecutive years of intercropping with annual herbaceous Fabaceae (A) and woody Fabaceae non-food intercrops (B). ES, effect size.

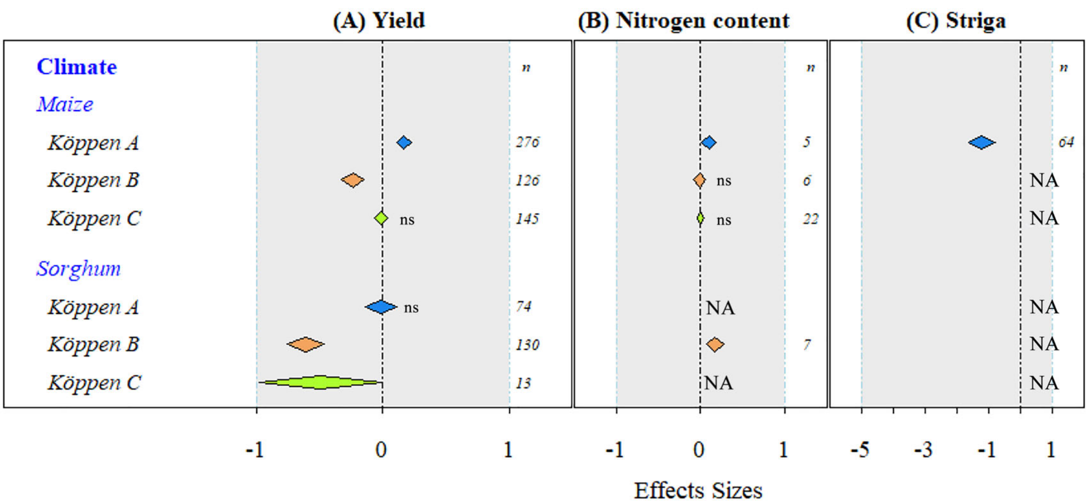

FIGURE 6 Effect sizes of maize and sorghum grain yield (A), nitrogen content (B), and striga infestation (C), as affected by Köppen climate class. Köppen A, tropical (Af, Am, and Aw); Köppen B, semi-arid (BSh and BSk); Köppen C, subtropical (Cwa, Cfa, Cwb, and Csb). NA indicates effect sizes for which the number of observations (n) was <5, which are deemed insufficiently reliable; ns, non-significant.

textured soils, but the small number of observations on medium-textured soils (n = 6) warrants great caution in interpretation.

SOM content at the start of the experiments positively influenced the cereal (maize and sorghum) yield ES for perennial woody Fabaceae ($p < 0.01$; Figure 9A) and perennial herbaceous Poaceae ($p < 0.001$; Figure 9B) NFICs. For perennial woody Fabaceae NFICs, ESs were always positive (ES > 0) on average and increased with increasing SOM content. For perennial herbaceous Poaceae NFICs, cereal yield ESs were negative on average at low SOM contents but became positive from an average SOM content of approximately 3%.

4 | DISCUSSION

In the Global South, where agriculture is largely dominated by smallholder farming systems, households often face resource constraints and high production risks. In such contexts, farmers tend to be risk-averse and prioritize immediate food production and stable cereal yields over longer term objectives such as soil conservation (Simutowe et al., 2024; Umar, 2014). Consequently, although NFICs may provide co-benefits such as fodder, nitrogen supply (legumes), mitigation of soil degradation processes, improvement of soil health, pest and disease control, or secondary food products, smallholder farmers generally avoid reducing cereal sowing density

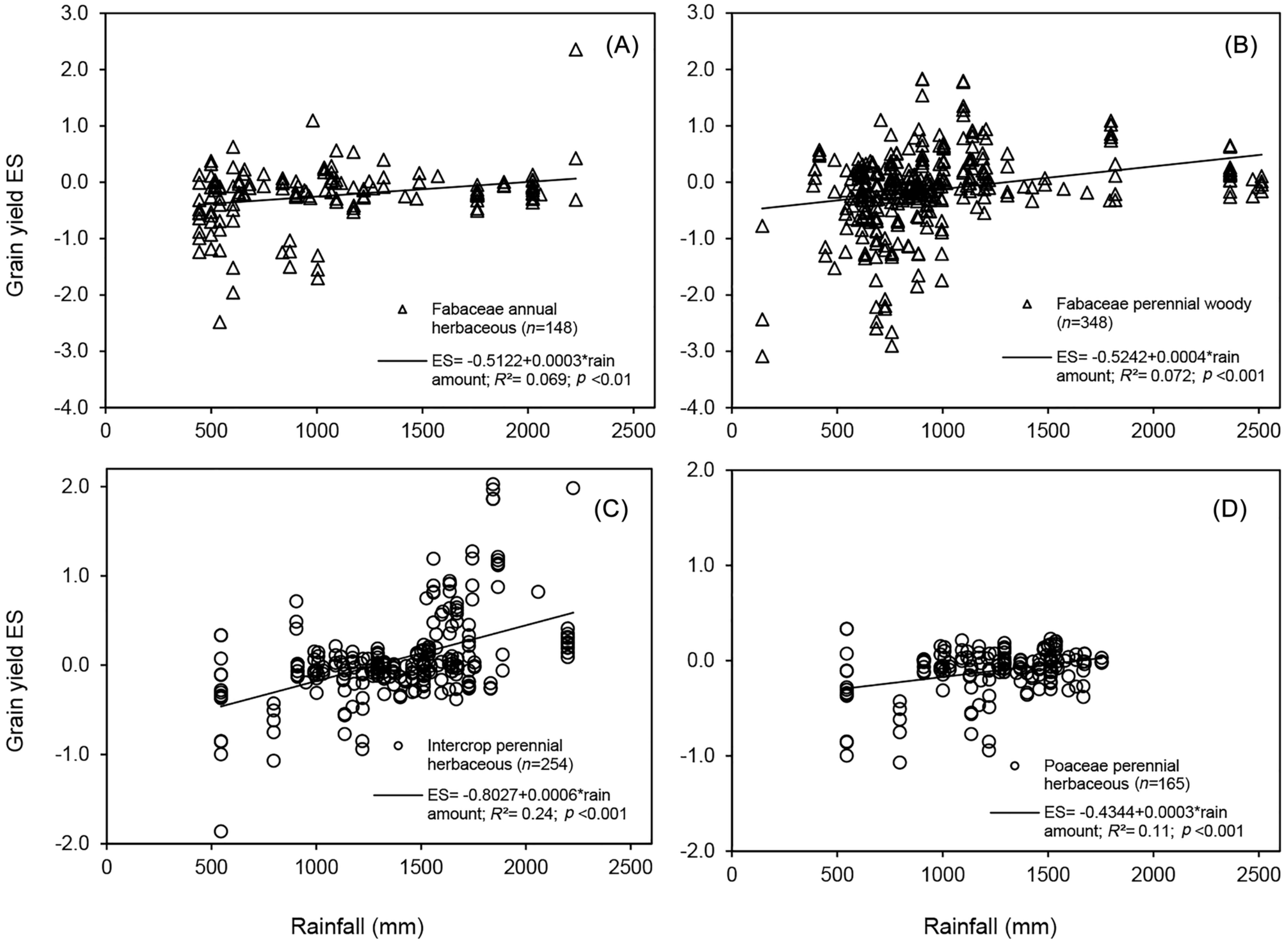

FIGURE 7 Relationship between the effect size of cereal (maize and sorghum) grain yield and annual rainfall for herbaceous Fabaceae (A), woody Fabaceae (B), perennial herbaceous non-food intercrops (Fabaceae and Poaceae) (C), and perennial herbaceous Poaceae non-food intercrops (D). ES, effect size.

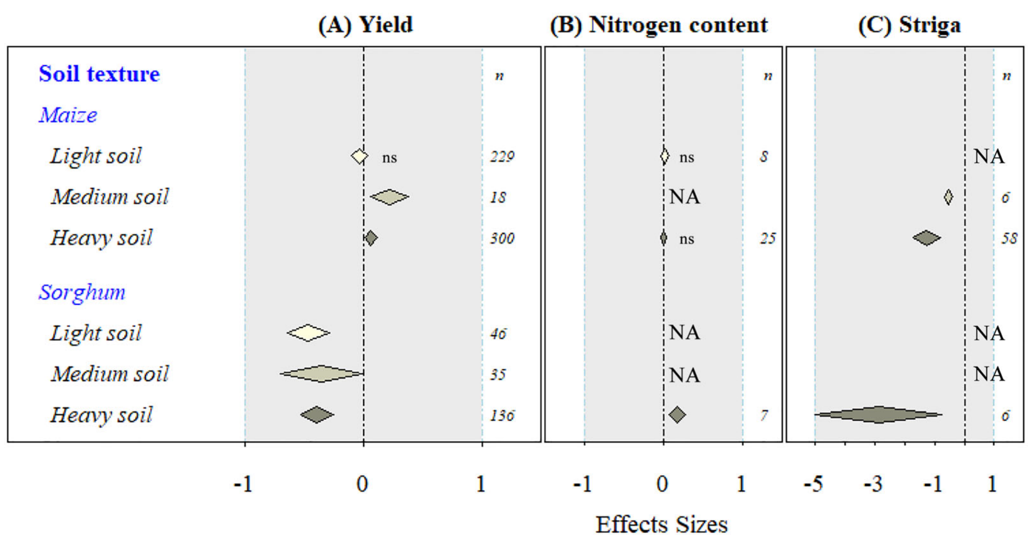

FIGURE 8 Effects sizes of maize and sorghum grain yield (A), nitrogen content (B), and striga infestation (C), as affected by soil texture. NA indicates effect sizes for which the number of observations (*n*) was <5, which are deemed insufficiently reliable; ns, non-significant.

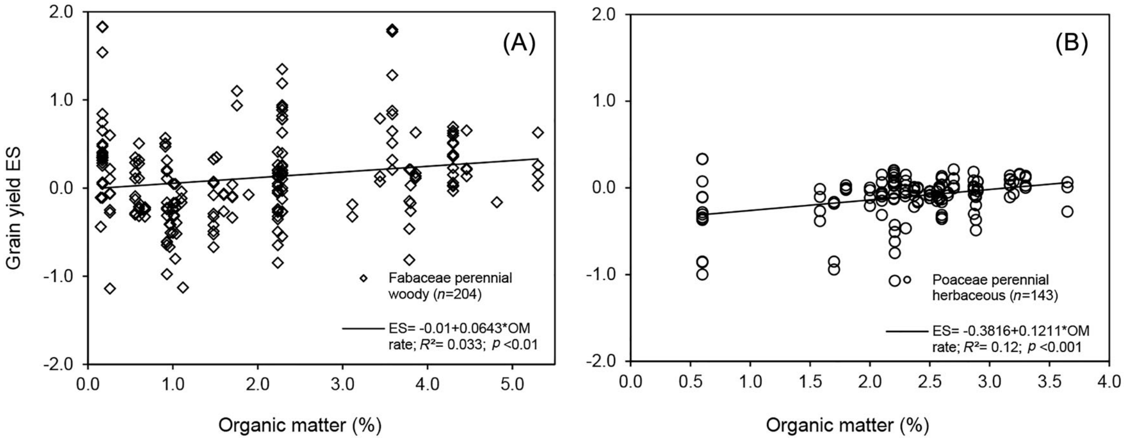

FIGURE 9 Relationship between effect size of cereal (maize and sorghum) grain yield and soil organic matter content for perennial woody Fabaceae (A) and perennial herbaceous Poaceae (B). ES, effect size.

when introducing intercrops. The results of this meta-analysis, which included only studies maintaining constant cereal density between sole cropping and intercropping systems, are therefore particularly relevant to these farming systems.

Overall, at constant cereal density, associating NFICs with maize had a neutral effect on maize yield, whereas sorghum yield was substantially reduced (−39%) compared to sole cropping (Figure 2). This contrasting response reflects differences in how maize and sorghum balance the competitive and facilitative effects of NFICs on resource use and growth. At constant sowing density of the cereals, adding NFICs will inevitably enhance competition for light, nutrients, and water. In the context of the present meta-analysis, competition for light is probably the least important given the erect growth and the tall height of maize and sorghum plants, although this will depend on the characteristics of the NFIC species, the date of sowing of the NFICs and, hence, its growth rate relative to the cereal, and the type of association (i.e., row or alley intercropping; Figure 3). In the absence of irrigation, competition for water will very much depend on the climatic zone where the associations are being tested. Competition for nutrients will depend on the nutrient requirements of the cereal and the NFICs, on the capacity of the soil to provide these nutrients, on nutrient management practices, but also on the ability of the NFICs to provide for some of their own nitrogen requirements (Thilakarathna et al., 2016; see further). Among the benefits of NFICs, one can list improved nitrogen and phosphorus nutrition of the associated cereal, release of allelopathic or bioactive compounds that suppress weeds, and insect pests control (Farooq et al., 2011; Michael & Carl, 2016), as well as long-term improvement in soil quality as a result of biomass restitution (Franzluebbers et al., 2021; Rowen et al., 2022; Silva et al., 2023). The results of the present meta-analysis must therefore be interpreted in light of the balance between these competing factors.

4.1 | Effect of climate and NFIC category on maize yield in intercropping system

Maize is cultivated in wetter tropical and subtropical environments ($n = 421$) than sorghum, which has an average annual rainfall of 1229 ± 481 mm in the studies compiled for this meta-analysis (Figures 1 and 5A). This probably explains why maize performed more favorably in intercropping systems than sorghum. Furthermore, the benefits of cereal–NFIC systems tend to increase with higher annual rainfall (Figure 7).

Besides the importance of moisture conditions, the performance of intercropping systems very much depended on the type of associated NFICs, that is, Fabaceae or Poaceae, and whether the latter are annual or perennial (Figure 2). In the absence of significant water stress, the overall positive effect of Fabaceae NFICs on maize yield is likely to be largely due to the well-documented benefits of legumes on the nitrogen nutrition of the associated crop (Thilakarathna et al., 2016). Fabaceae are known for their ability to fix nitrogen through their symbiotic association with Rhizobia (Carlsson & Huss-Danell, 2003; E. T. Wang et al., 2019). However, most of the nitrogen will be used by the NFIC itself and will become available to the cereal crop only after the aboveground NFIC biomass has been returned to the soil and decomposed, a process that has been referred to as "aboveground nitrogen transfer" (Thilakarathna et al., 2016). Nevertheless, cereal crops in association with leguminous crops may already acquire a significant portion of their nitrogen requirements during the first year of their association with legumes through belowground nitrogen transfer (S. Li et al., 2021; Thilakarathna et al., 2016), although this will depend on several factors, including stand age, background soil nitrogen content, and crop species (Lai et al., 2022). Three belowground nitrogen transfer pathways have been reported (Thilakarathna et al., 2016): (1) release of nitrogen following decomposition of root tissue, (2) exudation of soluble nitrogen compounds by the legume crop and subsequent uptake by the cereal, and (3) transfer of nitrogen through plant-associated mycorrhizae. Process (1)—release of nitrogen following decomposition of root tissue—is considered to be more important than the two others but will benefit the cereal mostly at later stages of development (or even in subsequent years) as some of the roots die off and start to decompose (Lesuffleur et al., 2013; Trannin et al., 2000). As opposed to process (1), processes (2)—the exudation of soluble nitrogen compounds by the legume crop and subsequent uptake by the cereal, and (3)—the transfer of nitrogen through plant-associated mycorrhizae—are believed to be quantitatively less important but could already contribute to the cereal nitrogen nutrition at early stages of development (Thilakarathna et al., 2016). Besides their benefits in terms of nitrogen nutrition, Fabaceae are also known to facilitate phosphorus uptake by the associated crop via the exudation of phosphorus-mobilizing compounds by roots and through microbially mediated (including rhizobia) solubilization of less readily available phosphorus (Tang et al., 2014). This has been reported to be most effective under suboptimal conditions of phosphorus shortage (Eichler-Löbermann et al., 2021).

These benefits for cereal nitrogen and phosphorus nutrition may explain the overall positive performance of Fabaceae-based intercropping systems as opposed to the overall negative performance of Poaceae-based intercropping systems. The observed decrease in maize yields when intercropped with Poaceae probably resulted from interspecific competition without the nitrogen and phosphorus nutrition benefits provided by leguminous NFICs, even though some grass species have been reported to acquire some of their nitrogen through associations with free-living, nitrogen-fixing bacteria (Steenhoudt & Vanderleyden, 2000). Besides, the generally higher carbon-to-nitrogen (C/N) ratio in the biomass of Poaceae compared to Fabaceae could lead to nitrogen immobilization (and subsequently to lower crop yields) from the second year of cultivation after the biomass from the previous year has been returned to the soil (Finney et al., 2016; Wells et al., 2013). On average, experiments with Fabaceae (2.4 years) lasted longer than those with Poaceae (1.6 years), allowing more time for soil improvement as a result of the cereal–NFIC association. This may also to some extent explain the overall better performance of maize–Fabaceae intercropping systems than maize–Poaceae intercropping systems compared to maize sole cropping.

In the case of Fabaceae-based intercropping systems, the benefits for maize appear to outweigh, on average, the negative effects of interspecific competition. However, this is strictly true only for perennial Fabaceae, annual Fabaceae having a negative impact on maize yield in intercropping systems (Figure 2). In the studies of this meta-analysis, annual Fabaceae were mostly sown simultaneously or after the main crop, while perennial Fabaceae were sown before (56%), simultaneously with (35%), and after (9%) the main crop. As a result, the growth cycle of annual Fabaceae is shorter than that of perennials. In addition, nodules on perennials will fix nitrogen throughout the entire growing season if conditions are favorable, whereas nodules on annual legumes generally lose their ability to fix nitrogen at the time of pod fill (Salon et al., 2001; Vessey, 1992). Consequently, perennial Fabaceae may accumulate more nitrogen for aboveground transfer. Besides, for perennial NFICs in pluri-annual experiments, the species will, de facto, be present before the main crop as from the second year. As a result, mechanism (1)—release of nitrogen following decomposition of root tissue—may become effective earlier in the growing season of the maize, whereas mechanisms (2)—exudation of soluble nitrogen compounds by the legume crop and subsequent uptake by the cereal—and (3)—transfer of nitrogen through plant-associated mycorrhizae—may remain effective over a longer duration. These various factors may thus explain the overall positive performance of intercropping systems with perennial Fabaceae. In the case of annual Fabaceae, it appears that the potential benefits in terms of nitrogen (and phosphorus) nutrition do not outweigh the losses caused by interspecific competition.

Besides the nutrition benefits, it seems likely that the NFIC biomass returned to the soil is greater for perennials than for annuals, which in the medium term would also benefit improvements in soil health. On average, annual Fabaceae in intercropping systems tend to have a negative impact on maize yield over the first 2–3 years. Although the general trend is positive, the strength of the relationship is fairly weak as a result of the limited number of observations for durations >3 (Figure 5A). The general trend is much more robust for perennial Fabaceae. As opposed to annual Fabaceae, the effect is neutral (rather than negative) in the first years and increases significantly over time (Figure 5B). Unfortunately, medium-term effects could not be tested for Poaceae-based intercropping systems in maize for lack of sufficient long-term experiments.

One could expect that NFICs that start growing before the main crop (either because they are planted before the main crop, or because they are inherited from the previous season if perennial) would enhance competition with the main crop. Delaying the sowing of intercrops is a common strategy to minimize competition with the main crop (Mhlanga et al., 2016; Uchino et al., 2009). However, for maize, this potentially negative effect does not appear to outweigh the benefits described above. An additional explanation for the limited competition in the early growth stages of maize might be that *Cajanus cajan* and similar woody leguminous NFICs have a slow growth rate and slow dry matter production (and hence nitrogen accumulation) during the early growth stages.

The latter has been attributed to their small seedling leaf area (Brakke & Gardner, 1987).

4.2 | Effect of climate and NFIC category on sorghum yield in intercropping system

The substantial yield reduction observed when sorghum was intercropped with Fabaceae indicates that the potential benefits of intercropping do not outweigh the losses resulting from interspecific competition, particularly competition for water. Sorghum is predominantly grown in semi-arid climates, with an average annual rainfall of 677 ± 162 mm in the studies compiled for this meta-analysis (Figures 1 and 5A). Competition for water may also explain the significantly larger reduction in sorghum yield in (woody) Fabaceae-based than in (herbaceous) Poaceae-based intercropping systems (Figure 2). The importance of competition for water is also clearly reflected in the differences in ESs between the tropical and semi-arid climatic zones (Figure 6). In the drier "semi-arid zone," the sorghum yield ES is much more negative than in the wetter "tropical zone."

From Figure 6, it is apparent that, within the same climatic zones (mostly semi-arid), sorghum–NFIC intercropping performs less well than maize–NFIC system. A likely explanation for this is that the sorghum–NFIC systems are dominated by (perennial) woody species of Fabaceae, whereas maize–NFIC systems encompass a wider range of species, including many observations related to intercropping with annual species. Annuals are expected to induce less competition for water than perennials as a result of the later sowing and lesser biomass production. Accordingly, for a given climatic zone and on average across all experimental observations, one can expect competition for water to be greater in sorghum–NFIC systems than in maize–NFIC systems.

4.3 | Implications and future research needs

This meta-analysis highlights several pathways for improving cereal-based intercropping systems in tropical and subtropical regions. The type of NFIC and the climatic zone emerged as the strongest determinants of intercropping performance, although their effects are partly confounded because maize and sorghum are typically cultivated in contrasting environments. Maize is predominantly grown in wetter tropical and subhumid climates (average annual rainfall 1229 ± 481 mm), where competition for water is less limiting and where all NFIC categories are represented in the literature. By contrast, sorghum is grown mainly in semi-arid zones (average rainfall 677 ± 162 mm) and, in the published studies, it was largely intercropped with perennial woody Fabaceae species, which are known to enhance belowground competition. This combination of environmental and biological constraints likely explains the consistently negative yield responses of sorghum in intercropping systems.

From a practical standpoint, the findings offer several actionable implications for farmers, agronomists, and development practitioners. Matching the NFIC type to the cereal crop and climatic context is critical. In tropical humid and subhumid regions, maize can be effectively intercropped with Fabaceae NFICs, particularly perennial woody or perennial herbaceous species that produce high-quality biomass while exerting moderate competitive pressure. Species such as *Gliricidia sepium* or *Desmodium spp*. may offer advantages in these environments. Conversely, in semi-arid climates where sorghum predominates, dense stands of woody Fabaceae species such as *Cajanus cajan* or *Leucaena leucocephala* should be avoided due to their high water and nutrient demand. In such systems, annual Fabaceae NFICs with lower competitive intensity (e.g., *Lablab*) may represent more suitable options, although further research is required because only a limited number of studies have evaluated such combinations. In such environments, farmers may need to select drought-tolerant annual Fabaceae NFICs and adopt planting configurations (e.g., strip or inter-row spacing) that limit resource competition.

Managing NFIC sowing density also emerged as a key factor. Perennial herbaceous Poaceae (e.g., *Brachiaria spp.*), which have high sowing densities, tend to reduce cereal yields due to intense early-season competition. Reducing seed rates or delaying sowing could mitigate this competition, particularly in water-limited environments. The evidence also suggests that the benefits of Fabaceae NFICs often materialize after multiple years at the same site. Yield improvements typically appeared only after the third year of intercropping, likely reflecting gradual enhancements in SOM, nutrient cycling, and microbial activity. This highlights the importance of long-term adoption and underscores the need for policies and advisory services that support farmers during the transition period.

Soil fertility also plays an important role in determining the magnitude of intercropping benefits. Positive effects were most consistent in soils with higher organic matter content, especially when woody Fabaceae or perennial Poaceae NFICs were used. The results also confirm the effectiveness of *Desmodium*-based systems for striga suppression in maize. The large reductions in *Striga* density highlight the continued relevance of these systems for smallholder farmers. However, despite sorghum's greater vulnerability to *Striga*, evidence for sorghum–*Desmodium* intercropping remains scarce, representing a notable research gap.

Several priority areas for future research emerge from this study. First, because several NFICs such as *Cajanus cajan* and *Brachiaria* spp. provide valuable forage, integrating crop–

livestock considerations—fodder value, biomass availability, and seasonal feed gaps—would align future research with the realities of smallholder mixed farming systems. Second, more studies are needed to explore *Striga* management options in sorghum-based systems, particularly using *Desmodium* species or other NFICs with known allelopathic properties. Third, many studies were short-term, whereas the results indicate that positive effects of Fabaceae NFICs often emerge only after several years. The scarcity of long-term experiments limits the assessment of system sustainability and temporal dynamics. Finally, limited and inconsistent reporting of management variables, for example, pruning intensity, residue management, planting dates, and water availability—restricted the ability to disentangle underlying mechanisms driving yield responses.

5 | CONCLUSION

This meta-analysis highlights the importance of NFIC traits—family (Poaceae or Fabaceae), life cycle (annual or perennial), and growth form (herbaceous or woody)—in determining cereal yield response to intercropping with NFICs at constant cereal crop density. Perennial Fabaceae notably improved maize yield, largely due to the high quality of their biomass residues and low sowing density, which reduced competition for water and nutrients. Climate also played a key role: maize benefited more in humid zones, whereas sorghum, often grown in semi-arid zones with woody Fabaceae, experienced yield reductions from resource competition. The analysis also revealed that positive yield effects from Fabaceae NFICs generally appear after 3 years at the same experimental site, highlighting the need for long-term experiments to properly assess the sustainability of such systems. Alley cropping with woody Fabaceae could therefore enhance maize yields, particularly when biomass is pruned and returned to the soil annually. Conversely, high seeding densities of perennial herbaceous NFICs, especially Poaceae, tended to reduce cereal yields due to competition, reflecting their small seed size and higher sowing rates. NFIC benefits in terms of increased nitrogen content in the cereal crop were limited, while *Desmodium* species effectively suppressed *Striga* in maize fields.

Overall, this synthesis demonstrates that intercropping with NFICs can enhance yield and pest control when properly adapted to cereal crop species and climatic conditions. These findings provide valuable insights for promoting sustainable intensification of cereal-based systems in tropical and subtropical regions.

AUTHOR CONTRIBUTIONS

Kamarou-Dine Seydou: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft; writing—review and editing. **Pierre G. Tovihoudji**: Conceptualization; methodology; supervision; validation; visualization; writing—review and editing. **Sissou Zakari**: Validation; visualization; writing—review and editing. **Pierrot Lionel Yemadje**: Visualization; writing—review and editing. **P. B. Irénikatché Akponikpè**: Visualization; writing—review and editing. **Charles L. Bielders**: Conceptualization; methodology; supervision; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

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