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REVIEW

Effects of management practices on legume productivity in smallholder farming systems in sub-Saharan Africa

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Abstract
Legumes play a key role in food and nutrition security, providing livestock feed and contributing to soil fertility, in mixed smallholder farms in sub-Saharan Africa (SSA). The environmental conditions under which smallholder farming is practiced are highly heterogeneous with large differences in management practices among farms resulting in variable legume productivity. A meta-analysis based on 128 publications was conducted to quantify the effects of intercropping, inoculation with rhizobia, minimum tillage and phosphorus application on legume grain and biomass yield and the amount of biological nitrogen fixation in a range of SSA contexts. To further explain the heterogeneity in the results, legume species, type of inoculant, P-application rate, altitude, rainfall, soil characteristics and non-legume companion crops were used as moderators. Intercropping as compared to sole cropping reduced legume biomass and grain yields to varying extents, although the total land equivalent ratio for the sum of the intercrops was higher than 1 (1.2–1.9) in all cases. Expressed as the relative land equivalent ratio (rLER) intercropping affected pigeonpea grain yield the least (rLER 0.9) and faba bean the most (rLER 0.3). The non-legume companion crops explained some of the heterogeneity where maize and sorghum significantly reduced the legume yields. Inoculation and P application increased legume grain and biomass yield and moderators such as legume species, type of inoculant, soil organic carbon and soil pH further explained the different effects of the management practices on legume productivity. Minimum tillage had no effect on legume productivity, although less data were available than for the other practices. We conclude that intercropping with legumes improves overall productivity and that application of P fertilizer and inoculants increase legume grain and biomass yield. The effect varies with crop species, soil type and other environmental conditions, and this needs to be factored into tailored recommendations supporting decision making in smallholder farming.

KEYWORDS
biological nitrogen fixation, fodder, grain legumes, inoculation, intercropping, land-equivalent area, meta-analysis, phosphorus application

1 | INTRODUCTION

The population of sub-Saharan Africa (SSA) is projected to double between 2019 and 2050, which will increase pressure on land and require farmers to improve crop management practices to keep pace with increasing food demands (United Nations, 2015, 2019). Most smallholder farmers practice mixed crop and livestock farming and depend on natural rainfall for crop production. Rainfall patterns and amounts are becoming increasingly unpredictable resulting in widening of crop yield gaps (Christiaensen & Demery, 2018; Herrero et al., 2010). Increasing crop diversity using legumes has been recommended as a way of improving productivity and sustainability of crop production in general, not least in smallholder farming (Daryanto et al., 2015; Justes et al., 2021; Kuyah et al., 2021; Mhango et al., 2013; Ojiem et al., 2014). Legumes are often grown on smallholder farms because they have the potential to provide human food and livestock feed, as well as improve soil fertility (Franke et al., 2018; Graham, 2003; Muoni et al., 2019). However, for several reasons, including low soil fertility, their productivity is low in SSA (Hassen et al., 2017; Ojiem et al., 2007). Furthermore, limited market access reduces incentives to invest in management to improve legume productivity (Christiaensen & Demery, 2018).

Legumes of various types: grain, herbaceous (legumes with soft stems grown for fodder or cover crops) and tree, may be incorporated into smallholder farms as intercrops, rotational crops, farm boundaries or hedgerows (Himmelstein et al., 2017). Intercropping of different types of legumes with starch-rich staple crops, here called non-legume crops, such as maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz.) is common in SSA (Odendo et al., 2011). Depending on the type of legumes and how they are incorporated in the cropping system, they can add several functions compared to sole cropping without legumes. Such functions include reduced risk of total crop failure, increased soil cover to protect the soil from direct sun and raindrop impact, improved resource use efficiency, reduced incidence of pests, diseases and weeds, provision of livestock feed and increased overall crop yield through improvements of soil fertility (Brooker et al., 2015; Chimonyo et al., 2016; Hassen et al., 2017). Legumes add nitrogen (N) to the cropping system through biological nitrogen fixation (BNF) potentially reducing fertilizer requirements in intercrops or subsequent crops. However, choice of crops to include in intercropping is important for optimizing resource use (De Costa & Surenthran, 2005). The efficiency in the use of resources, such as nutrients, water and light, can be improved by choosing species that are complementary or that directly benefit each other (Hauggaard-Nielsen et al., 2006; Justes et al., 2021), for example, by reducing pest and disease infestations (Finckh & Wolfe, 2017), enabling the crop rather than the weeds to utilize available N (Hauggaard-Nielsen et al., 2001) or by increasing mineral N and P availability (Hinsinger et al., 2011).

Most land in SSA is cultivated with minimal fertilizer application and is deficient in major nutrients, hence external inputs of mineral and organic fertilizer are needed (Jones et al., 2013; Okalebo et al., 2007). Phosphorus very often limits crop production in SSA (Bationo et al., 2012; Nziguheba et al., 2016; Okalebo et al., 2007; Vanlauwe et al., 2010). Phosphorus increases BNF in legumes, it stimulates root development in plants, improves crop resistance to pests and diseases by increasing plant vigour and improves fruit and flower formation (Dordas, 2008; Heydari et al., 2019; Vance, 2001). Soil pH determines P availability for plant uptake and the optimum pH is around 6.5. In more acid soils, P reacts with aluminium and iron and becomes less soluble, while at higher pH, P binds with calcium reducing its availability for plant uptake (Penn & Camberato, 2019).

Legume BNF requires effective strains of rhizobia to be available in the rhizosphere (Chekanai et al., 2018). This may be achieved by inoculation of seeds at sowing or appropriate rhizobia may exist naturally in the soil (Vanlauwe et al., 2019). However, rhizobial strains/species interact with specific legume groups, and farmers need to be aware of which inoculum to use when growing legumes for the first time (Andrews & Andrews, 2017). The population and diversity of rhizobia are affected by tillage practices. High rhizobial diversity has been observed in minimum tillage systems and this is attributed to low disruption of soil biotic communities (Ferreira et al., 2000). Minimum tillage also helps reduce soil erosion and runoff and reduces disruption of soil micro- and macro-organisms (Herrero et al., 2010; Thierfelder & Wall, 2009). Practices with minimum tillage have been recommended for improving soil conservation (Thierfelder & Wall, 2009), but the impact on minimum tillage on legume productivity is less well documented.

There is evidence that P fertilizer and inoculation can increase legume productivity and that intercrops involving legumes increase the combined crop yield (Ronner et al., 2016), but the importance and generality of their effects are not well documented in SSA. The response of legumes to inputs, such as P fertilizer and inoculation, is reported to be very variable, and that could relate to variation in crop management, climate and soil types in smallholder farms (Vanlauwe et al., 2019).

We address the above knowledge gaps by conducting a meta-analysis, an approach which synthesizes studies conducted under various environmental or agro-ecological conditions estimating a common effect size that reflects the magnitude of each factor of interest (Borenstein et al., 2011). Meta-analysis has been used to study various aspects of agricultural productivity in SSA, for example, the effect of intercropping on crop productivity, income and pest management (Himmelstein et al., 2017), long-term effects of conservation agriculture on maize grain yield (Rusinamhodzi et al., 2011) and the effect of herbaceous and woody legumes on maize yield (Sileshi et al., 2008). These studies suggest that environmental variables and management practices influence crop productivity in a consistent way despite the heterogeneity in smallholder farms in SSA. The specific objective of this study was to provide a quantitative synthesis of published research on the separate effects of intercropping, inoculation, P application and minimum tillage on legume grain and biomass yield and BNF, as well as how these effects are moderated by environmental and management factors, across SSA.

2 | MATERIALS AND METHODS

2.1 | Literature search

A literature search was conducted using the ISI Web of Science, Scopus and ProQuest search engines for primary studies presenting data on the effect of intercropping, phosphorus fertilization, inoculation and reduced tillage on legume productivity (i.e. grain and biomass yield) in SSA, covering all studies available online from 1945 to December 2018. The oldest paper included in this study was from 1980. These search engines were chosen because they allow use of the same search strings and also focus on peer-reviewed publications which introduce quality control of the publications used. The management practices included in the search are described in Table 1. The search strings included the following keywords: (a) for intercrop: TOPIC: (intercrop* OR crop mixture) AND TOPIC: [(grain yield) OR (biomass yield) OR (shoot yield)] AND TOPIC: (Africa[1]); (b) for phosphorus application: TOPIC: (phosphorus fertilization) AND TOPIC: (grain OR biomass OR shoot dry matter OR yield) AND TOPIC: (Africa1); (c) for inoculation: TOPIC: (inoculation OR rhizobia OR rhizobium) AND TOPIC: [BNF OR nitrogen derived from atmosphere (ndfa) OR (fixed nitrogen)] AND TOPIC: (Africa1) and (d) for minimum tillage: TOPIC: (till* OR no-till* OR zero till* OR minimum till* OR plough* OR conservation till* OR reduced till*) AND TOPIC: (grain OR biomass OR shoot dry matter OR yield) AND TOPIC: (Africa1). In all search strings, common and scientific names of legumes were added (listed

TABLE 1 Short description of the management practices included in this study: intercropping, P fertilizer application, inoculation and minimum tillage

Treatments	Description
Intercropping	Sowing legumes together with non-other crops such as carbohydrate- or starch-rich crops. Most commonly intercropped with legumes were maize, cassava and sometimes with other legumes in a double-up approach. The designs include one row legume and one row other crop or different proportions of legume, for example 25% legume and 75% maize, or 50:50 proportions for both crops
Sole cropping	One legume species grown using recommended plant population
Phosphorus (P) application	Studies that involved mineral P fertilizer application at sowing. The P fertilizer form varied with countries.
No phosphorus	Control where no P fertilizer was applied at sowing. Treatments with application of other nutrients such as N were included provided no P was added
Inoculation	Inoculation of seeds during planting of the legumes. The inocula used were either native or imported. All crops/experiments were conducted in SSA
No inoculation	Legume crop was grown without any inoculation. Some studies had this treatment receiving fertilizer application, mostly basal dressing for different P and potassium (K) application rates
Minimum tillage	Reducing soil disturbance by minimizing tillage. Methods used to reduce soil disturbance include plant basins, rip lines or direct seeding. The treatment considered those treatments with or without crop residue retention
Conventional ploughing	Use of mouldboard plough for land preparation and weed control. The ploughing depth is usually <20 cm and crop residues are used to feed livestock

in Table 2) and studies from North Africa were removed manually. Data reported in figures were extracted using WebPlotDigitizer (Rohatgi, 2015).

2.2 | Selection criteria

The articles included in the meta-analysis had to meet the following requirements: (1) the research reported was conducted in SSA; (2) the research reported was conducted either on-farm or on-station excluding green house and pot experiments (because they do not match the pedoclimatic conditions faced by farmers); (3) the experiment had to include specific contrasting groups (a control or 'standard' practice), that is, either intercropping versus sole cropping, minimum tillage versus conventional ploughing, P fertilizer application versus no P fertilizer application or inoculation versus no inoculation; (4) means, sample size and information on variation such as coefficient of variation (CV), standard deviation (SD) or standard error (SE) had to be reported for intervention and control groups. Data on the effect of management practices on legume grain yield, biomass yield and BNF were extracted from the selected publications and used as variables in the meta-analyses (Figure 1). Because the number of replicates in the datasets were small (Figure 3), we used Hedges' D as the measure of effect size since it works well for small sample sizes (Koricheva et al., 2013). $|d| = 0.2$, $|d| = 0.5$ and $|d| > 0.8$ indicate small effects, moderate effects and large effects respectively.

2.3 | Independence of observations

To ensure independence of data points, the following rules were set: (1) for a study with the same treatments applied at the same site for several years, average values were calculated per year and the number of years were treated as sample size; (2) when the treatments were applied at different locations, averages per location were calculated; (3) where authors published more than one paper based on partly the same data, only one of their publications was considered for data extraction and preference was placed on the paper with most data provided; (4) observations from the same study were considered independent if they studied different management practices, including fertilizer applications, applying different inoculum strains and different tillage methods (e.g. basins, rip lines or direct seeding); (5) the effect size variances in experiments sharing the same control were adjusted as described by Gleser and Olkin (2009), and paper was included as a random factor in multivariate meta-analysis models with REML (Viechtbauer, 2010).

2.4 | Land equivalent ratio and meta-analysis calculations

2.4.1 | Land equivalent ratio

Calculation of the total land equivalent ratio (totLER; Equation 1), defined as the relative area needed for sole crops to produce the same yield as intercrops (Mead & Willey, 1980), involved the summation of yield ratios of the component crops when intercropped over their sole cropped yield (Oyejola & Mead, 1982). Land equivalent ratio of individual crops in crop mixtures compared to their sole cropped yields is termed partial or relative land equivalent ratio (rLER; Equation 2) (Himmelstein et al., 2017). This metric was used to assess how individual crops respond to intercropping.

$$\text{totLER} = \frac{\text{Legume yield}_{\text{intercrop}}}{\text{Legume yield}_{\text{sole crop}}} + \frac{\text{Companion crop yield}_{\text{intercrop}}}{\text{Companion crop yield}_{\text{sole crop}}} \quad (1)$$

$$\text{rLER} = \frac{\text{Legume yield}_{\text{intercrop}}}{\text{Legume yield}_{\text{sole crop}}} \quad (2)$$

High rLER indicates that the companion crops have little negative effect on the crop investigated. The totLER and rLER were calculated using the data extracted for the intercropping meta-analysis and were subjected to analysis of variance where species was treated as a factor. Mean separation was done using least significant differences (LSD) in the Agricolae package in R version 3.6.1.

2.4.2 | *Meta-analysis*

We conducted separate meta-analyses using the Metafor package in R 3.4.2 (Viechtbauer, 2010) on the effects of (1) intercropping versus sole cropping, (2) P fertilizer application versus no P fertilizer application, (3) inoculation versus no inoculation and (4) minimum tillage versus conventional ploughing on (1) grain yield, (2) biomass yield (excluding grain) and (3) amount of fixed nitrogen (BNF) (Table 1). Overall analysis of the effect size of each intervention on grain and biomass yield and fixed N was conducted. Heterogeneity tests were carried out using the Q statistic and where this was significant, moderators (selected based on the reported information in the papers and knowledge as well as experience of authors) were analysed individually. We analysed the moderators individually because not all data points had information related to all moderators. We tested if the effect size of different levels of categorical moderators were significantly different from

TABLE 2 Legume species included in literature search forming the basis for the meta-analysis

Common name	Scientific name	Legume type	Included in meta-analysis	Number of studies
Lupins	*Lupinus angustifolius*	Grain	No	–
Lentils	*Lens culinaris*	Grain	No	–
Pigeonpea	*Cajanus cajan*	Grain	Yes	8
Chickpea	*Cicer arietinum*	Grain	Yes	3
Soybean	*Glycine max*	Grain	Yes	44
Common bean	*Phaseolus vulgaris*	Grain	Yes	29
Tepary bean	*Phaseolus acutifolius*	Grain	Yes	3
Lima bean	*Phaseolus lunatus*	Grain	No	–
Field pea	*Pisum sativum*	Grain	Yes	2
Faba bean	*Vicia faba*	Grain	Yes	3
Cowpea	*Vigna unguiculata*	Grain	Yes	53
Green gram	*Vigna radiata*	Grain	No	–
Groundnut	*Arachis hypogaea*	Grain	Yes	11
Bambara groundnut	*Vigna subterranea*	Grain	No	–
Sun hemp	*Crotalaria juncea*	Herbaceous	No	–
Lablab	*Lablab purpureus*	Herbaceous	Yes	2
Velvet bean	*Mucuna pruriens*	Herbaceous	Yes	9
Common vetch	*Vicia sativa*	Herbaceous	No	–
Jack bean	*Canavalia ensiformis*	Herbaceous	No	–
Silverleaf desmodium	*Desmodium uncinatum*	Herbaceous	No	–

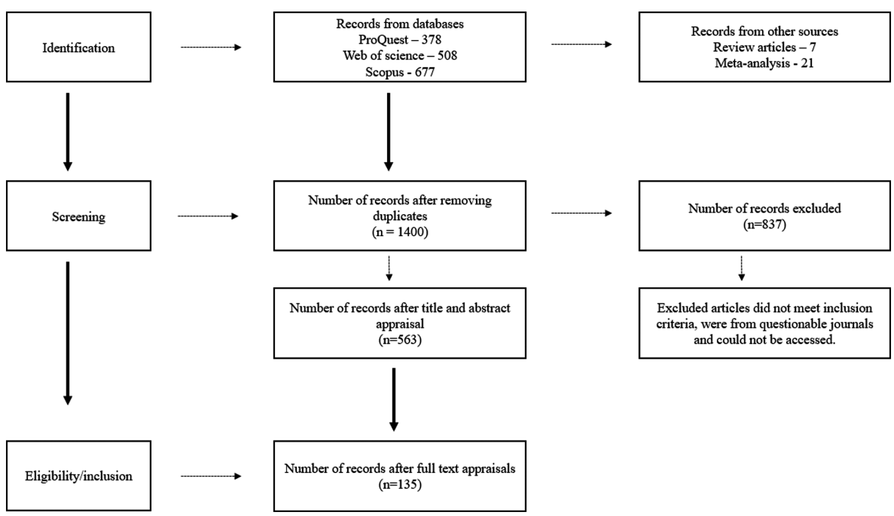

FIGURE 1 PRISMA diagram showing the numbers of papers retrieved and how they were excluded at various stages of the review process. Questionable journals were identified on https://www2.cabells.com/predatory

zero and if continuous moderators linearly modified the effect size. Moderators included in the meta-analysis were soil organic carbon (SOC), soil pH, legume species, soil clay content, altitude (in metres above sea level – m.a.s.l), inoculant type (for effect of inoculation on legumes), non-legume companion crops (for effect of intercropping on legumes) and rainfall. Soil organic carbon was determined by multiplying soil organic matter by 0.58 when it was not reported directly (Perie & Ouimet, 2008). The majority of soil pH measurements were taken by extracting soil water solution, while a few were measured in 0.01 M calcium chloride suspension which were adjusted to estimate pH in water by adding 0.8. All moderators except legume species, non-legume crop species and type of inoculant were analysed as continuous variables. Legume species and non-legume crops and type of inoculant were analysed if each species was represented by at least three data points. Pest management is also an important factor that influences legume productivity; however, it was not included in this study. Publication bias, the influence of research findings on the probability of them being published which arises due to underreporting of non-significant results or results inconsistent with current theories, was checked using the Rosenthal fail-safe number in OpenMee software (Orwin, 1983; Wallace et al., 2017). The Rosenthal's fail-safe number of publication bias gives the number of additional studies required to change the overall significance of the effect size from significant to non-significant or from non-significant to significant (fail-safe N; Nfs).

3 | RESULTS

3.1 | Publication bias

For the intercropping, P application and inoculation management practices, potential publication bias was unlikely to change the significance of the effects (Table 3). However, for minimum tillage, publication bias could have affected the results (Table 3). In this case, only 10 additional studies would be required to change the overall effect of minimum tillage from non-significant to significant.

3.2 | Intercropping

A total of 63 publications which provided 137 data points were used to investigate the effect of intercropping on legume grain yields. Legume grain and biomass yield were reported to indicate their contribution to food for human consumption and forage production. For all intercrops, the totLER values were >1, implying yield benefits compared to sole cropping. The effect of intercropping on totLER and rLER was significantly dependent on the type of grain legumes (range: 1.1–1.9 and 0.3–0.9 respectively; Figure 2). Intercrops involving pigeonpea had the highest totLER and rLER, while those with faba bean (*Vicia faba* L.) had the lowest totLER and rLER (Figure 2). Relative LER showed high values (>0.65) for pigeonpea (*Cajanus cajan* (L.) Millsp.), cowpea (*Vigna unguiculata* L.) and soybean (*Glycine max* (L.) Merr.) meaning that they performed well as intercrops (Figure 2b).

Intercropping had a negative overall effect on grain yield of the legume component as compared to sole legume cropping (average effect size Hedges' D = −1.949; $d > \pm 0.8$ indicating a large treatment effect, $p = <0.001$) (Figure 3a). In this model, heterogeneity was significant ($Q = 1499.2, p < 0.001$) suggesting that additional variables were needed to fully explain the results. Therefore, moderators were tested individually. The moderators tested were legume species, non-legume crop species, soil pH, altitude, clay content, SOC and annual rainfall. Legume species ($QM = 34.3, p < 0.001$), altitude ($QM = 7.7, p = 0.006$) and non-legume crop species ($QM = 23.5, p = 0.015$) explained significant amounts of heterogeneity in legume grain yield (Table 4; Figure 4a). Only pigeonpea, groundnut (*Arachis hypogea* L.) and faba bean grain yields were not significantly affected by intercropping, while the effect size for other legume species was large (ranged between −3.6 and −1.5; Figure 4a). Maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) significantly reduced the legume grain yields, but there was no significant effect of the other non-legume crop species (Figure 5). The negative effect of intercropping on legume grain

TABLE 3 Publication bias results for the studied management practices on grain and biomass yield and BNF using the Rosenthal approach in OPENMEE software for meta-analysis

Legume functions	Management practices	Observed significance level	Fail-safe N (Nfs)
Grain yield	Intercropping	<0.0001	23,387
	Inoculation	<0.0001	8341
	P application	<0.0001	15,273
	Minimum tillage	*NS*	10
Biomass yield	Intercropping	<0.0001	2857
	Inoculation	<0.0001	15,875
	P application	<0.0001	3455
Biological nitrogen fixation	Inoculation	<0.0001	1740

Note: Fail-safe number (Nfs) is the number of additional non-significant studies needed to reduce the overall effect to non-significance or the number of significant studies required to change from non-significant to significant. NS means not significant.

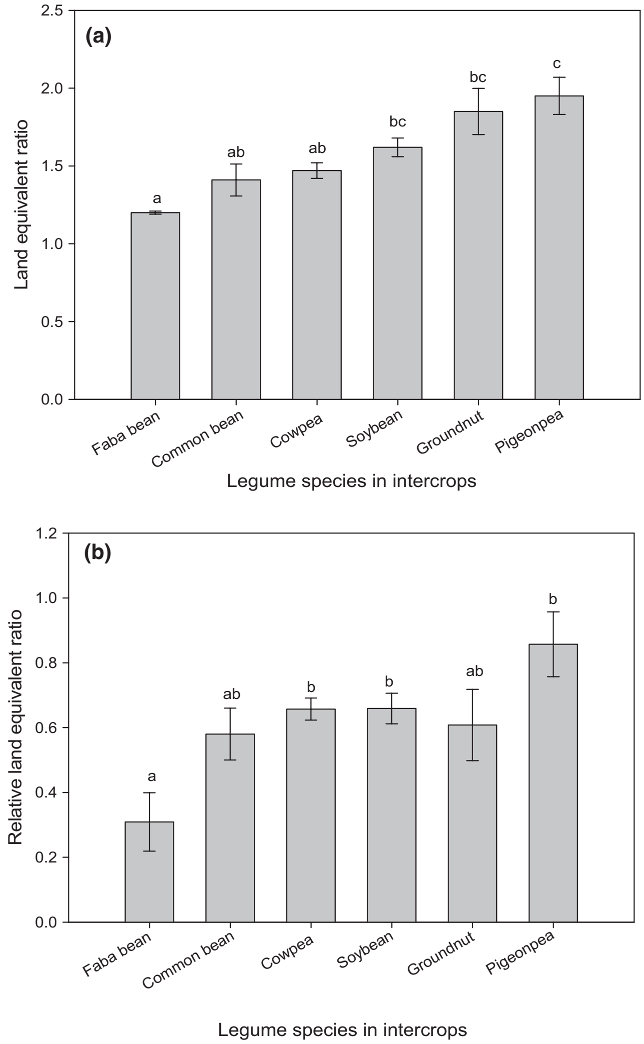

FIGURE 2 (a) Total land equivalent ratio (LER) for grain legume yield and companion crops yield (either maize, pearl millet, sorghum, cassava or wheat) and (b) relative LER for legumes grain yield under intercropping in sub-Saharan Africa. Bars with different letters are significantly different from each other and error bars indicate standard error

yield decreased with increasing altitude, SOC and soil pH (Table 4).

The effect of intercropping on legume biomass productivity was assessed using 20 publications, which resulted in 45 data points. The totLER for intercrop biomass yield with legumes ranged between 1.16 and 2.05. There were significant differences in rLER for biomass productivity of faba bean, mucuna (*Mucuna pruriens* L.), common bean (*Phaseolus vulgaris* L.), cowpea, soybean, groundnut and pigeonpea in intercropping. The largest rLER was observed with mucuna intercrop, while faba bean intercropping had the lowest rLER. The other legume species were not significantly different from each other. Intercropping had a large negative effect on legume biomass yield (average effect size = −3.6, $p < 0.001$) (Figure 3b). In this model, heterogeneity was significant (Q = 19,589.7, $p = 0.04$) and thus moderators could be tested. The same moderators were used to test biomass yield as for grain yield. Altitude, legume species and non-legume crop species explained a significant amount of the heterogeneity ((QM = 7.1, $p = 0.008$; QM = 30.4, $p = 0.006$ and QM = 44.6, $p < 0.001$ respectively). The negative effect of intercropping on legume biomass yield decreased with increasing altitude (Table 4). It was only with pigeonpea and faba bean that the legume biomass yield was significantly reduced compared to sole cropping (Figure 6a). Furthermore, intercropping reduced legume biomass yield when maize, barley or wheat was the non-legume crop, whereas there was no effect of intercropping on legume biomass yield when the non-legume crop was sorghum (Figure 5b).

3.3 | Phosphorus application

A total of 21 publications with 95 data points were considered in this analysis and P application had a positive effect on legume grain yield (effect size = 1.2, $p < 0.001$) (Figure 3a). Heterogeneity was significant in this model (Q = 40.8, $p < 0.001$), and therefore moderators were tested. The moderators tested were level of P application, legume species, soil pH, SOC, clay content, altitude and annual rainfall. Only SOC (QM = 9.4, $p = 0.002$) and legume species (QM = 36.3, $p < 0.001$) explained significant amounts of heterogeneity (Table 5; Figure 4b). Soybean, groundnut, cowpea and common bean grain yield were all positively affected by P application. In spite of P application being significant, utilizing the level of application (7–114 kg P ha^{-1}) as a moderator did not further explain the heterogeneity (QM =0.154, $p = 0.695$) of legume grain yields (Appendix S1).

For analysing legume biomass yield response to P application, 14 publications giving 61 data points were used. The biomass yield was significantly affected by P application (Figure 2b). A significant level of heterogeneity was observed (Q = 90.6, $p < 0.001$) and the same moderators as for legume grain yield were analysed individually. Altitude, SOC and legume species all explained significant amounts of heterogeneity (QM = 8.6, $p = 0.003$; QM = 4.2, $p = 0.041$; QM = 82.202, $p < 0.001$ respectively). The effect of P application decreased with increasing altitude and SOC (Table 5). Biomass yield of groundnut and cowpea increased with P application, while there was no effect on common bean (Figure 6b).

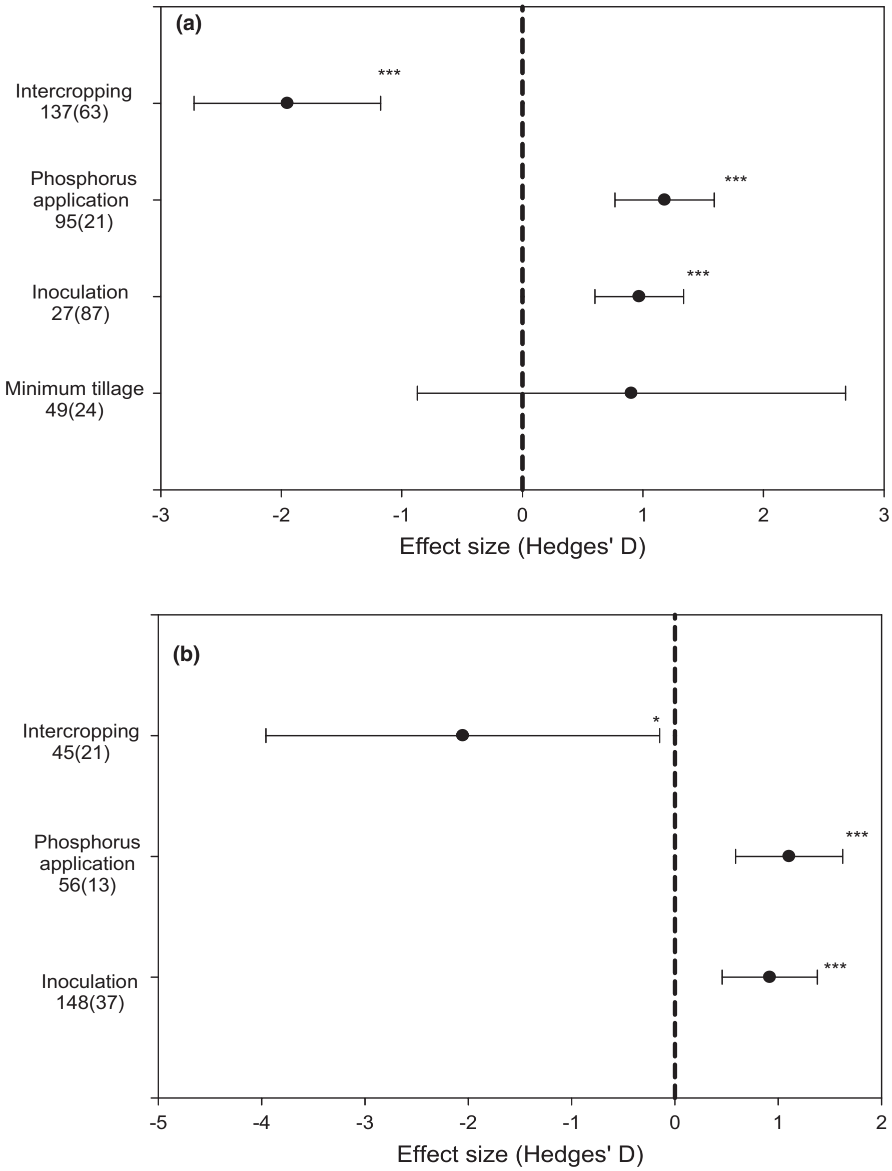

FIGURE 3 Effect of different management practices on (a) grain and (b) biomass yield of legumes in sub-Saharan Africa. Asterisks are significance codes: '***' 0.001; '**' 0.01; '*' 0.05. The dashed line is $x = 0$. The number of data points is given below the management practice and the number of publications is in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero

3.4 | Inoculation

The response of legume grain yield to inoculation was assessed using 27 studies, which yielded 88 data points (Figure 3a). The average effect size was 0.9 and the results indicate that inoculation had a positive overall effect on legume grain yield ($p < 0.001$). Heterogeneity was significant ($Q = 135.5$, $p < 0.001$) and the moderators legume species, inoculant used, SOC, soil pH, clay content, altitude and rainfall were tested individually. Legume species ($QM = 24.7$, $p < 0.001$) and inoculant type ($QM = 27.3$, $p < 0.001$) explained some of the heterogeneity. The effect of inoculation increased with increasing soil pH and levels of SOC (Table 6). All types of inoculants significantly increased grain yield (Table 6). The legume species included in the analysis were soybean, cowpea, chickpea and common bean (Figure 4c). Soybean and common bean were positively affected by inoculation, cowpea was negatively affected (Figure 4c). There was a trend towards chickpea being positively affected by inoculation, however there were few data pairs and large variation in the effects of inoculation on chickpea which probably rendered it non-significant.

The effect of inoculation on biomass productivity was analysed using 37 publications, which gave 148 data points. Inoculation had a positive overall effect on biomass productivity (Figure 3b). The average effect size was 0.55 and p-value was <0.001. Heterogeneity was significant ($Q = 176.7$, $p < 0.001$) and the moderators included in the model were legume species, rainfall, soil pH, clay content, SOC, altitude and type of inoculant used. Clay content ($QM = 10.9$, $p < 0.001$), SOC ($QM = 5.3$, $p = 0.021$), legume species ($QM = 12.9$, $p = 0.012$) and inoculant type ($QM = 17.6$, $p = 0.003$)

TABLE 4 Test of how rainfall, altitude, soil organic carbon, soil pH and clay content moderates the significant effect of intercropping on legume grain and biomass yield in smallholder farming in sub-Saharan Africa

				95% CI of estimate		
Moderators	**Data pairs (*n*)**	**Estimate**	**SE**	**Lower**	**Upper**	***p***
Grain yield						
Rainfall	101	−2.437	1.317	−5.021	0.146	0.146
Altitude	65	−0.001	0.001	−0.002	0.00	0.006
Soil organic carbon	38	−0.023	0.051	−0.123	0.077	0.654
Soil pH	69	−0.135	0.593	−1.297	1.028	0.821
Clay	54	−1.133	0.890	−2.878	0.614	0.268
Biomass yield						
Rainfall	32	−0.741	1.163	−3.016	1.538	0.271
Altitude	25	−0.982	0.482	−1.926	−0.038	0.008
Soil organic carbon	18	−0.162	0.114	−0.385	0.062	0.157
Soil pH	23	−0.380	0.665	−1.682	0.923	0.568
Clay	16	−1.513	1.332	−4.124	1.096	0.196

Note: All moderators are continuous and therefore the test statistics show their linear relationships with the effect of intercropping, and whether their slopes differ from zero. CI is confidence interval and SE is standard error of the estimate.

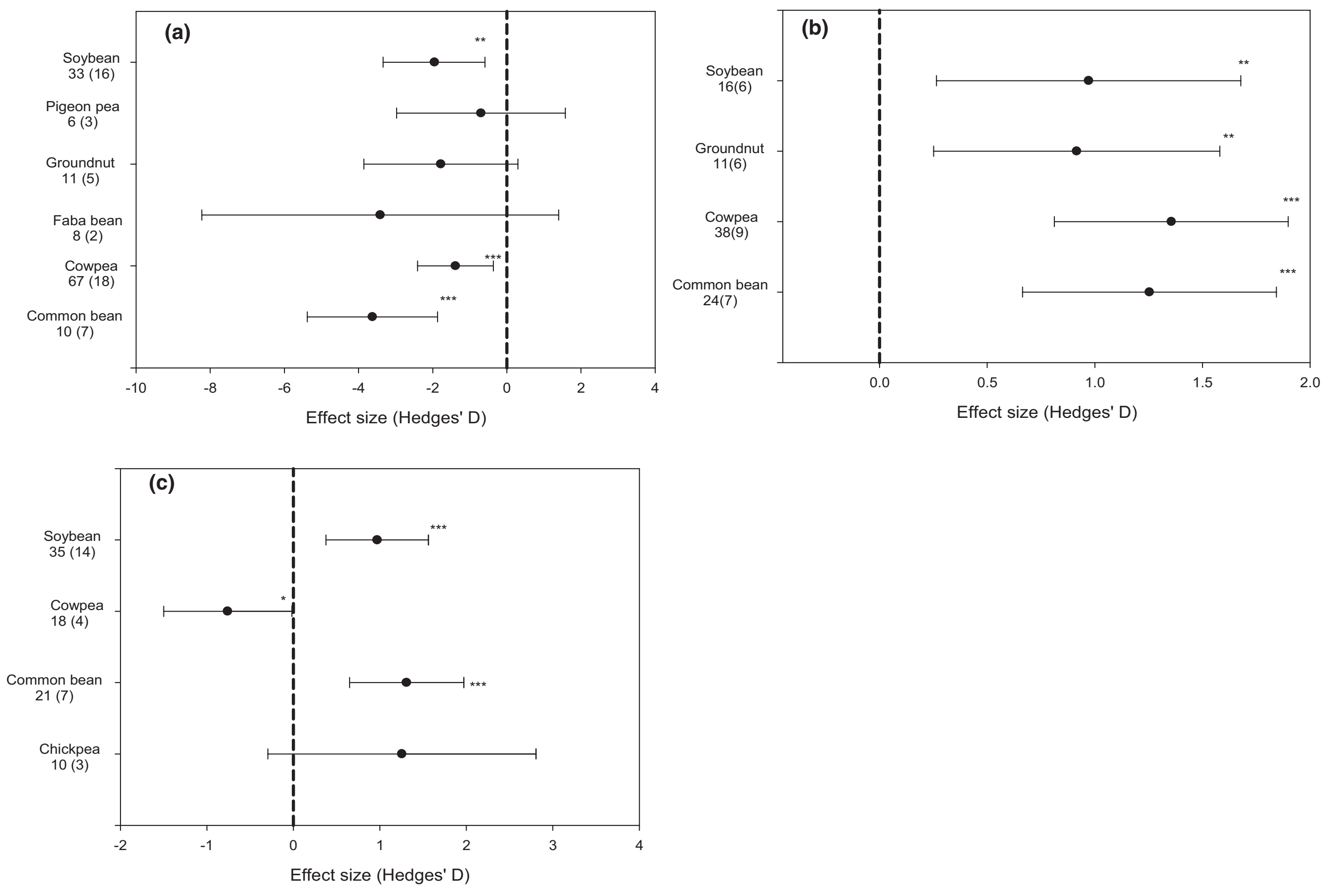

FIGURE 4 Legume species grain yield response to (a) intercropping, (b) P fertilizer application and (c) inoculation in sub-Saharan Africa. Asterisks are significance codes: '***' 0.001; '**' 0.01; '*' 0.05. The dashed line is $x = 0$. The number of data points is below the legume species and the number of publications is in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero

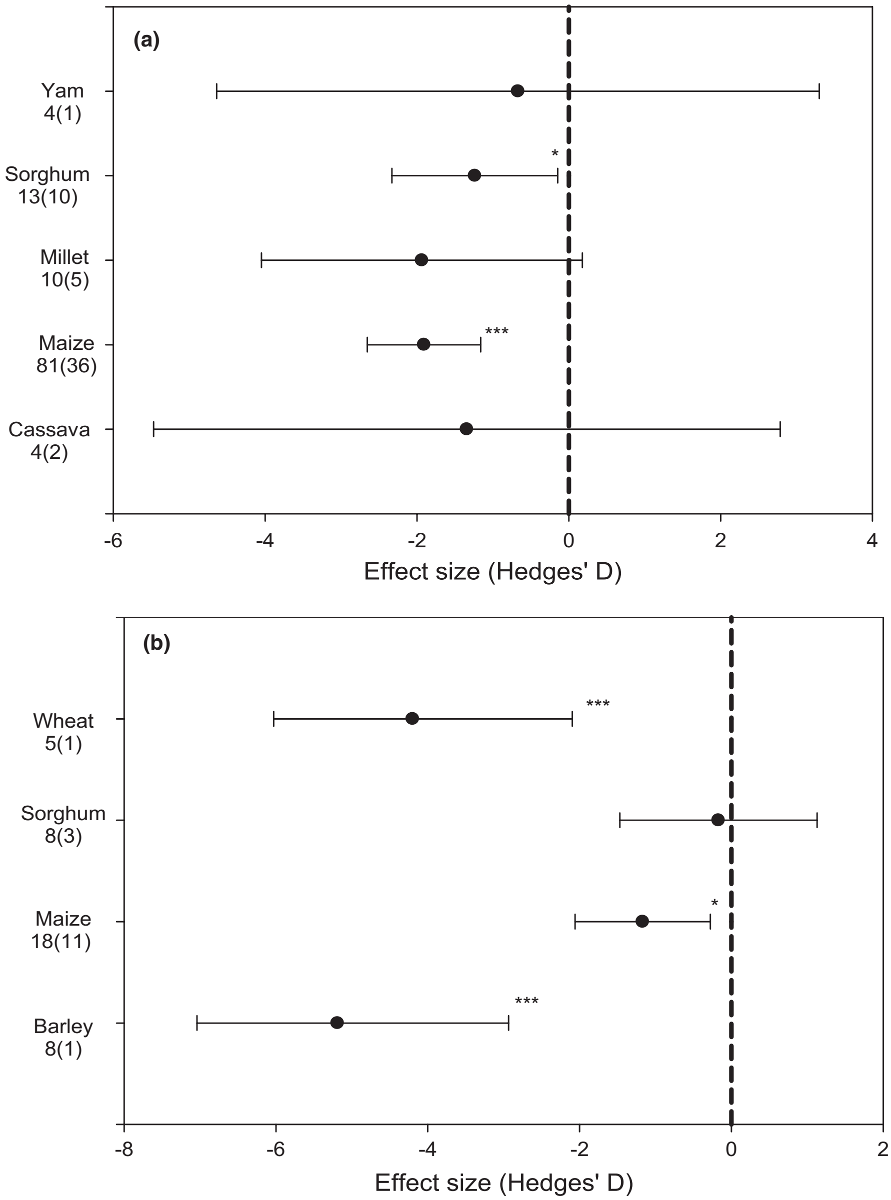

FIGURE 5 Effect of non-legume crop species on legume (a) grain and (b) biomass yield in intercropping systems in sub-Saharan Africa. Asterisks are significance codes: '***' 0.001; '**' 0.01; '*' 0.05. The dashed line is $x = 0$. The number of data points is below the legume species and the number of publications is in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero

explained further heterogeneity of biomass yield. The effect of inoculation increased with increasing SOC, but decreased with clay content (Table 6). Inoculation had a significant positive effect on groundnut and common bean biomass yield only (Figure 6c). Inoculation positively affected biomass yield with all inoculants except *Rhizobium tropici* (Table 6).

A total of 10 publications (24 data points) were used to assess the effect of inoculation on legume BNF. The results showed that inoculation had a positive effect on BNF (average effect size = 1.2, $p = 0.019$). Heterogeneity was significant ($Q = 73.6$, $p < 0.001$) and therefore annual rainfall, soil pH, SOC, legume species and soil clay content moderators were tested. Soil pH and SOC both explained significant amounts of heterogeneity ($QM = 5.1$, $p < 0.001$ and $QM = 4.9$, $p < 0.0001$) and the effect of inoculation on BNF increased with increasing soil pH and SOC (Table 6).

3.5 | Minimum tillage

Minimum tillage had no significant effect on legume grain yield compared with conventional ploughing and the average effect size was 0.9 (Figure 3a). A total of 24 publications, yielding 49 data points, were included in the analysis and heterogeneity was significant ($Q = 294.8$, $p < 0.001$). However, none of the moderators tested (SOC, annual rainfall, soil pH, clay content and legume species) explained the observed heterogeneity. There were not enough studies available to analyse the effect of minimum tillage on legume biomass productivity or BNF.

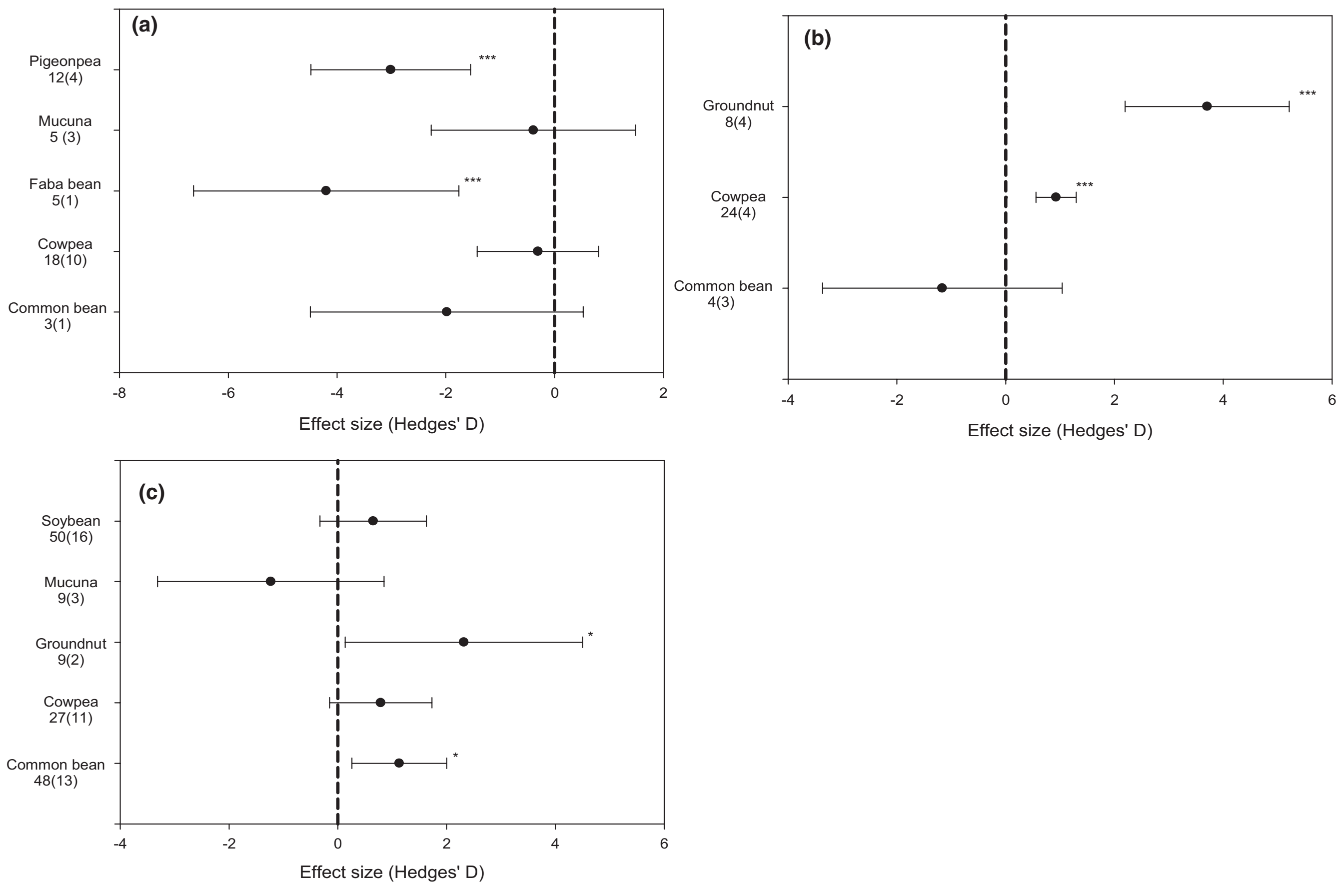

FIGURE 6 Legume species biomass yield response to (a) intercropping, (b) P fertilizer application and (c) inoculation in sub-Saharan Africa. Asterisks are significance codes: '***' 0.001; '**' 0.01; '*' 0.05. The dashed line is $x = 0$. The number of data points is below the legume species and the number of publications is in parenthesis. The error bars are confidence intervals and they test whether they were significantly different from zero

4 | DISCUSSION

The meta-analysis showed that intercropping, P application and inoculation all had significant impacts on legume productivity, but the effect of tillage was less clear. Although intercropping reduced the yield of the legume crop component, the overall grain and biomass yield was higher (totLER) than in sole cropping systems. The effects of the factors investigated were in general heterogeneous and affected by environmental and management moderators.

4.1 | Effect of intercropping on total LER, legume grain and biomass yield

The totLER of intercrops with legumes in the species mixture was >1, which shows that including legumes as companion crops increased overall productivity compared with sole crops in studies performed across a range of environmental and management conditions in SSA farming systems. These results support those of, for example, Himmelstein et al. (2017), Kermah et al. (2017) and Masvaya et al. (2017), who reported that intercropping has a positive overall effect on total yield. High productivity in intercrops can be related to reduction in weed and disease pressure (Agegnehu et al., 2008), soil conservation and maintenance (Muoni et al., 2020), nutrient capture and maximizing resource use efficiency (Chimonyo et al., 2016; Kermah et al., 2017).

The studies by Himmelstein et al. (2017), Kermah et al. (2017) and Masvaya et al. (2017) all used the totLER metrics to reach the conclusion that intercropping has a positive effect on productivity, however totLER assumes that the yields of the two crops in intercrops are proportional to those obtained when grown as sole crops (Mead & Willey, 1980) which might not be the case. Although totLER shows the overall productivity of the intercrops, rLER (individual species LER) helps to assess how individual species are performing in the intercrops.

The rLER results show that individual legume species responded differently to intercropping. Faba bean rLER was more negatively affected by intercropping than other species. The sensitivity of faba bean to competition during

TABLE 5 Test of how rainfall, altitude, soil organic carbon, soil pH, clay content and P application level moderates the significant effect of P application on legume grain and biomass yield in smallholder farming in sub-Saharan Africa

Moderators	Data pairs (*n*)	Estimate	SE	95% CI of estimate		*p*
				Lower	Upper	
Grain yield						
Rainfall	64	−0.001	0.001	−0.002	0.000	0.102
Altitude	63	0.891	1.154	−1.372	3.153	0.249
Soil organic carbon	72	1.718	0.263	1.222	2.329	0.002
Soil pH	87	1.598	1.415	−0.949	4.597	0.717
Clay	72	2.307	0.906	−0.519	4.093	0.090
P application level	94	−0.002	0.006	−0.015	0.010	0.695
Biomass yield						
Rainfall	45	0.001	0.001	−0.002	0.004	0.442
Altitude	29	−0.032	0.002	−0.036	−0.028	<0.001
Soil organic carbon	33	−0.098	0.048	−0.192	−0.005	0.039
P application level	55	0.062	0.021	−0.021	0.104	0.793
Soil pH	51	0.167	0.285	−0.391	0.726	0.557
Clay	42	0.054	0.028	−0.001	0.108	0.055

Note: All moderators are continuous and therefore the test statistics show their linear relationships with the effect of P application and whether their slopes differ from zero. CI is confidence interval and SE is standard error of the estimate.

the first two to three months of growth (Xiao et al., 2018) might contribute to this. Pigeonpea was not significantly affected by intercropping. Groundnut, soybean and cowpea had similar rLER values that were significantly lower than for pigeonpea. This could be because these crops have similar rooting depth to the non-legume crops, thus there could be more competition for resources with the non-legume crops than in pigeonpea which has a deeper root system (Singh et al., 2020). Moreover, since these crops are usually grown at narrower spacing in sole crops than in intercropping systems, plant density is generally lower than in sole crop systems.

Another reason why pigeonpea might be less affected than other legumes by the non-legume crops is that it is generally sown at a wider row spacing than other legumes and therefore a similar sowing density can be used in sole cropping and in intercropping with row crops like maize and sorghum (Rusinamhodzi et al., 2017). Pigeonpea has a slow initial growth rate and is a non-climber hence there will be little competition for resources with non-legume crops which grow rapidly in the early season (Jat et al., 2011; Kimaro et al., 2009; Saxena et al., 2018). However, in cases where pigeonpea is intercropped with crops with a slow initial growth rate, such as cassava, there is likely to be strong competition between the crops which will affect the yield (Cenpukdee & Fukai, 1992). Pigeonpea eventually produces a deep root system which helps it to exploit water and nutrient supply from the deeper horizons than the companion crops which can compensate for slow early growth with strong growth later in the season (Sekiya & Yano, 2004). Intercropping can be of particular importance in reducing disease prevalence in legumes. For example, sorghum reduces *Fusarium udum* that can severely damage pigeonpea grown as a sole crop (Saxena et al., 2018). Thus, pigeonpea shows many benefits for farmers in SSA when grown as an intercrop. However, its use is restricted by availability of certified seeds (Kaoneka et al., 2016).

When the non-legume crop species were included as moderators to explain some of the heterogeneity in the results of the meta-analysis, we found that maize and sorghum, which are among the most common cereals grown in SSA, significantly reduced the legume grain yields. This is largely due to interspecies competition since maize and sorghum are generally grown with the same density in intercrops as in sole crops, while for legume crops, seed rates are generally reduced in the intercrop. In terms of food security, farmers in SSA favour maize and sorghum rather than grain legumes as staples (Adebo, 2020; Kihara et al., 2020). Therefore, farmers tend to manage these crops to increase production of the cereal rather than the legumes (Snapp et al., 2018). The compatibility of legume species with other crops in intercropping can be increased through breeding varieties specifically for intercropping (Lithourgidis et al., 2011; Saxena et al., 2018), for example, breeding for traits such as high specific leaf area, chlorophyll content and reduced chlorophyll a/b ratio (Gong et al., 2015). Also developing novel management practices including novel spatial

TABLE 6 Test of how rainfall, altitude, soil organic carbon, soil pH, clay content, and inoculant moderates the significant effect of inoculation with rhizobia on legume grain and biomass yield and biological nitrogen fixation in smallholder farming in sub-Saharan Africa

				95% CI of estimate		
Moderators	**Data pairs (*n*)**	**Estimate**	**SE**	**Lower**	**Upper**	***p***
Grain yield						
Rainfall	47	0.155	0.937	−1.683	1.991	0.822
Altitude	42	0.998	0.888	−0.741	2.738	0.472
Soil organic carbon	50	0.071	0.027	0.017	0.124	0.009
Soil pH	71	0.096	0.044	0.01	0.181	0.028
Clay	46	−0.155	0.705	−1.536	1.226	0.774
Inoculant:						
Bradyrhizobium	40	0.841	0.223	0.404	1.277	<0.001
Mesorhizobium	9	1.520	0.572	0.399	2.640	0.008
Rhizobium	36	1.001	0.270	0.471	1.530	<0.001
Biomass yield						
Rainfall	39	0.001	0.001	0.000	0.002	0.083
Altitude	47	0.532	0.53	−0.507	1.571	0.833
Soil organic carbon	74	0.100	0.014	0.072	0.127	<0.001
Soil pH	105	0.007	0.059	−0.109	0.123	0.91
Clay	76	−0.561	0.645	−1.825	−0.702	<0.001
Inoculant:						
Bradyrhizobium	43	0.516	0.201	0.121	0.911	0.010
Rhizobium	52	0.926	0.295	0.347	1.505	0.002
Rhizobium gallicum	17	4.099	0.906	2.322	5.875	<0.001
Rhizobium tropici	12	0.529	0.403	−0.261	1.320	0.190
Biological nitrogen fixation						
Rainfall	8	3.378	11.145	−18.467	25.222	0.851
Soil organic carbon	20	0.629	0.128	0.378	0.880	<0.001
Soil pH	20	0.432	0.116	0.204	0.506	<0.001
Clay	21	2.687	1.312	0.117	5.257	0.823

Note: All moderators except inoculant are continuous and therefore the test statistics show their linear relationships with the effect of inoculation with rhizobia and whether their slopes differ from zero. Inoculant is a categorical moderator and then the test statistics show the effect size metrics for each level and whether they differ from zero. CI is confidence interval and SE is standard error of the estimate.

and temporal arrangements (Satorre, 2013) are viable options for designing productive legume-based intercrops.

Other moderators that explained some of the heterogeneity in the effects of intercropping on legume grain and biomass yield were soil pH and SOC. With increasing SOC and soil pH, the negative effect of intercropping on legume grain and biomass yields decreased. Since both high SOC and pH are related to soil fertility, it can be assumed that nutrients needed for legume growth and BNF are less limited at higher levels of SOC and soil pH (Voltr et al., 2021). The non-legume component crops are typically better nutrient scavengers than legumes and nutrient-poor conditions therefore favour the non-legume component compared to the legume when grown in a mixture (Jensen et al., 2020).

Our result also showed that the negative effects of intercropping on legume grain and biomass yield increased with altitude. High altitude is associated with a decrease in temperature which can affect crop performance and yield. The high-altitude studies (>2000 m.a.s.l) represent 15% of the dataset included in this analysis and they mainly focused on intercropping of faba bean.

4.2 | Effects of phosphorus application on legume grain and biomass yield

Phosphorus application had an overall positive effect on legume grain and biomass yield which is not unexpected given the low P status in most soils in SSA (Jones et al., 2013). Although many farmers in SSA utilize fertilizers and organic amendments including composts, animal manure and crop residues as sources of P, the quantities are often too low to meet the demands (Nziguheba et al., 2016).

Application of P-containing fertilizer increases the availability of P for plant uptake. However, testing P application level as a moderator did not further explain the variation in legume grain yield response to P application. This suggests that some studies may have applied more P than the crops required.

Soil organic carbon further explained the variation in the effect of P application on legume grain and biomass yield. While the effects on the grain yield increased with SOC, a negative relation was found between SOC and biomass yield. These results agree with Yang et al., (2019) who reported that soil organic matter influences the adsorption and desorption of P and thereby the availability of P to crops.

Although literature indicates that P levels increase BNF (Kolawole, 2012; Rurangwa et al., 2018; Snapp et al., 2018), we could not conduct a meta-analysis of the effects of P application on BNF in SSA because there were relatively few published studies available from this geographical area.

4.3 | Effects of inoculation on legume grain and biomass yield and biologically fixed nitrogen

Our overall analysis showed that inoculation of legumes at sowing increases grain and biomass yield, and BNF. When type of inoculant (*Rhizobium* species) was included as a moderator, the heterogeneity in the response was further explained. Vanlauwe et al. (2019) found that the exotic and indigenous strains used in inoculants survive in a wide range of soil types. The effect of inoculation on biomass yield was negatively affected by soil clay content. This might be due to low soil N in course-textured soils low in clay, which encourages more BNF in these soils to meet the N demands of the crops (Mapfumo et al., 2000). Differences in past field management practices affect rhizobial strains involved in BNF (Kermah et al., 2018). Although the rhizobial strains can survive in a wide range of soils, re-inoculation is necessary within a short space of time (Zengeni et al., 2006).

Some legume species respond better to inoculation in terms of grain and biomass yield than others as we observed in this analysis (Vanlauwe et al., 2019). Only soybean and common bean responded positively to inoculation. However, other authors have shown that common bean do not always respond positively to inoculation as the imported rhizobia are not always able to survive in the harsh soil conditions (Chekanai et al., 2018; Vanlauwe et al., 2019). Cowpea can form symbiotic N fixing relationships with a wide range of rhizobial strains (Laranjo et al., 2008; Ndungu et al., 2018) and un-inoculated cowpea may produce reasonable yields in association with existing soil rhizobia. Results of the meta-analysis on effects of inoculation for chickpea were not significant, however this could be related to the few data points in the analysis, since it is known that chickpea requires a specific strain (*Mesorhizobium*) for N fixation (Giller, 2001).

4.4 | Effects of minimum tillage on legume productivity

Our analysis suggests that minimum tillage had no effect on legume grain yields, but publication bias results indicate that there is a need for more studies before drawing firm conclusions. Minimum tillage reduces disturbance of rhizobial populations which improves the build-up of established strains (Van Kessel & Hartley, 2000). In our analysis, the duration of the studies for this topic ranged between 1 and 7 years and they had no significant effect on grain yield. Thus, there is a need for further assessment of the impact of minimum tillage on legume productivity and how this interacts with other management factors in the short- and long term.

5 | CONCLUSIONS

Given predicted pressure on land use, it is critical to understand what may constrain future agricultural productivity and food production growth in developing countries. Key to sustaining livelihoods and supporting soil health in SSA is the management of legume crops to obtain protein-rich food, fodder and soil fertility benefits. Compared to sole crops, intercropping was found to increase the total productivity (totLER), but reduce legume grain and biomass yield to different extents depending on crop species. The rLER ranged from 0.9 for pigeonpea to 0.3 for faba bean with soybean, cowpea, groundnut and common bean being intermediate (rLER 0.60–0.65). P application and inoculation (with *Rhizobium* species) positively affected legume grain and biomass yield and BNF (inoculation) across diverse farm and farming conditions in SSA. The heterogeneity in the results was explained by moderators such as legume species, non-legume crop in intercropping, type of inoculant used, SOC and soil pH. Based on the results we can conclude that:

Intercropping resulted in a higher total yield (totLER), but lowered legume crop grain and biomass yield (rLER) compared to sole legume cropping. There were large differences in yield reduction between legume species (pigeonpea < soybean, cowpea, groundnut, common bean < faba bean) which was also affected by the non-legume crop where maize and sorghum significantly reduced legume yield. The high totLER in legume intercropping shows the potential to improve overall crop productivity in smallholder farms making it an attractive option for adoption. Pigeonpea is particularly compatible for intercropping because its yield is only reduced to a small degree due to different crop growth habits and differences in time of demand for resources when grown with non-legume crops like sorghum and maize.

Phosphorus application was found to be crucial for legume productivity in SSA, and all legume species included in the analysis responded positively to the addition of P. Soil pH and SOC increased the effect of P application on legume grain yields, thus these soil fertility factors seem to be crucial to improving legume productivity.

Inoculation helped to increase legume grain yield, biomass yield and BNF for some legume crop species (e.g. soybean and common bean). Variation in legume grain and biomass yield and BNF response to inoculation were related to one or more of the factors SOC, type of inoculant used and soil pH where higher levels enhanced the effect of inoculants.

Few studies were found which assessed the effect of minimum tillage on legume productivity. This is because in SSA legume crops are commonly used as support crops for other staple food crops including maize and cassava. Hence, there is need for further research on how legumes respond to minimum tillage in SSA.

By combining studies from different parts of SSA in a meta-analysis, we can conclude that despite the heterogeneity of farming systems, environmental and socio-economic conditions, legumes respond consistently to intercropping, P application and inoculation management practices. The study also elucidated factors (moderators) explaining some of the heterogeneity in the response to the management practices which can be utilized to tailor recommendations. Even though the management practices studied generally increased productivity in terms of legume grain and biomass yield and BNF (inoculation), tailored adaptive management in terms of legume and non-legume crop species selection for intercropping, type of inoculant used and improving soil conditions (increase SOC and pH) will further improve the effects of the studied management practices.

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CONFLICT OF INTEREST

Authors declare no conflict of interest exists.

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ENDNOTE

[1] Angola OR Benin OR Botswana OR 'Burkina Faso' OR Burundi OR Cameroon OR 'Central African Republic' OR Chad OR Comoros OR 'Congo Brazzaville' OR 'Democratic Republic of Congo' OR DRC OR 'Côte d'Ivoire' OR Djibouti OR 'Equatorial Guinea' OR Eritrea OR Ethiopia OR Gabon OR Gambia OR Ghana OR Guinea OR 'Guinea-Bissau' OR Kenya OR Lesotho OR Liberia OR Libya OR Madagascar OR Malawi OR Mali OR Mauritania OR Mauritius OR Mozambique OR Namibia OR Niger OR Nigeria OR Rwanda OR 'Sao Tome and Principe' OR Senegal OR Seychelles OR 'Sierra Leone' OR Somalia OR 'South Africa' OR 'South Sudan' OR Sudan OR Swaziland OR Tanzania OR Togo OR Tunisia OR Uganda OROR Zambia OR Zimbabwe.

REFERENCES

Adebo, O. A. (2020). African sorghum-based fermented foods: Past, current and future prospects. *Nutrients*, *12*(4), 1111. https://doi.org/10.3390/nu12041111

Agegnehu, G., Ghizaw, A., & Sinebo, W. (2008). Yield potential and land-use efficiency of wheat and faba bean mixed intercropping. *Agronomy for Sustainable Development*, *28*, 257–263. https://doi.org/10.1051/agro:2008012

Andrews, M., & Andrews, M. E. (2017). Specificity in legume-rhizobia symbioses. *International Journal of Molecular Sciences*, *18*, 705. https://doi.org/10.3390/ijms18040705

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Pkth, P., Smaling, E., Thiom-biano, L., & Waswa, B. (2012). Knowing the African soils to improve fertilizer recommendations. In J. Kihara (Ed.), *Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa Improving soil fertility recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT)* (pp. 19–42). Springer.

Borenstein, M., Hedges, L. V., Higgins, J. P., & Rothstein, H. R. (2011). *Introduction to meta-analysis*. John Wiley & Sons, https://doi.org/10.1002/9780470743386

Brooker, R. W., Bennett, A. E., Cong, W.-F., Daniell, T. J., George, T. S., Hallett, P. D., Hawes, C., Iannetta, P. P. M., Jones, H. G., Karley, A. J., Li, L., McKenzie, B. M., Pakeman, R. J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C. A., Zhang, C., … White, P. J. (2015). Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*, *206*, 107–117. https://doi.org/10.1111/nph.13132

Cenpukdee, U., & Fukai, S. (1992). Cassava/legume intercropping with contrasting cassava cultivars. 1. Competition between component crops under three intercropping conditions. *Field Crops Research*, *29*, 113–133. https://doi.org/10.1016/0378-4290(92)90082-K

Chekanai, V., Chikowo, R., & Vanlauwe, B. (2018). Response of common bean (*Phaseolus vulgaris* L.) to nitrogen, phosphorus and rhizobia inoculation across variable soils in Zimbabwe. *Agriculture, Ecosystems & Environment*, *266*, 167–173. https://doi.org/10.1016/j.agee.2018.08.010

Chimonyo, V. G. P., Modi, A. T., & Mabhaudhi, T. (2016). Water use and productivity of a sorghum–cowpea–bottle gourd intercrop system. *Agricultural Water Management*, *165*, 82–96. https://doi.org/10.1016/j.agwat.2015.11.014

Christiaensen, L., & Demery, L. (2018). *Agriculture in Africa: Telling myths from facts, Directions in Development ed*. The World Bank.

Daryanto, S., Wang, L., & Jacinthe, P.-A. (2015). Global synthesis of drought effects on food legume production. *PLoS One*, *10*(6), e0127401. https://doi.org/10.1371/journal.pone.0127401

De Costa, W. A. J. M., & Surenthran, P. (2005). Tree-crop interactions in hedgerow intercropping with different tree species and tea in Sri Lanka: 1. Production and Resource Competition. *Agroforestry Systems*, *63*, 199–209. https://doi.org/10.1007/s10457-005-1090-8

Dordas, C. (2008). Role of nutrients in controlling plant diseases in sustainable agriculture. A review. *Agronomy for Sustainable Development*, *28*, 33–46. https://doi.org/10.1051/agro:2007051

Ferreira, M. C., de S. Andrade, D., de O. Chueire, L. M., Takemura, S. M., & Hungria, M. (2000). Tillage method and crop rotation effects on the population sizes and diversity of bradyrhizobia nodulating soybean. *Soil Biology & Biochemistry*, *32*, 627–637. https://doi.org/10.1016/S0038-0717(99)00189-3

Finckh, M. R., & Wolfe, M. S. (2017). CHAPTER 4.4: Biodiversity enhancement. In *Plant diseases and their management in organic agriculture, IPM* (pp. 153–174). The American Phytopathological Society. https://doi.org/10.1094/9780890544785.013

Franke, A. C., van den Brand, G. J., Vanlauwe, B., & Giller, K. E. (2018). Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agriculture, Ecosystems & Environment*, *261*, 172–185. https://doi.org/10.1016/j.agee.2017.09.029

Giller, K. E. (2001). *Nitrogen fixation in tropical cropping systems*. CAB International.

Gleser, L., & Olkin, I. (2009). Stochastically dependent effect sizes. In H. Cooper, L. V. Hedges, & J. C. Valentine (Eds.), *The Handbook of Research Synthesis and Meta-Analysis* (pp. 357–376). Russell Sage Foundation.

Gong, W. Z., Jiang, C. D., Wu, Y. S., Chen, H. H., Liu, W. Y., & Yang, W. Y. (2015). Tolerance vs. avoidance: two strategies of soybean (*Glycine max*) seedlings in response to shade in intercropping. *Photosynthetica*, *53*, 259–268. https://doi.org/10.1007/s11099-015-0103-8

Graham, P. H., & Vance, C. P. (2003). Legumes: Importance and constraints to greater use. *Plant Physiology*, *131*, 872–877. https://doi.org/10.1104/pp.017004

Hassen, A., Talore, D. G., Tesfamariam, E. H., Friend, M. A., & Mpanza, T. D. E. (2017). Potential use of forage-legume intercropping technologies to adapt to climate-change impacts on mixed crop-livestock systems in Africa: a review. *Regional Environmental Change*, *17*, 1713–1724. https://doi.org/10.1007/s10113-017-1131-7

Hauggaard-Nielsen, H., Ambus, P., & Jensen, E. S. (2001). Interspecific competition, N use and interference with weeds in pea–barley intercropping. *Field Crops Res*, *70*, 101–109. https://doi.org/10.1016/S0378-4290(01)00126-5

Hauggaard-Nielsen, H., Andersen, M. K., Jørnsgaard, B., & Jensen, E. S. (2006). Density and relative frequency effects on competitive interactions and resource use in pea–barley intercrops. *Field Crops Research*, *95*, 256–267. https://doi.org/10.1016/j.fcr.2005.03.003

Herrero, M., Thornton, P. K., Notenbaert, A. M., Wood, S., Msangi, S., Freeman, H. A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Rao, P. P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., & Rosegrant, M. (2010). Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science*, *327*, 822–825. https://doi.org/10.1126/science.1183725

Heydari, M. M., Brook, R. M., & Jones, D. L. (2019). The role of phosphorus sources on root diameter, root length and root dry matter of barley (*Hordeum vulgare* L.). *Journal of Plant Nutrition*, *42*, 1–15. https://doi.org/10.1080/01904167.2018.1509996

Himmelstein, J., Ares, A., Gallagher, D., & Myers, J. (2017). A meta-analysis of intercropping in Africa: impacts on crop yield, farmer income, and integrated pest management effects. *International Journal of Agricultural Sustainability*, *15*, 1–10. https://doi.org/10.1080/14735903.2016.1242332

Hinsinger, P., Brauman, A., Devau, N., Gérard, F., Jourdan, C., Laclau, J.-P., Le Cadre, E., Jaillard, B., & Plassard, C. (2011). Acquisition of phosphorus and other poorly mobile nutrients by roots. Where do plant nutrition models fail? *Plant and Soil*, *348*, 29. https://doi.org/10.1007/s11104-011-0903-y

Jat, R., Meena, H., Singh, A., Surya, J. N., & Misra, J. (2011). Weed management in groundnut (*Arachis hypogaea* L.) in India - a review. *Agricultural Review*, *32*, 155–171.

Jensen, E. S., Carlsson, G., & Hauggaard-Nielsen, H. (2020). Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. *Agronomy for Sustainable Development*, *40*, 5. https://doi.org/10.1007/s13593-020-0607-x

Jones, A., Breuning-Madsen, H., Brossard, A., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M., & Zougmore, R. (2013). *Soil atlas of Africa*. European Commission, Publications Office of the European Union, Luxembourg.

Justes, E., Bedoussac, L., Dordas, C., Frak, E., Louarn, G., Boudsocq, S., Journet, E.-P., Lithourgidis, A., Pankou, C., & Zhang, C. (2021). The 4C approach as a way to understand species interactions determining intercropping productivity. *Frontiers of Agricultural Science and Engineering*, *8*, 387–399.

Kaoneka, S. R., Saxena, R. K., Silim, S. N., Odeny, D. A., Ganga Rao, N. V. P. R., Shimelis, H. A., Siambi, M., & Varshney, R. K. (2016). Pigeonpea breeding in eastern and southern Africa: challenges and opportunities. *Plant Breed*, *135*, 148–154. https://doi.org/10.1111/pbr.12340

Kermah, M., Franke, A. C., Adjei-Nsiah, S., Ahiabor, B. D. K., Abaidoo, R. C., & Giller, K. E. (2017). Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. *Field Crops Res*, *213*, 38–50. https://doi.org/10.1016/j.fcr.2017.07.008

Kermah, M., Franke, A. C., Adjei-Nsiah, S., Ahiabor, B. D. K., Abaidoo, R. C., & Giller, K. E. (2018). N2-fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana. *Agriculture, Ecosystems & Environment*, *261*, 201–210. https://doi.org/10.1016/j.agee.2017.08.028

Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., & Piikki, K. (2020). Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. *Environmental Geochemistry and Health*, *42*(9), 3015–3033. https://doi.org/10.1007/s10653-019-00499-w

Kimaro, A., Timmer, V., Chamshama, S., Ngaga, Y., & Kimaro, D. (2009). Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops. *Agriculture, Ecosystems & Environment*, *134*, 115–125. https://doi.org/10.1016/j.agee.2009.06.002

Kolawole, G. O. (2012). Effect of phosphorus fertilizer application on the performance of maize/soybean intercrop in the southern Guinea savanna of Nigeria. *Archives of Agronomy and Soil Science*, *58*, 189–198. https://doi.org/10.1080/03650340.2010.512723

Koricheva, J., Gurevitch, J., & Mengersen, K. (2013). *Handbook of meta-analysis in ecology and evolution*. Princeton University Press.

Kuyah, S., Sileshi, G. W., Nkurunziza, L., Chirinda, N., Ndayisaba, P. C., Dimobe, K., & Öborn, I. (2021). Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A Review. *Agronomy for Sustainable Development*, *41*(2), 1–21. https://doi.org/10.1007/s13593-021-00673-4

Laranjo, M., Alexandre, A., Rivas, R., Velázquez, E., Young, J. P. W., & Oliveira, S. (2008). Chickpea rhizobia symbiosis genes are highly conserved across multiple Mesorhizobium species. *FEMS Microbiology Ecology*, *66*, 391–400. https://doi.org/10.1111/j.1574-6941.2008.00584.x

Lithourgidis, A. S., Dordas, C. A., Damalas, C. A., & Vlachostergios, D. N. (2011). Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*, *5*, 396–410.

Mapfumo, P., Mpepereki, S., & Mafongoya, P. (2000). Pigeonpea rhizobia prevalence and crop response to inoculation in Zimbabwean smallholder-managed soils. *Experimental Agriculture*, *36*(4), 423–434. https://doi.org/10.1017/S0014479700001009

Masvaya, E. N., Nyamangara, J., Descheemaeker, K., & Giller, K. E. (2017). Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa? *Field Crops Research*, *209*, 73–87. https://doi.org/10.1016/j.fcr.2017.04.016

Mead, R., & Willey, R. (1980). The concept of a 'land equivalent ratio' and advantages in yields from intercropping. *Experimental Agriculture*, *16*(3), 217–228. https://doi.org/10.1017/S0014479700010978

Mhango, W. G., Snapp, S. S., & Phiri, G. Y. K. (2013). Opportunities and constraints to legume diversification for sustainable maize production on smallholder farms in Malawi. *Renewable Agriculture and Food Systems*, *28*, 234–244. https://doi.org/10.1017/S1742170512000178

Muoni, T., Barnes, A. P., Öborn, I., Watson, C. A., Bergkvist, G., Shiluli, M., & Duncan, A. J. (2019). Farmer perceptions of legumes and their functions in smallholder farming systems in east Africa. *International Journal of Agricultural Sustainability*, *1–14*, https://doi.org/10.1080/14735903.2019.1609166

Muoni, T., Koomson, E., Oborn, I., Marohn, C., Watson, C., Bergkvist, G., Barnes, A., Cadisch, G., & Duncan, A. J. (2020). Reducing soil erosion in smallholder farming systems in east Africa through the introduction of different crop types. *Experimental Agriculture*, *56*(2), 183–195. https://doi.org/10.1017/S0014479719000280

Ndungu, S. M., Messmer, M. M., Ziegler, D., Gamper, H. A., Mészáros, É., Thuita, M., Vanlauwe, B., Frossard, E., & Thonar, C. (2018). Cowpea (*Vigna unguiculata* L. Walp) hosts several widespread bradyrhizobial root nodule symbionts across contrasting agro-ecological production areas in Kenya. *Agriculture, Ecosystems & Environment*, *261*, 161–171. https://doi.org/10.1016/j.agee.2017.12.014

Nziguheba, G., Zingore, S., Kihara, J., Merckx, R., Njoroge, S., Otinga, A., Vandamme, E., & Vanlauwe, B. (2016). Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification. *Nutrient Cycling in Agroecosystems*, *104*, 321–340. https://doi.org/10.1007/s10705-015-9729-y

Odendo, M., Bationo, A., & Kimani, S. (2011). Socio-Economic Contribution of Legumes to Livelihoods in Sub-Saharan Africa. In A. Bationo, B. Waswa, J. M. Okeyo, F. Maina, J. Kihara, & U. Mokwunye (Eds.), *Fighting Poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management* (pp. 27–46). Springer Netherlands. https://doi.org/10.1007/978-94-007-1536-3_2

Ojiem, J. O., Franke, A. C., Vanlauwe, B., de Ridder, N., & Giller, K. E. (2014). Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. *Field Crops Research*, *168*, 75–85. https://doi.org/10.1016/j.fcr.2014.08.004

Ojiem, J. O., Vanlauwe, B., de Ridder, N., & Giller, K. E. (2007). Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. *Plant and Soil*, *292*, 119–135. https://doi.org/10.1007/s11104-007-9207-7

Okalebo, J. R., Othieno, C. O., Woomer, P. L., Karanja, N. K., Semoka, J. R. M., Bekunda, M. A., Mugendi, D. N., Muasya, R. M., Bationo, A., & Mukhwana, E. J. (2007). Available technologies to replenish soil fertility in East Africa. In A. Bationo, B. Waswa, J. Kihara, & J. Kimetu (Eds.), *Advances in integrated soil fertility management in Sub-Saharan Africa: Challenges and opportunities* (pp. 45–62). Springer Netherlands.

Orwin, R. G. (1983). A fail-safe N for effect size in meta-analysis. *Journal of Educational Statistics*, *8*, 157–159.

Oyejola, B. A., & Mead, R. (1982). Statistical Assessment of Different Ways of Calculating Land Equivalent Ratios (LER). *Experimental Agriculture*, *18*, 125–138. https://doi.org/10.1017/S0014479700013600

Penn, C. J., & Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture*, *9*, 120. https://doi.org/10.3390/agriculture9060120

Perie, C., & Ouimet, R. (2008). Organic carbon, organic matter and bulk density relationships in boreal forest soils. *Canadian Journal of Soil Science*, *88*, 315–325. https://doi.org/10.4141/CJSS06008

Rohatgi, A. (2015). WebPlotDigitizer User Manual Version 3.9. *URL HttparohatgiinfoWebPlotDigitizer*, 1–23.

Ronner, E., Franke, A. C., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., Bala, A., van Heerwaarden, J., & Giller, K. E. (2016). Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. *Field Crops Research*, *186*, 133–145. https://doi.org/10.1016/j.fcr.2015.10.023

Rurangwa, E., Vanlauwe, B., & Giller, K. E. (2018). Benefits of inoculation, P fertilizer and manure on yields of common bean and soybean also increase yield of subsequent maize. *Agriculture, Ecosystems & Environment*, *261*, 219–229. https://doi.org/10.1016/j.agee.2017.08.015

Rusinamhodzi, L., Corbeels, M., Van Wijk, M. T., Rufino, M. C., Nyamangara, J., & Giller, K. E. (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development*, *31*, 657. https://doi.org/10.1007/s13593-011-0040-2

Rusinamhodzi, L., Makoko, B., & Sariah, J. (2017). Ratooning pigeonpea in maize-pigeonpea intercropping: Productivity and seed cost reduction in eastern Tanzania. *Field Crops Research*, *203*, 24–32. https://doi.org/10.1016/j.fcr.2016.12.001

Satorre, E. H. (2013). Spatial Crop Structure spatial crop structure in Agricultural Systems. In P. Chritou, R. Savin, B. A. Costa-Pierce, I. Misztal, & C. B. A. Whitelaw (Eds.), *Sustainable food production* (pp. 1513–1528). Springer New York. https://doi.org/10.1007/978-1-4614-5797-8_223

Saxena, K. B., Choudhary, A. K., Saxena, R. K., & Varshney, R. K. (2018). Breeding pigeonpea cultivars for intercropping: synthesis and strategies. *Breeding Science*, *68*, 159–167. https://doi.org/10.1270/jsbbs.17105

Sekiya, N., & Yano, K. (2004). Do pigeon pea and sesbania supply groundwater to intercropped maize through hydraulic lift?—Hydrogen stable isotope investigation of xylem waters. *Field Crops Research*, *86*, 167–173. https://doi.org/10.1016/j.fcr.2003.08.007

Sileshi, G., Akinnifesi, F. K., Ajayi, O. C., & Place, F. (2008). Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant and Soil*, *307*, 1–19. https://doi.org/10.1007/s11104-008-9547-y

Singh, D., Mathimaran, N., Boller, T., & Kahmen, A. (2020). Deep-rooted pigeon pea promotes the water relations and survival of shallow-rooted finger millet during drought despite strong competitive interactions at ambient water availability. *PLoS One*, *15*, e0228993. https://doi.org/10.1371/journal.pone.0228993

Snapp, S., Rahmanian, M., & Batello, C. (2018). *Pulse Crops for Sustainable Farms in Sub-Saharan Africa*. UN. https://doi.org/10.18356/6795bfaf-en

Thierfelder, C., & Wall, P. C. (2009). Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil Tillage Research*, *105*, 217–227. https://doi.org/10.1016/j.still.2009.07.007

United Nations. (2015). *Population 2030: Demographic challenges and opportunities for sustainable development planning (ST/ESA/SER.A/389)*. Economic and Social Affairs. ed. United Nations. Department of Economic and Social Affairs, Population Division.

United Nations. (2019). *World Population Prospects 2019: Highlights (ST/ESA/SER.A/423)*. UN.

Van Kessel, C., & Hartley, C. (2000). Agricultural management of grain legumes: has it led to an increase in nitrogen fixation? *Field Crops Research*, *65*, 165–181. https://doi.org/10.1016/S0378-4290(99)00085-4

Vance, C. P. (2001). Symbiotic nitrogen fixation and phosphorus acquisition. Plant nutrition in a world of declining renewable resources. *Plant Physiology*, *127*, 390. https://doi.org/10.1104/pp.010331

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K. D., Smaling, E., Woomer, P. L., & Sanginga, N. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture*, *39*, 17–24. https://doi.org/10.5367/000000010791169998

Vanlauwe, B., Hungria, M., Kanampiu, F., & Giller, K. E. (2019). The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future. *Agriculture, Ecosystems & Environment*, *284*, 106583. https://doi.org/10.1016/j.agee.2019.106583

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor Package. *Journal of Statistical Software 36*, 1–48.

Voltr, V., Menšík, L., Hlisnikovský, L., Hruška, M., Pokorný, E., & Pospíšilová, L. (2021). The Soil Organic Matter in Connection with Soil Properties and Soil Inputs. *Agronomy*, *11*, 779. https://doi.org/10.3390/agronomy11040779

Wallace, B. C., Lajeunesse, M. J., Dietz, G., Dahabreh, I. J., Trikalinos, T. A., Schmid, C. H., & Gurevitch, J. (2017). OpenMEE: Intuitive, open-source software for meta-analysis in ecology and evolutionary biology. *Methods in Ecology and Evolution*, *8*, 941–947.

Xiao, J., Yin, X., Ren, J., Zhang, M., Tang, L., & Zheng, Y. (2018). Complementation drives higher growth rate and yield of wheat and saves nitrogen fertilizer in wheat and faba bean intercropping. *Field Crops Research*, *221*, 119–129. https://doi.org/10.1016/j.fcr.2017.12.009

Yang, X., Chen, X., & Yang, X. (2019). Effect of organic matter on phosphorus adsorption and desorption in a black soil from Northeast China. *Soil Tillage Research*, *187*, 85–91. https://doi.org/10.1016/j.still.2018.11.016

Zengeni, R., Mpepereki, S., & Giller, K. E. (2006). Manure and soil properties affect survival and persistence of soyabean nodulating rhizobia in smallholder soils of Zimbabwe. *Applied Soil Ecology*, *32*, 232–242. https://doi.org/10.1016/j.apsoil.2005.06.001

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