

Romero Antonio, Miriam E.; Faye, Amy; Betancur-Corredor, Bibiana; Baumüller, Heike; von Braun, Joachim

Article — Published Version

Productivity effects of agroecological practices in Africa: insights from a systematic review and meta-analysis

Food Security

Suggested Citation: Romero Antonio, Miriam E.; Faye, Amy; Betancur-Corredor, Bibiana; Baumüller, Heike; von Braun, Joachim (2024) : Productivity effects of agroecological practices in Africa: insights from a systematic review and meta-analysis, Food Security, ISSN 1876-4525, Springer Netherlands, Dordrecht, Vol. 17, Iss. 1, pp. 207-229,
<https://doi.org/10.1007/s12571-024-01504-6>

This Version is available at:

<https://hdl.handle.net/10419/319046>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<http://creativecommons.org/licenses/by/4.0/>



Productivity effects of agroecological practices in Africa: insights from a systematic review and meta-analysis

Miriam E. Romero Antonio¹ · Amy Faye¹ · Bibiana Betancur-Corredor² · Heike Baumüller¹ · Joachim von Braun¹

Received: 26 June 2024 / Accepted: 20 October 2024 / Published online: 18 November 2024
© The Author(s) 2024

Abstract

Scholars have proposed agroecology as a promising method for promoting sustainable and socially just agricultural production systems. However, the extent to which agroecological practices will generate the yields required to ensure sufficient food globally remains unclear. This notion is particularly true in the context of Africa, where agricultural productivity is low but levels of hunger and malnutrition are high. To address this knowledge gap, this article undertakes a systematic review of empirical studies to assess the overall status of agroecology-related research in Africa. Using descriptive and meta-analytical methods, we evaluate empirical evidence on the effect of agroecological practices on land and labour productivity. Our analysis of 501 peer-reviewed articles reveals that the body of agroecology-related literature in Africa has been growing in the past 10 years from approximately 10 to more than 70 studies per annum before and after 2014, respectively, with a strong focus on East Africa, particularly Kenya. The majority of the reviewed studies relate to but do not mention agroecology in the title or abstract. Thus, solely relying on studies that use the term may introduce bias and overlook valuable research contributions to the field. The meta-analysis could identify 39 agronomic studies with 392 observations in which agroecological practices were compared to monocrop systems (defined as plots where similar plants grow alongside each other simultaneously and sequentially from one season to the next) with or without inputs as the control groups. The meta-analysis indicates that agroecological practices are associated with a positive and significant difference in land productivity, compared to that for monocrop systems especially so when monocrops are grown without inputs. However, the size and direction of yield differs by practice, crop, climatic factor, soil property and type of control.

Keywords Systematic review · Meta-analysis · Agroecology · Agricultural practices · Agroecological practices · Africa · Land productivity · Labour productivity · Fertilisers · Soil nitrogen · Soil carbon · Soil phosphorus · Soil fertility · Soil water

✉ Miriam E. Romero Antonio
mromeroa@uni-bonn.de

Amy Faye
afaye@uni-bonn.de

Bibiana Betancur-Corredor
bbetancu@uni-bonn.de

Heike Baumüller
hbaumueller@uni-bonn.de

Joachim von Braun
jvonbraun@uni-bonn.de

¹ Division of Economic and Technological Change, Center for Development Research (ZEF), University of Bonn, Genscherallee 3, D-53113 Bonn, Germany

² Division of Ecology and Natural Resources Management, Center for Development Research (ZEF), University of Bonn, Genscherallee 3, D-53113 Bonn, Germany

1 Introduction

The functioning of the current global food system generates multi-faceted and escalating environmental and health issues. The increasing incidence of disasters caused or exacerbated by the climate crisis is adversely affecting food production (Mbow et al., 2019; UNDRR, 2019). As a result, the global food system fails to produce sufficient amounts of healthy, nutritious and affordable food (FAO et al., 2020; Mannar et al., 2020) to combat hunger and malnutrition and, thereby, achieve ‘Zero Hunger’ as highlighted in Sustainable Development Goal (SDG) 2 (Hodson et al., 2023). Thus, a sustainable food system approach is required to address these multi-faceted problems (von Braun et al., 2021). To protect nature and biodiversity, an urgent need emerges to adopt sustainable production methods that generate high yields in

small areas of land without compromising the environment (Giller et al., 2021a, b; Pretty & Bharucha, 2014).

Agroecology is considered an approach to sustainable agricultural production that applies ecological principles to agriculture while promoting socially just systems and empowering diverse actors across food value chains (Altieri, 1995; Altieri & Nicholls, 2005; High Level Panel of Experts on Food Security and Nutrition [HLPE], 2019; Niggli et al., 2023). Other related approaches, such as organic (Lockeretz, 2007; Reganold & Wachter, 2016), climate-smart (FAO, 2010; Lipper et al., 2014), conservation (Hobbs et al., 2008) and regenerative (Lal, 2020) agriculture or sustainable intensification (Pretty, 1997; Garnett et al., 2013; Pretty et al., 2011), are also centred on certain aspects of sustainability (see Table S1 in the supplementary material for details on the characteristics of these approaches). However, they differ from agroecology in terms of dependence on ecological processes and external inputs, overall system design and focus on specific outcomes (Manshanden et al., 2023; Snapp et al., 2021; Wezel et al., 2015). Agroecology takes a holistic approach that encompasses the ecological, social, cultural and economic dimensions of food systems with a strong emphasis on the intensification of knowledge and the embrace of the entire global food system (Ewert et al., 2023; Wezel et al., 2015).

In Africa, a number of scholars strongly advocate for the adoption of agroecology as a means of increasing productivity, conserving natural resources on which agriculture depends and ensuring social justice and the economic viability of farming (Altieri & Nicholls, 2005; AFSA, 2016; Bjornlund et al., 2020; IPES-Food, 2020; Mdee et al., 2019; Mousseau, 2015; Peano et al., 2020; Viability Project Team, 2023). Thus far, however, this advocacy has been primarily based on isolated case studies, which does not enable the establishment of causality and limits the generalisation of findings to other contexts. Indeed, a few findings may lead scholars and practitioners to question the viability of agroecology (e.g. conservation agriculture, see Corbeels et al., 2014; Giller et al., 2009; or ecological intensification, see Ritzema et al., 2017; Tittonell & Giller, 2013). For instance, Corbeels et al. (2014) analysed conservation agriculture and illustrated that its positive impact on yields and farm income occurs over time and is not always consistent across the fields of farmers. Therefore, an intertemporal trade-off is made between potential future benefits and the immediate needs of farmers, which may lead to the non- or disadoption of conservation agriculture practices. Mugwanya (2019) even suggested that it may constitute a poverty trap for African farmers. Therefore, evidence on the impact of agroecological practices on production and poverty in Africa is inconclusive and limited. The few systematic reviews available include a few African countries or regions, employ a pre-selected list of agroecological practices and mainly

focus on the role of agroecological practices in the mitigation and adaptation of climate change (D'Annolfo et al., 2017; Debray et al., 2019; Dittmer et al., 2023; Leippert et al., 2020; Snapp et al., 2021).

The current body of research fails to offer a sufficient basis for concluding whether or not and how agroecological practices contribute to a holistically sustainable production and productivity in African food systems. To address this knowledge gap, the current article first assesses the volume and focus of the literature on agroecological practices in Africa. We then analyse their effects on land and labour productivity using descriptive and meta-analytical methods. The research focuses on yields per hectare to assess land productivity and returns to labour and net benefits to evaluate labour productivity.

The study contributes to the existing literature in the following ways. It is the first to conduct a systematic review of the literature on agroecological practices in Africa. Contrary to other reviews, it takes a broad approach for defining agroecological practices by focusing on the first six principles of agroecology (as defined by the HLPE, 2019; Table 1) as the main search criteria instead of exclusively relying on the term *agroecology* or a pre-defined list of agroecological practices. Thereby, this approach provides a more comprehensive and representative sample of available empirical evidence than those used in other reviews. Moreover, this study is the first to focus on land and labour productivity as important outcomes of the adoption of agroecological practices. Finally, the study is the first to use formal, robust meta-analytical methods for assessing the effects of land productivity as a result of agroecological practices.

2 Definition and research questions

The literature has identified different components of agroecology (CIDSE, 2018; FAO, 2018; Nicholls et al., 2017). Based on these definitions, the HLPE put forward 13 principles that encompass not only the management of the agricultural and ecological aspects of agri-food systems but also socioeconomic, cultural and political principles with a wide scope (HLPE, 2019; Wezel et al., 2020). Principles one to six specifically target the improvement of resource efficiency and the increase of resilience, that is, recycling (biomass or local renewable resources), input reduction, soil health¹, animal health, biodiversity and synergy (enhancement of beneficial biological interactions). The remaining principles

¹ Of these principles, “soil health” is the least well defined for practical analyses. To guide our categorization of practice as contributing to soil health, we considered its definition and properties in Büne-mann et al. (2018), Doran and Zeiss (2000), Karlen et al. (1997), Pankhurst et al. (1997) and Sainju et al. (2022) (as elaborated in Section 7).

Table 1 Principles of agroecology as identified by the high level panel of experts on Food Security and Nutrition (HLPE)

1. Recycling. Preferentially use local renewable resources and close (as far as possible) resource cycles of nutrients and biomass.
2. Input reduction. Reduce or eliminate dependency on purchased inputs and increase self-sufficiency
3. Soil health. Secure and enhance soil health and functioning for improved plant growth particularly by managing organic matter and enhancing soil biological activity.
4. Animal health. Ensure animal health and welfare.
5. Biodiversity. Maintain and enhance diversity of species, functional diversity and genetic resources and, thereby, maintain overall agroecosystem biodiversity in time and space at field, farm and landscape scales.
6. Synergy. Enhance positive ecological interaction, synergy, integration and complementarity among the elements of agroecosystems (animals, crops, trees, soil and water).
7. Economic diversification. Diversify on-farm incomes by ensuring that small-scale farmers have greater financial independence and value addition opportunities while enabling them to respond to demand from consumers.
8. Co-creation of knowledge. Enhance co-creation and horizontal sharing of knowledge, including local and scientific innovation, especially through farmer-to-farmer exchange.
9. Social values and diets. Build food systems based on the culture, identity, tradition, social and gender equity of local communities that provide healthy, diversified, seasonally and culturally appropriate diets.
10. Fairness. Support dignified and robust livelihoods for all actors engaged in food systems, especially small-scale food producers, based on fair trade, fair employment and fair treatment of intellectual property rights.
11. Connectivity. Ensure proximity and confidence between producers and consumers through the promotion of fair and short distribution networks and by re-embedding food systems into local economies.
12. Land and natural resource governance. Strengthen institutional arrangements to improve, including the recognition and support of family farmers, smallholders and peasant food producers as sustainable managers of natural and genetic resources.
13. Participation. Encourage social organisation and greater participation in decision-making by food producers and consumers to support decentralised governance and local adaptive management of agricultural and food systems.

Source: HLPE (2019)

cover issues related to economic diversification and social equity (Table 1).

This article does not intend to evaluate agroecology in general and, therefore, does not put forward a conceptual or operational definition of the concept. Instead, it focuses on the effect of agroecological practices on land and labour productivity at the plot level.² Conceptually, it defines agroecological practices following that of Wezel et al. (2009) as “practices or techniques that contribute to a more environmentally friendly, ecological, organic or alternative agriculture” (p. 511). A set of practices with global consensus that can be referred to as agroecological to guide our empirical analysis does not exist. Wezel et al. (2014) and Nicholls et al. (2017) have put forward the most comprehensive reviews of agroecological practices to which we relate (Table 2).

Thus, instead of relying on a pre-defined list, we operationalise our conceptual definition by defining

agroecological practices as a set of agricultural practices that meet a minimum of two out of the first six principles identified by the HLPE (2019; Table 1). We restrict the analysis to the first six principles, because they apply to the field level (as defined by the HLPE, 2019)³ and are most likely to influence land and labour productivity, because they are directly applied to the production level. Examples of possible linkages between the six AE principles and land and labour productivity are provided in Table S2 in the supplementary material.

We consider two or more principles, because the existing body of research focuses on a number of these principles instead of directly and explicitly addressing all six principles.

We pose the following research questions:

1. What is the current state in terms of the volume and focus of research on agroecological practices in Africa?
2. What evidence exists regarding the effects of agroecological practices on land and labour productivity in Africa?

² In the literature that we surveyed, the terms *plot* and *field* are frequently used to describe the considered scale of agronomic experiments. Field-level experiments are typically conducted in on-farm fields or in research stations (Gomez & Gomez, 1984). In on-farm agronomic experiments, fields are chosen within farms selected for the purpose of the experiment. The fields of farmers are then subdivided into plots (the smallest experimental unit) and categorised as treatment and control plots (Gomez & Gomez, 1984; Petersen, 1994). In the current study, agroecological practices are applied to treatment plots, while control plots are monocrop plots. Therefore, the term *plot* is suitable to indicate the scale of our analysis.

³ Only one of the first six principles of the HLPE (i.e. input reduction) has not been categorized as applying to the field level. However, inputs are applied on the field, and changes in input use will pose implications for land and labour productivity at the field level; thus, the principle was included in the definition.

Table 2 Agroecological practices and their contribution to ecological principles

AE practice	Definition	Principles that AE practices contribute					
		Recycling	Input reduction	Soil health	Animal health	Biodiversity	Synergy
Cultivar choice	Use of resistant crops to biotic and abiotic stresses (and mixing them) or crops with selected traits that enhance rhizosphere activities (e.g., mycorrhiza, plant growth-promoting rhizobacteria).		X	X			
Split fertilisation	Fertiliser application (chemical and organic) with several operations		X	X			
Biofertiliser	Application of living micro-organisms to seed, plant surfaces, or soil		X	X			
Organic fertilisation	Application of exclusively organic or mixed with inorganic fertilisation	X	X	X		X	X
Drip irrigation	Use of drip irrigation (without or in combination with cover crops or mulch).	X	X	X			
Natural pesticides/ Botanical pesticides	Pesticides derived from plants or plant extracts		X			X	
Biological pest control	Control of weeds, pests, and diseases based on introduction of natural enemies, pheromones			X		X	X
Crop choice and rotations	Integration of different crops in rotations (including cover crops)	X	X	X		X	
Intercropping and relay intercropping	Intercropping: Coexistence of two or more crops on the same field at the same time. Relay intercropping: Undersowing of relay crops in already existing crops (e.g., undersowing of legumes in cereals)	X	X	X		X	X
Agroforestry with timber, fruit or nut trees/fruit or nut trees	Alley intercropping with crops and rows of woody vegetation. Scattered fruit trees in meadows.	X	X	X	X	X	X
Allelopathic plants	Integration of allelopathic plants in crop rotation (including as intercrops or cover crop). Trap crops or push-pull strategies.	X	X	X		X	X
Animal integration	Animal production that integrates fodder shrubs planted at higher densities, intercropped with improved, highly-productive pastures and timber trees all combined in a system that can be directly grazed by livestock enhances total productivity without need of external inputs.	X	X	X	X		X

Adapted from Nicholls et al. (2017) and Wezel et al. (2014). In Wezel et al. (2014) there are other practices related to tillage

This article solely focuses on agronomic experiments. To examine land productivity, we compare the performance of agroecological practices with monocrop systems with or without chemical inputs (e.g. fertilisers, herbicides or other pesticides). For the purpose of this article, we define a *monocrop system* as a cropping system where “similar plants grow alongside each other simultaneously and sequentially from one season to the next” (Azam-Ali, 2003, p. 978).⁴ The outcome of interest is expressed in yields (kg) per hectare. We assess average yield changes across studies, which are disaggregated by tested agroecological practices, crop, type of control (i.e. monocrop systems with and without inputs), climatic conditions and soil characteristics. The study is guided by the practices listed in Table 2. However, we excluded tillage, because which tillage practice can be classified as agroecological in the context of Africa is unclear (Corbeels et al., 2020; Pittelkow et al., 2015). Therefore, the choice of control–treatment pairs is limited to those with the same tillage options. Data are aggregated from all identified practices and meta-analysis (Borenstein et al., 2021) is employed to provide estimates of effect sizes. A meta-analysis examines the sources of heterogeneity of a given variable across experiments. As such, a formal statistical meta-analysis can detect meaningful effects, which may be overlooked in individual studies or experiments, due to its statistical power (Stanley et al., 2008; Doucouliagos, 2016). Effect size in the context of meta-analysis measures the strength or magnitude and direction (positive or negative) of a relationship or difference between groups (agroecological treatment versus control), which enable readers to understand the practical significance of the results across studies.

3 Materials and methods

3.1 Literature search

We conducted a comprehensive literature search of peer-reviewed articles related to agroecological practices in Africa following the Preferred Reporting Items for Systematic Reviews and Meta-analysis framework (Page et al., 2021). The study focused only on peer-reviewed publications to assess robust scientific evidence. The keywords employed correspond to the selected six ecological principles. We deliberately opted not to use the term ‘agroecology’ as a search term to enable the inclusion of a comprehensive selection of the current research on agroecological practices in Africa. The search also

combined keywords for agricultural sector and geographical coverage by region within Africa (see Fig. 1 and Table S3 in the supplementary material for further details). One librarian verified and searched for the list of keywords across four reference databases, namely, AgEcon, PubMed, Web of Science and EconLit. To account for earlier studies on agroecology, we did not impose any time limit for the search. Further details on search criteria, screening process and data extraction are provided in Section S3 in the supplementary material.

3.2 Data analysis

Meta-analysis was conducted using the log response ratio as the measure of effect size ($LRR = \ln(x_i/x_c)$), where x_i is the crop yield in the treatment and x_c is the yield of the control. A positive effect size ($LRR > 0$) indicates increased crop yield as a result of treatment, whereas a negative effect size ($LRR < 0$) denotes reduced crop yield. We estimate the percentage difference as *percent difference* = $(e^{LRR} - 1) \times 100$ (Rosenberg et al., 2013). The estimation of heterogeneity (i.e. τ^2) was conducted using restricted maximum likelihood estimation (Viechtbauer, 2005). Alongside the estimation of τ^2 , the study also reported the Q-test for heterogeneity (Cochran, 1954) and the I^2 statistic (Higgins & Thompson, 2002). To determine any detected heterogeneity ($\tau^2 > 0$), a prediction interval for the true outcomes was provided (Riley et al., 2011). We also assessed the presence of outliers and influential studies within the model using studentised residuals and Cook’s distances (Viechtbauer, 2010). Studies with studentised residuals exceeding the $100 * (1 - 0.05/(2 \times k))$ th percentile of a standard normal distribution were identified as potential outliers (we employed Bonferroni’s correction with two-sided $\alpha = 0.05$ for k observations in the meta-analysis). Additionally, studies with Cook’s distances that exceed the median plus six times the interquartile range of Cook’s distances were deemed influential. To examine funnel plot asymmetry, the study employed the rank correlation (Begg & Mazumdar, 1994) and regression (Sterne & Egger, 2005) tests in which the standard error of the observed outcomes serve as a predictor. Analysis was conducted using R (version 4.1.2; R Core Team, 2019) and the *metafor* package (version 3.0.2) (Viechtbauer, 2010).

Studies with missing standard deviations were included in the meta-analysis, because their systematic exclusion could be a source of bias (Burgess et al., 2013). For this reason, the study used a multiple imputation approach to estimate the missing standard deviations for studies that reported only mean values and number of replicates for experimental and control groups but did not report measures of precision. The missing standard deviations were imputed using multiple

⁴ We acknowledge that this control group differs from that traditionally used in the African context, which frequently include crop rotation or intercropping (Dixon et al., 2000; Ruthenberg, 1980).

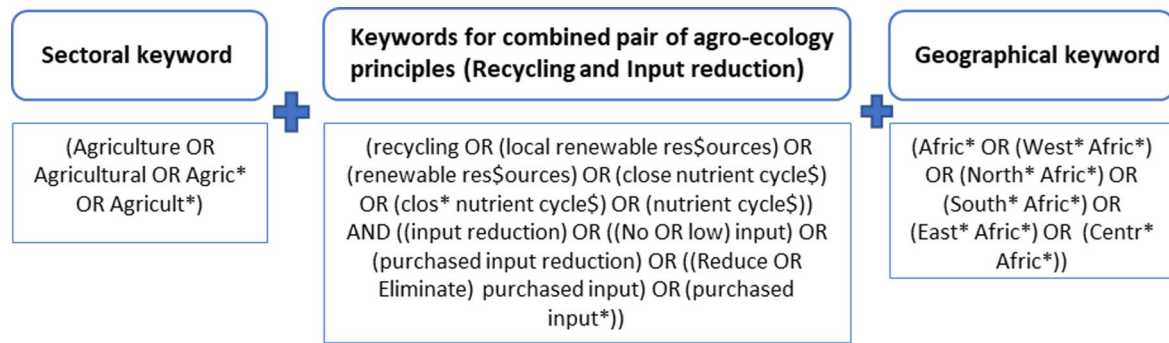


Fig. 1 Illustration of the search strategy

imputation by chain equations using the R package *mice* (Buuren & Groothuis-Oudshoorn, 2011). The estimated variances of the effect size are pooled estimates of 100 imputed datasets using the pool function of the *mice* package, which combines the estimates from repeated complete data analyses by applying the combination rules of Rubin (2004).

The majority of studies reported multiple outcomes (i.e. multiple growth seasons, different treatment conditions, use of common controls or measurements for different within-site locations or different crops). To avoid the need for aggregation at the study level, the study considered the non-independence of data following Pustejovsky and Tipton (2022), who combined the dependence structures that emerge from a multi-level data structure (i.e. observations within studies) and correlated effect sizes within studies using the *clubSandwich* (Pustejovsky & Tipton, 2017) and *metafor* (Viechtbauer, 2010) packages in R.

Additionally, the study performed mixed-effect meta-regressions, including observation and study identifier as random effects, to estimate the coefficients of the fixed-effect moderators of the effect size (i.e. soil physicochemical properties, climatic conditions and crop). Soil texture was grouped into classes as reported in the studies or calculated from the particle size distribution using an online soil texture calculator⁵. Climate zones were determined based on the Köppen classification system (Kottek et al., 2006), which uses five major climate categories with further subdivisions according to seasonal distribution, amount of rainfall and temperature regime.

4 Results

4.1 Current state of research on agroecological practices in Africa

The selection criteria yielded 501 publications that address agroecological practices according to the definition of the study. The number of publications that focus on

agroecological practices in Africa has increased since 2015 (Fig. 2). This result may align with the increasing interest in the subject prompted by the First and Second International Symposium on Agroecology by the FAO in 2014 and 2018, respectively. The majority of this body of literature focuses on East Africa, especially Kenya (Fig. 3). With the exception of South Africa, the extensive literature on Southern Africa (Botswana, Eswatini, Lesotho and Namibia) was lacking. For West Africa, the majority of publications focus on Nigeria and Burkina Faso with a small number in Cameroon, Niger, Mali and Senegal. Similarly, we noted a limited research on agroecological practices in North Africa.

Figure 4 illustrates the first six agroecological principles of the HLPE examined in the publications. The majority investigate impact on soil health (87%) followed by input reduction (67%) and biodiversity (64%), but few address issues related to animal health (4%).

Figure 5 displays the frequency of the number of principles per publication. When using the definition established for agroecological practices as a threshold, we immediately observed a trend towards the examination of multiple principles. This result also justifies the inclusion of a minimum of two principles in the definition. A key finding in the present work is that nearly 86% of peer-reviewed publications extracted from the literature corpus do not use the term agroecology in the titles or abstracts, yet they address agroecological principles. This finding implies that the body of research on agroecological practices extends far beyond the obvious solely based on studies that explicitly refer to agroecology in their titles. Alternatively, it suggests that the research community has loosely defined and/or not yet widely integrated agroecology as a concept into the African context (Bellwood-Howard & Ripoll, 2020; Wezel et al., 2015).

⁵ Available at <https://www.nrcs.usda.gov/resources/education-and-teaching-materials/soil-texture-calculator>.

Fig. 2 Number of publications on agroecological practices, as in our definition, per year between 1990 and 2021 ($n = 501$)

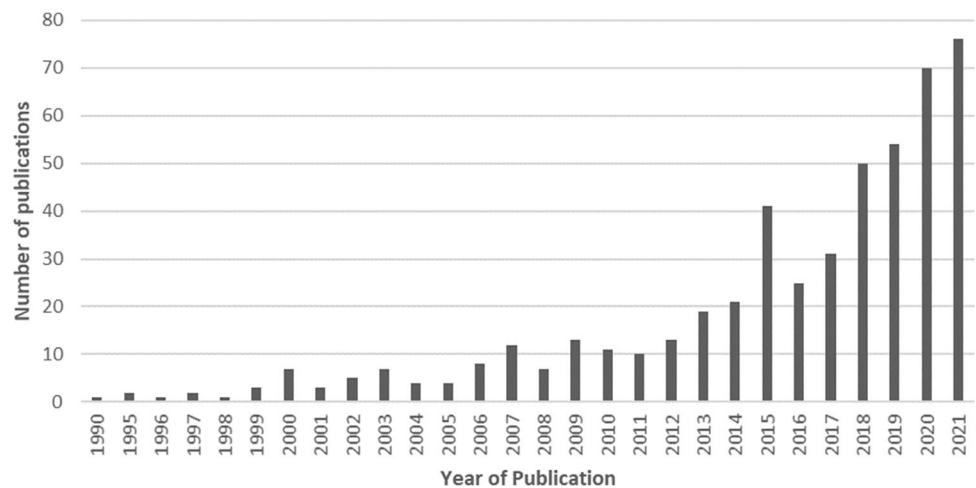
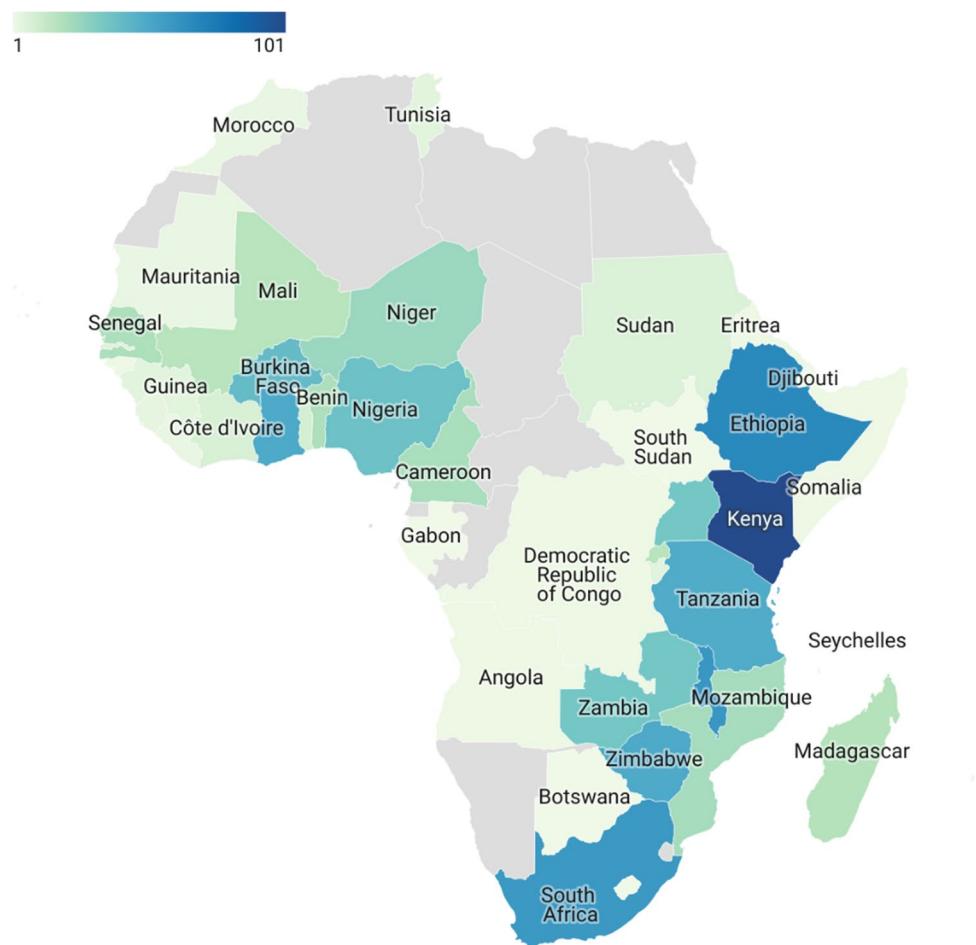


Fig. 3 Distribution of publications by country of study from 1990 to 2021 ($n = 501$). Note: Map generated with Datawrapper

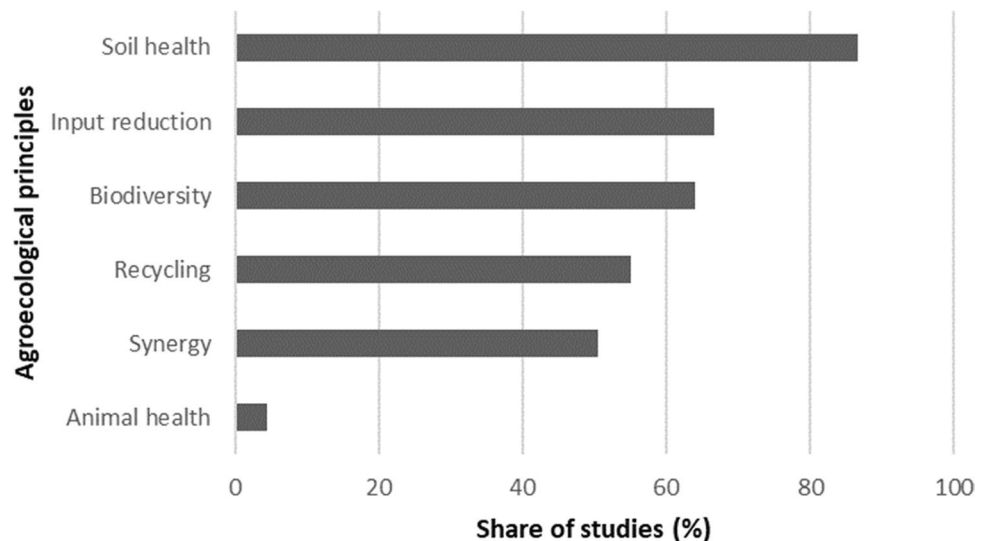


4.2 Existing research on the effects of agroecological practices on land productivity in Africa

We reviewed a total of 94 publications to examine the effect of agroecological practices on land productivity, which provide quantitative data on yield. Out of them, 39 were

eligible for further analysis according to the established criteria. This selection led to the inclusion of agronomic experiments conducted in different settings on farms and research stations across 15 countries (see also Section 4 in the supplementary material). Out of these agronomic experiments, 79% were conducted over a relatively short period (up to 3 years), 19% were established with a duration of

Fig. 4 Principles covered by the studies ($n = 501$). Note: Each bar corresponds to the frequency with which each principle is covered in the peer-reviewed publications



four years and 2% only over the course of 8 years. Given the lack of long-term experiments⁶ in the sample, conducting an analysis of the long-term effects of agroecological practices was impossible.

Out of the 39 publications, 392 observations were identified in which agroecological practices were compared to monocrop systems with or without inputs as the control groups (see reference to data repository in the data availability statement). Thus, the sample includes a wide range of practices and crops across diverse climate zones and soil types. The most frequently considered crop was maize followed by soybean. Crop rotation and intercropping were the most frequently tested agroecological practices (Fig. S2 in the supplementary material).

In this section, we specifically focus on studies that tested agroecological practices in on-farm plots, which are more accurate in addressing the growing conditions faced by farmers, while studies in research stations may lead to overestimations (Tittonell & Giller, 2013; Gomez & Gomez, 1984). Within this subset of 14 studies conducted on farms, 139 experiments compare agroecological practices to monocrop systems with inputs and 61 experiments compare agroecological practices to monocrop systems without inputs. Further details on the selected studies can be found in Section 5 in the supplementary material.

Broadly speaking, the findings from the 14 studies suggest that agroecological practices are associated with yield increase compared with control (monocrop systems with or without inputs), although not in all cases. However, the extent and direction of yield changes may vary according

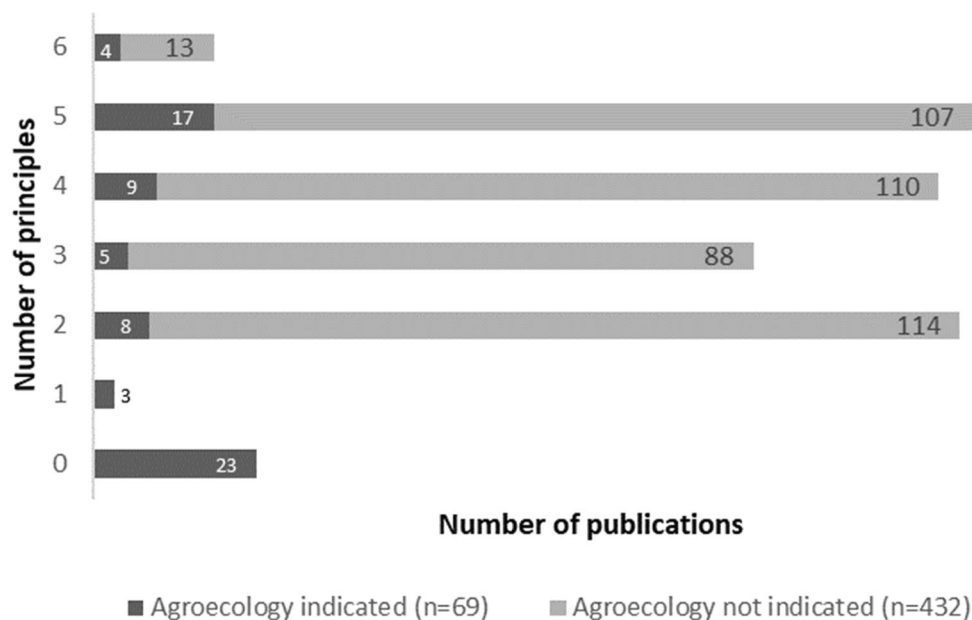
to crop type, contextual factor (e.g. soil characteristics and climatic conditions) and the nature of the control (i.e. with or without inputs). This section summarizes the findings of the reviewed studies to provide a general overview of possible impact pathways without going into the statistical details of the analyses which are assessed in the meta-analysis in the following section.

Crop rotation The studies find mixed results on the effects of cereal–legume rotation on land productivity. In Kenya, Ojiem et al. (2014) assess the effect of rotating maize with green manure legumes (velvet bean, crotalaria and jackbean) or grain legumes (common bean, soybean, groundnut, lima bean, local landrace and lablab) in different agroecological zones and varying levels of soil fertility within these zones⁷. Ojiem et al. (2014) find that growing maize after harvesting green manure legumes led to an increase of maize yields by 54% compared with maize monocrop systems with inputs. The authors attribute this yield increase to higher nitrogen (N) soil content generated by green manure legumes. After harvesting a grain legume, maize cultivation led to yields that were generally equivalent to or slightly higher than those achieved in maize monocrop systems with inputs. The results of Ojiem et al. (2014) further suggest that legume–maize rotations exhibited limited yield response within the time frame considered in locations with low rainfall and poor soil fertility. In contrast, Franke et al. (2010) observe that maize yields increased when rotated with grain legumes compared with a monocrop system with inputs in Nigeria. The largest yield increase occurs in the maize–groundnut

⁶ Long-term experiments commonly run for 20 years or more (Rasmussen et al., 1998).

⁷ The scientific names of the plants indicated in this article are specified in the publicly available dataset to this study (see reference to data repository in the data availability statement).

Fig. 5 Frequency of principles per publications that explicitly indicated to study agroecology in the title or abstract or not ($n = 501$)



rotation (an increase of up to 280%). Similarly, Kaizzi et al. (2007) observed higher sorghum yields (an increase of 80%) when rotating sorghum with the grain legume cowpea compared with growing sorghum in a no-input monocrop system in Uganda.

Intercropping Two studies find that maize yields were lower in legume intercropping systems compared with maize monocrop systems with inputs (i.e. Kebede et al., 2018; Kermah et al., 2017). In Ethiopia, Kebede et al., 2018 show that intercropping maize with common bean or with desmodium (including or excluding napier grass) exerts no effect on maize yields but generates other benefits accrued from companion crops. Kermah et al. (2017) observe lower yields for both crops when intercropping maize with legumes. However, the fact that the land equivalent ratio (i.e. the relative land area required for as sole crops to produce the same yield as intercropping; Willey, 1979) is higher in locations with low soil of nitrogen (N) and phosphate (P) content suggests that intercropping may offer greater advantages in less fertile soils. Contrary to this finding, Franke et al. (2010) show that maize–cowpea (relay) intercropping in Nigeria produce higher maize yields compared with a monocrop system with inputs; the largest increase (147%) was observed in soil with low P content. Similarly, in millet production, Debenport et al. (2015) demonstrate that intercropping millet with woody shrubs exhibits a notable yield increase compared with that of a monocrop system with inputs. The authors speculate that the increase may be associated with the enhanced presence of bacterial and fungal communities in the root zone of the millet, which leads to higher yields.

Fallow Limited evidence on the impact of fallow implies that an improved fallow helps increase rice production in low-input systems. Improved fallow involves planting uncultivated land with specific crops or trees that help improve soil fertility (Ajayi et al., 2003). In a study conducted in Ghana, Langyintuo and Dogbe (2005) demonstrate that rice production increases by 10% in a no-input monocrop system when natural fallow was replaced with an improved fallow of a leguminous species, but exhibited no significant change compared with that of a monocrop system with inputs. Nevertheless, according to this study, beyond a certain time threshold (2–3 years) of the practice, further yield increase may require other sources of fertiliser.

Organic fertiliser Four studies illustrate that using only organic fertiliser (e.g. compost, manure or fermented organic matter) is linked to increased yields compared with those of no-input monoculture systems (Ayaga et al., 2006; Kaizzi et al., 2007; Mbau et al., 2015; Ngwira et al., 2013). Mbau et al. (2015) underscore that the application of different types of compost (e.g. *Tithonia diversifolia* trimmings, maize stover, bagasse, filtermud,⁸ sugarcane straw and cow manure) can double maize yields in Kaizzi et al. (2007) report that the application of a very large amount of 2.5 t ha⁻¹ of manure in Uganda increases sorghum yields by up to 46% compared with those of a no-input monocrop system. By combining 30 kg ha⁻¹ of N fertiliser with manure, an additional increase of 36% in sorghum yields can be achieved. Similarly, Ngwira et al. (2013) find that the sole application of bokash leads to doubled maize yields in

⁸ Filtermud is a by-product of the sugarcane milling and sugar refining processes.

Malawi or a threefold increase when combining bokash with 46 kg ha⁻¹ of N compared with a no-input monocrop system. Along the same line, Ayaga et al. (2006) in Kenya observe increased maize yields when combining N with manure, but that the additional application of P to this combination can double yields. In this study, yields varied across sites according to P content in the soil. For example, an additional P input can lead to an increase of 143% in soils with a limited availability of P (2.1 mg P kg⁻¹ soil) compared with an increase of 36% in locations where the availability of P is higher (7.5 mg P kg⁻¹ soil); meanwhile, the increase was 49 and 7%, respectively, without P application.

Rhizobium inoculation Two studies indicate that the application of P and N fertilisers combined with rhizobium inoculation leads to a twofold increase in common bean yield and a 50% increase in chickpea yield compared with those of no-input monocrop systems (Chekanai et al., 2018; Wolde-meskel et al., 2018). In Zimbabwe, Chekanai et al. (2018) report that the yield increase was higher in non-degraded soils compared with those in degraded (acidic) soil.

Soil and water conservation practices According to Kiboi et al. (2017) and Kebenei et al. (2021), these practices are seemingly promising in increasing yields, particularly in dry areas and degraded soils. Kiboi et al. (2017) find that in the semi-arid conditions of Kenya, tied ridging exerts a stronger effect on the level of maize yield (77% increase) compared with those of a monocrop system. Meanwhile, under sub-humid agroecological conditions, mulching performs better on yields (37% increase). Similarly, Kebenei et al. (2021) show that the use of zai pits⁹ is associated with increases in sorghum yield with or without mineral fertilisers. Cultivation involving zai pits exhibits higher levels of soil pH, electrical conductivity, organic carbon (C), soil P and N compared with those of conventional treatments. The zai pit system enables the retention of nutrients, prevention of their loss through runoff, promotion of soil moisture and, thus, enhancement of soil fertility, which is similar to other water conservation practices (e.g. tied ridging, mulching and ripe lines).

4.3 Labour productivity in small-holder farming

Labour is a critical component of agroecological practices in general and of agriculture systems in Africa in particular (Pretty & Bharucha, 2014). However, the availability of

data on labour productivity in agroecological practices is limited. Out of the five selected publications, three address maize (Franke et al., 2010 in Nigeria; Ojiem et al., 2014 in Kenya; Kermah et al., 2017 in Ghana), while the other two address cassava (Makinde et al., 2019) and rice (Langyintuo & Dogbe, 2005). Thus, the current review focuses on studies that highlighted maize to enable a comparison across studies. The three studies were conducted in on-farm settings and established in varying soil fertility conditions. Only one study estimates a return on labour (USD per day; Ojiem et al., 2014)¹⁰, while the two other studies provided profitability analyses¹¹, and given the scarcity of data, we refrain from pointing toward any conclusive evidence.

Maize-legume rotation Ojiem et al. (2014) find that the labour requirements for land cultivation are comparable among crops in Kenya (50–54 days ha⁻¹ on average). Grain legumes require weeding three times versus twice for green manure legumes, but additional days are required for biomass cutting and soil incorporation (43–48 days per t ha⁻¹ of biomass). Harvesting grain legumes require nearly twice the time required for harvesting maize per hectare, with soybean and groundnut requiring the most time (22–26 days compared with 9 days for maize). If one accounts for post-harvest activities for threshing and shelling, groundnut is found to be the most labour-intensive legume crop. In Nigeria, Franke et al. (2010) observe that maize–legume rotation required more hours of labour compared with the cultivation of maize alone due to the additional time spent on sowing.¹²

In Ghana, Kermah et al. (2017) conclude that returns on labour are lower on average than the usual daily wage (1.30 USD day) in agroecological zones with low rainfall (1,200 mm per year) and particularly in soil with poor fertility (0.7–1.2 and 0.6–1.3 USD per day for grain legumes and green manure legumes, respectively). Agroecological zones with moderate rainfall (1,600 mm year) exhibited the highest return on labour (1.9–2.6 USD day for grain legumes and 1.6–1.8 USD day for green manure legumes). Nevertheless, the economic analysis by Kermah et al. (2017) demonstrates

⁹ In this method, small pits are dug to trap wind-blown sediment and capture water from surface runoff. A small amount of organic matter is added to each pit. The technique has traditionally been used in western Sahel to restore degraded drylands and increase soil fertility (Fatondji et al., 2009).

¹⁰ Ojiem et al. (2014) estimate labour requirements through observations in the trials and by cross-validating farmers' estimates of labour requirements in their own fields with participating and neighbouring farmers. Labour was valued at USD 1.30 per day (assuming eight working hours per day).

¹¹ Franke et al. (2010) assessed labour demand by interviewing participating farmers fortnightly on time spent on field activities related to the trials. Costs were calculated using records of wages of selected states. Kermah et al. (2017) based the labour cost for each activity on the local daily wage per person to perform the activity.

¹² While other changes in labour demand could also be observed between the treatments and control, they relate to the design of the treatment, notably the application of synthetic and/or organic fertiliser in the treatment. See Franke et al. (2010) for details.

that rotation with grain legumes is more profitable in high-rainfall and high-soil fertility zones. Franke et al. (2010) observe similar results in Nigeria. While intercropping soybean and groundnut with maize require considerably more labour, the practice is more profitable than a monocrop system due to the prices for grain and stover.

Maize–legume intercropping Kermah et al. (2017) show that labour days for sowing, fertiliser application, and weeding are 18% higher for intercrops compared with those of monocrops in Ghana. The extra time required for these activities in a within-row intercrop consistently results in higher overall costs compared with those of a monocrop or to a distinct row intercrop pattern. Nevertheless, the increase in grain yield due to intercropping leads to larger net benefits compared with single maize or legume crops.

5 Meta-analysis of agroecological practices and land productivity

We conduct a hierarchical correlated random-effect meta-analysis to statistically test the relative effect of agroecological practices, as previously defined, on land productivity. The final dataset includes 392 observations from 39 studies (the list of studies can be found in Section S5 of the supplementary material). The agroecological practices selected from these studies are compared with those of monocrop systems with or without chemical input application.

The results indicate that agroecological practices are associated with a positive and significant (LRR = 0.33, p -value: 0.0011) difference in land productivity compared with that for monoculture systems (with or without input application). The average log response ratio from the random-effect model is 0.2985 (95% CI: 0.2295 to 0.3674).

On average, agroecological practices had 39% higher yields compared with monocrop systems (without or with inputs) in the respective systems. Based on the Q-test for heterogeneity, other factors may modulate the results ($Q_E(391) = 25207$, $p < 0.0001$, $\tau^2 = 0.4316$, $I^2 = 98.9\%$). Section 5.1 to 5.5 discuss the additional factors that may explain the heterogeneity which include the type of control group (Fig. 6), the type of agroecological practice (Fig. 7), crop considered (Fig. 8), climatic zones (Fig. 9) and soil properties (3, Fig. 10). Not all studies provided the same information for all covariates; thus, standard errors and resulting confidence intervals are typically greater in the sub-analyses, which leads to non-significant estimates of the mean effect size for each level of the considered covariate in a few cases. The main objective of the consideration of these additional factors is to document significant yield differences (positive or negative) that may be exerted by the categorical covariates on land productivity based on data reported by primary studies.

We conduct a sensitivity analysis and a publication bias test (see Section S5 in the supplementary material) to assess the robustness of the results. The rank correlation test indicates a funnel plot asymmetry ($p < 0.0001$) whereas the regression test does not display significant asymmetry ($p = 0.25$). Therefore, these test results suggest the absence of publication bias in the findings.

5.1 Yield changes disaggregated by type of control

The results indicate that agroecological practices show significantly higher yields (61%, $p = 0.0006$) than those of no-input monocrop systems. In contrast, when compared with monocrop systems with inputs, agroecological practices show a relatively smaller increase of 26% ($p = 0.046$, Fig. 6). Substantial residual heterogeneity is observed ($Q_E = 1.2E7$, $p < 0.001$), which implies that factors apart from random

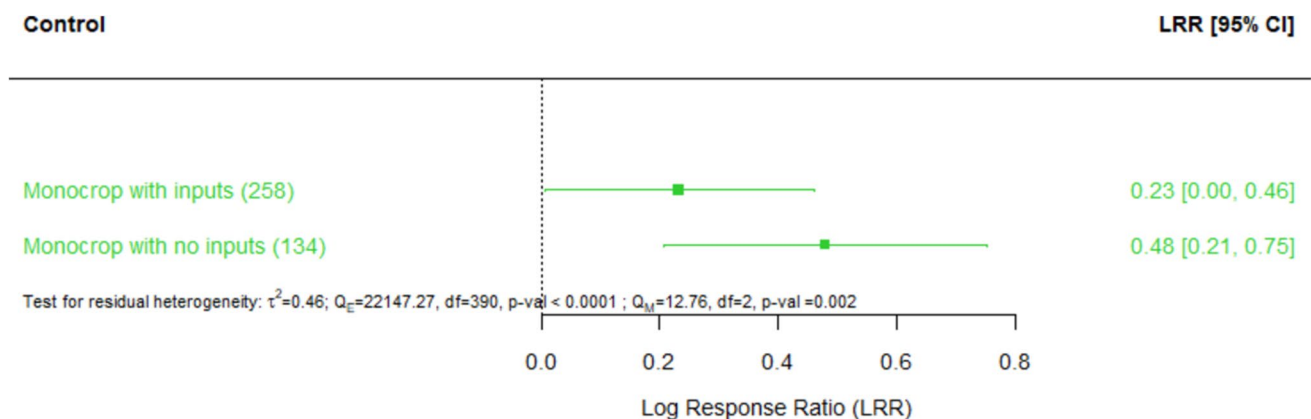
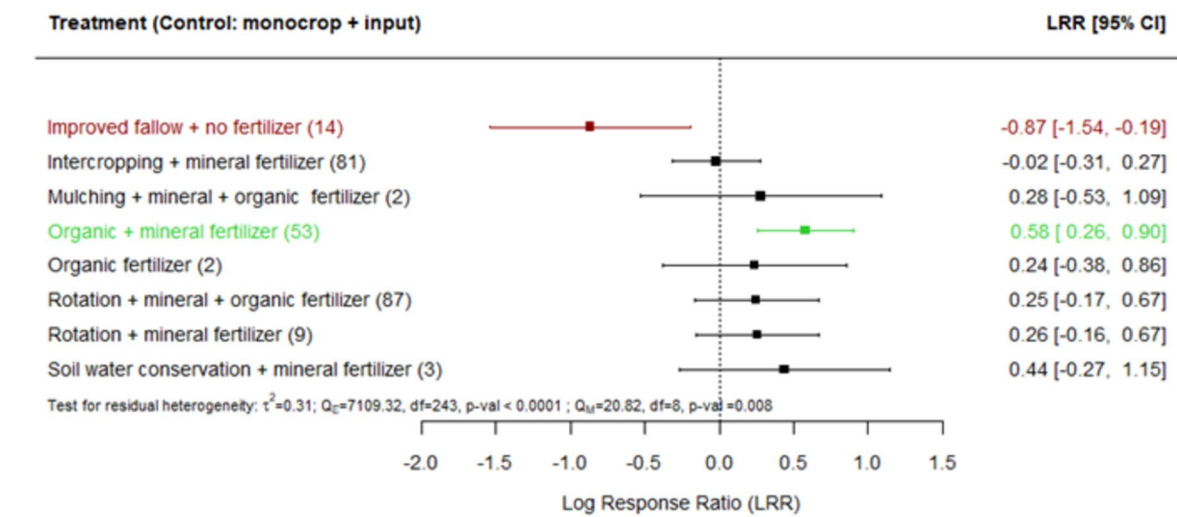


Fig. 6 Effects of agroecological practices on crop yield by control group. Note: Forest plot shows the mean effect. 95% confidence intervals in blankets and sample sizes are enclosed in parentheses

a)



b)

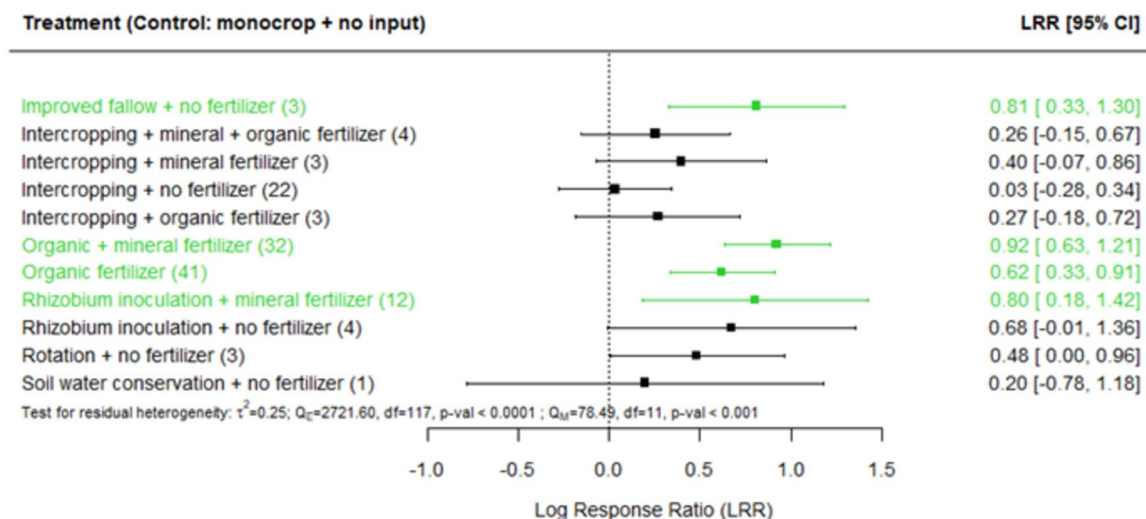


Fig. 7 Agroecological practices tested in the selected studies compared with monocrop systems with inputs (a) and no-input monocrop systems (b). Note: Forest plot shows the mean effect. 95% confidence intervals in blankets and sample sizes are enclosed in parentheses

chance contribute to the variability. The omnibus test for moderators (Hedges & Pigott, 2004) points to significant differences between the two control types: monocrop systems with and without inputs (Fig. 6, $Q_M = 12.63$, $p = 0.002$).

5.2 Yield changes disaggregated by type of control and agroecological practices

We find mixed results for the effect of agroecological practices in comparison with control groups (Fig. 7). If a monocrop system with inputs is the control group, then the

simultaneous application of organic and mineral fertilisers in the treatment group show in a significant positive effect ($p = 0.0004$, Fig. 7), which is associated with a substantial crop yield increase of 79%. Eight studies across five countries in Africa, which is a fair representation of different agroecosystems, consider this practice (the application of organic and mineral fertilisers). In experiments that report on the volume of organic fertilisers, 2.6 t ha⁻¹ of manure and 4 t ha⁻¹ of compost were applied on average in combination with mineral fertiliser and on average 4.5 t ha⁻¹ of manure alone. In contrast, the combination of improved

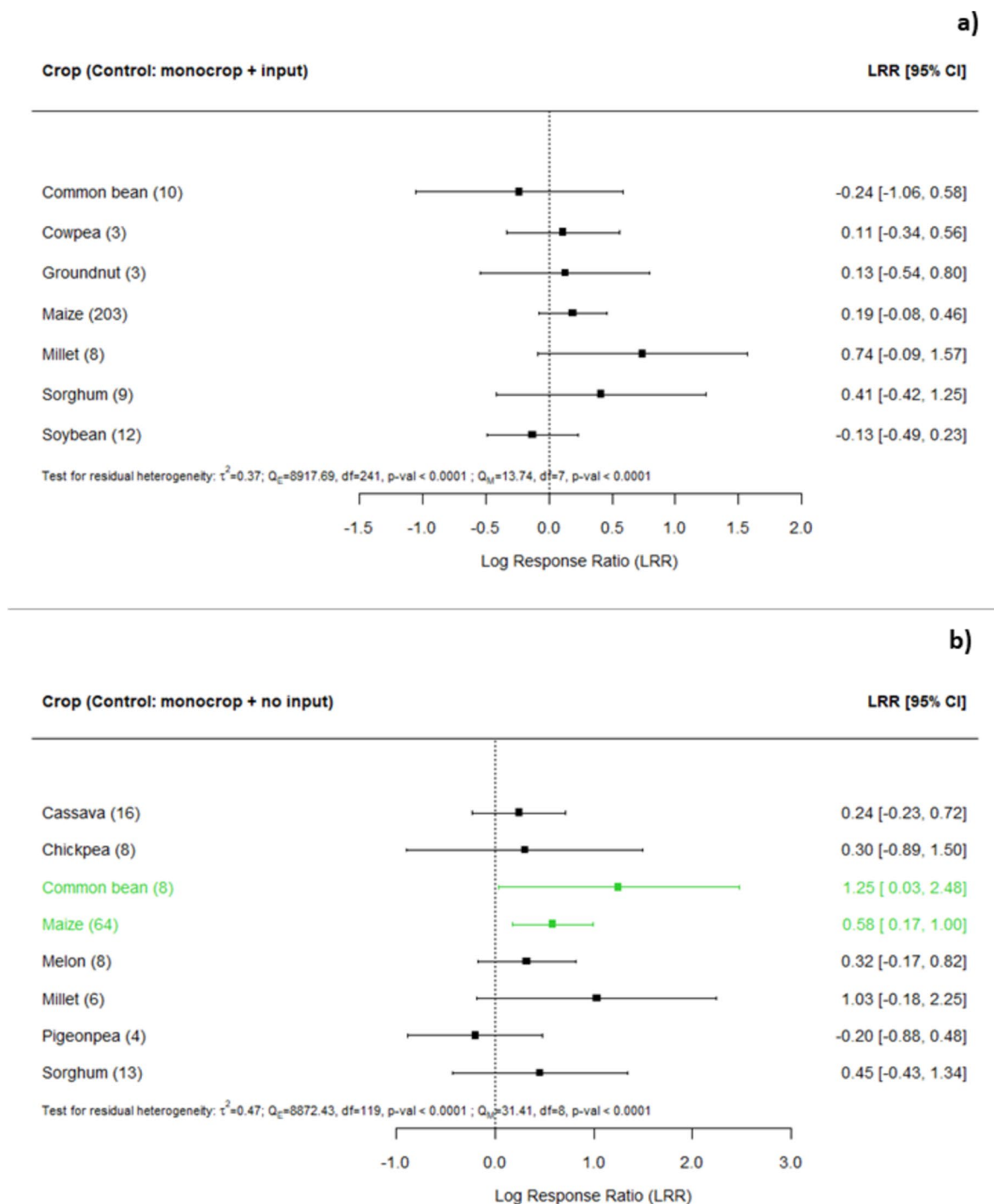


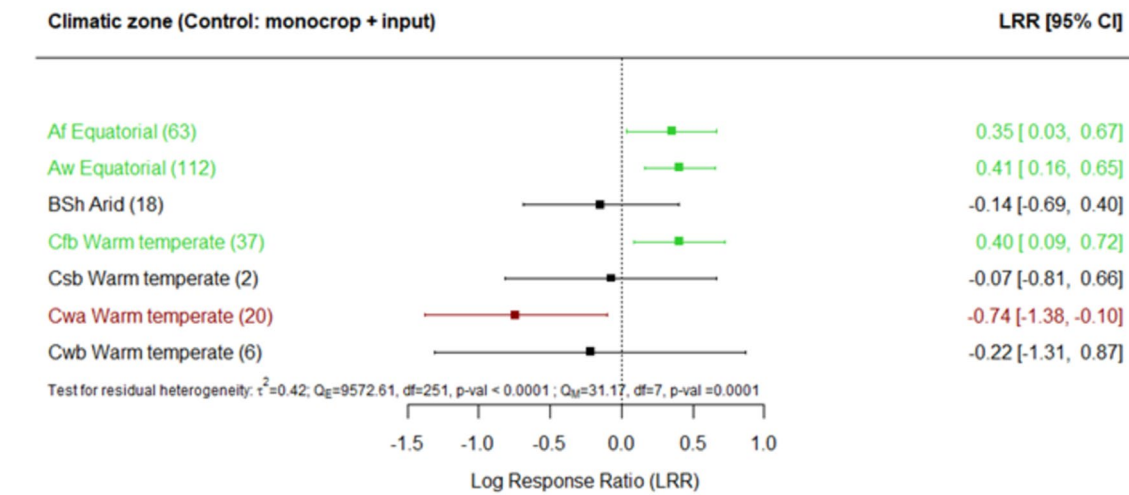
Fig. 8 Crops tested in the selected studies compared with monocrop systems with inputs (a) and no-input monocrop systems (b). Note: Forest plot shows the mean effect. 95% confidence intervals in blankets and sample sizes are enclosed in parentheses

fallow without fertiliser application significantly reduces yields ($p=0.012$).

We examine a wide range of agroecological practices and find positive and significant effects (from $p < 0.0001$ to $p < 0.05$) on yields in studies that used a no-input monocrop system as a control group (Fig. 7). The differences in

yields after the application of organic fertiliser in combination with mineral fertiliser or alone are especially large (152%, $p = 8e-09$; and 86%, $p = 4e-05$ increase, respectively) compared with those of no-input monocrop systems. Eight studies assess various types of organic fertilisers (manure, compost or biochar) with a focus on maize

a)



b)

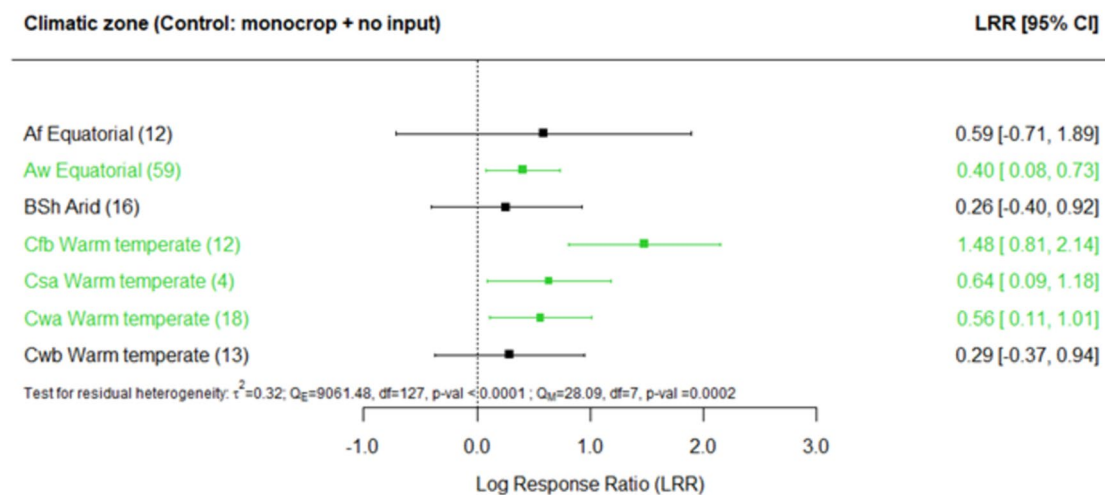


Fig. 9 Climatic zones in the selected studies that compared between monocrop systems with inputs (a) and without input (b). Note: Forest plot shows the mean effect. 95% confidence intervals in blankets and sample sizes are in parentheses

production. On average, these experiments span two years. The studies reporting amounts applied of only manure, compost or biochar applications are 6, 20 and 7.5 t ha⁻¹, respectively, on average. The combined application of organic and mineral fertiliser is on average 2.5, 11 and 0.75 t ha⁻¹ of manure, compost and biochar, respectively, in these studies.

Significant ($p=0.0122$) and positive effects on crop yields were achieved through rhizobium inoculation with a mineral fertiliser (an increase of 123%; Chekanai et al., 2018; Wolde-Meskel et al., 2018). Improved fallow using mucuna legumes also exhibited a positive and significant

effect ($p=0.0014$; Kaizzi et al., 2007). However, these practices were only tested in single studies.

5.3 Yield changes disaggregated by type of control and crop

Maize is the most frequently tested crop, while others focus on common bean, cowpea, groundnut, millet, sorghum and soybean (Fig. 8). Agroecological practices exert a positive and significant effect on maize yields (an increase of 80%; $p=0.0062$) only if the control group is a no-input monocrop system. For all other crops reported in the studies, the

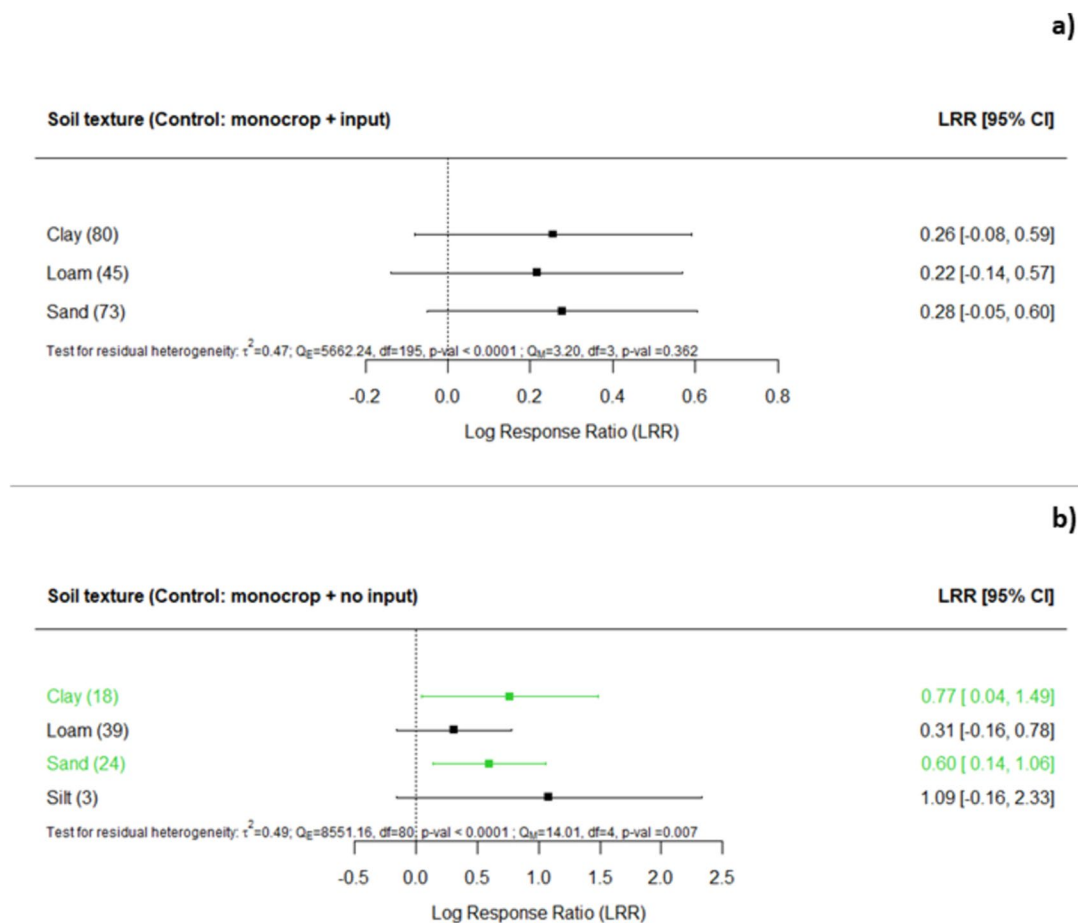


Fig. 10 Soil textures (USDA classification) reported in the studies that compared to monocrop systems with (a) and without (b) chemical input application. Note: Forest plot shows the mean effect. 95% confidence intervals in blankets and sample sizes are enclosed in parentheses

estimated confidence intervals of the effect sizes are broader and non-significant. Agroecological practices are associated with a large and statistically significant ($p=0.0468$) yield increase (249%) in common bean yields. However, this nearly 2.5-fold yield increase is observed in a single study in Zimbabwe (Chekanai et al., 2018), in this case, rhizobium inoculation and mineral fertiliser application.

5.4 Yield variation disaggregated by type of control and climatic zones

The effects of agroecological practices on crop yields significantly differ ($Q_M = 19.47$, $p = 0.002$) among climatic zones when compared with monocrop systems with inputs (Fig. 9a). Positive effects on yields are observed in studies conducted in equatorial rainforest zones (Af: 41% yield increase, $p = 0.031$), tropical zones with dry winter (Aw: 50% yield increase, $p=0.0014$) and temperate zones without dry season and warm summers (Cfb: 49% yield increase, $p=0.0135$). Negative effects on yield are observed in

temperate zones with dry winters and hot summers (Cwa: 100% yield decrease, $p=0.023$).

Compared with yields observed in no-input monocrop systems, agroecological practices perform well across the majority of climatic zones on average (Fig. 9b). The largest positive effect on yield is observed in two studies conducted in temperate zones without dry season and warm summers (Cfb: 337% increase, $p=2e-05$). Positive effects on yield are also observed in studies conducted in tropical zones with dry winter (Aw: 49% yield increase, $p=0.0164$) and warm temperate zones with dry winters and hot summers (Csa: 90% yield increase, $p=0.024$). In contrast to monocrop systems with inputs, positive effects are observed in temperate zones with dry winters and hot summers (Cwa: 75% yield increase, $p=0.016$).

5.5 Yield variation disaggregated by type of control and soil properties

We observe no significant differences regarding the effects on crop yields according to the soil textures

($Q_M = 2.99$, $p = 0.393$) reported in the body of studies (Fig. 10). However, the effect differs by type of control. Although the effects are statistically nonsignificant ($p = 0.098$) in studies that used monocrop systems with inputs as a control group, agroecological practices used in clay ($p = 0.0407$) and sandy soils ($p = 0.0133$) are associated with a positive and significant effect on yields when compared with those of no-input monocrop systems.

Similarly, soils with high pH and high N content are associated with a positive and significant ($p = 0.004$) effect of agroecological practices only if compared to no-input monocrop systems. Specifically, the effects of agroecological practices on crop yields are positively and significantly correlated with soil pH ($p = 0.007$, Table 3), showing a 15% increase per unit of soil pH ($p = 0.01$). A significant correlation is also found with N content ($p = 0.01$), with a 45% increase per gram of N per kilogram of soil in studies that use a no-input monocrop system as the control group (Table 3). Furthermore, a significantly positive relationship is observed between mean annual precipitation and the effects of agroecological treatments on crop yields (0.05% yield increase per mm of annual rainfall; $p = 0.0004$) in studies that involve monocrop systems without inputs as control. In contrast, the relationships among soil pH, nitrogen and organic C and P with treatment effects are statistically nonsignificant ($p > 0.3$) for experiments in which the control is a monocrop system with inputs.

6 Discussion

This study is the first comprehensive endeavour to assess the relationship between agroecological practices with land and labour productivity in Africa. Through a systematic literature review, it examined the status of research on agroecological practices in Africa. Moreover, it focused on a sub-sample of studies conducted in on-farm settings to analyse the effect of agroecological practices on land and labour productivity. It then analysed the relationship between agroecological practices and yield variation using meta-analytical methods based on agronomic studies conducted on farms and research stations. In contrast to other studies, our search strategy excluded the term agroecology in detecting the relevant literature. Instead, we developed a detailed search strategy to identify any relevant literature that assesses agroecological practices, even if such practices are not explicitly mentioned as involving agroecology.

This strategy yielded 501 references. Analysis of these studies illustrates that the literature related to agroecological practices in Africa is growing but is anchored in a few countries, notably Kenya. We believe that a key result of this work is that the body of research on agroecological practices

Table 3 Soil properties by type of control

Control	Site condition	Model results			Residual heterogeneity					
		Coefficient estimate	% change	Std. error	Sample size	p-value	τ^2	Q_E	p-value	Q_M
Monocrop system + inputs	Mean annual precipitation	-6.3010^{-5}	-0.01	6.20E-05	258	0.315	0.463	15,257	<0.0001	0.137
	N	0.015	1.51	0.29	9	0.96	1.83	593.6	<0.0001	0.003
Monocrop system + no input	Organic C	0.015	1.51	0.033	7	0.66	2.8	321.44	<0.0001	0.217
	Mean annual precipitation	4.70E-04	0.05	0.0001	134	0.0004	0.473	12,622	<0.0001	13.22
	pH	0.14	15.03	0.05	30	0.007	0.417	244.04	<0.0001	8.72
	N	0.38	46.23	0.122	30	0.004	0.438	257.65	<0.0001	9.72
	Organic C	0.025	2.53	0.011	29	0.06	0.69	172.9	<0.0001	5.2
	P	0.012	1.21	0.009	26	0.165	0.722	170.02	<0.0001	2.06

extends beyond studies that explicitly indicate agroecology in their titles or abstracts. In fact, the majority of the selected articles did not mention agroecology, which indicates that solely relying on studies that use that term may be biased, which overlooks valuable research contributions in the field.

In summary, the body of studies retrieved implied that agroecological practices exert a positive and significant (p -value = 0.0011) effect on land productivity compared with monocrop systems, including on-farm settings. However, relative yield increases vary if they are disaggregated according to agroecological practice, crop, type of control, climatic factor or soil type. However, separately considering the selected studies and the empirical evidence they represent for each of the abovementioned factors may be extremely limited to draw final conclusions; thus, our results indicate possible interactions between them.

Agroecological practices seemingly exert a significant positive effect on increasing yields compared with monocrop systems without chemical inputs. Among the agroecological practices tested, organic fertilisers mainly consistently demonstrated yield gains compared with those of monocrop systems with or without inputs. The current results also indicate that these yield gains could be greatly enhanced by combining organic with mineral fertilisers even at small quantities. The effects of other practices, such as crop rotation, intercropping and fallow, are mixed with variability among the types of crops grown and the nature of crop, among other factors. We also find limited diversity among the tested crops with an emphasis on cereals and a few legumes and a notable absence of vegetables and of other key staples produced in Africa, such as yams, plantain, sweet potato or Irish potato (FAO, 2024). These omissions constitute a major gap in the ongoing research in Africa. Moreover, except for one agronomic study (Kebede et al., 2018), none has assessed the impact of pest management practices. This aspect represents an important research gap, particularly in the African context, in which poor plant health is prevalent and significantly contributes to large reductions in yield (Acuña et al., 2023; Savary et al., 2019).

The current study demonstrates that the effect of agroecological practices on land productivity is not uniform across soil types and climatic zones. The importance of soil properties in influencing the results is a common thread in the selected studies. Yet, we were unable to establish the specific relationship between soil properties and yields due to the scarcity of soil data across the studies. This point constitutes another serious gap in the ongoing research in Africa. Evidence also implies that intercropping with legumes may be particularly suitable for soil with poor conditions to increase maize yields. However, a few species of legumes appear more suitable in achieving this than others. Evidence on the role of climatic factors is particularly limited. While they are expected to play a role, the direction

and scale of impact remain unclear. Studies that assessed the effects of agroecological practices on labour productivity are few. The available studies indicate that agroecological practices frequently involve more labour. For instance, the case is true for weeding, organic fertiliser application and cutting/incorporating biomass into soil. However, despite high labour costs, the profits reported by the studies were higher than those of monocrop systems under certain conditions. Higher profits were reported if the practice resulted in higher grain yields or when higher prices could be generated from legumes grown as part of intercropping or crop rotation. This finding illustrates that changes in labour requirements and associated costs should be jointly assessed. The gains from adopting agroecological practices which may offset the additional costs: adoption studies should consider this other research gap. The adoption of practice-adapted farm mechanisation may further reduce such additional labour requirements, which increases labour productivity in the implementation of agroecological practices (Dahlin & Rusinamhodzi, 2019; Daum et al., 2021).

Bearing in mind the limited availability of empirical evidence, the present study suggests that agroecological practices could offer opportunities for increasing land productivity in maize production in Africa where access to chemical inputs remains a significant challenge (AGRA, 2023) and agro-ecological practices may offer viable alternatives. Indeed, African farming systems have long been characterised by agroecology-related practices, even if the term was not used, such as intercropping, integrated crop-livestock systems and organic fertiliser (Dixon et al., 2000; Ruthenberg, 1980). Evidence indicates that yields could increase due to the adoption of agroecological practices compared with monocrop systems, especially if combined with even only small amounts of mineral fertilisers. Notably, however, the amounts of organic fertiliser applied in experiments are considerably higher than those considered currently feasible in the African context. Thus, obtaining yield gains from the increased application of organic fertilisers should be interpreted with caution and, in any case, would pose serious implications for labour and transport demands.

Given the large and growing labour force in rural Africa (AGRA, 2023), additional labour requirements may not necessarily be a significant constraint with the assumption that sufficient profit can be generated through the adoption of agroecological practices, which would cover additional labour costs. A large available agricultural workforce alone is insufficient guarantee for the success of the adoption (Leonardo et al., 2015). Thus, incentivising people to work in farming and enhance the skills of farmers are seemingly critical to the successful implementation of agroecological practices. Such success could depend on additional components such as the promotion of the practice-specific mechanisation and digitalisation of agriculture to attract the youth back to farming.

7 Limitations and areas for future research

This work has its limitations. First, the small number of the selected studies may restrict the general value of the current findings. A limited number of studies also prevented the further disaggregation of data to shed more light on factors that may influence the impact of agroecological practices on land and labour productivity.

The limited number of studies also did not enable a detailed examination of the interactions between factors on the outcomes of agroecological practices. For instance, a few studies did not provide yield data on a yearly or seasonal basis. Therefore, we needed to use average mean yields across years, which prevented the consideration of seasonal variations in crop performance. In addition, although we carefully assessed the quality of experimental set-ups to ensure that agroecological practices (i.e. treatment group) were well-implemented, a possible bias remains, which may emerge from the use of comparison (control) groups which over- or under-represent the African reality. As a result of these shortcomings (derived from data available from the literature), we were unable to disaggregate and compare actual and potential yields¹³, that is, those under scenarios of optimal management of (1) water, (2) nutrients and (3) weeds, pathogens and animal pests. Future research should consider these factors in their experimental set-ups to enable a comparison of results across studies. In particular, the role of climatic factors and soil properties¹⁴ remains under-researched. Importantly, these studies will need to take into account changing agronomic conditions that may result from the changing climate in the coming decades.

Another limitation is related to the inability to observe the influence of different levels of application of mineral fertilisers. Analysis could not disaggregate the data on the basis of specific amounts of N or P due to the small sample

size. Given the potential variability in the rates of fertiliser application across studies, assessing the impact of different levels of the application of chemical fertilisers together with agroecological practices on crop yields would be valuable to future research.

Other reviews suggest that higher yields can be achieved by combining several agroecological practices (Beillouin et al., 2019; MacLaren et al., 2022; Pittelkow et al., 2015; Sapkota et al., 2021). However, we were unable to assess the effects of combinations of agroecological practices due to the limited scope of such practices in the examined literature. Thus, additional research on testing combinations of agroecological practices is required.

Studies on the impacts of agroecological practices on labour productivity constitute a major research gap from the perspective of the present study. Future research should not only focus on changes in labour requirements but also assess the conditions under which changes in labour would be offset by additional profits and the role of off-farm labour (Giller et al., 2021). In addition, the role of innovations in the reduction of higher labour needs in agroecological practices and associated costs should be investigated further, ideally as cost–benefit analyses that comprehensively cover the entire operation of a farm. Particular attention should be paid to impacts on women who comprise an important proportion of the labour force in African agriculture.

The time dimension of the current experiments in Africa represents yet another limitation. The majority of the selected studies were short-term and typically spanned only 2 to 3 years. Despite being a meaningful duration, it overlooks the vagaries of climate, pathogens, pests and weed infestation. Agroecological practices typically require longer-term evaluation to observe substantial effects, because the manifestation of changes in soil fertility, biodiversity, pathogens, animal pests and weeds and, generally, ecosystem functioning, may take more than three years (Rasmussen et al., 1998). Therefore, the relatively short duration of the experiments, which were typically financially and project-limited similar to others today, may limit the ability of the study to capture the full effects of agroecological practices. Long-term experiments that is, experiments that exceed 20 years in duration, are necessary for investigating the complex causal effects of agroecological practices.

¹³ Potential yield refers to “the maximum yield that could be reached by a crop in given environments” (Evans & Fischer, 1999, p. 1545). *Actual yield* reflects “the current state of soils and climate, average skills of the farmers, and their average use of technology” (Sadras et al. 2015, p. 6).

¹⁴ Note that soil properties can be considered as potential soil health indicators (Sainju et al., 2022). In the literature that we surveyed, the term “soil health” mentioned by the HLPE was not necessarily used. Instead, the terms “soil fertility”, “soil carbon”, “soil nitrogen”, “soil phosphorus” etc., were mainly employed. We interpreted them as contributing to the HLPE’s “soil health” principle. However, future research on this principle should be conscious of its diverse meanings. Drawing on Karlen et al. (1997), Doran and Zeiss (2000) define *soil health* as “the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health” (p3). These authors, along with others (e.g. Bünemann et al., 2018), use interchangeably soil health and

Footnote 14 (continued)

soil quality. However, Pankhurst et al. (1997) argue that although the two concepts overlap, soil quality focuses more on the soil’s capacity to meet human needs such as growing a crop, whilst soil health focuses more on the soil’s continued capacity to sustain plant growth and maintain its functions. Therefore, when the concept of soil health is explicitly used, it requires a concrete definition.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12571-024-01504-6>.

Acknowledgements We are very grateful to Prof. Matthias Becker, who guided us throughout the analysis of this study. This work was supported by the Program of Accompanying Research for Agricultural Innovation (PARI), which is funded by the German Federal Ministry of Economic Cooperation and Development (BMZ) (project number: 2014.0690.9). Bibiana Betancur-Corredor is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) with project number: BE 7694/1–1. The authors would like to thank the reviewers for their insightful comments and suggestions. We also appreciate the responses from authors that were contacted throughout the analysis.

Author contributions MR and AF contributed equally as lead authors to the concept of manuscript, the data sets, analyses and writing. BB designed and executed the meta-analyses. JvB and HB conceptualised the study and participated in the writing, review and interpretation of findings.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability The data used for the quantitative analysis is available in an online data repository: Romero Antonio, M., Faye, A, Betancur-Corredor, B., Baumüller, H., & von Braun, J. (2024). Agroecology in Africa: A systematic review and meta-analysis - Dataset. <https://doi.org/10.60507/FK2/FPSKMP>, bonndata.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Acuña, I., Andrade-Piedra, J., Andrivon, D., et al. (2023). A global assessment of the state of plant health. *Plant Disease*, 107, 3649–3665. <https://doi.org/10.1094/PDIS-01-23-0166-FE>
- AFSA. (2016). *Agroecology: The bold future of Farming in Africa*. AFSA & TOAM.
- AGRA. (2023). *Africa Agriculture Status Report – Empowering Africa's Food System for the future*. Alliance for a Green Revolution in Africa.
- Ajayi, O. C., Franzel, S., Kuntashula, E., & Kwesiga, F. (2003). Adoption of improved fallow technology for soil fertility management in Zambia: Empirical studies and emerging issues. *Agroforestry Systems*, 59, 317–326. <https://doi.org/10.1023/B:AGFO.0000005232.87048.03>
- Altieri, M. A. (1995). *Agroecology: The science of sustainable agriculture*. Westview Press.
- Altieri, M. A., & Nicholls, C. I. (2005). *Agroecology and the Search for a Truly Sustainable Agriculture* (1st edition). United Nations Environmental Programme, Environmental Training Network for Latin America and the Caribbean.
- Ayaga, G., Todd, A., & Brookes, P. C. (2006). Enhanced biological cycling of phosphorus increases its availability to crops in low-input sub-saharan farming systems. *Soil Biology and Biochemistry*, 38(1), 81–90. <https://doi.org/10.1016/j.soilbio.2005.04.019>
- Azam-Ali, S. N. (2003). Multicropping. In B. Thomas (Ed.) *Encyclopedia of Applied Plant Sciences* (pp. 978–984). Academic Press. <https://doi.org/10.1016/B0-12-227050-9/00041-7>
- Begg, C. B., & Mazumdar, M. (1994). Operating characteristics of a rank correlation test for publication bias. *Biometrics*, 50(4), 1088. <https://doi.org/10.2307/2533446>
- Beillouin, D., Ben-Ari, T., & Makowski, D. (2019). Evidence map of crop diversification strategies at the global scale. *Environmental Research Letters*, 14(12), 123001. <https://doi.org/10.1088/1748-9326/ab4449>
- Bellwood-Howard, I., & Ripoll, S. (2020). Divergent understandings of agroecology in the era of the African Green Revolution. *Outlook on Agriculture*, 49(2), 103–110. <https://doi.org/10.1177/0030727020930353>
- Bjornlund, V., Bjornlund, H., & Van Rooyen, A. F. (2020). Why agricultural production in sub-saharan Africa remains low compared to the rest of the world – a historical perspective. *International Journal of Water Resources Development*, 36(sup1), S20–S53. <https://doi.org/10.1080/07900627.2020.1739512>
- Borenstein, M., Hedges, L. V., Higgins, J. P., & Rothstein, H. R. (2021). *Introduction to meta-analysis*. Wiley.
- Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., De Goede, R., & Brussaard, L. (2018). Soil quality—A critical review. *Soil Biology and Biochemistry*, 120, 105–125.
- Burgess, S., White, I. R., Resche-Rigon, M., & Wood, A. M. (2013). Combining multiple imputation and meta-analysis with individual participant data. *Statistics in Medicine*, 32(26), 4499–4514. <https://doi.org/10.1002/sim.5844>
- 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>
- CIDSE (2018). *The principles of agroecology. Towards, just, resilient and sustainable food systems*. <https://www.cidse.org/publications/just-food/food-and-climate/the-principles-of-agroecology.html>. Accessed 10 July 2022.
- Cochran, W. G. (1954). The combination of estimates from different experiments. *Biometrics*, 10(1), 101. <https://doi.org/10.2307/3001666>
- Corbeels, M., de Graaff, J., Ndah, T. H., Penot, E., Baudron, F., Naudin, K., Andrieu, N., Chirat, G., Schuler, J., Nyagumbo, I., Rusinamhodzi, L., Traore, K., Mzoba, H. D., & Adolwa, I. S. (2014). Understanding the impact and adoption of conservation agriculture in Africa: A multi-scale analysis. *Agriculture Ecosystems & Environment*, 187, 155–170. <https://doi.org/10.1016/j.agee.2013.10.011>
- Corbeels, M., Naudin, K., Whitbread, A. M., Kühne, R., & Letourmy, P. (2020). Limits of conservation agriculture to overcome low crop yields in sub-saharan Africa. *Nature Food*, 1(7), 447–454. <https://doi.org/10.1038/s43016-020-0114-x>
- D'Annolfo, R., Gemmill-Herren, B., Graeub, B., & Garibaldi, L. A. (2017). A review of social and economic performance of agroecology. *International Journal of Agricultural Sustainability*, 15(6), 632–644. <https://doi.org/10.1080/14735903.2017.1398123>
- Dahlin, S., & Rusinamhodzi, L. (2019). Yield and labor relations of sustainable intensification options for smallholder farmers in sub-saharan Africa. A meta-analysis. *Agronomy for Sustainable Development*. <https://doi.org/10.1007/s13593-019-0575-1>
- Daum, T., Capezone, F., & Birner, R. (2021). Using smartphone app collected data to explore the link between mechanization

- and intra-household allocation of time in Zambia. *Agriculture and Human Values*, 38(2), 411–429. <https://doi.org/10.1007/s10460-020-10160-3>
- Debenport, S. J., Assigbetse, K., Bayala, R., Chapuis-Lardy, L., Dick, R. P., & McSpadden Gardener, B. B. (2015). Association of shifting populations in the root zone microbiome of millet with enhanced crop productivity in the Sahel Region (Africa). *Applied and Environmental Microbiology*, 81(8), 2841–2851. <https://doi.org/10.1128/AEM.04122-14>
- Debray, V., Wezel, A., Lambert-Derckimba, A., Roesch, K., Lieblein, G., & Francis, C. A. (2019). Agroecological practices for climate change adaptation in semiarid and subhumid Africa. *Agroecology and Sustainable Food Systems*, 43(4), 429–456. <https://doi.org/10.1080/21683565.2018.1509166>
- Dittmer, K. M., Rose, S., Snapp, S. S., Kebede, Y., Brickman, S., Shelton, S., Egler, C., Stier, M., & Wollenberg, E. (2023). Agroecology can promote climate change adaptation outcomes without compromising yield in Smallholder systems. *Environmental Management*. <https://doi.org/10.1007/s00267-023-01816-x>
- Dixon, J., Garrity, D. P., Boffa, J. M., Williams, T., Amede, O., Auricht, T., Lott, C., R., & Mburathi, G. (2000). *Farming systems and food security in Africa: Priorities for science and policy under global change*. Routledge.
- Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, 15, 3–11.
- Doucoulagos, C. (2016). Meta-regression analysis: Producing credible estimates from diverse evidence. *IZA World of Labor*, 320. <https://doi.org/10.15185/izawol.320>
- Evans, L. T., & Fischer, R. A. (1999). Yield potential: Its definition, measurement and significance. *Crop Science*, 39, 1544–1551.
- Ewert, F., Baatz, R., & Finger, R. (2023). Agroecology for a sustainable agriculture and food system: From local solutions to large-scale adoption. *Annual Review of Resource Economics*, 15(1). <https://doi.org/10.1146/annurev-resource-102422-090105>
- FAO (2024). FAO Stat, Production quantities of primary crops in 2022. FAO. Downloaded on 12 September 2024.
- FAO (2010). *Climate smart agriculture: policies, practices and financing for food security, adaptation and mitigation*. In Hague Conference on Agriculture, Food Security and Climate Change.
- FAO. (2018). *The 10 elements of agroecology. Guiding the transition to sustainable food and agriculture systems*. <https://www.fao.org/agroecology/overview/overview10elements/en/>. Accessed 13 July 2022.
- FAO, IFAD, UNICEF, WFP and WHO. (2020). The state of food security and nutrition in the world 2020. *Transforming food systems for affordable healthy diets*. UN Food and Agriculture Organization. <https://doi.org/10.4060/ca9692en>
- Fatondji, D., Martius, C., Zougmore, R., Vlek, P. L. G., Bielders, C. L., & Koala, S. (2009). Decomposition of organic amendment and nutrient release under the Zai technique in the Sahel. *Nutrient Cycling in Agroecosystems*, 85, 225–239. <https://doi.org/10.1007/s10705-009-9261-z>
- Franke, A. C., Berkhout, E. D., Iwuofor, E. N. O., Nziguheba, G., Dercon, G., Vandeplas, I., & Diels, J. (2010). Does Crop-Livestock integration lead to improved crop production in the Savanna of West Africa? *Experimental Agriculture*, 46(4), 439–455. <https://doi.org/10.1017/S0014479710000347>
- Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P. K., Toulmin, C., Vermeulen, S. J., & Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. *Science*, 341(6141), 33–34. <https://doi.org/10.1126/science.1234485>
- Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research*, 114(1), 23–34. <https://doi.org/10.1016/j.fcr.2009.06.017>
- Giller, K. E., Delaune, T., Silva, J. V., Descheemaeker, K., Van De Ven, G., Schut, A. G. T., Van Wijk, M., Hammond, J., Hochman, Z., Taulya, G., Chikowo, R., Narayanan, S., Kishore, A., Bresciani, F., Teixeira, H. M., Andersson, J. A., & Van Ittersum, M. K. (2021a). The future of farming: Who will produce our food? *Food Security*, 13(5), 1073–1099. <https://doi.org/10.1007/s12571-021-01184-6>
- Giller, K. E., Delaune, T., Silva, J. V., Van Wijk, M., Hammond, J., Descheemaeker, K., Van De Ven, G., Schut, A. G. T., Taulya, G., Chikowo, R., & Andersson, J. A. (2021b). Small farms and development in sub-saharan Africa: Farming for food, for income or for lack of better options? *Food Security*, 13(6), 1431–1454. <https://doi.org/10.1007/s12571-021-01209-0>
- Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research*. Wiley.
- Hedges, L. V., & Pigott, T. D. (2004). The power of statistical tests for moderators in meta-analysis. *Psychological Methods*, 9(4), 426.
- Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, 21(11), 1539–1548. <https://doi.org/10.1002/sim.1186>
- HLPE (2019). *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome*.
- Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), 543–555.
- Hodson, E., Niggli, U., Kitajima, K., Lal, R., & Sadoff, C. (2023). Boost nature positive production. In von J. Braun, K. Afsana, L. Fresco, & M. Hassan (Eds.), *Science and innovations for Food systems Transformation* (pp. 319–340). Springer. https://doi.org/10.1007/978-3-031-15703-5_17. Open Access.
- IPES-Food. (2020). The added value (s) of agroecology: Unlocking the potential for transition in West Africa. In *International panel of experts on sustainable food systems*. https://www.ipes-food.org/_img/upload/files/IPES-Food_FullReport_WA_EN.pdf. Accessed 29.10.2024.
- Kaizzi, K. C., Byalebeka, J., Wortmann, C. S., & Mamo, M. (2007). Low input approaches for soil fertility management in Semiarid Eastern Uganda. *Agronomy Journal*, 99, 847–853. <https://doi.org/10.2134/agronj2006.0238>
- Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., & Schuman, G. E. (1997). Soil quality: A concept, definition, and framework for evaluation. *Soil Science Society of America Journal*, 61, 4–10.
- Kebede, Y., Baudron, F., Bianchi, F., & Tittonell, P. (2018). Unpacking the push-pull system: Assessing the contribution of companion crops along a gradient of landscape complexity. *Agriculture Ecosystems & Environment*, 268, 115–123. <https://doi.org/10.1016/j.agee.2018.09.012>
- Kebenei, M. C., Mucheru-Muna, M., Muriu-Ng'ang'a, F., & Ndung'u, C. K. (2021). Zai technology and integrated nutrient management for improved soil fertility and increased sorghum yields in Kitui County, Kenya. *Frontiers in Sustainable Food Systems*, 5(714212). <https://doi.org/10.3389/fsufs.2021.714212>
- 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 Research*, 213, 38–50. <https://doi.org/10.1016/j.fcr.2017.07.008>
- Kiboi, M. N., Ngetich, K. F., Diels, J., Mucheru-Muna, M., Mugwe, J., & Mugendi, D. N. (2017). Minimum tillage, tied ridging and mulching for better maize yield and yield stability in the Central Highlands of Kenya. *Soil and Tillage Research*, 170, 157–166. <https://doi.org/10.1016/j.still.2017.04.001>

- Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, 15(3), 259–263. <https://doi.org/10.1127/0941-2948/2006/0130>
- Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of Soil and Water Conservation*, 75(5), 123A–124A.
- Langyintuo, A., & Dogbe, W. (2005). Characterizing the constraints for the adoption of a improved fallow in rice production systems in northern Ghana. *Agriculture Ecosystems & Environment*, 110(1–2), 78–90. <https://doi.org/10.1016/j.agee.2005.05.004>
- Leipert, F., Darmaun, M., Bernoux, M., & Mphesha, M. (2020). The potential of agroecology to build climate-resilient livelihoods and food systems. *FAO and Biovision*. <https://doi.org/10.4060/cb0438en>
- Leonardo, W. J., Van De Ven, G. W. J., Udo, H., Kanellopoulos, A., Siteo, A., & Giller, K. E. (2015). Labour not land constrains agricultural production and food self-sufficiency in maize-based smallholder farming systems in Mozambique. *Food Security*, 7(4), 857–874. <https://doi.org/10.1007/s12571-015-0480-7>
- Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., & Torquebiau, E. F. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4(12), 1068–1072.
- Lockeretz, W. (Ed.). (2007). *Organic farming: An international history*. CABI.
- MacLaren, C., Mead, A., van Balen, D., Claessens, L., Etana, A., de Haan, J., Haagsma, W., Jäck, O., Keller, T., Labuschagne, J., Myrbeck, A., Necpalova, M., Nziguheba, G., Six, J., Strauss, J., Swanepoel, P. A., Thierfelder, C., Topp, C., Tshuma, F., & Storkey, J. (2022). Long-term evidence for ecological intensification as a pathway to sustainable agriculture. *Nature Sustainability*, 5(9), 770–779. <https://doi.org/10.1038/s41893-022-00911-x>
- Makinde, E. A., Saka, J. O., & Makinde, J. O. (2019). Economic evaluation of soil fertility management options on cassava-based cropping systems in the rain forest ecological zone of south western Nigeria. *African Journal of Crop Science*, 7(1), 001–007.
- Mannar, V., Micha, R., Allemandi, L., Afshin, A., Baker, P., Battersby, J., Bhutta, Z., Corvalan, C., Di Cesare, M., Chen, K., Dolan, C., Hayashi, C., Fonseca, J., Grummer-Strawn, L., Rao, A., Rosenzweig, C., & Schofield, D. (2020). *2020 global nutrition report: Action on equity to end malnutrition*. UK Development Initiatives Poverty Research.
- Manshanden, M., Jellema, A., Sukkel, W., Jongeneel, R., Brazao Vieira Alho, C., De Miguel Garcia, A., De Vos, L., & Geerling-Eiff, F. (2023). Regenerative agriculture in Europe: An overview paper on the state of knowledge and innovation in Europe. *Wageningen Economic Research*. <https://doi.org/10.18174/629483>
- Mbau, S. K., Karanja, N., & Ayuke, F. (2015). Short-term influence of compost application on maize yield, soil macrofauna diversity and abundance in nutrient deficient soils of Kakamega County, Kenya. *Plant and Soil*, 387(1–2), 379–394. <https://doi.org/10.1007/s11104-014-2305-4>
- Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubiello, F. N., & Xu, Y. (2019). Food Security. In P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Peltzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (Eds.), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. <https://doi.org/10.1017/9781009157988.007>
- Mdee, A., Wostry, A., Coulson, A., & Maro, J. (2019). A pathway to inclusive sustainable intensification in agriculture? Assessing evidence on the application of agroecology in Tanzania. *Agroecology and Sustainable Food Systems*, 43(2), 201–227. <https://doi.org/10.1080/21683565.2018.1485126>
- Mousseau, F. (2015). The untold success story of agroecology in Africa. *Development*, 58(2–3), 341–345. <https://doi.org/10.1057/s41301-016-0026-0>
- Mugwanya, N. (2019). Why agroecology is a dead end for Africa. *Outlook on Agriculture*, 48(2), 113–116. <https://doi.org/10.1177/0030727019854761>
- Ngwira, A. R., Nyirenda, M., & Taylor, D. (2013). Toward sustainable agriculture: An evaluation of compost and inorganic fertilizer on soil nutrient status and productivity of three maize varieties across multiple sites in Malawi. *Agroecology and Sustainable Food Systems*, 37(8), 859–881. <https://doi.org/10.1080/21683565.2013.763889>
- Nicholls, C. I., Altieri, M. A., & Vazquez, L. (2017). Agroecological principles for the conversion of farming systems. In *Agroecological practices for sustainable agriculture* (pp. 1–18). World Scientific. https://doi.org/10.1142/9781786343062_0001
- Niggli, U., Sonneveld, M., & Kummer, S. (2023). Pathways to advance agroecology for a successful transformation to sustainable food systems. In von J. Braun, A. Kaosar, L. O. Fresco, & M. H. A. Hassan (Eds.), *Science and innovations for Food systems transformations*. Springer. https://doi.org/10.1007/978-3-031-15703-5_18
- 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>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 71. <https://doi.org/10.1136/bmj.n71>
- Pankhurst, C. E., Doube, B. M., & Gupta, V. V. S. R. (1997). Biological indicators of soil health: Synthesis. In C. E. Pankhurst, B. M. Doube, & V. V. S. R. Gupta (Eds.), *Biological indicators of soil health*. CAB International.
- Peano, C., Massaglia, S., Ghisalbetti, C., & Sottile, F. (2020). Pathways for the amplification of agroecology in African sustainable urban agriculture. *Sustainability*, 12(7), 2718. <https://doi.org/10.3390/su12072718>
- Petersen, R. G. (1994). *Agricultural field experiments: Design and analysis*. CRC Press.
- Pittelkow, C. M., Liang, X., Linquist, B. A., van Groenigen, K. J., Lee, J., Lundy, M. E., van Gestel, N., Six, J., Venterea, R. T., & van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, 517(7534), 365–368. <https://doi.org/10.1038/nature13809>
- Pretty, J. N. (1997). The sustainable intensification of agriculture. *Natural Resources Forum*, 21(4), 247–256.
- Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, 114(8), 1571–1596. <https://doi.org/10.1093/aob/mcu205>
- Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, 9(1), 5–24. <https://doi.org/10.3763/ijas.2010.0583>
- Pustejovsky, J. E., & Tipton, E. (2017). *clubSandwich: Cluster-robust (sandwich) variance estimators with small-sample corrections (Version 0.3. 5)[Computer software]*.
- Pustejovsky, J. E., & Tipton, E. (2022). Meta-analysis with robust variance estimation: Expanding the range of Working models. *Prevention Science*, 23(3), 425–438. <https://doi.org/10.1007/s11121-021-01246-3>
- R Core Team. (2019). *R: A language and environment for statistical computing*. R foundation for statistical computing. <https://www.R-project.org/>. Accessed 6 Aug 2022.
- Rasmussen, P. E., Goulding, K. W. T., Brown, J. R., Grace, P. R., Janzen, H. H., & Ko'rschens, M. (1998). Long-term

- agroecosystem experiments: Assessing Agricultural sustainability and global change. *Science*, 282, 893–896. <https://doi.org/10.1126/science.282.5390.893>
- Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants*, 2(2), 1–8.
- Riley, R. D., Higgins, J. P. T., & Deeks, J. J. (2011). Interpretation of random effects meta-analyses. *BMJ*, 342(Feb10 2), d549–d549. <https://doi.org/10.1136/bmj.d549>
- Ritzema, R. S., Frelat, R., Douchamps, S., Silvestri, S., Rufino, M. C., Herrero, M., Giller, K. E., López-Ridaura, S., Teufel, N., Paul, B. K., & Van Wijk, M. T. (2017). Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from East and West Africa. *Food Security*, 9(1), 115–131. <https://doi.org/10.1007/s12571-016-0638-y>
- Rosenberg, M. S., Rothstein, H. R., & Gurevitch, J. (2013). Effect sizes: Conventional choices and calculations. In *Handbook of meta-analysis in ecology and evolution* (pp. 61–71).
- Rubin, D. B. (Ed.). (2004). *Multiple imputation for nonresponse in surveys* (pp. i–xxix). Wiley. <https://doi.org/10.1002/9780470316696.fmatter>
- Ruthenberg, H. (1980). *Farming systems in the tropics* (3rd ed.). Oxford University Press.
- Sadras, V. O., Cassman, K. G. G., Grassini, P., Hall, A. J., Bastiaansen, W. G. M., Laborte, A. G., Milne, A. E., Sileshi, G., & Steduto, P. (2015). *Yield gap analysis of field crops – methods and case studies*. UN Food and Agriculture Organization.
- Sainju, U. M., Liptzin, D., & Jabro, J. D. (2022). Relating soil physical properties to other soil properties and crop yields. *Scientific Reports*, 12(1), 22025.
- Sapkota, T. B., Jat, M. L., Rana, D. S., Khatri-Chhetri, A., Jat, H. S., Bijarniya, D., Sutaliya, J. M., Kumar, M., Singh, L. K., Jat, R. K., Kalvaniya, K., Prasad, G., Sidhu, H. S., Rai, M., Satyanarayana, T., & Majumdar, K. (2021). Crop nutrient management using Nutrient Expert improves yield, increases farmers' income and reduces greenhouse gas emissions. *Scientific Reports*, 11(1), 1564. <https://doi.org/10.1038/s41598-020-79883-x>
- Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, 3(3), 430–439.
- Snapp, S., Kebede, Y., Wollenberg, E., Dittmer, K. M., Brickman, S., Egler, C., & Shelton, S. (2021). Agroecology and climate change rapid evidence review: Performance of agroecological approaches in low- and middle- income countries. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). <https://hdl.handle.net/10568/113487>
- Stanley, T. D., Doucouliagos, C., & Jarrell, S. B. (2008). Meta-regression analysis as the socio-economics of economics research. *The Journal of Socio-Economics*, 37(1), 276–292. <https://doi.org/10.1016/j.socsec.2006.12.030>
- Sterne, J. A. C., & Egger, M. (2005). Regression methods to detect publication and other Bias in Meta-Analysis. In H. R. Rothstein, A. J. Sutton, & M. Borenstein (Eds.), *Publication Bias in Meta-Analysis* (pp. 99–110). John Wiley & Sons, Ltd. <https://doi.org/10.1002/0470870168.ch6>
- Tittonell, P., & Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research*, 143, 76–90. <https://doi.org/10.1016/j.fcr.2012.10.007>
- UNDRR. (2019). *Global Assessment Report on Disaster Risk reduction*. United Nations Office for Disaster Risk Reduction.
- van Buuren, S., & Groothuis-Oudshoorn, K. (2011). *{mice}: Multivariate Imputation by Chained Equations in R*. 45, 1–67. <https://doi.org/10.18637/jss.v045.i03>
- Viability Project Team (2023). *Agroecological practices are widely used by African farmers* [Working Paper 2.]. CIFOR-ICRAF: The Transformative Partnership Platform on Agroecology. <https://doi.org/10.17528/cifor-icraf/008817>
- Viechtbauer, W. (2005). Bias and Efficiency of Meta-Analytic Variance Estimators in the Random-effects Model. *Journal of Educational and Behavioral Statistics*, 30(3), 261–293. <https://doi.org/10.3102/10769986030003261>
- Viechtbauer, W. (2010). Conducting Meta-analyses in R with the metafor Package. *Journal of Statistical Software*, 36(3). <https://doi.org/10.18637/jss.v036.i03>
- von Braun, J., Afsana, K., Fresco, L., & Hassan, D. (2021). Food systems: Seven priorities to end hunger and protect the planet. *Nature*, 597, 28–30. <https://doi.org/10.1038/d41586-021-02331-x>
- Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology as a science, a movement and a practice. A review. *Agronomy for Sustainable Development*, 29, 503–515. <https://doi.org/10.1051/agro/2009004>
- Wezel, A., Casagrande, M., Celette, F., Vian, J. F., Ferrer, A., & Peigné, J. (2014). Agroecological practices for sustainable agriculture. A review. *Agronomy for Sustainable Development*, 34(1), 1–20. <https://doi.org/10.1007/s13593-013-0180-7>
- Wezel, A., Soboksa, G., McClelland, S., Delespesse, F., & Boissau, A. (2015). The blurred boundaries of ecological, sustainable, and agroecological intensification: A review. *Agronomy for Sustainable Development*, 35(4), 1283–1295. <https://doi.org/10.1007/s13593-015-0333-y>
- Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, 40(6), 40. <https://doi.org/10.1007/s13593-020-00646-z>
- Willey, R. W. (1979). Intercropping — its importance and research needs. 1. Competition and yield advantages. *Field Crop Abstract*, 32, 1–10.
- Wolde-meskel, E., van Heerwaarden, J., Abdulkadir, B., Kassa, S., Aliyi, I., Degefu, T., Wakweya, K., Kanampiu, F., & Giller, K. E. (2018). Additive yield response of chickpea (*Cicer arietinum* L.) to rhizobium inoculation and phosphorus fertilizer across smallholder farms in Ethiopia. *Agriculture Ecosystems & Environment*, 261, 144–152. <https://doi.org/10.1016/j.agee.2018.01.035>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Miriam E. Romero Antonio is a Senior Researcher at the Center for Development Research (ZEF) at the University of Bonn, Germany. As an agricultural economist, she specializes in impact evaluation in the fields of food security and environment. Her research has primarily centered on exploring different aspects of agroecology in Africa and examining the urban food policies in Asia. In 2018, she obtained her Ph.D. in agricultural economics from the University of Göttingen. Following this, she worked as a technical consultant to the Food and Agriculture Organization (FAO) to support the implementation of regional projects related to urban food systems, including food environments, nutrition, food safety and mapping value chains. Her work also included assessments of the impact of COVID-19 on supply chains in the Asian regions and resilience among smallholder farmers.



Amy Faye is a Senior Researcher at the Center for Development Research (ZEF) at the University of Bonn, Germany. She holds a Bachelor degree in Mathematics and Economics from the University Toulouse 1 Capitole and a Master's degree in industrial organization from the Toulouse School of Economics. She was a research grant holder at the Senegalese Institute of Agricultural Research (ISRA) from 2012 to 2016 and a full-time researcher in the same institution after holding her PhD from 2018 to 2020.

Her Ph.D. research focused on bio-economic modeling of climate change impacts on irrigation water availability and analyzing taxation policy to manage groundwater resources in the northern coastal area of Senegal. She has collaborated with national and international organizations and universities such as IFPRI, LUKE, the University of Michigan, Cornell University. Amy has also worked on many other topics among which agricultural sustainability, the water-energy-food nexus, institutions of collective action.



Bibiana Betancur-Corredor is a Senior Researcher at the Center for Development Research (ZEF) at the University of Bonn, Germany, dedicated to agriculture and biodiversity conservation efforts. She holds a doctorate in agriculture from the University of Bonn, completed in 2018. Following her studies, she contributed to research at the University of York (UK), focusing on modeling the impacts of tillage intensification on soil structure. Transitioning to the Senckenberg Institute for Biodiversity

Research (Germany) in 2019, she conducted assessments on the global impacts of intensive agriculture on soil fauna. She is a member of the Society of Research Synthesis Methods and serves on the scientific committee of the International Network on Soil Biodiversity (NET-SOB). With a dedication to environmental science and her academic and research experience, Bibiana remains committed to advancing sustainable agricultural practices and biodiversity conservation.



Heike Baumüller is a Senior Researcher and Coordinator of the Program of Accompanying Research for Agricultural Innovation (PARI) at the Centre for Development Research (ZEF) at the University of Bonn, Germany. Her research focuses on the role of digital technologies in raising the productivity of small-holder farmers, improving the functioning of agricultural markets and facilitating agroprocessing in Africa. Previously, she was a Senior Researcher at Chatham House, London, and a

Programme Manager at the International Centre for Sustainable Development, Geneva, researching the environmental and socio-economic dimensions of trade and investment in natural resources. She holds a PhD in Agricultural Sciences from the University of Bonn.



Joachim von Braun is Distinguished Professor for Economic and Technological change at Bonn University, in the Center for Development Research (ZEF). His research is on economic development, food nutrition and agriculture, bioeconomy, science and technology policy. von Braun is President of the Pontifical Academy of Sciences of the Vatican, and member of German National Academy of Science Leopoldina, and other academies. In 2020 and 2021 he served as Chair of the

Scientific Group for the Food Systems Summit 2021 of the UN Secretary General. He was Director-General of the International Food Policy Research Institute (IFPRI) based in Washington DC.