



Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis

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Accepted: 5 August 2019 / Published online: 9 September 2019
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Abstract

Agricultural landscapes are increasingly being managed with the aim of enhancing the provisioning of multiple ecosystem services and sustainability of production systems. However, agricultural management that maximizes provisioning ecosystem services can often reduce both regulating and maintenance services. We hypothesized that agroforestry reduces trade-offs between provisioning and regulating/maintenance services. We conducted a quantitative synthesis of studies carried out in sub-Saharan Africa focusing on crop yield (as an indicator of provisioning services), soil fertility, erosion control, and water regulation (as indicators of regulating/maintenance services). A total of 1106 observations were extracted from 126 peer-reviewed publications that fulfilled the selection criteria for meta-analysis of studies comparing agroforestry and non-agroforestry practices (hereafter control) in sub-Saharan Africa. Across ecological conditions, agroforestry significantly increased crop yield, total soil nitrogen, soil organic carbon, and available phosphorus compared to the control. Agroforestry practices also reduced runoff and soil loss and improved infiltration rates and soil moisture content. No significant differences were detected between the different ecological conditions, management regimes, and types of woody perennials for any of the ecosystem services. Main trade-offs included low available phosphorus and low soil moisture against higher crop yield. This is the first meta-analysis that shows that, on average, agroforestry systems in sub-Saharan Africa increase crop yield while maintaining delivery of regulating/maintenance ecosystem services. We also demonstrate how woody perennials have been managed in agricultural landscapes to provide multiple ecosystem services without sacrificing crop productivity. This is important in rural livelihoods where the range of ecosystem services conveys benefits in terms of food security and resilience to environmental shocks.

Keywords Available phosphorus · Infiltration · Runoff · Soil erosion · Soil organic carbon · Soil moisture content · Trade-off

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1 Introduction

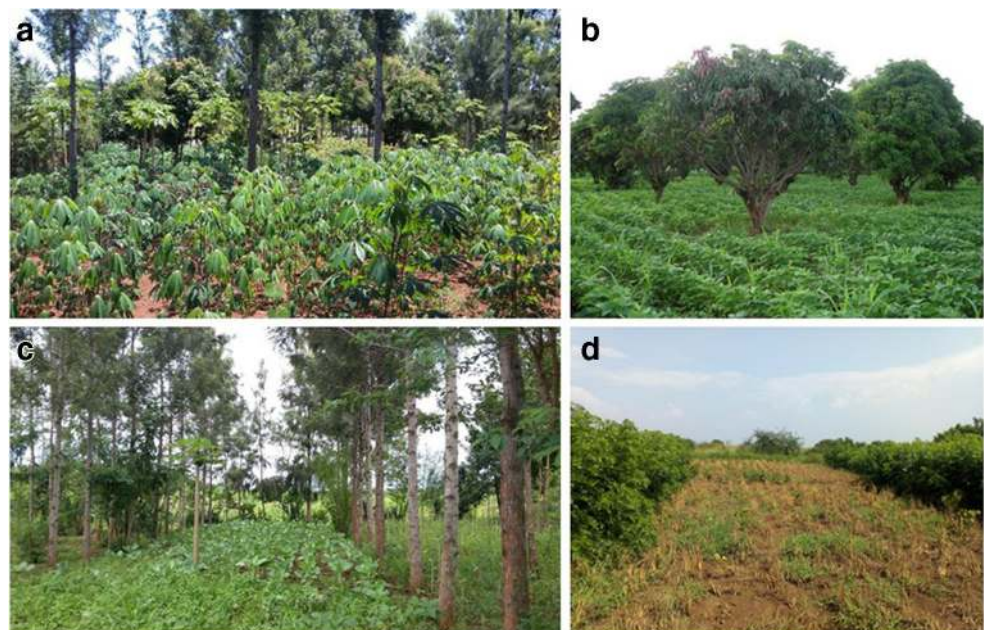
The smallholder agricultural sector in sub-Saharan Africa (SSA) is heavily constrained by declining per capita land holdings (Montpellier Panel 2013) and loss of soil fertility and productivity (Sanchez 2015). Therefore, sustainable intensification of smallholder agriculture has been recognized as a crucial component of the strategy towards increasing food production in the region (Snapp et al. 2010; Montpellier Panel 2013). Sustainable intensification is also now recognized as one of the cornerstones of climate-smart agriculture, i.e., agriculture that achieves the triple objectives of increasing productivity, adaptation to climate change, and mitigating greenhouse gas emissions (Campbell et al. 2014). It is apparent that intensification of agriculture in SSA will continue to play a role in feeding the growing population (Tully et al. 2015; van Ittersum et al. 2016). This poses the challenge of creating conditions for sustainable agriculture that can harness regulating/maintenance services (Bommarco et al. 2013). Agroforestry is considered as one of the sustainable intensification practices, and now widely promoted in SSA as it provides low-input, resource-conserving farming approaches that are socially relevant and relate well to livelihood and ecosystem functions (Carsan et al. 2014).

Agroforestry can help to maintain food supplies in many landscapes in SSA while at the same time increasing their climate resilience (Mbow et al. 2014). The practice involves deliberate growing of woody perennials in association with food crops and pastures (Fig. 1). Agroforestry is viewed as a sustainable alternative to monoculture systems because of its ability to provide multiple ecosystem services (Asbjornsen et al. 2013; Kuyah et al. 2016). In some areas, agroforestry

is preferred over monoculture systems, because it can combine provisioning ecosystem services with environmental benefits (Jose 2009). For example, agroforestry can raise carbon stocks in agricultural systems, maintain or improve soil fertility, regulate soil moisture content, control erosion, enhance pollination, and supply food (e.g., fruits and nuts), fuelwood, fodder, medicines, and other products (Kuyah et al. 2016, 2017). Ecosystem services of agroforests are affected by tree-crop-environment interactions. These interactions can occur aboveground, for example through interception of radiant energy and rainfall by foliage and moderation of temperatures by canopies (Kajembe et al. 2016; Luedeling et al. 2016) or belowground, e.g., in resource use (nutrient, water, space) competition, or complementarity (Monteith et al. 1991; Rao et al. 1998). Primarily, tree-crop-environment interactions influence biomass production, nutrient uptake and availability, storage and availability of water in the soil, water uptake by trees and crops, loss by evapotranspiration, and crop yields (Monteith et al. 1991). Despite the great number of studies investigating the role of agroforestry practices in ecosystem service provision, evidence is still inconclusive concerning the overall effects of agroforestry and the influence of ecological conditions, management, and type of woody perennials on crop yield, soil fertility, erosion control, and water regulation. This makes it difficult to assess the degree to which different ecological conditions and agroforestry practices influence ecosystem service provision, and to anticipate their respective consequences on crop yield.

The extent to which different ecosystem services are delivered in agroforestry is context-specific, and can depend on the environmental conditions, tree species and crops, and how the components of agroforestry are managed in the landscape. A

Fig. 1 Agroforestry practices common in sub-Saharan Africa. **a** Homegarden (a mosaic landscape with cassava, pawpaw, *Mangifera indica* L. and *Grevillea robusta* A.Cunn. ex R.Br. in Uganda). **b** Dispersed intercropping (*M. indica* in maize-bean intercrop in Malawi). **c** Intercropping with annual crops between widely spaced rows of trees (collard intercropped with *G. robusta*). **d** Alley cropping (climbing beans planted between hedges of *Gliricidia sepium* (Jacq.) Kunth ex Walp. in Rwanda)



number of studies that summarize literature on ecosystem services of agroforestry in SSA have been published (Bayala et al. 2014; Félix et al. 2018; Sileshi et al. 2014; Sinare and Gordon 2015; Kuyah et al. 2016). These studies have shown that agroforestry has the capacity to enhance delivery of ecosystem services, but it can also, in certain circumstances, have negative impacts. However, it is not clear whether and to what extent changes in ecosystem services reported in the literature are due to changes in ecological or management conditions and which are due to other causes. Experimental studies on the effect of agroforestry on soil fertility, erosion control, water regulation, and crop production services offer varying conclusions, most suggesting that the ecological contexts (e.g., climatic conditions, edaphic factors), management factors (e.g., the type of agroforestry practice), and the preferred tree or crop species are the most important factors (e.g., Angima et al. 2000, 2002; Kinama et al. 2007; Lal 1989a; Ndoli et al. 2017; Nyadzi et al. 2003; Nyamadzawo et al. 2003; Nyamadzawo et al. 2008a). Many of these findings are confounded by external effects, for example, the effect of trees on soil fertility and water regulation, and the consequent impact on crop yield. These varying conclusions call for a greater understanding of the conditions under which agroforestry favorably affects selected ecosystem services, and when the effect is likely to be negative. By understanding the contexts in which specific agroforestry practices are beneficial, and when they are likely to have no or a negative effect, advisory and policy recommendations can be improved.

We conducted a meta-analysis on studies which have investigated differences in crop yields, soil fertility, erosion control, and water regulation between agroforestry and non-agroforestry systems in SSA. Compared to traditional narrative reviews, meta-analytic methods are more objective, allow computation of effect sizes, and have improved control of type II errors (Harrison 2011; Koricheva et al. 2013). Meta-analyses have been conducted on agroforestry practices, but with a particular focus on regions such as semi-arid West Africa (Bayala et al. 2014; Félix et al. 2018; Sinare and Gordon 2015), or specific ecosystem services such as pest regulation (Pumariño et al. 2015), or certain crops and functional groups of woody perennials, such as the effect of woody and herbaceous legumes on maize yield (Sileshi et al. 2008), the impact of particular trees as organic nutrient sources on maize yield (Chivenge et al. 2011), and on the effects of specific agroforestry systems such as coffee and cacao agroforestry (De Beenhouwer et al. 2013). A meta-analysis has also been conducted on the effect of agroforestry on ecosystem services in the temperate region (Torralba et al. 2016). However, the impacts of agroforestry on crop yield, soil fertility, erosion control, and water regulation have not been quantitatively compared for SSA. Therefore, this study aims to determine the overall effect of agroforestry on these ecosystem services and tries to answer the following questions:

- (1) What is the impact of agroforestry on crop yield, soil fertility, erosion control, and water regulation?
- (2) Under which ecological conditions (agro-ecological zone, elevation, and soil type) does agroforestry have a positive or a negative effect?
- (3) What is the impact of management (site of trial and agroforestry practice) on agroforestry's effect on crop yield, soil fertility, erosion control, and water regulation?
- (4) How do different shrub and tree species differ regarding their potential to regulate these ecosystem services?

2 Materials and methods

2.1 Literature survey and criteria for inclusion

A literature search was conducted in Web of Science to identify published studies that provide data on the effect of agroforestry on ecosystem services, covering all years from 1945 until June 2018. The following search string was used: TS = [(infiltrat* OR "soil water" OR "soil moisture" OR "water regulation" OR "erosion" OR "available phosphorus" OR "Olsen phosphorus" OR "soil fertility" OR "total phosphorus" OR "total nitrogen" OR "soil organic carbon" OR "crop yield") AND (agroforest* OR "alley crop*" OR hedgerow OR parkland OR "improved fallow" OR "planted fallow" OR "contour planting" OR "boundary tree*" OR "shade tree" OR "live fence" OR woodlot OR "fodder bank" OR "home\$garden" OR "wind\$break" OR "shelter\$belt" OR "dispersed intercropping") AND (Africa OR sub-Saharan Africa)]. Other sources include a recent structured vote count review (Kuyah et al. 2016), a meta-analysis by Sileshi et al. (2008) and a narrative review by Sileshi et al. (2014). All studies and bibliographies were screened for other relevant publications.

Potential studies were reviewed for inclusion in the analysis according to the following criteria: (1) Paper published in a peer-reviewed scientific journal; unpublished literature and grey literature were excluded. (2) Study conducted on a research station or farmer's field in SSA. (3) Study investigated the effect of trees on ecosystem services with a suitable control, i.e., a tree-based system compared with tree-less, or investigation beneath tree crowns compared with investigation outside tree crowns. (3) Original field observation or experimental studies, excluding laboratory studies, greenhouse experiments, modeling studies, anecdotal observations, and reviews. (4) Studies reporting quantitative information on the sample size and the mean value of the response variable; the standard deviation or variance of the mean value was extracted when reported by the authors.

2.2 Data compilation and classification

Data on indicators of ecosystem services, including crop yield, soil fertility (available P, total N and SOC), erosion control

(runoff and soil loss), and water regulation (infiltration rate and soil moisture content) were identified and extracted from the studies. We followed the Common International Classification of Ecosystem Services (Haines-Young and Potschin 2018). Accordingly, crop yield was considered a provisioning service, while soil fertility, erosion control, and water regulation were considered regulation/maintenance services. The publications that reported soil fertility, erosion control, and water regulation were screened to extract data on crop yield. Thus, crop yield was considered only if one of the regulating/maintenance services was also measured. Data that were only reported in figures were extracted using WebPlotDigitizer (Rohatgi 2016). The geographic coordinates of the studies were used to gather information such as the agro-ecological zone, elevation, soil type, and rainfall from available government databases and Google Search, where this information was not reported directly in the publication. Missing rainfall data (total precipitation) were obtained through the SamSamWater Climate Tool (New et al. 2002).

Data were categorized into a range of subgroups covering ecological conditions (agro-ecological zones, elevation, and soil type), and management (site of trial and agroforestry practice) and types of woody perennials (growth form and nitrogen fixation). Agro-ecological zones were classified as humid or semi-arid as described in HarvestChoice (2010). Elevation was classified as highland (above 1200 m) and lowland (below 1200 m), corresponding to cool and warm thermal zones (HarvestChoice 2010). Thermal zones were included to account for the effect that changes in elevation may have on crops (HarvestChoice 2010). The soil types were strictly based on the Harmonized Soil Atlas of Africa following the World Reference Base for Soil Resources classification and correlation system (Dewitte et al. 2013). Woody perennials were classified as (1) shrubs or trees based on growth form and their management within crop fields, and (2) nitrogen fixing or non-fixing based on their ability to fix atmospheric nitrogen. Shrubs denote short woody plants, often with multiple stems arising at or near the ground (Orwa et al. 2009). Shrubs can be coppicing or non-coppicing, and are normally planted in hedgerows, alleys, or fallows to provide fodder, green manure, wood, or stakes (Orwa et al. 2009). Trees denote tall woody plants with a single stem that supports the canopy upward (Orwa et al. 2009). Trees are normally dispersed in crop fields or parklands, and are often pruned or pollarded to provide wood, or cut for timber (Orwa et al. 2009).

Agroforestry practices were categorized based on descriptions provided by the studies reviewed. The following agroforestry practices and technologies were identified from the studies. Eight categories referred directly to the structure of the agroforestry system:

1. Alley cropping, where crops are grown between rows of trees or shrubs.
2. Hedgerows, where shrubs are planted in closely spaced rows aimed at forming a barrier, enclosing or separating fields.
3. Dispersed intercropping, where trees are scattered in crop fields.
4. Multistrata agroforests, where perennial tree crops such as coffee, cocoa, or tea are intercropped with shade trees.
5. Parklands, where multipurpose trees are scattered on farmlands; crops are grown beneath the crowns of trees such as *Faidherbia albida*, *Parkia biglobosa*, or *Vitellaria paradoxa*.
6. Windbreaks, where trees are planted in one or more rows to provide shelter or protection from wind.
7. Boundary planting, where trees are planted to demarcate farms or farm enterprises.
8. Planted fallows (improved fallows), where land is rested from cultivation, during which fast-growing species are planted, e.g., to replenish soil fertility and provide products such as wood.

Boundary plantings and windbreaks were not included in the analysis because we did not find enough studies for systematic analysis. Only one study (with two data points) reporting on boundary planting and two studies (with four data points) reporting on windbreaks met the selection criteria. Multistrata agroforests involving plantations of coffee, tea and cocoa, and homegardens were not in the analysis.

The literature also revealed two important categories of management that referred to the use of agroforestry products for soil amendments and protection:

1. Biomass transfer where harvested leaves and twigs, or material pruned from trees outside the field, are incorporated into the soil prior to planting to improve soil fertility. Trees inside the fields can also be rejuvenated by pruning and prunings incorporated in the soil for crop production.
2. Mulch, where pruning materials are used as protective covering on the surface to suppress weeds, conserve soil moisture, prevent soil erosion, and enrich the soil.

Subgroup analyses were conducted on soil types (Acrisols, Andosols, Arenosols, Cambisols, Ferralsols, Lixisols, Luvisols, and Nitisols) and agroforestry practices (alley cropping, dispersed intercropping, hedgerow, planted fallow, and crops planted under tree canopies in parkland agroforestry systems) and agroforestry technologies (biomass transfer and mulching) that had a minimum of fifteen observations from at least three studies. We did not compare effects of specific tree and shrub species, or responses of different crops to agroforestry because of a small number of observations in each category and the need to avoid the small sample size problem caused by fragmentation of data. Comparison of small sample sizes is known to result in Simpson's Paradox, a statistical

problem in which a trend that appears in several small sets of data disappears when these sets are combined (Pearl 2014).

2.3 Independence of data points

Meta-analytic techniques require independence of data points being analyzed (Borenstein et al. 2009; Koricheva et al. 2013). However, some publications report multiple results from a single study, for example, when various experiments are undertaken within a study. Including multiple observations in such analyses can inflate sample sizes, increase the significance levels, and increase the probability of type I errors (Sileshi et al. 2008), while leaving out results from multiple observations in each study can lead to loss of information (Gurevitch and Hedges 1999). We countered the problem of non-independence of data points in several ways: (1) Observations from the same study were considered independent records and included separately in the analysis if they were measured for different locations, seasons, tree species, or crop species. Treating multiple results in this way may not strictly meet the assumption that each observation is independent of all others (Gurevitch and Hedges 1999), but it allowed full examination of the different aspects of agroforestry that affect ecosystem service provision. (2) When a study reported data from multiple fertilizer rates, row spacings or tillage practices, measurements for treatments with recommended rates or common farmer practices were selected for analysis. (3) When a study reported repeated measurements at different times within the experimental period separately (e.g., sampling date), we selected the observation where the measurement was highest in the control group. (4) When a study reported results of experiments with groups of trees during different years, measurement from the final year, which exhibits the maximum effect/benefits on ecosystem services, was selected. (5) Studies reporting on SOC measurements between 0 and 100 cm depth were selected for analysis.

2.4 Data analysis

The response ratio (RR) was used as the index of effect size as it is a common metric for assessing ecosystem services in agricultural landscapes (Sileshi et al. 2008; Chivenge et al. 2011; De Beenhouwer et al. 2013; Pumariño et al. 2015; Torralba et al. 2016). RR was calculated as the ratio of measured response variable in agroforestry to that in non-agroforestry using the following formula:

$$RR = \left(\bar{X}_{AF} \right) / \left(\bar{X}_{NA} \right)$$

where \bar{X} is the mean for the indicator of the ecosystem service, and the subscripts AF and NA indicate agroforestry and non-agroforestry groups. Non-agroforestry includes sole cropping, continuous cropping without trees, and plots outside tree

crowns in the case of parklands. RR were calculated for all pairs (agroforestry and non-agroforestry) of independent data points, hereafter referred to as observations.

Bootstrapping methods were used to estimate 95% confidence intervals around weighted means of RR for different categorical variables through the application of 10,000 iterations using the boot package in the R programming language 3.4.2 (R Core Team 2018). Non-parametric weighting of the RR ensured that studies with larger sample sizes carried more weight than those with smaller sample sizes (Adams et al. 1997). Typically, effect sizes of individual studies are weighted by the inverse of their sampling variance (Gurevitch and Hedges 1999). However, a major limitation to conducting a meta-analysis is lack of variance estimates presented in primary studies (Gurevitch and Hedges 1999). Leaving out studies that lack variance estimates disadvantages the analysis and may lead to bias in the results (Wiebe et al. 2006). In this review, standard deviations were missing in most studies, but the sample sizes were available. Weights for RR were therefore calculated using sample sizes as described by Adams et al. (1997) using the following formula:

$$\text{Weights} = (N_{AF} \times N_{NA}) / (N_{AF} + N_{NA})$$

where N is the sample size and the subscripts AF and NA indicate agroforestry and non-agroforestry.

Meta-analyses can be affected by underreporting of statistically non-significant results and/or those that are inconsistent with the current theory (Koricheva et al. 2013). This means that a meta-analysis can overestimate effect sizes if studies finding significant effects are more likely to be published than studies finding no effect (Borenstein et al. 2009). Publication bias was checked using the rank correlation test. A rank correlation test is based on correlating the standardized treatment effect with the variance of the treatment effect using Kendall's tau as the measure of association (Begg and Mazumdar 1994). Accordingly, significant correlation indicates that larger effect sizes in one direction are more likely to be published than smaller effect sizes (Begg and Mazumdar 1994; Sterne et al. 2000).

Analyses of trade-offs were performed on studies that recorded both yield and soil fertility or water regulation. The number of observations that showed, for example, increase in both yield and soil fertility (win-win), an increase in yield with a corresponding decline in soil fertility (trade-offs), or a decrease in both yield and soil fertility (lose-lose) were identified. A similar approach was applied to associations among total N, available P, SOC, and soil moisture content. The percentage of observations belonging to win-win, trade-offs, and lose-lose situations was calculated and the data were plotted in a Cartesian plane to facilitate visualization. Spearman's rank correlation tests were performed between effect sizes of different ecosystem service indicators to determine whether they co-varied positively.

The effect of agroforestry on a given ecosystem service was considered to be statistically significant if the 95% CI of the mean effect did not overlap with $RR = 1$. For crop yield, soil fertility, and water regulation, RR values significantly larger than 1 were interpreted as evidence for beneficial effects of agroforestry, while RR values significantly smaller than 1 were interpreted as negative effects. This was inverted for soil loss and runoff; RR values significantly smaller than 1 were interpreted as indications of beneficial effects of agroforestry. The sign of RR for the effects of agroforestry on erosion control was changed, so that all beneficial effects of agroforestry were reflected in positive values. Violin plots were produced using packages “plyr” (Wickham 2016), “dplyr” (Wickham et al. 2018b), “reshape” (Wickham 2017), and ‘ggplot2’ (Wickham et al. 2018a) in the R programming language 3.4.2 (Core Team 2018). Violin plots reveal the full distribution of the data. The proportion (%) of observations with response ratio below or above one ($RR < 1$, $RR > 1$) was calculated to determine the share of observations below or above the null hypothesis value.

3 Results and discussion

Kendall’s rank correlation did not show presence of bias for crop yield ($\tau = 0.050$, $N = 389$, $P = 0.200$), total N ($\tau = -0.093$, $N = 389$, $P = 0.109$), SOC ($\tau = -0.054$, $N = 389$, $P = 0.329$), and available P ($\tau = -0.138$, $N = 502$, $P = 0.018$), but showed presence of bias for water regulation ($\tau = -0.234$, $N = 96$, $P < 0.001$), and erosion control ($\tau = -0.107$, $N = 72$, $P < 0.001$). The significant correlations found for water regulation and erosion control indicate that studies with non-significant effects were less likely to have been published. It is also possible that the bias emerges due to the fact that some studies could have been deemed “failures” because the trees did not establish properly. For example, in an earlier meta-analysis Sileshi et al. (2008) noted that out of 93 sites where improved fallow trials were established in southern Africa, maize was harvested from only 72 sites as a result of poor establishment of the legumes. The difficulty to capture such studies is one of the limitations of this analysis, and indeed any other similar meta-analysis (Sileshi et al. 2008).

Despite the publication bias revealed above, overall the analysis showed that agroforestry can increase crop yield, and improve soil fertility, erosion control, and water regulation compared to the control (Fig. 2). Average crop yield was almost twice as high in agroforestry as in non-agroforestry systems; soil fertility was improved by a factor of 1.2, control of runoff and soil loss was five and nine times better with agroforestry, and infiltration was three times higher in agroforestry compared to the control. These are important insights into agroforestry, which is a land use option that is very common in SSA, where smallholder farms constitute ~ 80% of all farms, and roughly

70% of the population depend on agriculture for their livelihoods (Alliance for a Green Revolution 2014). At a farm scale, farmers are likely to invest in trees that provide food (fruits and nuts), fodder, fiber, or fuel while at the same time improving soil fertility, erosion control, and water regulation for sustainable production. On a larger geographic scale, agroforestry trees accrue benefits for many people and the environment, and farmers providing the services receive them as co-benefits.

Significant positive effects of agroforestry on ecosystem services were found across ecological and management conditions (Table 1). Exceptions were detected for some agroforestry practices (e.g., hedgerows) and some soil types where agroforestry had negative effects. This suggests that agroforestry’s potential for ecosystem service delivery cuts across the different ecological and management conditions involved. The 126 publications we reviewed present a mix of ecological, management, and biological characteristics that typify smallholder farming systems in SSA. The overall positive effects across contexts can be attributed to advances in the knowledge and practice of agroforestry. With decades of research and centuries of practice, agroforestry practitioners can now match some tree species to ecological conditions, select the right combinations of trees and crops, and productively manage trees on farms.

3.1 Crop yield

Crop yield was analyzed for 397 observations from 61 publications for studies conducted in 17 countries (Fig. 3). Close to half of the observations were from studies conducted in Kenya (10 studies, 108 observations) and Nigeria (10 studies, 77 observations). Other than agroforestry practice and soil type, there were no differences between any of the categories of agro-ecological zone, elevation, type of trial, growth form, or nitrogen fixation. Crop yield was higher in both humid and semi-arid situations compared to the control (Table 1). A similar pattern was observed for elevation, where agroforestry increased crop yield for trials at lowland and highland locations compared to the control. With regard to soil types, yields were two times higher under agroforestry with Acrisols, Cambisols, Lixisols, Luvisols, and Nitisols compared to controls (Fig. 3). These soils also had the highest number of cases with $RR > 1$. On the contrary, Arenosols and Andosols had some occurrences where the RR was less than 1 (Fig 3). Low crop yield associated with Arenosols and Andosols could be attributed to differences in soil quality. Arenosols have low nutrient and water storage capacity because of their coarse texture, which presents a limitation on crop growth (Hartemink and Huting 2008; IUSS 2014). Moreover, Arenosols generally occur in regions that are characterized by arid and semi-arid climates, where rainfall is erratic (Hartemink and Huting 2008). Andosols have high P retention capacity that makes applied P fertilizer unavailable for crop

Fig. 2 Results of meta-analysis of agroforestry vs. non-agroforestry effects on provision of ecosystem services across sub-Saharan Africa. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry effects. RR < 1 and RR > 1 represent the proportion (%) of observations with response ratio below or above 1 respectively. Values in brackets indicate the number of studies reviewed (N) and the number of observations (NO)

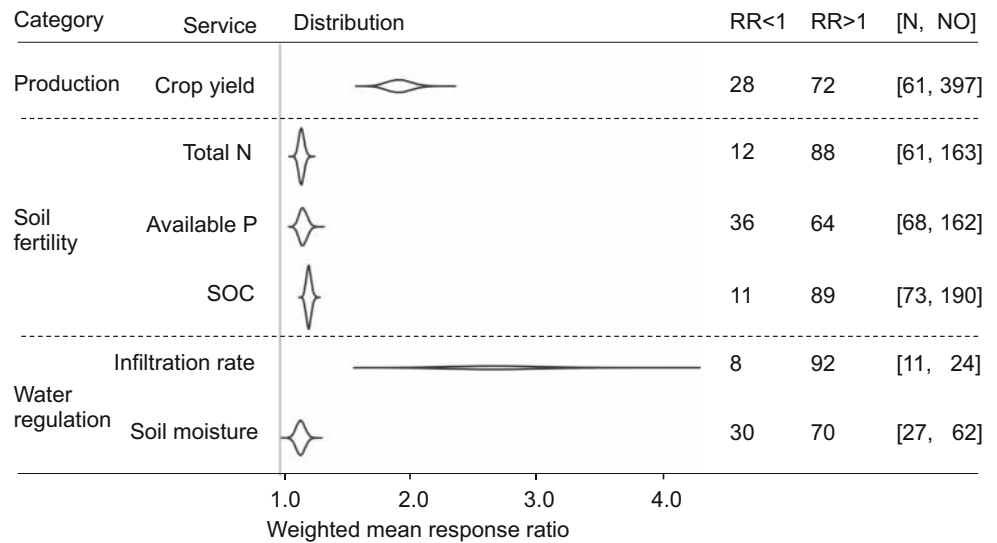


Table 1 The effects of agroforestry on crop yield, total nitrogen, available phosphorus, soil organic carbon (SOC), and water regulation (infiltration and soil moisture). Table values are the weighted mean response ratio (RR) and the 95% confidence interval (CI). Effects are significantly different from 0, if the 95% CI does not include 1. NA not available

Context	Category	Crop yield		Total N		Available P		SOC		Water regulation		
		RR	95% CI	RR	95% CI	RR	95% CI	RR	95% CI	RR	95% CI	
Agro-ecological zone	Humid	2.0	1.8–2.2	1.2	1.1–1.3	1.2	1.2–1.3	1.2	1.2–1.3	1.2	1.1–1.3	
	Semi-arid	1.9	1.6–2.2	1.1	1.1–1.2	1.1	1.0–1.2	1.2	1.2–1.3	1.7	1.5–2.1	
Elevation	Highland	2.0	1.7–2.4	1.1	1.1–1.2	1.2	1.1–1.3	1.2	1.2–1.3	1.7	1.4–2.1	
	Lowland	1.9	1.7–2.1	1.2	1.1–1.3	1.2	1.1–1.3	1.2	1.2–1.3	1.4	1.2–1.8	
Soil type	Acrisols	2.4	2.0–3.2	1.1	1.0–1.3	1.1	1.0–1.4	NA	NA	NA	NA	
	Andosols	1.2	1.0–1.4	NA	NA	1.3	1.1–1.7	1.1	1.0–1.1	NA	NA	
	Arenosols	1.5	0.9–2.5	NA	NA	NA	NA	NA	NA	NA	NA	
	Ferralsols	NA	NA	1.2	1.1–1.3	NA	NA	1.2	1.2–1.3	NA	NA	
	Cambisols	2.0	1.5–2.9	NA	NA	NA	NA	NA	NA	NA	NA	
	Lixisols	1.8	1.3–2.4	NA	NA	NA	NA	1.3	1.2–1.4	3.9	2.8–5.2	
	Luvisols	2.0	1.6–2.6	1.1	1.0–1.2	1.1	1.0–1.2	1.2	1.2–1.4	1.3	1.1–1.4	
	Nitisols	2.1	1.9–2.4	1.3	1.2–1.4	1.4	1.3–1.6	1.2	1.2–1.3	1.2	1.0–1.3	
	Type of trial	On-farm	2.0	1.8–2.2	1.1	1.1–1.2	1.1	1.1–1.2	1.2	1.2–1.3	1.4	1.2–1.8
		On-station	1.9	1.7–2.2	1.2	1.2–1.3	1.2	1.1–1.4	1.3	1.2–1.3	1.8	1.5–2.2
Agroforestry practice	Alley cropping	2.1	1.8–2.5	1.3	1.1–1.5	1.1	0.9–1.3	1.1	1.0–1.2	NA	NA	
	Biomass transfer	2.3	2.0–2.5	1.1	1.1–1.2	1.4	1.2–1.6	1.2	1.1–1.2	NA	NA	
	Hedgerow	0.9	0.9–1.0	NA	NA	1.5	1.3–1.9	NA	NA	NA	NA	
	Intercrop	1.3	1.1–1.7	1.1	0.9–1.2	1.1	1.0–1.1	1.2	1.1–1.3	1.1	1.0–1.2	
	Mulch	1.6	1.3–2.5	NA	NA	NA	NA	NA	NA	NA	NA	
	Planted fallow	2.6	2.2–3.3	1.2	1.1–1.3	1.3	1.2–1.6	1.4	1.3–1.5	2.3	1.9–2.9	
	Under canopy	NA	NA	1.1	1.1–1.2	1.1	1.0–1.2	1.2	1.2–1.4	1.2	1.1–1.3	
Growth form	Tree	1.8	1.6–2.2	1.2	1.1–1.2	1.2	1.1–1.3	1.2	1.2–1.3	1.4	1.2–1.9	
	Shrub	2.0	1.8–2.3	1.2	1.1–1.2	1.2	1.1–1.3	1.2	1.2–1.3	1.8	1.5–2.3	
Nitrogen fixation	N-fixing	2.0	1.8–2.2	1.2	1.1–1.2	1.2	1.1–1.3	1.2	1.2–1.3	1.7	1.5–2.1	
	Non-fixing	1.8	1.6–2.5	1.2	1.1–1.2	1.1	1.1–1.2	1.2	1.2–1.3	1.1	1.0–1.2	

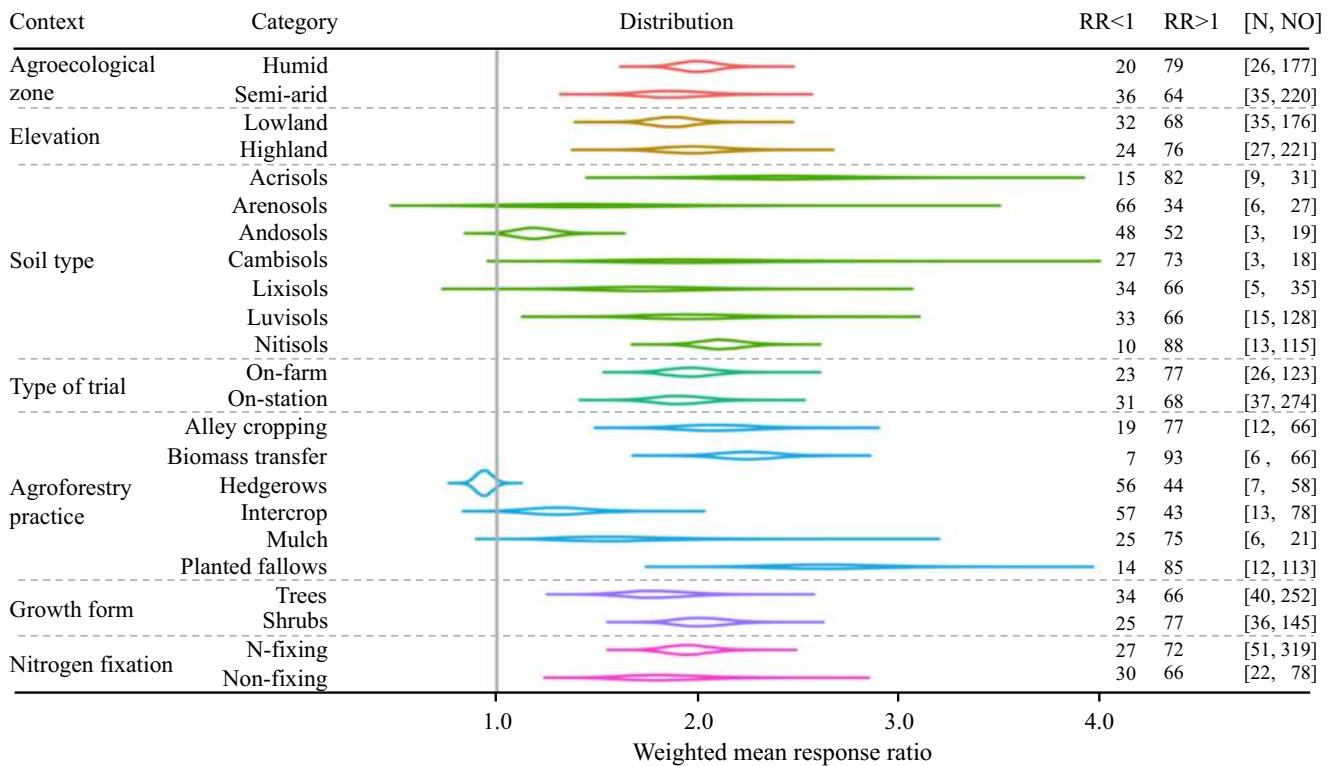


Fig. 3 Results of meta-analysis of agroforestry vs. non-agroforestry effects on crop yield under different conditions across sub-Saharan Africa. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry effects. RR < 1 and RR > 1 represent the

proportion (%) of observations with response ratio below or above 1. Values in brackets indicate the number of studies reviewed (N) and the number of observations (NO)

uptake (Batjes 2011). In addition, Andosols are nutrient-rich, and the risk of non-response to applied nutrients on fertile soil is known to be high due to a phenomenon termed “saturated fertility” effect (Sileshi et al. 2010).

Agroforestry increased crop yield for trials conducted on both farms and research stations in 77 and 68% of all cases (Fig. 3 and Table 1). Among agroforestry practices, crop yield was higher than controls when alley cropping, biomass transfer, and planted fallows were used, but not for hedgerows (Table 1). Alley cropping, biomass transfer, and planted fallows increased crop yield in 77, 93, and 85% of all cases, while hedgerows increased crop yield in 54%. Agroforestry increased crop yield when either trees or shrubs were grown compared to controls. Similarly, crop yield was enhanced when both nitrogen-fixing or non-fixing species were grown compared to controls.

The findings provide evidence that agroforestry can significantly increase crop yield. The studies reviewed suggest a combination of causes for increased crop yield, for example improved soil fertility due to nitrogen input from biological nitrogen fixation and nutrient cycling in organic inputs from trees (Bayala et al. 2002; Sileshi and Mafongoya 2003), improved water regulation through increased infiltration and higher soil moisture content (Chirwa et al. 2003; Makumba et al. 2006), improved microclimate (Rhoades 1995), and better soil physical properties (Chirwa et al. 2004). In most of the studies, yield was increased

sufficiently to offset reduction caused by the presence of trees. However, a few studies reported a yield reduction due to competition for water and nutrients when the trees were not pruned (Bayala et al. 2002; Muthuri et al. 2005; Ndoli et al. 2017). Reductions in crop yield were also attributed to effects of shading (Rao et al. 1998; Bayala et al. 2002). Further meta-analyses can test if pruning and shade levels are indeed factors that lead to reduced crop yield.

3.2 Total nitrogen, available phosphorus, and soil organic carbon

A total of 515 observations were identified from 92 publications that fulfilled the selection criteria for studies investigating the effects of agroforestry on soil fertility. Among these, 61 publications reported total N, 68 reported available P, and 73 reported SOC for studies conducted in 19 countries (Fig. 2). Agroforestry improved total N (RR 1.2; 95% CI 1.1–1.2), SOC (RR 1.2; 95% CI 1.2–1.3) and available P (RR 1.2; 95% CI 1.1–1.2) compared to the control. Agroforestry also improved total N, available P, and SOC for all categories of agro-ecological zones and elevation compared to controls (Table 1). Compared to controls, agroforestry improved total N, available P, and SOC for all soil types except on Acrisols and Luvisols in the case of total N, and Andosols in the case of SOC (Table 1). The lower effect of

agroforestry on Acrisols could be attributed to their chemical and physical limitations, which also constrain tree growth. Acrisols suffer from soil acidity, aluminum toxicity, low nutrient reserves, nutrient imbalance, and multiple nutrient deficiencies (IUSS 2014). Although Luvisols are inherently fertile, they are susceptible to crusting, compaction, and low moisture-retention (IUSS 2014). These constraints could have limited tree growth thereby reducing litter inputs to the soil on both soils. On the other hand, the low response on Andosols could be attributed to the “saturated fertility” effect described under crop yield.

There were no significant differences among agro-ecological zones, elevation, and type of trial. Over 80% of the cases in humid and semi-arid environments, as well as lowland and highland sites had $RR > 1$ for studies investigating total N (Fig. 4) and SOC (Fig. 5); a smaller proportion was found for available P (Fig. 6). All observations for total N and SOC in agroforestry under Ferralsols had $RR > 1$ (Figs. 4 and 5). Agroforestry increased total N, SOC, and available P for trials conducted on farms as well as on stations compared to controls (Figs. 4, 5, and 6). A lower proportion of cases were determined for available P (about 60%) compared to over 80% for total N and SOC for trials conducted on farms and on stations. Other than intercropping ($RR < 1 = 35\%$) in the case of total N (Fig. 4), and alley cropping ($RR < 1 = 62$) in the case of available P (Fig. 6), soil fertility improved with agroforestry for all practices tested

compared to controls. Agroforestry with all types of woody vegetation had a significant effect on total N, SOC, and available P compared to controls, although the proportion of observations with $RR > 1$ was low for available P, ranging between 58 and 68% for the different variables (Fig. 6). The differences among agroforestry practices and woody perennials used were not statistically significant.

The analysis has demonstrated that soil was more fertile in agroforestry than in controls. SOC showed a stronger increase in agroforestry than other indicators of soil fertility. Trees increase SOC by photosynthetic fixation of carbon from the atmosphere, and by transferring this carbon to the soil via litter and root decay. We infer that trees were the main source of nitrogen and soil organic carbon, since crop residues are usually removed with the harvest. Some studies reported a strong correlation between total N and SOC (Jonsson et al. Jonsson et al. 1999a; Bayala et al. 2002). Trees improve nitrogen primarily through inputs from biological nitrogen fixation (Sileshi and Mafongoya 2003), and recycling of nitrogen from above (litter) and belowground (roots) organic inputs (Rhoades 1995; Jonsson et al. 1999a). A few cases of decline in total N were attributed to uptake by trees (Teklay et al. 2006; Isaac et al. 2007; Ndoli et al. 2017).

Available P was the least improved indicator of soil fertility. Unlike nitrogen and carbon, trees do not provide phosphorus but improve its availability and uptake by recycling the

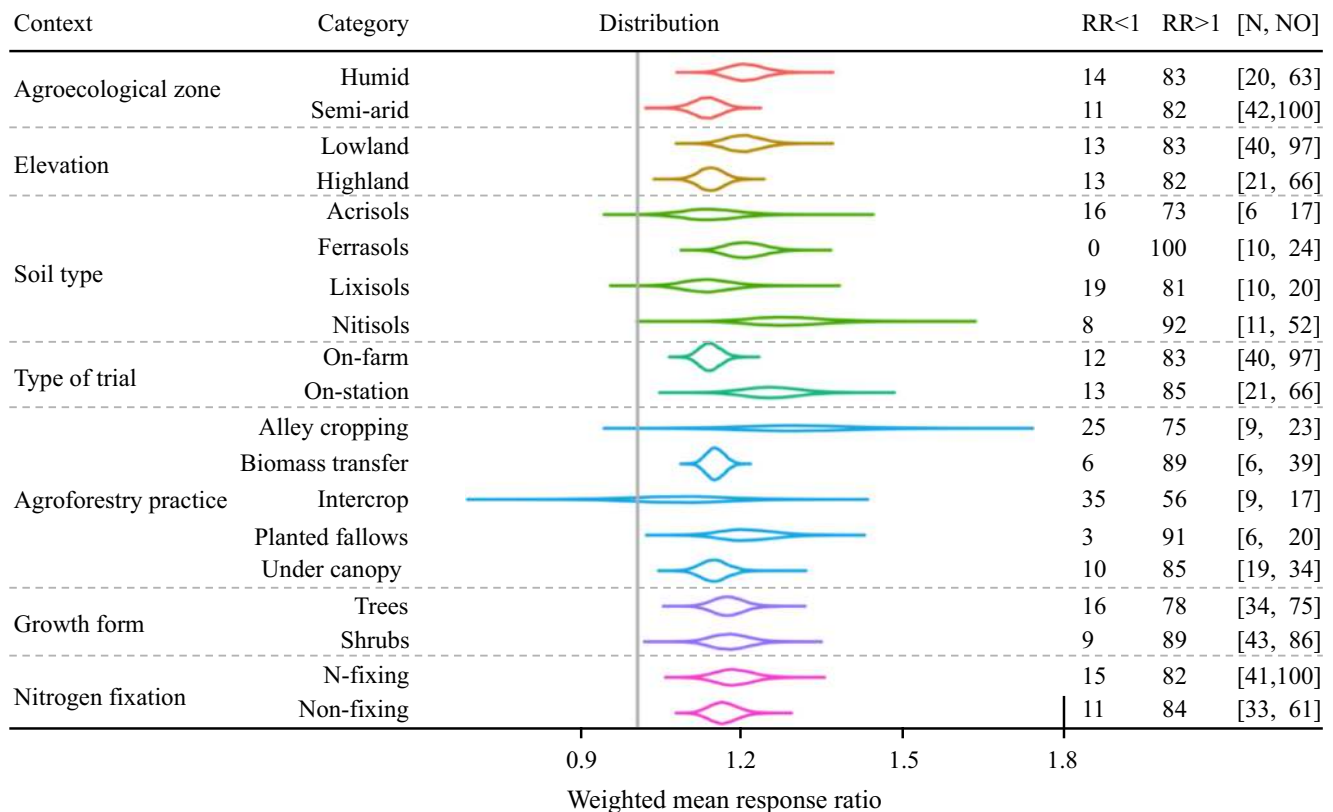


Fig. 4 Results of meta-analysis of agroforestry vs. non-agroforestry effects on total nitrogen under different conditions. Violin plots represent bootstrapped t_0 values of agroforestry minus non-agroforestry

effects. $RR < 1$ and $RR > 1$ represent the proportion (%) of observations with response ratio below or above 1. Values in brackets indicate the number of studies reviewed (N) and the number of observations (NO)

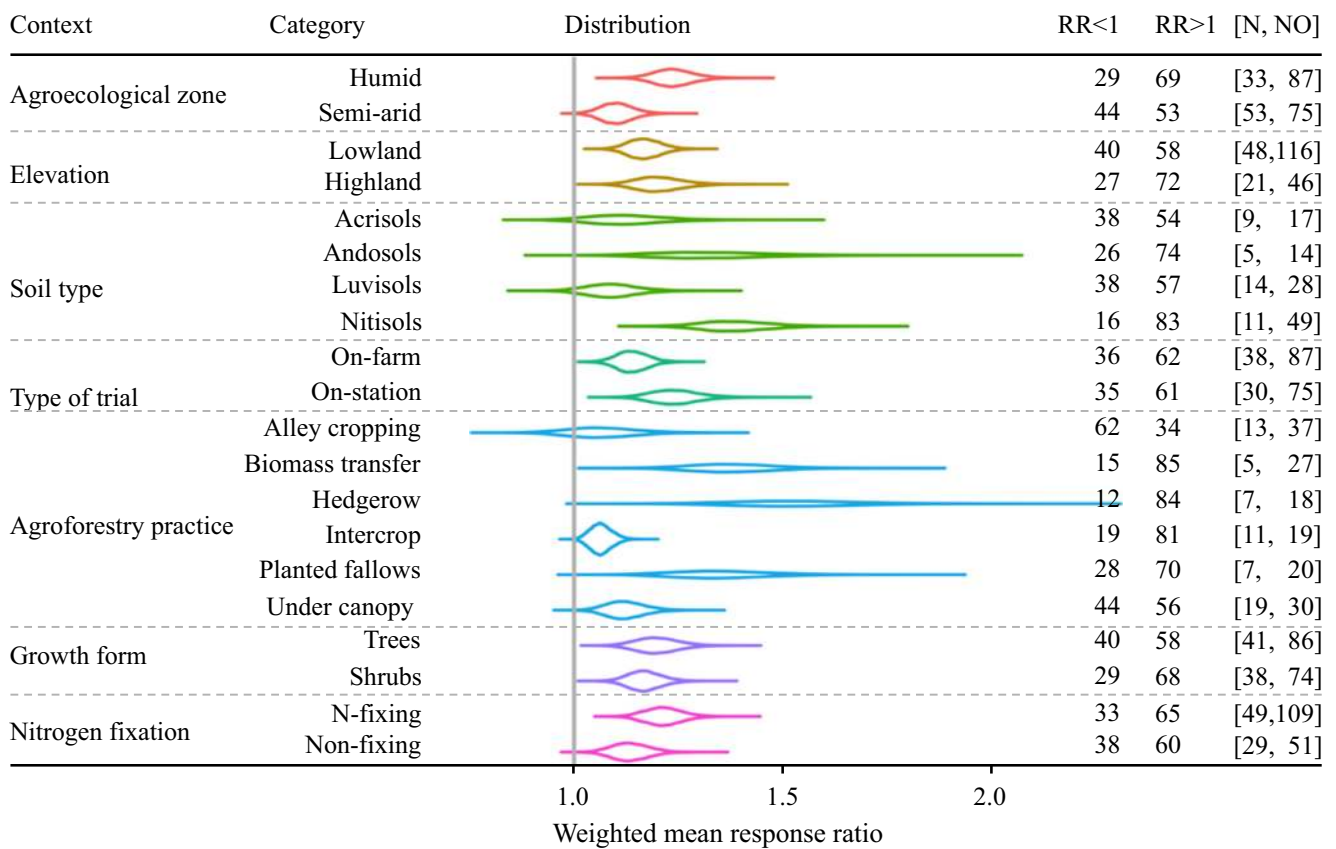


Fig. 5 Results of meta-analysis of agroforestry vs. non-agroforestry effects on soil organic carbon under different conditions. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry

effects. RR < 1 and RR > 1 represent the proportion (%) of observations with response ratio below or above 1. Values in brackets indicate the number of studies reviewed (N) and number of observations (NO)

nutrient from organic inputs. This occurs when tree roots retrieve nutrients that have leached to soil layers not accessed by crop roots and recycle them to the topsoil as litter (Sileshi et al. 2014). However, trees may fail to improve phosphorus availability when the nutrient is not recycled and released in accessible form. This may explain some of the situations where available P was lower in tree-based compared to tree-less systems (Kho et al. 2001; Bayala et al. 2002; Isaac et al. 2007).

3.3 Erosion control

Out of seven studies conducted on erosion control, 49 observations were identified for runoff and 49 for soil loss. The studies were conducted in Kenya, Nigeria, and Zimbabwe. Our findings show that agroforestry performed best in terms of erosion reduction ecosystem services, five and ten times better than controls for runoff (RR: 5.0; 95% CI: 3.3-7.9) and soil loss (RR: 9.7; 95% CI: 5.9-17.3). However, these very large effect sizes could also be due to publication bias as demonstrated by the high Kendall's rank correlation coefficients. If we had found more published studies (larger sample sizes), we expect the effect sizes to be more modest than the figures we reported here. Erosion control with

agroforestry was more effective in both humid (RR 7.2; 95% CI 4.8 to 13.9) and semi-arid zones (RR 8.0; 95% CI 4.8 to 16.7) compared to controls. Similarly, erosion control with agroforestry was more effective when either shrubs (RR 6.9; 95% CI 4.6 to 11.4) or trees (RR 11.1; 95% CI 6.1 to 24.7) were planted. There were no significant differences in the effects between humid and semi-arid sites, or between trees and shrubs. Comparisons for soil erosion were not performed for elevation, soil type, site of trial, agroforestry practice, and growth form due to a low number of studies in those categories.

Trees have been shown to reduce soil loss by forming barriers that slow runoff and capture sediments (Angima et al. 2000, 2002), protecting soil aggregates from direct raindrops (Lal 1989a; Omoro and Nair 1993; Nyamadzawo et al. 2003), and improving soil structure (Lal 1989a). Without soil cover, direct raindrops on bare soils increase detachment of soil particles, which lowers infiltration and can stimulate runoff and soil loss. Carbon inputs from decomposing litter and decaying tree roots can be increased to stabilize soil structure (Salako et al. 2001). Runoff rates were low on plots with trees because of reduced overland flow (Omoro and Nair 1993) and increased infiltration (Nyamadzawo et al. 2003). A study at

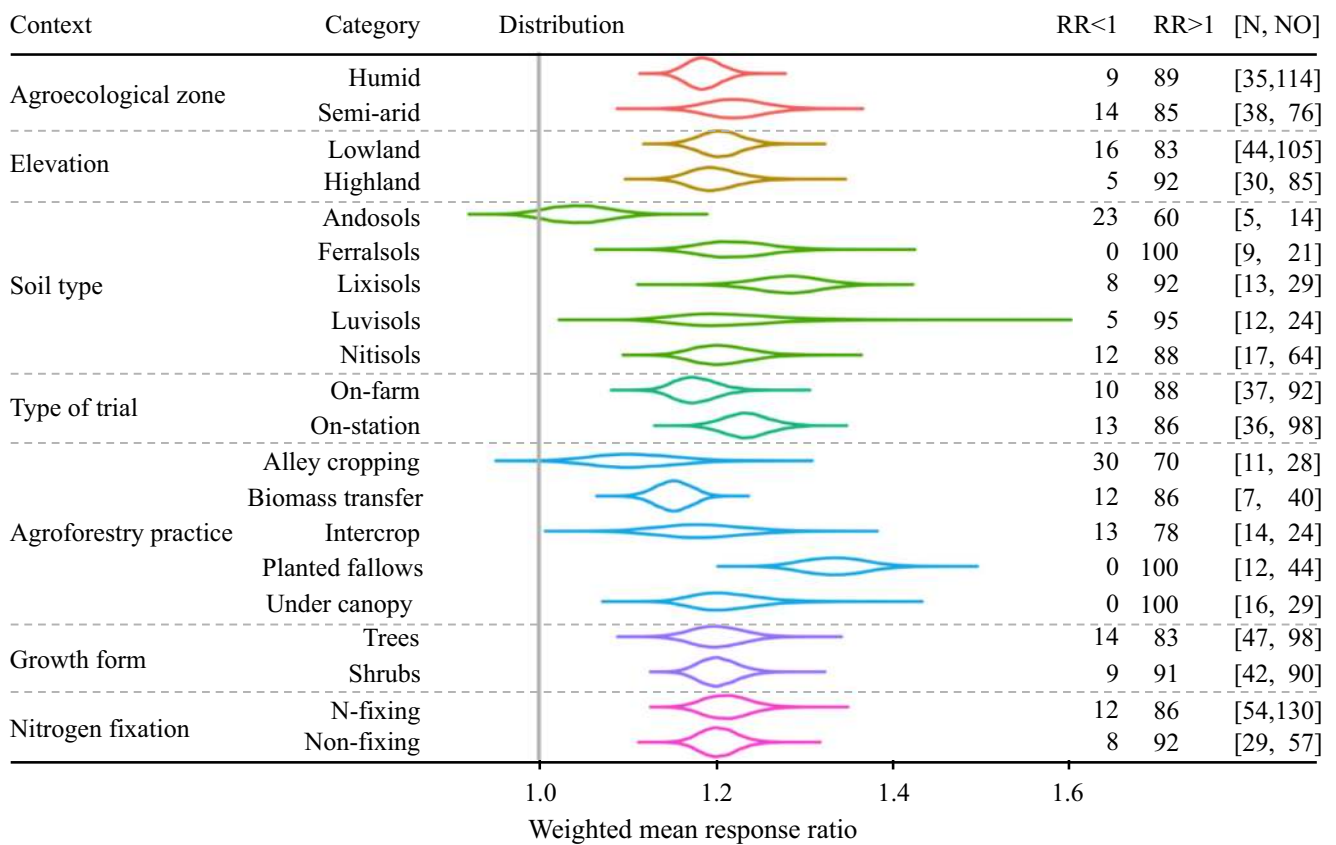


Fig. 6 Results of meta-analysis of agroforestry vs. non-agroforestry effects on available phosphorus under different conditions. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry

effects. RR < 1 and RR > 1 represent the proportion (%) of observations with response ratio below or above 1. Values in brackets indicate the number of studies reviewed (*N*) and the number of observations (*NO*)

Domboshawa in Zimbabwe showed that vegetation reduces the amount of rainfall transformed into runoff by increasing the time to ponding and runoff (Nyamadzawo et al. 2003).

3.4 Water regulation

Studies on water regulation were conducted in 12 countries. In total, 96 observations were identified from 38 studies that fulfilled the selection criteria. Out of the 38 studies, 11 had 34 observations reporting on infiltration rates, while 27 studies with 62 observations reported on soil moisture content (Fig. 2). Agroforestry improved infiltration and soil moisture content compared to the control (Fig. 2). However, the effect of agroforestry on infiltration (RR 2.7; 95% CI 2.1–5) was greater than that on soil moisture (RR 1.6; 95% CI 1.1–1.2). Over 90% of all the observations had RR > 1 compared to 70% for soil moisture. However, the large effect sizes found for infiltration rates could be due to publication bias.

The effect of agroforestry on water regulation was greater across agro-ecological zones, elevations, soil types, type of trials, agroforestry practices, and woody species compared to controls (Table 1). Water regulation was more strongly improved under agroforestry in semi-arid than in humid locations (Table 1). There

were no significant differences among elevations and types of trial. The effects of agroforestry on water regulation were significantly greater on Lixisols (RR > 1 = 100%) compared to Luvisols and Nitisols. This is probably due to smaller effects of agroforestry in more fertile, free-draining Nitisols and Luvisols in humid and subhumid areas. Lixisols were mainly associated with experiments in semi-arid areas, e.g., in Machakos in eastern Kenya (Jackson and Wallace 1999) and Domboshawa in Zimbabwe (Nyamadzawo et al. 2008a), where trees have been shown to improve water infiltration and soil moisture; while Nitisols were associated with experiments in humid areas, e.g., Ibadan in Nigeria (Adejuyigbe et al. 1999; Salako et al. 2001), Embu in Kenya (Angima et al. 2002), and Ginchi in Ethiopia (Kidanu et al. 2004), where the effect of agroforestry on water regulation was low. Water regulation by agroforestry was higher in planted fallows than in intercropping situations or in experiments under a canopy. No differences were detected for the effects of agroforestry when trees or shrubs were planted. The effect of agroforestry was greater when nitrogen-fixing species were used than when non-nitrogen-fixing species were planted.

Productivity of agricultural lands can be constrained by water availability in the soil, which largely depends on infiltration and retention. The effects of agroforestry were stronger

for infiltration than for soil moisture, suggesting that the primary mechanism through which trees improve water regulation is improved infiltration, since effects of trees on soil moisture content are subject to uptake and transpiration by trees. Empirical studies attributed high infiltration rates in agroforestry to improved hydraulic conductivity of the soil and better porosity (Nyamadzawo et al. 2003, 2007). On the contrary, lower infiltration in controls was attributed to soil compaction due to degradation of soil structure (Salako et al. 2001; Chirwa et al. 2003; Sanou et al. 2010). For example, soils in planted fallows had more macropores and large pore sizes because of improved aggregation (Chirwa et al. 2004; Nyamadzawo et al. 2008a) and presence of channels formed when roots die and decompose (Chirwa et al. 2003). Agroforestry has been shown to improve soil moisture compared to control by reducing loss of water from the soil through evaporation and transpiration by crops (Rhoades 1995; Siriri et al. 2013), increasing water infiltration, and improving water storage capacity (Makumba et al. 2006; Nyamadzawo et al. 2012a). Trees with a dense canopy and intense litter fall can reduce evaporation from the soil surface by modifying microclimate (Rhoades 1995; Siriri et al. 2013).

3.5 Win-wins and trade-offs

Our findings suggest possibilities of both win-wins and trade-offs in agroforestry production. This confirms the proposition that win-win scenarios are possible between agricultural production and ecosystem services, and that trade-offs can also occur and may have the potential to be managed (Foley et al. 2009; Power 2010). Agroforestry improved both yield and soil fertility indicators leading to a win-win situation in 72, 76, and 53% of the pairwise observations for crop yield and total N, crop yield and SOC, and crop yield and available P, respectively (Fig. 7a–c). Win-win outcomes also dominated studies reporting both total N and SOC (80%), but were less common for total N and available P (55%) as well as SOC and available P (59%). Win-win scenarios occur in situations where trees improve soil fertility, and soil moisture is not limiting or trees are managed to minimize competition.

A small number of studies showed trade-offs and lose-lose outcomes between crop yield and total N (28%) and crop yield and SOC (24%). Close to half of the studies (47%) revealed trade-offs and lose-lose outcomes between yield and available P, while a third of the studies showed trade-offs between available P and total N (32%), and available P and SOC (31%). Trade-offs occur when competition for nutrients or water (or light) outweighs the benefits of improved yield or enhanced provision of an ecosystem service. For example, transpiration in agroforestry can exceed that of tree-less plots if trees are not pruned to reduce water demand (Jonsson et al. 1999a; Bayala et al. 2002; Muthuri et al. 2005; Ndoli et al. 2017). In this case, the benefits of modified microclimate and improved soil structure are

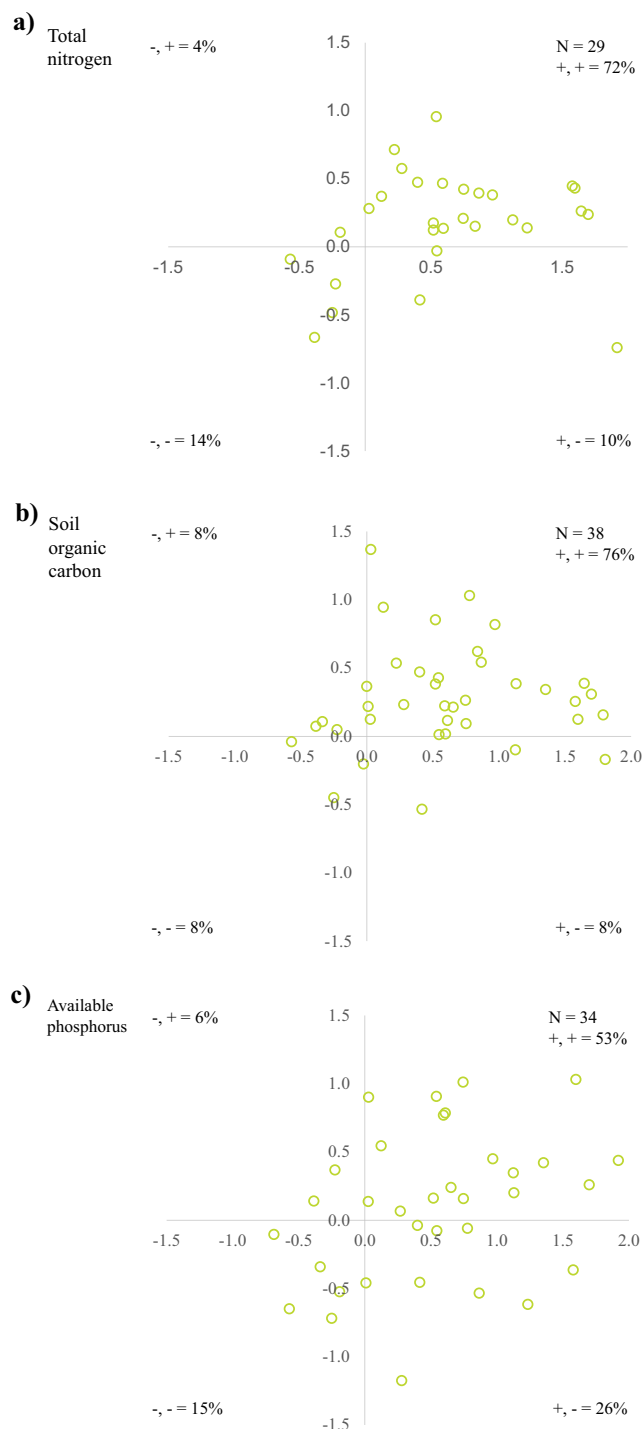


Fig. 7 Graphical representation of trade-offs among different ecosystem service indicators. a) crop yield versus total nitrogen, b) crop yield versus soil organic carbon, and c) crop yield versus available phosphorus. Win-win (+, +), win-lose (+, -), lose-lose (-, -), and lose-win (-, +) outcomes among ecosystem services are indicated by increase (+) or decrease (-) of a service. The percentages indicate the proportions of studies in each category

negated by high transpiration and uptake by trees, leading to low soil moisture. Trade-offs involving available P and soil moisture indicate that improved yield does not necessarily

signify that all other ecosystem services are provided at higher levels.

Spearman's rank correlation did not show a significant relationship between crop yield and total N ($r_s = 0.222$, $N = 29$, $P = <0.247$) or crop yield and SOC ($r_s = 0.196$, $N = 38$, $P = 239$). On the other hand, positive and significant correlations were found between crop yield and available P ($r_s = 0.360$, $N = 34$, $P < 0.05$), suggesting that soil nutrient availability was a main driver of crop yield in this meta-analysis. Correlation between SOC and total N ($r_s = 0.433$, $N = 45$, $P < 0.05$), and SOC and available P ($r_s = 0.277$, $N = 49$, $P < 0.05$) were positive and significant. However, the correlation between total N and available P was positive but not significant ($r_s = 0.277$, $N = 47$, $P < 0.060$). The relationship between crop yield and soil moisture was negative but not significant ($r_s = -0.294$, $N = 12$, $P = 0.354$). The lack of significant relationships between crop yield and total N or crop yield and SOC indicates that yield may not consistently covary with soil fertility. This suggests that beneficial effects of agroforestry on yield do not primarily stem from improved total soil nitrogen and SOC, but from a set of complex interdependent relationships among resources (light, water, and nutrients). Holding other factors of production constant, soil fertility is known to improve yield. Therefore, the lack of significant correlation between crop yield and some indicators of soil fertility can be attributed to differences in ecological conditions, management, tree and shrub species, and crops included in the studies reviewed. Correlations between crop yield and runoff, soil loss, or infiltration were not tested because of an insufficient number of studies that did not allow pairwise comparison.

4 Conclusions

We have shown that agroforestry can be a means to increase crop yield without compromising provision of regulating/maintenance ecosystem services. This is critical in SSA where some soils have lost their productive capacity due to low soil organic matter and nutrient mining, and where smallholder farmers may not be able to increase production through inputs such as fertilizer or irrigation. Trade-offs involving low available P and soil moisture content reflect possibilities for competition for water and nutrient resources. Selection of the right tree for the right place, optimal tree-crop combination, and management of tree canopies can be used to minimize the trade-offs that result from competition and shading. Agroforestry was effective at enhancing the ecosystem services studied in most situations. It is important to determine the resilience of these ecosystem services under the changing conditions in SSA.

Funding Information Open access funding provided by Swedish University of Agricultural Sciences. This study was funded by the

Alexander von Humboldt Foundation through the International Climate Protection Fellowship.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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References

- Adams DC, Gurevitch J, Rosenberg MS (1997) Resampling Tests for meta analysis of ecological data. *Ecology* 78:1277–1283. <https://doi.org/10.2307/2265879>
- Alliance for a Green Revolution (2014) Africa Agriculture status report: Climate change and smallholder agriculture in sub-Saharan Africa. Nairobi, Kenya
- Angima SD, Neill MKO, Omwega AK, Stott DE (2000) Use of Tree/Grass Hedges for Soil Erosion Control in the Central Kenyan Highlands. *J Soil Water Conserv* 55:478–482
- Angima SD, Stott DE, O'Neill MK et al (2002) Use of calliandra-Napier grass contour hedges to control erosion in central Kenya. *Agric Ecosyst Environ* 91:15–23. [https://doi.org/10.1016/S0167-8809\(01\)00268-7](https://doi.org/10.1016/S0167-8809(01)00268-7)
- Asbjornsen H, Hernandez-Santana V, Liebman ZM et al (2013) Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renew Agr Food Syst* 1:1–25. <https://doi.org/10.1017/S1742170512000385>
- Batjes NH (2011) Global distribution of soil phosphorus retention potential. Wageningen, ISRIC-World Soil Information (with dataset), ISRIC Report 2011/06.
- Bayala J, Teklehaimanot Z, Ouedraogo SJ (2002) Millet production under pruned tree crowns in a parkland system in Burkina Faso. *Agrofor Syst* 54:203–214. <https://doi.org/10.1023/A:1016058906682>
- Bayala J, Sanou J, Teklehaimanot Z et al (2014) Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. *Curr Opin Environ Sustain* 6:28–34
- Begg CB, Mazumdar M (1994) Operating characteristics of a rank correlation test for publication bias. *Biometrics* 50:1088–1101
- Bommarco R, Kleijn D, Potts SG (2013) Ecological intensification: Harnessing ecosystem services for food security. *Trends Ecol Evol* 28:230–238. <https://doi.org/10.1016/j.tree.2012.10.012>
- Borenstein M, Hedges L V, Higgins JPT, Rothstein RH (2009) Introduction to meta-analysis. John Wiley & Sons, Ltd
- Campbell BM, Thornton P, Zougmore R et al (2014) Sustainable intensification: What is its role in climate smart agriculture? *Curr Opin Environ Sustain* 8:39–43. <https://doi.org/10.1016/j.cosust.2014.07.002>
- Carsan S, Stroebel A, Dawson I et al (2014) Can agroforestry option values improve the functioning of drivers of agricultural intensification in Africa? *Curr Opin Environ Sustain* 6:35–40. <https://doi.org/10.1016/j.cosust.2013.10.007>
- Chirwa TS, Mafongoya PL, Chintu R (2003) Mixed planted-fallows using coppicing and non-coppicing tree species for degraded Acrisols in eastern Zambia. *Agrofor Syst* 59:243–251. <https://doi.org/10.1023/B:AGFO.0000005225.12629.61>

- Chirwa TS, Mafongoya PL, Mbewe DNM, Chishala BH (2004) Changes in soil properties and their effects on maize productivity following *Sesbania sesban* and *Cajanus cajan* improved fallow systems in eastern Zambia. *Biol Fert Soils* 40:20–27. <https://doi.org/10.1007/s00374-004-0740-8>
- Chivenge P, Vanlauwe B, Six J (2011) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant Soil* 342:1–30. <https://doi.org/10.1007/s11104-010-0626-5>
- Core Team R (2018) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- De Beenhouwer M, Aerts R, Honnay O (2013) A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. *Agric Ecosyst Environ* 175:1–7. <https://doi.org/10.1016/j.agee.2013.05.003>
- Dewitte O, Jones A, Spaargaren O et al (2013) Harmonisation of the soil map of Africa at the continental scale. *Geoderma* 211–212:138–153. <https://doi.org/10.1016/j.geoderma.2013.07.007>
- Félix GF, Scholberg JMS, Clermont-Dauphin C et al (2018) Enhancing agroecosystem productivity with woody perennials in semi-arid West Africa. A meta-analysis. *Agron Sustain Dev* 38:57. <https://doi.org/10.1007/s13593-018-0533-3>
- Foley JA, Defries R, Asner GP et al (2009) Global consequences of land use. *Science* 309:570–574. <https://doi.org/10.1126/science.1111772>
- Gurevitch J, Hedges LV (1999) Statistical issues in ecological meta-analyses. *Ecology* 80:1142–1149
- Haines-Young R, Potschin M (2018) Common international classification of ecosystem services (CICES) V5.1. Guidance on the application of the revised structure. Nottingham
- Harrison F (2011) Getting started with meta-analysis. *Methods Ecol Evol* 2:1–10. <https://doi.org/10.1111/j.2041-210X.2010.00056.x>
- Hartemink AE, Huting J (2008) Land cover, extent, and properties of arenosols in Southern Africa. *Arid Land Res Manag* 22:134–147
- HarvestChoice (2010) Agro-ecological zones of sub-Saharan Africa. In: *Int. Food Policy*. <http://harvestchoice.org/node/8853>
- Isaac ME, Ulzen-Appiah F, Timmer VR, Quashie-Sam SJ (2007) Early growth and nutritional response to resource competition in cocoa-shade intercropped systems. *Plant Soil* 298:243–254. <https://doi.org/10.1007/s11104-007-9362-x>
- IUSS (2014) World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.
- Jonsson K, Ong CK, Odongo JCW (1999a) Influence of scattered nere and karite trees on microclimate, soil fertility and millet yield in Burkina Faso. *Exp Agric* 35:39–53
- Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. *Agrofor Syst* 76:1–10. <https://doi.org/10.1007/s10457-009-9229-7>
- Kajembe J, Lupala I, Kajembe G et al (2016) The role of selected agroforestry trees in temperature adaptation on *Coffea arabica*: a case study of the Moshi district, Tanzania. In: *Climate change and multi-dimensional sustainability in African agriculture*. Springer, Cham, pp 553–566
- Kho RM, Yacouba B, Yayé M et al (2001) Separating the effects of trees on crops: the case of *Faidherbia albida* and millet in Niger. *Agrofor Syst* 52:219–238
- Koricheva J, Gurevitch J, Mengersen K (2013) *Handbook of meta-analysis in ecology and evolution*. Princeton University Press, New Jersey
- Kuyah S, Öborn I, Jonsson M et al (2016) Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. *journal has since changed name to Ecosystems and People* 12: 255–273. <https://doi.org/10.1080/21513732.2016.1214178>
- Kuyah S, Öborn I, Jonsson M (2017) Regulating ecosystem services delivered in agroforestry systems. In: Dagar JC, Tewari VP (eds) *Agroforestry: Anecdotal to modern science*. Springer Singapore, Singapore, pp 797–815
- Lal R (1989a) Agroforestry systems and soil surface management of a tropical alfisol .2. water runoff, soil-erosion, and nutrient loss. *Agrofor Syst* 8:97–111
- Luedeling E, Smethurst PJ, Baudron F et al (2016) Field-scale modeling of tree-crop interactions: Challenges and development needs. *Agric Syst* 142:51–69. <https://doi.org/10.1016/j.agry.2015.11.005>
- Makumba W, Janssen B, Oenema O et al (2006) The long-term effects of a gliricidia-maize intercropping system in Southern Malawi, on gliricidia and maize yields, and soil properties. *Agric Ecosyst Environ* 116:85–92. <https://doi.org/10.1016/j.agee.2006.03.012>
- Mbow C, Smith P, Skole D et al (2014) Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr Opin Environ Sustain* 6:8–14. <https://doi.org/10.1016/j.cosust.2013.09.002>
- Monteith J, Ong C, Corlett J (1991) Microclimate interactions in agroforestry systems. *For Ecol Manag* 45:31–44. [https://doi.org/10.1016/0378-1127\(91\)90212-E](https://doi.org/10.1016/0378-1127(91)90212-E)
- Montpellier Panel (2013) *Sustainable intensification: a new paradigm for African agriculture*. London
- Muthuri CW, Ong CK, Black CR et al (2005) Tree and crop productivity in Grevillea, Alnus and Paulownia-based agroforestry systems in semi-arid Kenya. *For Ecol Manag* 212:23–39. <https://doi.org/10.1016/j.foreco.2005.02.059>
- Ndoli A, Baudron F, Schut AGT et al (2017) Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda. *Field Crops Res* 213:1–11. <https://doi.org/10.1016/j.fcr.2017.07.020>
- New M, Lister D, Hulme M, Makin I (2002) A high-resolution data set of surface climate over global land areas. *Clim Res* 21:1–25. <https://doi.org/10.3354/cr021001>
- Nyamadzawo G, Nyamugafata P, Chikowo R, Giller KE (2003) Partitioning of simulated rainfall in a kaolinitic soil under improved fallow-maize rotation in Zimbabwe. *Agrofor Syst* 59:207–214. <https://doi.org/10.1023/B:AGFO.0000005221.67367.f0>
- Nyamadzawo G, Chikowo R, Nyamugafata P, Giller KE (2007) Improved legume tree fallows and tillage effects on structural stability and infiltration rates of a kaolinitic sandy soil from central Zimbabwe. *Soil Tillage Res* 96:182–194. <https://doi.org/10.1016/j.still.2007.06.008>
- Nyamadzawo G, Nyamugafata P, Chikowo R, Giller K (2008a) Residual effects of fallows on selected soil hydraulic properties in a kaolinitic soil subjected to conventional tillage (CT) and no tillage (NT). *Agrofor Syst* 72:161–168. <https://doi.org/10.1007/s10457-007-9057-6>
- Nyamadzawo G, Nyamugafata P, Wuta M, Nyamangara J (2012a) Maize yields under coppicing and non coppicing fallows in a fallow-maize rotation system in central Zimbabwe. *Agrofor Syst* 84:273–286. <https://doi.org/10.1007/s10457-011-9453-9>
- Omoro LMA, Nair PKR (1993) Effects of mulching with multipurpose-tree prunings on soil and water run-off under semi-arid conditions in Kenya. *Agrofor Syst* 22:225–239
- Orwa C, Mutua A, Kindt R, et al (2009) *Agroforestry database: a tree reference and selection guide*. 1–5
- Pearl J (2014) Comment: Understanding Simpson’s paradox. *Am Stat* 68: 8–13. <https://doi.org/10.1080/00031305.2014.876829>
- Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. *Philos Trans R Soc Lond Ser B Biol Sci* 365:2959–2971. <https://doi.org/10.1098/rstb.2010.0143>
- Pumariño L, Sileshi GW, Gripenberg S et al (2015) Effects of agroforestry on pest, disease and weed control: A meta-analysis. *Basic Appl Ecol* 16:573–582. <https://doi.org/10.1016/j.baee.2015.08.006>
- Rao MR, Nair PKR, Ong CK (1998) Biophysical interactions in tropical agroforestry systems. *Agrofor Syst* 38:3–50

- Rhoades C (1995) Seasonal pattern of nitrogen mineralization and soil moisture beneath *Faidherbia albida* (syn *Acacia albida*) in central Malawi. *Agrofor Syst* 29:133–145
- Rohatgi A (2016) WebPlotDigitizer 3.10. See <https://automeris.io/WebPlotDigitizer/>
- Salako FK, Hauser S, Babalola O, Tian G (2001) Improvement of the physical fertility of a degraded Alfisol with planted and natural fallows under humid tropical conditions. *Soil Use Manag* 17:41–47
- Sanchez PA (2015) En route to plentiful food production in Africa. *Nat Plants* 1:1–2. <https://doi.org/10.1038/NPLANTS.2014.14>
- Sanou J, Zougmore R, Bayala J, Teklehaimanot Z (2010) Soil infiltrability and water content as affected by Baobab (*Adansonia digitata* L.) and Néré (*Parkia biglobosa* (Jacq.) Benth.) trees in farmed parklands of West Africa. *Soil Use Manag* 26:75–81. <https://doi.org/10.1111/j.1475-2743.2009.00250.x>
- Sileshi G, Mafongoya PL (2003) Effect of rotational fallows on abundance of soil insects and weeds in maize crops in eastern Zambia. *Appl Soil Ecol* 23:211–222. [https://doi.org/10.1016/S0929-1393\(03\)00049-0](https://doi.org/10.1016/S0929-1393(03)00049-0)
- Sileshi G, Akinnifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant Soil* 307:1–19
- Sileshi G, Akinnifesi FK, Debusho LK, Beedy T, Ajayi OC, Mong'omba S (2010) Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. *Field Crop Res* 116:1–13
- Sileshi GW, Mafongoya PL, Akinnifesi FK et al (2014) Agroforestry: Fertilizer trees. *Encycl Agric Food Syst* 1:222–234. <https://doi.org/10.1016/B978-0-444-52512-3.00022-X>
- Sinare H, Gordon LJ (2015) Ecosystem services from woody vegetation on agricultural lands in Sudano-Sahelian West Africa. *Agric Ecosyst Environ* 200:186–199
- Siriri D, Wilson J, Coe R et al (2013) Trees improve water storage and reduce soil evaporation in agroforestry systems on bench terraces in SW Uganda. *Agrofor Syst* 87:45–58
- Snapp SS, Blackie MJ, Gilbert RA et al (2010) Biodiversity can support a greener revolution in Africa. *Proc Natl Acad Sci* 107:20840–20845. <https://doi.org/10.1073/pnas.1007199107>
- Sterne JA, Gavaghan D, Egger M (2000) Publication and related bias in meta-analysis: power of statistical tests and prevalence in the literature. *J Clin Epidemiol* 53:1119–1129. [https://doi.org/10.1016/S0895-4356\(00\)00242-0](https://doi.org/10.1016/S0895-4356(00)00242-0)
- Teklay T, Nyberg G, Malmer A (2006) Effect of organic inputs from agroforestry species and urea on crop yield and soil properties at Wondo Genet, Ethiopia. *Nutr Cycl Agroecosyst* 75:163–173. <https://doi.org/10.1007/s10705-006-9020-3>
- Torralba M, Fagerholm N, Burgess PJ et al (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agric Ecosyst Environ* 230:150–161. <https://doi.org/10.1016/j.agee.2016.06.002>
- Tully K, Sullivan C, Weil R, Sanchez P (2015) The State of soil degradation in sub-Saharan Africa: Baselines, trajectories, and solutions. *Sustainability* 7:6523–6552. <https://doi.org/10.3390/su7066523>
- van Ittersum MK, van Bussel LGJ, Wolf J et al (2016) Can sub-Saharan Africa feed itself? *Proc Natl Acad Sci* 113:14964–14969. <https://doi.org/10.1073/pnas.1610359113>
- Wickham H (2016) Package ‘plyr.’ Version 1.8.4. Tools for splitting, applying and combining data. <http://had.co.nz/plyr>
- Wickham H (2017) Package ‘reshape.’ Version 0.8.7. Flexibly Reshape Data. <http://had.co.nz/reshape>
- Wickham H, Chang W, Henry L (2018a) Package ‘ggplot2.’ Version 3.0.0. Create elegant data visualisations using the grammar of graphics. <http://ggplot2.tidyverse.org>
- Wickham H, François R, Henry L, Müller K (2018b) Package ‘dplyr.’ Version 0.7.6. A grammar of data manipulation. <http://dplyr.tidyverse.org>
- Wiebe N, Vandermeer B, Platt RW et al (2006) A systematic review identifies a lack of standardization in methods for handling missing variance data. *J Clin Epidemiol* 59:342–353. <https://doi.org/10.1016/j.jclinepi.2005.08.017>

References of the meta-analysis

- Abdallah F, Noumi Z, Ouled-Belgacem A et al (2012) The influence of *Acacia tortilis* (Forssk.) ssp. raddiana (Savi) Brenan presence, grazing, and water availability along the growing season, on the understory herbaceous vegetation in southern Tunisia. *J Arid Environ* 76: 105–114. <https://doi.org/10.1016/j.jaridenv.2011.06.002>
- Abdelkadir A, Schultz RC (2005) Water harvesting in a ‘runoff-catchment’ agroforestry system in the dry lands of Ethiopia. *Agrofor Forum* 63:291–298. <https://doi.org/10.1007/s10457-005-5746-1>
- Abule E, Smit GN, Snyman HA (2005) The influence of woody plants and livestock grazing on grass species composition, yield and soil nutrients in the Middle Awash Valley of Ethiopia. *J Arid Environ* 60: 343–358. <https://doi.org/10.1016/j.jaridenv.2004.04.006>
- Adejuyigbe CO, Tian G, Adeoye GO (1999) Soil microarthropod populations under natural and planted fallows in southwestern Nigeria. *Agrofor Syst* 47:263–272. <https://doi.org/10.1017/CBO9781107415324.004>
- Aihou K, Sanginga N, Vanlauwe B et al (1998) Alley cropping in the moist savanna of West-Africa: I. Restoration and maintenance of soil fertility on “terre de barre” soils in Benin Republic. *Agrofor Syst* 42:213–227. <https://doi.org/10.1023/A:1006114116095>
- Akinnifesi FK, Makumba W, Kwesiga FR (2006) Sustainable maize production using gliricidia/maize intercropping in southern Malawi. *Exp Agric* 42:441–457. <https://doi.org/10.1017/S0014479706003814>
- Akinnifesi FK, Makumba W, Sileshi G et al (2007) Synergistic effect of inorganic N and P fertilizers and organic inputs from *Gliricidia sepium* on productivity of intercropped maize in Southern Malawi. *Plant Soil* 294:203–217. <https://doi.org/10.1007/s11104-007-9247-z>
- Anim-Kwapong GJ, Osei-Bonsu K (2009) Potential of natural and improved fallow using indigenous trees to facilitate cacao replanting in Ghana. *Agrofor Syst* 76:533–542. <https://doi.org/10.1007/s10457-008-9196-4>
- Aweto AO, Iyanda AO (2003) Effects of *Newbouldia laevis* on soil subjected to shifting cultivation in the Ibadan area, southwestern Nigeria. *Land Degrad Dev* 14:51–56. <https://doi.org/10.1002/ldr.517>
- Banful B, Dzietror A, Ofori I, Hemeng OB (2000) Yield of plantain alley cropped with *Leucaena leucocephala* and *Flemingia macrophylla* in Kumasi, Ghana. *Agrofor Syst* 49:189–199. <https://doi.org/10.1023/A:1006335710243>
- Baumert S, Khamzina A, Vlek PLG (2014) Soil organic carbon sequestration in *Jatropha curcas* systems in burkina faso. *Land Degrad Dev* 27:1813–1819. <https://doi.org/10.1002/ldr.2310>
- Bayala J, Mando A, Ouedraogo SJ, Teklehaimanot Z (2003) Managing *Parkia biglobosa* and *Vitellaria paradoxa* prunings for crop production and improved soil properties in the sub-Saharan zone of Burkina Faso. *Arid Land Res Manag* 17:283–296. <https://doi.org/10.1080/15324980301596>
- Bayala J, Balesdent J, Marol C et al (2006) Relative contribution of trees and crops to soil carbon content in a parkland system in Burkina Faso using variations in natural ^{13}C abundance. *Nutr Cycl Agroecosyst* 76:193–201. <https://doi.org/10.1007/s10705-005-1547-1>
- Bayala J, Ouedraogo SJ, Ong CK (2009) Early growth performance and water use of planted West African provenances of *Vitellaria paradoxa* C. F. Gaertn (karite) in Gonse, Burkina Faso. *Agrofor Syst* 75:117–127. <https://doi.org/10.1007/s10457-008-9167-9>

- Beedy TL, Snapp SS, Akinnifesi FK, Sileshi GW (2010) Impact of *Gliricidia sepium* intercropping on soil organic matter fractions in a maize-based cropping system. *Agric Ecosyst Environ* 138:139–146. <https://doi.org/10.1016/j.agee.2010.04.008>
- Birhane E, Gebremeskel K, Tadesse T et al (2018) Integrating *Faidherbia albida* trees into a sorghum field reduces striga infestation and improves mycorrhiza spore density and colonization. *Agrofor Syst* 92:643–653. <https://doi.org/10.1007/s10457-016-0027-8>
- Blaser WJ, Oppong J, Yeboah E, Six J (2017) Shade trees have limited benefits for soil fertility in cocoa agroforests. *Agric Ecosyst Environ* 243:83–91. <https://doi.org/10.1016/j.agee.2017.04.007>
- Boffa JM, Taonda SJB, Dickey JB, Knudson DM (2000) Field-scale influence of karite (*Vitellaria paradoxa*) on sorghum production in the Sudan zone of Burkina Faso. *Agrofor Syst* 49:153–175. <https://doi.org/10.1023/A:1006389828259>
- Bright MBH, Diedhiou I, Bayala R et al (2017) Long-term *Piliostigma reticulatum* intercropping in the Sahel: Crop productivity, carbon sequestration, nutrient cycling, and soil quality. *Agric Ecosyst Environ* 242:9–22. <https://doi.org/10.1016/j.agee.2017.03.007>
- Bünemann EK, Smithson PC, Jama B et al (2004) Maize productivity and nutrient dynamics in maize-fallow rotations in western Kenya. *Plant Soil* 264:195–208. <https://doi.org/10.1023/B:PLSO.0000047749.43017.f0>
- Danso AA, Morgan P (1993a) Alley cropping maize (*Zea mays* var. Jeka) with cassia (*Cassia siamea*) in The Gambia: crop production and soil fertility. *Agrofor Syst* 21:133–146. <https://doi.org/10.1007/BF00705225>
- Danso AA, Morgan P (1993b) Alley cropping rice (*Oryza sativa* var. Barafita) with cassia (*Cassia siamea*): soil fertility and crop production. *Agrofor Syst* 21:147–158. <https://doi.org/10.1007/BF00705226>
- Deans JD, Diagne O, Lindley DK et al (1999) Nutrient and organic-matter accumulation in *Acacia senegal* fallows over 18 years. *For Ecol Manag* 124:153–167. [https://doi.org/10.1016/S0378-1127\(99\)00063-8](https://doi.org/10.1016/S0378-1127(99)00063-8)
- Deng B, Tammeorg P, Luukkanen O et al (2017) Effects of *Acacia seyal* and biochar on soil properties and sorghum yield in agroforestry systems in South Sudan. *Agrofor Syst* 91:137–148. <https://doi.org/10.1007/s10457-016-9914-2>
- Diakhaté S, Villenave C, Diallo NH et al (2013) The influence of a shrub-based intercropping system on the soil nematofauna when growing millet in Senegal. *Eur J Soil Biol* 57:35–41. <https://doi.org/10.1016/j.ejsobi.2013.04.003>
- Diakhaté S, Gueye M, Chevallier T et al (2016) Soil microbial functional capacity and diversity in a millet-shrub intercropping system of semi-arid Senegal. *J Arid Environ* 129:71–79. <https://doi.org/10.1016/j.jaridenv.2016.01.010>
- Dossa EL, Khouma M, Diedhiou I et al (2009) Carbon, nitrogen and phosphorus mineralization potential of semiarid Sahelian soils amended with native shrub residues. *Geoderma* 148:251–260. <https://doi.org/10.1016/j.geoderma.2008.10.009>
- Dossa EL, Diedhiou S, Compton JE et al (2010) Spatial patterns of P fractions and chemical properties in soils of two native shrub communities in Senegal. *Plant Soil* 327:185–198. <https://doi.org/10.1007/s11104-009-0044-8>
- Egbe EA, Ladipo DO, Nwoboshi LC, Swift MJ (1998) Potentials of *Milletia thonningii* and *Pterocarpus santalinoides* for alley cropping in humid lowlands of West Africa. *Agrofor Syst* 40:309–321. <https://doi.org/10.1023/A:1006058427012>
- El Tahir BA, Ahmed DM, Ardö J et al (2009) Changes in soil properties following conversion of *Acacia senegal* plantation to other land management systems in North Kordofan State, Sudan. *J Arid Environ* 73: 499–505. <https://doi.org/10.1016/j.jaridenv.2008.11.007>
- Fadl KEM, El sheikh SE (2010) Effect of *Acacia senegal* on growth and yield of groundnut, sesame and roselle in an agroforestry system in North Kordofan state, Sudan. *Agrofor Syst* 78:243–252. <https://doi.org/10.1007/s10457-009-9243-9>
- Gaafar AM, Salih AA, Luukkanen O et al (2006) Improving the traditional *Acacia senegal*-crop system in Sudan: The effect of tree density on water use, gum production and crop yields. *Agrofor Syst* 66: 1–11. <https://doi.org/10.1007/s10457-005-2918-y>
- Gindaba J, Rozanov A, Negash L (2005) Trees on farms and their contribution to soil fertility parameters in Badessa, eastern Ethiopia. *Biol Fert Soils* 42:66–71. <https://doi.org/10.1007/s00374-005-0859-2>
- Gindaba J, Rozanov A, Negash L (2007) Depletion of nutrients in adjacent crop lands by *Eucalyptus camaldulensis*. *Biol Fert Soils* 24:47–50. <https://doi.org/10.1080/02571362.2007.10634780>
- Hadgu KM, Kooistra L, Rossing WAH, van Bruggen AHC (2009) Assessing the effect of *Faidherbia albida* based land use systems on barley yield at field and regional scale in the highlands of Tigray, Northern Ethiopia. *Food Secur* 1:337–350. <https://doi.org/10.1007/s12571-009-0030-2>
- Hagos MG, Smit GN (2005) Soil enrichment by *Acacia mellifera* subsp. detinens on nutrient poor sandy soil in a semi-arid southern African savanna. *J Arid Environ* 61:47–59. <https://doi.org/10.1016/j.jaridenv.2004.08.003>
- Hailemariam M, Birhane E, Asfaw Z, Zewdie S (2013) Arbuscular mycorrhizal association of indigenous agroforestry tree species and their infective potential with maize in the rift valley, Ethiopia. *Agrofor Syst* 87:1261–1272. <https://doi.org/10.1007/s10457-013-9634-9>
- Hailu T, Negash L, Olsson M (2000) *Milletia ferruginea* from southern Ethiopia: Impacts on soil fertility and growth of maize. *Agrofor Syst* 48:9–24. <https://doi.org/10.1023/A:1006274912762>
- Hall NM, Kaya B, Dick J et al (2005) Effect of improved fallow on crop productivity, soil fertility and climate-forcing gas emissions in semi-arid conditions. *Biol Fert Soils* 42:224–230. <https://doi.org/10.1007/s00374-005-0019-8>
- Hauser S, Norgrove L, Duguma B, Asaah E (2005) Soil water regime under rotational fallow and alternating hedgerows on an Ultisol in southern Cameroon. *Agrofor Syst* 64:73–82. <https://doi.org/10.1007/s10457-005-2442-0>
- Hulugalle NR, Ndi JN (1993) Effects of no-tillage and alley cropping on soil properties and crop yields in a Typic Kandiodult of southern Cameroon. *Agrofor Syst* 22:207–220. <https://doi.org/10.1007/BF00705234>
- Ikerra ST, Semu E, Mrema JP (2006) Combining *Tithonia diversifolia* and minjingu phosphate rock for improvement of P availability and maize grain yields on a chromic Acrisol in Morogoro, Tanzania. *Nutr Cycl Agroecosyst* 76:249–260. <https://doi.org/10.1007/s10705-006-9007-0>
- Jackson NA, Wallace JS (1999) Soil evaporation measurements in an agroforestry system in Kenya. *Agric For Meteorol* 94(3–4): 203–215
- Jackson NA, Wallace JS, Ong CK (2000) Tree pruning as a means of controlling water use in an agroforestry system in Kenya. *For Ecol Manag* 126:133–148. [https://doi.org/10.1016/S0378-1127\(99\)00096-1](https://doi.org/10.1016/S0378-1127(99)00096-1)
- Jaiyeoba IA (1996) Amelioration of soil fertility by woody perennials in cropping fields: Evaluation of three tree species in the semi-arid zone of Nigeria. *J Arid Environ* 33:473–482. <https://doi.org/10.1006/jare.1996.0083>
- Jama BA, Nair PKR, Rao MR (1995) Productivity of hedgerow shrubs and maize under alley cropping and block planting systems in semi-arid Kenya. *Agrofor Syst* 31:257–274. <https://doi.org/10.1007/BF00712078>
- Jones RB, Wendt JW, Bunderson WT, Itimu OA (1996) Leucaena + maize alley cropping in Malawi. Part 1: Effects of N, P, and leaf application on maize yields and soil properties. *Agrofor Syst* 33: 281–294. <https://doi.org/10.1007/BF00055428>

- Jonsson K, Ong CK, Odongo JCW (1999b) Influence of scattered *néré* and *karité* trees on microclimate, soil fertility and millet yield in Burkina Faso. *Exp Agric* 35:39–53
- Kamara CS, Haque I (1992) *Faidherbia albida* and its effects on Ethiopian highland Vertisols. *Agrofor Syst* 18:17–29. <https://doi.org/10.1007/BF00114814>
- Kang BT, Wilson GF, Sipkens L (1981) Alley cropping maize (*Zea mays* L.) and leucaena (*Leucaena leucocephala* Lam) in southern Nigeria. *Plant Soil* 63:165–179. <https://doi.org/10.1007/BF02374595>
- Kang BT, Grimme H, Lawson TL (1985) Alley cropping sequentially cropped maize and cowpea with *Leucaena* on a sandy soil in Southern Nigeria. *Plant Soil* 85:267–277. <https://doi.org/10.1007/BF02139631>
- Kang B, Salako F, Akobundu I et al (1997) Amelioration of a degraded Oxic Paleustalf by leguminous and natural fallows. *Soil Use Manag* 13:130–135. <https://doi.org/10.1111/j.1475-2743.1997.tb00572.x>
- Kang BT, Caveness FE, Tian G, Kolawole GO (1999) Longterm alley cropping with four hedgerow species on an Alfisol in southwestern Nigeria - effect on crop performance, soil chemical properties and nematode population. *Nutr Cycl Agroecosyst* 54:145–155. <https://doi.org/10.1023/A:1009757830508>
- Kater LJM, Kante S, Budelman A (1992) *Karité* (*Vitellaria paradoxa*) and *néré* (*Parkia biglobosa*) associates with crops in South Mali. *Agrofor Syst* 18:89–105
- Kimaro AA, Timmer VR, Mugasha AG et al (2007) Nutrient use efficiency and biomass production of tree species for rotational woodlot systems in semi-arid Morogoro, Tanzania. *Agrofor Syst* 71:175–184. <https://doi.org/10.1007/s10457-007-9061-x>
- Kimaro AA, Timmer VR, Chamshama SAO et al (2009) Competition between maize and pigeonpea in semi-arid Tanzania: effect on yields and nutrition of crops. *Agric Ecosyst Environ* 134:115–125. <https://doi.org/10.1016/j.agee.2009.06.002>
- Kinama JM, Stigter CJ, Ong CK et al (2007) Contour hedgerows and grass strips in erosion and runoff control on sloping land in semi-arid Kenya. *Arid Land Res Manag* 21:1–19. <https://doi.org/10.1080/15324980601074545>
- Lal R (1989b) Agroforestry systems and soil surface management of a tropical alfisol: III Changes in soil chemical properties. *Agrofor Syst* 8:113–132. <https://doi.org/10.1007/BF00123116>
- Livesley SJ, Gregory PJ, Buresh RJ (2004) Competition in tree row agroforestry systems. 3. Soil water distribution and dynamics. *Plant Soil* 264:129–139
- Mafongoya PL, Jiri O (2016) Soil nitrogen and physical properties and maize yields after mixed planted fallows of tree and herbaceous legumes. *Nutr Cycl Agroecosyst* 105:75–84. <https://doi.org/10.1007/s10705-016-9776-z>
- Makumba W, Akinnifesi FK, Janssen B, Oenema O (2007) Long-term impact of a *gliricidia*-maize intercropping system on carbon sequestration in southern Malawi. *Agric Ecosyst Environ* 118:237–243. <https://doi.org/10.1016/j.agee.2006.05.011>
- Mathuva MN, Rao MR, Smithson PC, Coe R (1998) Improving maize (*Zea mays*) yields in semiarid highlands of Kenya: agroforestry or inorganic fertilizers? *Field Crops Res* 55:57–72. [https://doi.org/10.1016/S0378-4290\(97\)00067-1](https://doi.org/10.1016/S0378-4290(97)00067-1)
- Mekonnen K, Glatzel G, Sieghardt M (2009) Diversity of farm forestry tree and shrub species, and their socio-economic and soil fertility improving roles in the central highlands of Ethiopia. *Int. Tree Crops J* 19:167–184. <https://doi.org/10.1080/14728028.2009.9752662>
- Mucheru-Muna M, Mugendi D, Kung'u J et al (2007) Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agrofor Syst* 69:189–197. <https://doi.org/10.1007/s10457-006-9027-4>
- Mugwe J, Mugendi D, Mucheru-Muna M et al (2009) Effect of selected organic materials and inorganic fertilizer on the soil fertility of a Humic Nitisol in the central highlands of Kenya. *Soil Use Manag* 25:434–440. <https://doi.org/10.1111/j.1475-2743.2009.00244.x>
- Mureithi JG, Tayler RS, Thorpe W (1994) The effects of alley cropping with *Leucaena leucocephala* and of different management practices on the productivity of maize and soil chemical properties in lowland coastal Kenya. *Agrofor Syst* 27:31–51. <https://doi.org/10.1007/BF00704833>
- Mureithi JG, Tayler RS, Thorpe W (1995) Productivity of alley farming with leucaena (*Leucaena leucocephala* Lam. de Wit) and Napier grass (*Pennisetum purpureum* K. Schum) in coastal lowland Kenya. *Agrofor Syst* 31:59–78
- Murovhi RN, Materchera SA (2006) Nutrient cycling by *Acacia erioloba* (syn. *Acacia giraffae*) in smallholder agroforestry practices of a semi-arid environment in the north west province, South Africa. *South Afr For J* 208:23–30. <https://doi.org/10.2989/10295920609505258>
- Ndiaye M, Ganry F, Oliver R (2000) Alley cropping of maize and *Gliricidia sepium* in the sudanese sahel region: Some technical feasibility aspects. *Arid Soil Res Rehabil* 14:317–327. <https://doi.org/10.1080/08903060050136432>
- Noumi Z, Abdallah F, Torre F et al (2011) Impact of *Acacia tortilis* ssp. *raddiana* tree on wheat and barley yield in the south of Tunisia. *Acta Oecol* 37:117–123. <https://doi.org/10.1016/j.actao.2011.01.004>
- Nyamadzawo G, Chikowo R, Nyamugafata P et al (2008b) Soil organic carbon dynamics of improved fallow-maize rotation systems under conventional and no-tillage in Central Zimbabwe. *Nutr Cycl Agroecosyst* 81:85–93. <https://doi.org/10.1007/s10705-007-9154-y>
- Nyamadzawo G, Nyamugafata P, Wuta M et al (2012b) Infiltration and runoff losses under fallowing and conservation agriculture practices on contrasting soils, Zimbabwe. *Water SA* 38:233–240. <https://doi.org/10.4314/wsa.v38i2.8>
- Nziguheba G, Merckx R, Palm CA (2005) Carbon and nitrogen dynamics in a phosphorus-deficient soil amended with organic residues and fertilizers in western Kenya. *Biol Fert Soils* 41:240–248. <https://doi.org/10.1007/s00374-005-0832-0>
- O'Neill MK, Angima SD, Duinker B, Okoba BO (2002) Fodder production from contour hedges in the Central Kenyan Highlands. *J Sustain Agric* 20:57–67. <https://doi.org/10.1300/J064v20n03>
- Odhiambo HO, Ong CK, Deans JD et al (2001) Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry system in Kenya. *Plant Soil* 235:221–233. <https://doi.org/10.1023/A:1011959805622>
- Okogun JA, Sanginga N, Mulongoy K (2000) Nitrogen contribution of five leguminous trees and shrubs to alley cropped maize in Ibadan, Nigeria. *Agrofor Syst* 50:123–136. <https://doi.org/10.1023/A:1006471303235>
- Onyewotu LOZ, Ogirigi MA, Stigter CJ (1994) A study of competitive effects between a *Eucalyptus camaldulensis* shelterbelt and an adjacent millet (*Pennisetum typhoides*) crop. *Agric Ecosyst Environ* 51: 281–286. [https://doi.org/10.1016/0167-8809\(94\)90139-2](https://doi.org/10.1016/0167-8809(94)90139-2)
- Onyewotu LOZ, Stigter CJ, Oladipo EO, Owonubi JJ (2004) Air movement and its consequences around a multiple shelterbelt system under advective conditions in semi-arid Northern Nigeria. *Theor Appl Climatol* 79:255–262. <https://doi.org/10.1007/s00704-004-0068-1>
- Partey ST, Thevathasan NV (2013) Agronomic potentials of rarely used agroforestry species for smallholder agriculture in Sub-Saharan Africa: an exploratory study. *Commun Soil Sci Plant Anal* 44: 1733–1748. <https://doi.org/10.1080/00103624.2013.769563>
- Rao MR, Mathuva MN (2000) Legumes for improving maize yields and income in semi-arid Kenya. *Agric Ecosyst Environ* 78:123–137. [https://doi.org/10.1016/S0167-8809\(99\)00125-5](https://doi.org/10.1016/S0167-8809(99)00125-5)
- Reyes T, Quiroz R, Luukkanen O, De Mendiburu F (2009) Spice crops agroforestry systems in the East Usambara Mountains, Tanzania: Growth analysis. *Agrofor Syst* 76:513–523. <https://doi.org/10.1007/s10457-009-9210-5>

- Saka AR, Bunderson WT, Itimu OA et al (1994) The effects of *Acacia albida* on soils and maize grain yields under smallholder farm conditions in Malawi. *For Ecol Manag* 64:217–230. [https://doi.org/10.1016/0378-1127\(94\)90296-8](https://doi.org/10.1016/0378-1127(94)90296-8)
- Salako FK, Babalola O, Hauser S, Kang BT (1999) Soil macroaggregate stability under different fallow management systems and cropping intensities in southwestern Nigeria. *Geoderma* 91:103–123. [https://doi.org/10.1016/S0016-7061\(99\)00006-3](https://doi.org/10.1016/S0016-7061(99)00006-3)
- Schroth G, Zech W (1995) Root length dynamics in agroforestry with *Gliricidia sepium* as compared to sole cropping in the semi-deciduous rainforest zone of West Africa. *Plant Soil* 170:297–306. <https://doi.org/10.1007/BF00010482>
- Schroth G, Oliver R, Balle P et al (1995) Alley cropping with *Gliricidia sepium* on a high base status soil following forest clearing: effects on soil conditions, plant nutrition and crop yields. *Agrofor Syst* 32: 261–276. <https://doi.org/10.1007/BF00711714>
- Shisanya CA, Mucheru MW, Mugendi DN, Kung'u JB (2009) Effect of organic and inorganic nutrient sources on soil mineral nitrogen and maize yields in central highlands of Kenya. *Soil Tillage Res* 103: 239–246. <https://doi.org/10.1016/j.still.2008.05.016>
- Siaw D, Kang BT, Okali DUU (1991) Alley cropping with *Leucaena leucocephala* (Lam.) De Wit and *Acacia barteri* (Hook.f.) Engl. *Agrofor Syst* 14:219–231. <https://doi.org/10.1007/BF00115737>
- Sida TS, Baudron F, Kim H, Giller KE (2018) Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agric For Meteorol* 248:339–347. <https://doi.org/10.1016/j.agrformet.2017.10.013>
- Sileshi G, Mafongoya PL (2006) Variation in macrofaunal communities under contrasting land use systems in eastern Zambia. *Appl Soil Ecol* 33:49–60. <https://doi.org/10.1016/j.apsoil.2005.09.003>
- Sileshi G, Mafongoya PL, Kwesiga F, Nkunika P (2005) Termite damage to maize grown in agroforestry systems, traditional fallows and monoculture on nitrogen-limited soils in eastern Zambia. *Agric For Meteorol* 7:61–69
- Teklay T, Malmer A (2004) Decomposition of leaves from two indigenous trees of contrasting qualities under shaded-coffee and agricultural land-uses during the dry season at Wondo Genet, Ethiopia. *Soil Biol Biochem* 36:777–786. <https://doi.org/10.1016/j.soilbio.2003.12.013>
- Thor Smestad B, Tiessen H, Buresh RJ (2002) Short fallows of *Tithonia diversifolia* and *Crotalaria grahamiana* for soil fertility improvement in western Kenya. *Agrofor Syst* 55:181–194. <https://doi.org/10.1023/a:1020501627174>
- Tian G, Kang BT, Kolawole GO et al (2005) Long-term effects of fallow systems and lengths on crop production and soil fertility maintenance in West Africa. *Nutr Cycl Agroecosyst* 71:139–150. <https://doi.org/10.1007/s10705-004-1927-y>
- Tilander Y, Bonzi M (1997) Water and nutrient conservation through the use of agroforestry mulches, and sorghum yield response. *Plant Soil* 197:219–232. <https://doi.org/10.1023/A:1004263930096>
- Tilander Y, Ouedraogo G, Yougma F (1995) Impact of tree coppicing on tree-crop competition in parkland and alley farming systems in semi-arid Burkina Faso. *Agrofor Syst* 30:363–378. <https://doi.org/10.1007/BF00705220>
- Traore K, Ganry F, Oliver R, Gigou J (2004) Litter production and soil fertility in a *Vitellaria paradoxa* parkland in a catena in southern Mali. *Arid Land Res Manag* 18:359–368. <https://doi.org/10.1080/15324980490497393>
- Vanlauwe B, Aihou K, Tossah BK et al (2005) Senna siamea trees recycle Ca from a Ca-rich subsoil and increase the topsoil pH in agroforestry systems in the West African derived savanna zone. *Plant Soil* 269: 285–296. <https://doi.org/10.1007/s11104-004-0599-3>
- Wendt JW, Jones RB, Bunderson WT, Itimu OA (1996) *Leucaena* + maize alley cropping in Malawi. Part 2: Residual P and leaf management effects on maize nutrition and soil properties. *Agrofor Syst* 33:295–305. <https://doi.org/10.1007/BF00055429>
- Wezel A, Rajot JL, Herbrig C (2000) Influence of shrubs on soil characteristics and their function in Sahelian agro-ecosystems in semi-arid Niger. *J Arid Environ* 44:383–398. <https://doi.org/10.1006/jare.1999.0609>
- Wick B, Kühne RF, Vlek PLG (1998) Soil microbiological parameters as indicators of soil quality under improved fallow management systems in south-western Nigeria. *Plant Soil* 202:97–107. <https://doi.org/10.1023/A:1004305615397>
- Wilson TD, Brook RM, Tomlinson HF (1998) Interactions between nere (*Parkia biglobosa*) and under-planted sorghum in parkland system in Burkina Faso. *Exp Agric* 34:85–99
- Yamoah CF, Agboola AA, Wilson GF (1986) Nutrient contribution and maize performance in alley cropping systems. *Agrofor Syst* 4:247–254. <https://doi.org/10.1007/BF02028359>

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