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META-ANALYSIS

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

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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

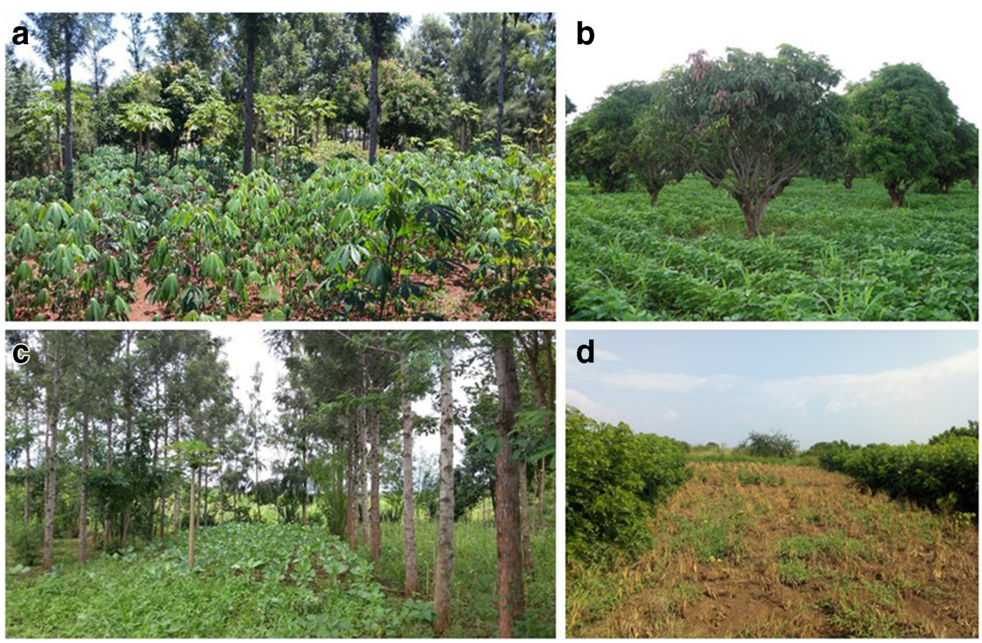

Fig. 1 Agroforestry practices common in sub-Saharan Africa. **a** Homegarden (a mosaic landscape with cassava, pawpaw, *Mangifera indica* L. and *Grevillea robusta* A.Cunn. ex R.Br. in Uganda). **b** Dispersed intercropping (*M. indica* in maize-bean intercrop in Malawi). **c** Intercropping with annual 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:

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

where $\overline{X}$ 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:

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

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 course 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

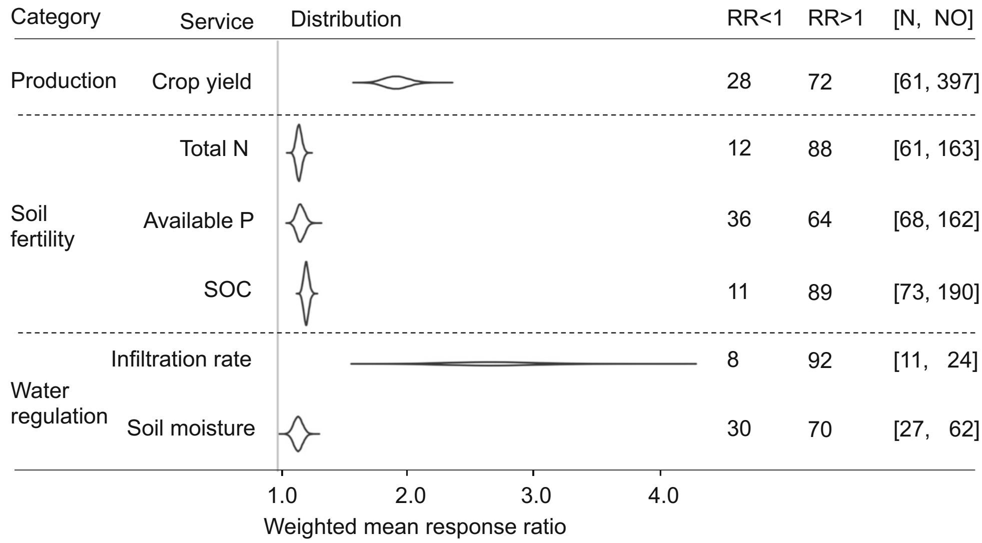

Fig. 2 Results of meta-analysis of agroforestry vs. non-agroforestry effects on provision of ecosystem services across sub-Saharan Africa. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry effects. RR < 1 and RR > 1 represent the proportion (%) of observations with 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

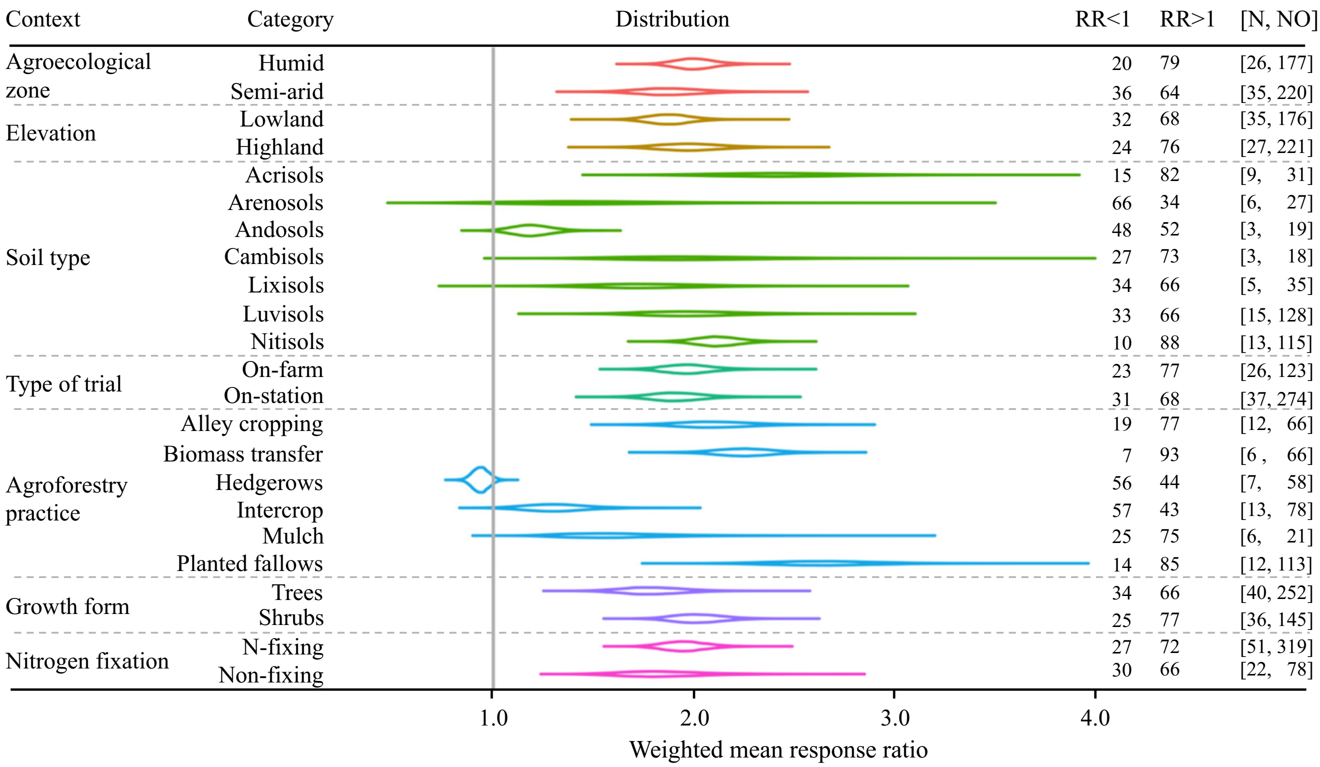

Fig. 3 Results of meta-analysis of agroforestry vs. non-agroforestry effects on crop yield under different conditions across sub-Saharan Africa. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry effects. RR < 1 and RR > 1 represent the proportion (%) of observations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

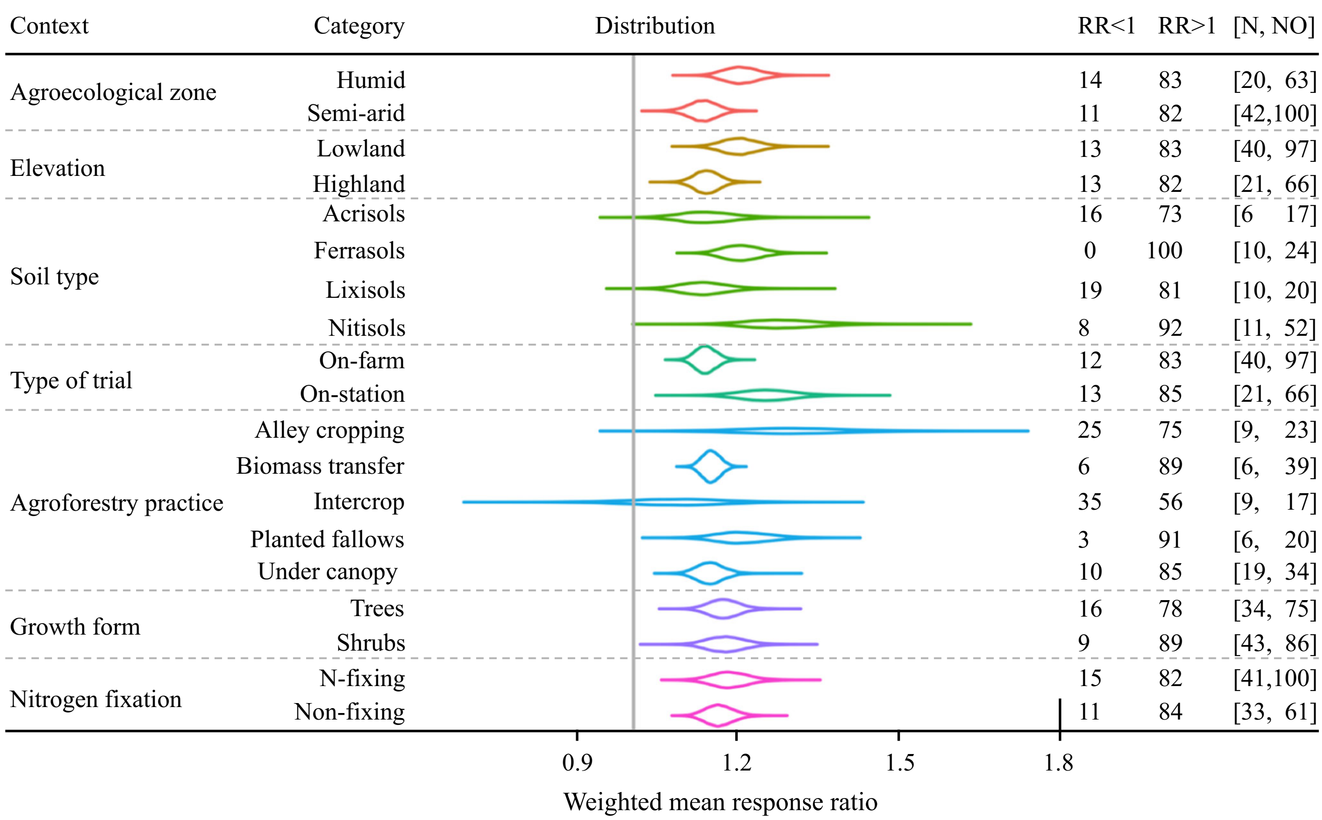

Fig. 4 Results of meta-analysis of agroforestry vs. non-agroforestry effects on total nitrogen under different conditions. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry effects. RR < 1 and RR > 1 represent the proportion (%) of observations with response ratio below or above 1. Values in brackets indicate the number of studies reviewed (*N*) and the number of observations (NO)

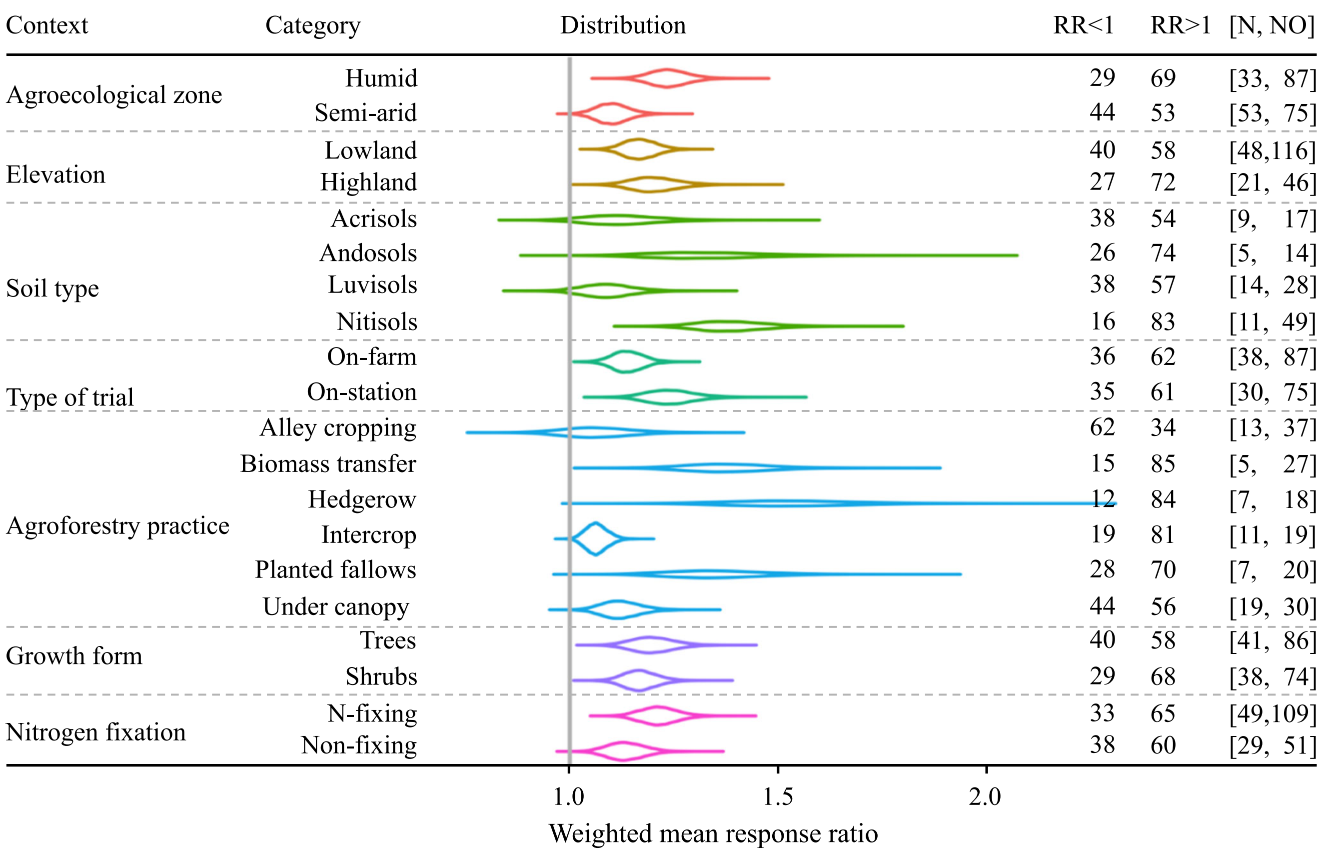

Fig. 5 Results of meta-analysis of agroforestry vs. non-agroforestry effects on soil organic carbon under different conditions. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry effects. RR < 1 and RR > 1 represent the proportion (%) of observations with response ratio 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

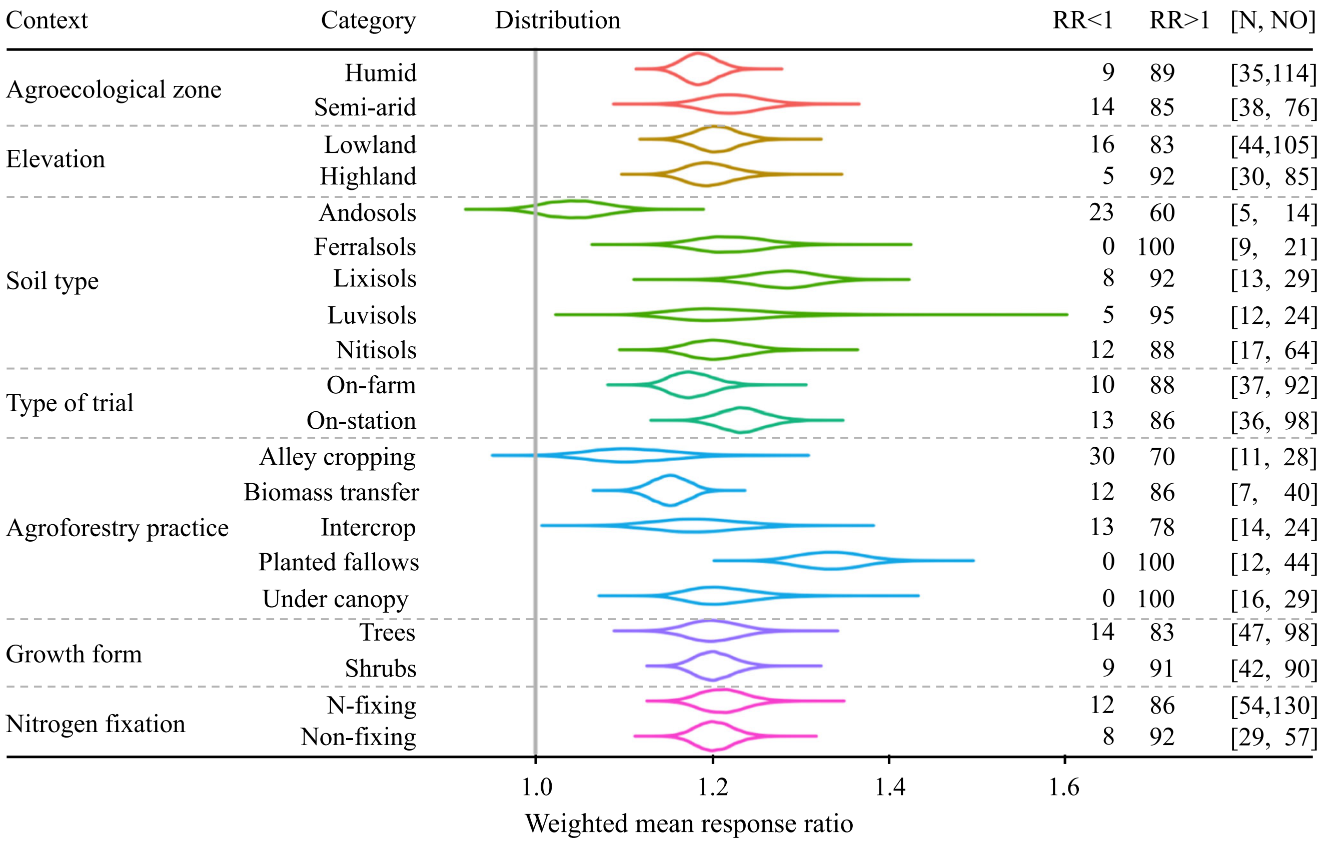

Fig. 6 Results of meta-analysis of agroforestry vs. non-agroforestry effects on available phosphorus under different conditions. Violin plots represent bootstrapped t0 values of agroforestry minus non-agroforestry effects. RR < 1 and RR > 1 represent the proportion (%) of observations with response ratio 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

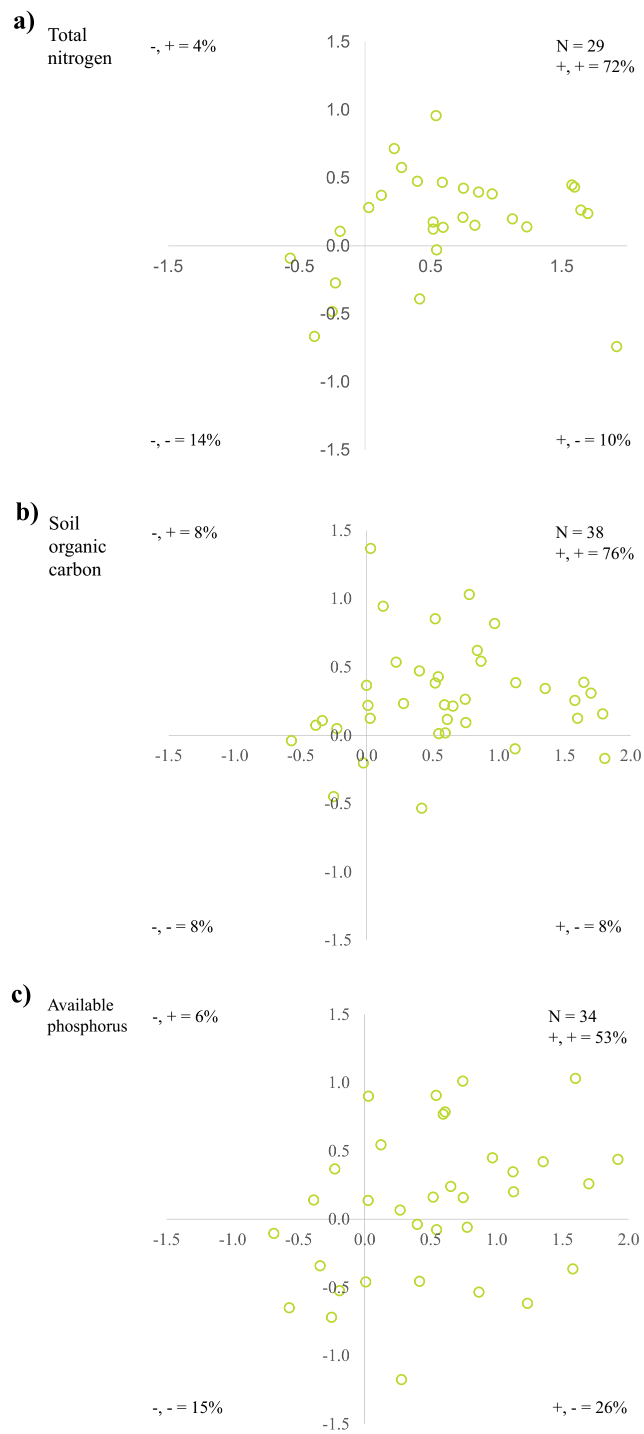

Fig. 7 Graphical representation of trade-offs among different ecosystem service indicators. a) crop yield versus total nitrogen, b) crop yield versus soil organic carbon, and c) crop yield versus available phosphorus. Win-win (+, +), win-lose (+, −), lose-lose (−,−), and lose-win (−, +) outcomes among 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.

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Compliance with ethical standards

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

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