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MARSCHNER REVIEW

# Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis

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**Abstract** The combined application of organic resources (ORs) and mineral fertilizers is increasingly gaining recognition as a viable approach to address soil fertility decline in sub-Saharan Africa (SSA). We conducted a meta-analysis to provide a comprehensive and quantitative synthesis of conditions under which ORs, N fertilizers, and combined ORs with N fertilizers positively or negatively influence *Zea mays* (maize) yields, agronomic N use efficiency and soil organic C (SOC) in SSA. Four OR quality classes were assessed; classes I (high quality) and II (intermediate quality) had >2.5% N while classes III (intermediate quality) and IV (low quality) had <2.5% N and classes I and III had <4% polyphenol and <15% lignin. On the average, yield responses over the control were 60%, 84% and 114% following the addition of ORs, N fertilizers and ORs + N fertilizers, respectively. There was a general increase in yield responses with increasing OR quality and OR-N quantity, both when ORs were added alone or with N fertilizers. Surprisingly, greater OR residual effects were observed with high quality ORs and declined with decreasing OR quality. The greater yield responses with ORs + N fertilizers than either resource alone were mostly due to extra N added and not improved N utilization efficiency because negative interactive effects were, most often, observed when combining ORs with N fertilizers. Additionally, their agronomic N use efficiency was not different from sole added ORs but lower than N fertilizers added alone. Nevertheless, positive interactive effects were observed in sandy soils with low quality ORs whereas agronomic use efficiency was greater when smaller quantities of N were added in all soils. Compared to sole added ORs, yield responses for the combined treatment increased with decreasing OR quality and greater yield increases were observed in sandy (68%) than clayey soils (25%). While ORs and ORs + N fertilizer additions increased SOC by at least 12% compared to the control, N fertilizer additions were not different from control suggesting that ORs are needed to increase SOC. Thus, the addition of ORs will likely improve nutrient storage while crop yields are increased and more so for high quality ORs. Furthermore, interactive effects are seldom occurring, but agronomic N use efficiency of ORs + N fertilizers were greater with low quantities of N added, offering potential for increasing crop productivity.

**Keywords** Organic resource quality · Interactive effects · Integrated soil fertility management · Yield response · Meta-analysis · Agronomic N use efficiency · N fertilizer

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## Abbreviations

| | |
|---|---|
| OR(s) | Organic resource(s) |
| SSA | Sub-Saharan Africa |
| SOC | Soil organic carbon |
| MAP | Mean annual precipitation |

## Introduction

Enhanced food crop production in sub-Saharan Africa (SSA) is critically dependent on external nutrient inputs, especially N and P. This is mainly because of negative soil nutrient balances caused by continuous cultivation with little or no addition of nutrients (Cobo et al. 2010; Sanchez 2002; Smaling et al. 1997). While mineral fertilizers are widely used globally to overcome nutrient deficiencies, their use remains very low in SSA with average application rates of 8 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ (Crawford and Jayne 2010; Morris et al. 2007; Smaling 2006). Fertilizer use has been limited mainly because of low availability and lack of purchasing capacity by the smallholder farmers in SSA (Morris et al. 2007). Ironically, in SSA, where more than half the population lives on less than US \$1 $\mathrm{day^{-1}}$, fertilizer costs are two to eight times more expensive than in the rest of the world (Bationo et al. 2006).

Organic resources (ORs), ranging from animal manures, household composts, crop residues, leguminous cover crops, to leguminous and non-leguminous trees and shrubs, are often used as major nutrient sources to crops. However, their use in most African cropping systems is usually limited by low availability (Giller et al. 1998; Mugwira and Murwira 1997; Rufino et al. 2010). Application of ORs usually leads to increased crop yields (Kimetu et al. 2004; Mugwira 1984; Vanlauwe et al. 2001b) but depressed yields with OR use have also been reported (Mugwira and Murwira 1997; Nhamo 2002). The differential yield responses following OR application have been attributed mainly to differences in OR quality and soil fertility status (Giller and Cadisch 1995; Koné et al. 2008; Palm et al. 2001a). Quality of ORs is often defined using their N, lignin and polyphenol concentrations (Constantinides and Fownes 1994; Melillo et al. 1982). Based on the same parameters, Palm et al. (2001a) proposed four OR quality classes and developed a decision support tool for the management of OR N. They proposed to directly apply high quality ORs which have a fast nutrient release, class I (>2.5% N, <4% polyphenol, <15% lignin) and to surface apply low quality ORs, class IV (<2.5% N, >15% lignin) for erosion control. Class IV ORs induce N immobilization that can last for extended periods of time. On the other hand, intermediate quality ORs, i.e. class II (>2.5% N, >4% polyphenol or >15% lignin) and class III ORs (<2.5% N, <4% polyphenol, and <15% lignin), are to be added in combination with N fertilizers to alleviate a slow nutrient release due to biochemical recalcitrance for class II ORs and low N content for class III ORs.

The combined application of ORs and fertilizers is increasingly gaining recognition as one of the appropriate ways of addressing soil fertility depletion, especially in low-external input systems in SSA and forms an integral part of integrated soil fertility management (Vanlauwe et al. 2010a, 2002a). Greater yield benefits can be achieved following the combined application of ORs and fertilizers compared to either resource applied alone (Mucheru-Muna et al. 2007; Nziguheba et al. 2002; Vanlauwe et al. 2002a). Nutrient cycling and the associated yield benefits derived from combining ORs and fertilizers are dependent on a number of factors including climate, bio-physico-chemical soil environment and OR quality and there are intricate interactions among these factors (Chivenge et al. 2009; Giller and Cadisch 1995; Palm et al. 2001a). For example, Tian et al. (2007) observed increases in rate of decomposition and nutrient release with increase in OR quality in wetter climates but in drier climates decomposition and nutrient release was faster with low quality ORs than high quality ORs. Low quality ORs have a mulching effect that influence soil microclimate and thus enhance their decomposition (Lavelle et al. 1993; Tian et al. 2007, 1993).

While the combined addition of intermediate quality ORs with N fertilizers or the sole addition of high quality ORs can enhance nutrient cycling and increase crop yields, their effects on soil organic C (SOC) build-up may be negative. The addition of fertilizers with intermediate quality ORs may increase OR decomposition (Sakala et al. 2000; Zingore et al. 2003) and thus may result in reduced SOC stabilization compared to OR added alone. The addition of intermediate and low quality ORs may result in greater SOC concentrations than high quality ORs (Bossuyt et al. 2001; Six et al. 2001). However, recent studies have shown no long-term effects of OR quality on SOC dynamics (Chivenge 2008; Gentile et al. 2010). Nevertheless, there may be interactions with other factors such as soil texture and rainfall (Chivenge 2008; Feller and Beare 1997).

Although narrative reviews provide useful summaries of the knowledge of a given discipline, meta-analysis offers a more precise and quantitative synthesis of treatment effects by statistically comparing results from multiple studies (Gurevitch and Hedges 1999; Rosenburg et al. 2000). This approach has been borrowed primarily from medical, physical and behavioral sciences (Gurevitch and Hedges 1999) and has been used recently for ecological studies (de Graaff et al. 2006; Gurevitch et al. 2000; Knorr et al. 2005; van Groenigen et al. 2006) and agricultural experiments (Miguez and Bollero 2005; Sileshi et al. 2008; Tirol-Padre and Ladha 2006). Meta-analyses methods provide a robust synthesis of results from independent studies in a manner that is both objective and statistically defensible (Ainsworth et al. 2007; Hungate et al. 2009). Meta-analytic procedures were used in the current study to analyze the effects of the addition of ORs, N fertilizers and ORs in combination with N fertilizers on *Zea mays* (maize) productivity and SOC and interactions among different factors. Although publication and research bias cannot be ruled out, we believe that the studies included in this meta-analysis were sufficient to capture the diversity of soils, climate and OR quality classes that are generally used by smallholder farmers in SSA.

The objectives of this study were to provide a comprehensive and quantitative synthesis of conditions under which ORs, N fertilizers, and ORs + N fertilizers positively or negatively influence maize yields and SOC build-up. The specific objectives were to determine;

i) maize yield and SOC responses to the application of ORs, N fertilizers, and ORs + N fertilizers,
ii) the influence of OR quality, both when applied alone or in combination with N fertilizers, on maize yield and SOC responses,
iii) effects of OR-N and fertilizer-N quantities on maize yield and SOC responses,
iv) the interactive effects of combining ORs with N fertilizers and how these could be influenced by OR quality and OR-N quantities,
v) the interactions of the above with soil texture and mean annual precipitation (MAP).

## Materials and methods

### Database compilation

We identified 57 studies carried out in smallholder farms and experimental stations under rain-fed field conditions in SSA where ORs and N fertilizers were added separately and in combination with each other (See Appendix 1). To be included in our meta-analysis, the studies should have reported maize yields following the combined addition of ORs with N fertilizers, sole ORs, and/or sole N fertilizers. Data from the same experiment but reported in more than one publication were not repeated, the publication with the most complete dataset was used. Twelve of the 57 studies also reported measurements of SOC. Published data reported in tables were taken directly from the publications while results presented in graphs were digitized and measured to estimate the values. Sixteen studies were carried out over a single season while only nine studies were carried out over at least 5 years. Twenty-three studies tested the repeated application of ORs over at least two seasons while five tested the residual effects of the ORs. Residual effects were estimated based on observations made in the second season when ORs were only applied in the preceding season and crops planted in both the first and second season. Crop residues were removed from the field for other uses such as fodder or were grazed in situ, except in cases where they were used as the OR treatment.

The studies used in the meta-analysis covered 104 experimental field sites in 12 countries in SSA (Benin, Burkina Faso, Cote d'Ivoire, Ethiopia, Ghana, Kenya, Malawi, Nigeria, Tanzania, Togo, Zambia, and Zimbabwe) and represent the humid rainforest, the moist savanna, the dry savanna, the sudano sahelian, and the guinea savanna agro-ecological zones. Amounts of N supplied by ORs ranged from 6 to 547 $\mathrm{kg\,N\,ha^{-1}}$ annually; while fertilizer-N ranged from 20 to 175 $\mathrm{kg\,N\,ha^{-1}}$ per season; and the total N in the combined treatments ranged between 33 and 667 $\mathrm{kg\,N\,ha^{-1}}$ annually. The ranges of N addition differentiated in the current meta-analysis (Table 1) are based on the N response

**Table 1** Categorical variables used in describing the experimental conditions

| Categorical variable | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|
| Soil texture | Sand (<20% clay) | Loam (20–32% clay) | Clay (>32% clay) | |
| Mean annual precipitation | Low | Medium | High | |
| | <600 mm | 600–1000 mm | >1000 mm | |
| Organic resource class[a] | Class I >2.5% N, <4% polyphenol, <15% lignin | Class II >2.5% N, >4% polyphenol or >15% lignin | Class III <2.5% N, <4% polyphenol, <15% lignin | Class IV <2.5% N, >4% polyphenol or >15% lignin |
| Organic resource N | Low | Medium | High | |
| | ≤30 $\mathrm{kgNha^{-1}}$ | 30–100 $\mathrm{kgNha^{-1}}$ | >100 $\mathrm{kgNha^{-1}}$ | |
| Fertilizer-N | Low | Medium | High | |
| | ≤30 $\mathrm{kgNha^{-1}}$ | 30–100 $\mathrm{kgNha^{-1}}$ | >100 $\mathrm{kgNha^{-1}}$ | |

[a] Organic resource classification according to Palm et al. (2001a).

curve. The 0–30 $\mathrm{kgNha^{-1}}$ and 31–100 $\mathrm{kgNha^{-1}}$ ranges represent the linear and curve-linear parts of the N response curve, respectively whereas at >100 kg $\mathrm{Nha^{-1}}$ the curve plateaus (Murwira et al. 2002; Oikeh et al. 1998; Vanlauwe et al. 2001a). However, it is worth noting that the N response varies from site to site and is dependent on other factors such as soil texture and climate (Bationo et al. 2005; Murwira et al. 2002). In order to calculate N addition rates of ORs, OR-N amounts were taken directly from the publications or were calculated based on the % N and quantities of ORs applied. Where the OR-N content was not reported but total added biomass was indicated, average % N contents from the Organic Resource Database (Palm et al. 2001a) were used to estimate OR-N quantities added.

Mean annual precipitation ranged from 500 to 1800 mm. The categories of MAP used in the meta analysis (Table 1) were based on precipitation and approximated FAO guidelines for agro-climatic zoning (Fischer et al. 2001). Soil textures ranged from sandy (2% clay; 98% sand) to clayey (75% clay; 10% sand) and the categorical textural classes are based on the textural triangle (Shirazi and Boersma 1984). Crop yield responses, interactive effects of combined application of ORs and N fertilizers, agronomic N use efficiency and SOC changes were used as the response variables. For the purposes of meta-analysis, we established discrete levels of the categorical variables and coded each variable (Table 1). Table 2 summarizes the number of observations for the categories.

## Meta-analysis

Data was analyzed using MetaWin 2.1 software (Rosenburg et al. 2000). An effect size of each observation was calculated as the natural log of the response ratio (r). The response ratio was calculated using the equation:

$$r = \mathrm{X_e}/\mathrm{X_c}, \tag{i}$$

where $\mathrm{X_e}$ is the mean for the treatment (i.e. ORs, N fertilizers, or ORs N + fertilizers) and $\mathrm{X_c}$ is the mean of the control group (Rosenburg et al. 2000). Yields observed with the no input control were used as $\mathrm{X_c}$ when control was compared to ORs, N fertilizers, or ORs + N fertilizers. Where the combined treatment was compared to either ORs or N fertilizers, $\mathrm{X_c}$ was the mean of ORs or N fertilizer treatment, respectively, and $\mathrm{X_e}$ was the mean for the combined treatment. For clarity, in figures presenting percent yield responses $[(\mathrm{X_e}\text{-}\mathrm{X_c})*100/\mathrm{X_c}]$ under different treatments are compared to the control for ORs, N fertilizers and ORs + N fertilizers, or to ORs or N fertilizers when the combined treatment was evaluated. Mean effect size for each categorical variable was calculated with bias-corrected 95% confidence intervals generated by the bootstrapping procedure in MetaWin using 4999 iterations. Maize yield responses and SOC changes to addition of ORs, N fertilizers, or ORs + N fertilizers for each categorical variable were considered to be significant if the 95% confidence intervals did not overlap each other.

**Table 2** Summary of number of studies and data points of the observations made under different categories

| Category | Level | Organic resource quality class[a] | | | | Organic resource N (kgNha$^{-1}$) | | | | Fertilizer N (kgNha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | Low ≤30 | Medium 31–100 | High >100 | Residual | Low ≤30 | Medium 31–100 | High >100 |
| | Number of data points (number of studies) | | | | | | | | | | | |
| Soil texture | Sand | 75 (5) | 75 (5) | 232 (18) | 30 (2) | 98 (11) | 127 (10) | 99 (5) | 59 (2) | 22 (6) | 143 (13) | 168 (4) |
| | Loam | 87 (11) | 73 (10) | 188(13) | 30 (2) | 45 (6) | 77 (10) | 152 (10) | 52 (4) | 6 (1) | 151 (14) | 184 (4) |
| | Clay | 135 (11) | 167(12) | 348 (19) | 24 (2) | 71 (18) | 85 (15) | 112 (7) | 50 (1) | 16 (4) | 546 (23) | 169 (7) |
| Mean annual precipitation (mm) | ≤600 | 58 (2) | 46 (1) | 113 (6) | 10 (1) | 52 (7) | 48 (6) | 22 (2) | – | 48 (7) | 46 (4) | 50 (1) |
| | 601–1000 | 135 (13) | 95 (13) | 255 (18) | 34 (3) | 77 (9) | 162 (13) | 135 (8) | 67 (3) | – | 230 (18) | 206 (8) |
| | >1000 | 152 (11) | 209 (12) | 400 (23) | 40 (2) | 85 (10) | 387 (21) | 206 (9) | 94 (3) | 16 (4) | 564 (26) | 265 (6) |

[a] Organic resource classification according to Palm et al. (2001a).

Interactive effects of the combined application of ORs with N fertilizers on maize yields were calculated according to Vanlauwe et al. (2001c) using the equation:

$$\begin{aligned} & \mathit{Interactive\ Effects}\ \left(kg\ ha^{-1}\right) \\ & \quad = Y_{comb} - Y_{con} - (Y_{OR} - Y_{con}) \\ & \qquad - \left(Y_{fert} - Y_{con}\right) \end{aligned} \tag{ii}$$

where $Y_{con}$, $Y_{fert}$, $Y_{OR}$, $Y_{comb}$ are mean grain yield (kgha$^{-1}$) in the control, the sole N fertilizers, the sole ORs and the ORs + N fertilizers, respectively. The interactive effects were considered to be significant if the 95% confidence interval did not overlap zero. Interactive effects represent extra maize grain yields obtained following the combined application of ORs with N fertilizers compared to the sum of the two when added separately (Vanlauwe et al. 2001c). Positive interactive effects imply extra grain yield whereas negative interactive effects show lower grain yield observed with the combined addition of ORs and N fertilizers compared to the addition of either resource alone. Since it was not possible to obtain the statistics for each of the interactive effects without the availability of all the raw data of all the replicates, we used an unweighted analysis where standard deviation was considered to be the same for all data. However, individual studies had different sample sizes but the calculated unweighted effect sizes would not take into consideration variances brought about by these different sample sizes.

Agronomic N use efficiency of the addition of ORs, N fertilizers or ORs + N fertilizers was calculated as the kg yield increase over the control per kgN applied (Cassman et al. 1998) using the equation:

$$\begin{aligned} & \mathit{Agronomic\ N\ use\ efficiency} \\ & \quad = \frac{(Y_{trt} - Y_{con})(kg\ ha^{-1})}{Total\ N\ applied(kg\ N\ ha^{-1})} \end{aligned} \tag{iii}$$

Where $Y_{trt}$ represents the yield for OR, N fertilizer, or OR + N fertilizer treatments, $Y_{con}$ represents the yield in the control treatment, and total N applied represents N applied in the OR, N fertilizer or the combined treatment. Similar to interactive effects, an unweighted effect size was calculated for agronomic N use efficiency and used in the meta-analysis.

An unweighted effect size was also calculated and used for meta-analysis for SOC changes because some studies did not report standard deviations. In addition, since there were few studies that reported SOC measurements, it was essential not to omit studies and maintain a larger sample size. Effect sizes of ORs and ORs + N fertilizers over the no input control were calculated as the natural log of the response ratio of ORs or ORs + N fertilizers over the control. The initial C contents were not always available and hence SOC changes over time were not calculated.

Because there are many interactions among the factors that influence maize yield and SOC responses, agronomic N use efficiencies and interactive effects, there are many ways that the data could have been presented. However, we looked at the possible interactions and selected only the data that showed the most interesting trends.

## Results

### Maize yields

#### *Overall responses*

For all the treatments, i.e. ORs, N fertilizers and ORs + N fertilizers, maize yield responses over the control were greater when the control yield was low but as the yield of the control increased, the yield responses became smaller (Fig. 1). Additionally, most of the studies that had lower control yield but with greater yield responses were on sandy soils (Fig. 1).

Maize yield responses were positively influenced by the addition of ORs, N fertilizers and ORs + N fertilizers (Fig. 2a). The sole addition of ORs and N fertilizers resulted in 60% and 84% greater maize yields than the no input control, respectively (Fig. 2a). The combined application of ORs + N fertilizers more than doubled maize yields (114%) compared to the no input control. The combined application of ORs + N fertilizers increased maize yields compared to sole applied ORs and N fertilizers by 33% and 17%, respectively (Fig. 2b).

#### *Fertilizer-N alone*

When sole N fertilizer was compared to the no input control, greater yield responses were observed in experiments where ≤30 kg fertilizer-N$\,$ha$^{-1}$ was added compared to the control than when 31–100 kg fertilizer-N$\,$ha$^{-1}$ was added (Fig. 3a). However, the yield difference between the control and the N fertilizer treatment was 936 kg$\,$ha$^{-1}$ following the addition of ≤30 kg fertilizer-N$\,$ha$^{-1}$ compared to >1450 kg ha$^{-1}$ when greater amounts of fertilizer-N were added (Fig. 3b). Yield responses to N fertilizer addition were greater in clayey and sandy soils than loamy soils (Fig. 3a) but the yield difference was greatest in clayey soils, while there were no differences between loamy and sandy soils (Fig. 3b). Although maize yield responses were greater in areas receiving ≤600 mm MAP than in areas receiving 600–1000 mm MAP, absolute yield differences were lowest where MAP was ≤600 mm (691 kg$\,$ha$^{-1}$) whereas the yield difference was more than double in areas where MAP was >600 mm (>1450 kg$\,$ha$^{-1}$; Fig. 3).

#### *Organic resource alone*

Organic resource quality and OR-N quantity added influenced maize yield responses, but interactions with soil texture were observed (Fig. 4). Independent of soil texture for sole applied ORs, greater yield responses were observed with ORs in classes I and II, but there were no differences between these two classes for all soil textures (Fig. 4a). Lowest yield responses were observed with class IV ORs, with depressed yields in sandy soils by up to 45% (Fig. 4a). Looking at all soils combined, there seems to be three distinct OR quality classes where classes I and II ORs would be combined into one class, i.e. high quality, whereas classes III and IV ORs would be the intermediate and low quality classes, respectively (Fig. 4a).

Overall, yield responses tended to increase with increasing OR-N quantity but distinct differences were only observed in clayey soils (Fig. 4b). Across all soil textures, mean yield responses were 100% in experiments where >100 kg OR-N$\,$ha$^{-1}$ was added, whereas in experiments where <30 kg OR-N$\,$ha$^{-1}$ was added, yield responses were only 8% (Fig. 4b). Residual effects of ORs applied in one season were positive in the subsequent season with crop yield responses of 38% over the no input control when all textures were combined but in sandy soils there were slightly negative but not significant (Fig. 4b). In clayey soils, residual effects of ORs were greater (49%) than where ≤30 kg OR-N$\,$ha$^{-1}$ (15%) was added but less than where greater OR-N quantities were added (Fig. 4b). Surprisingly, in the loamy soils, residual effects of ORs resulted in the greatest yield responses (69%) which were, however, not significantly different from when >100 kg OR-N$\,$ha$^{-1}$ was added (Fig. 4b).

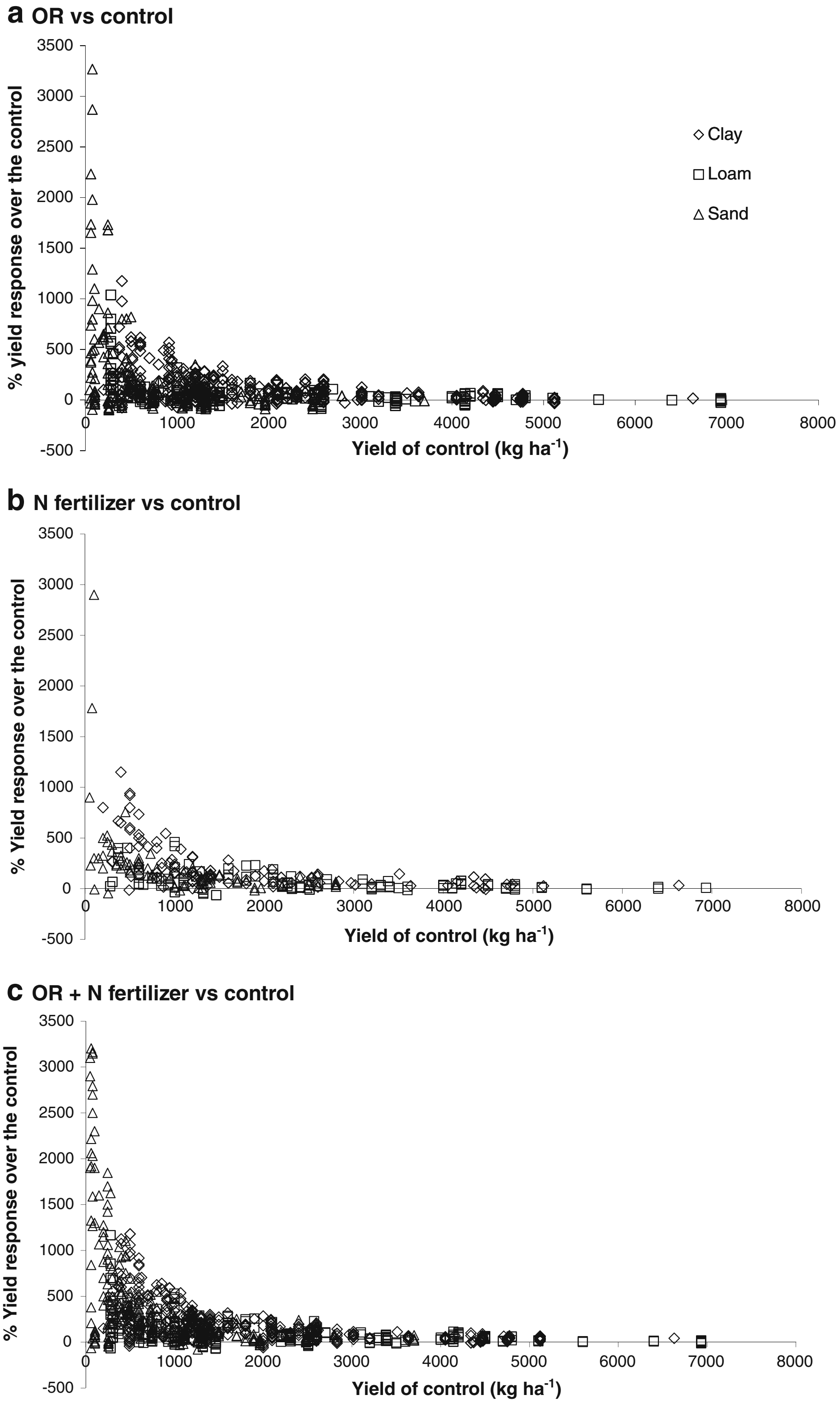


**Fig. 1** The relationship of the yield responses over the no input control to the addition of **a** organic resources (ORs), **b** N fertilizers, and **c** ORs + N fertilizers with the yield of the control

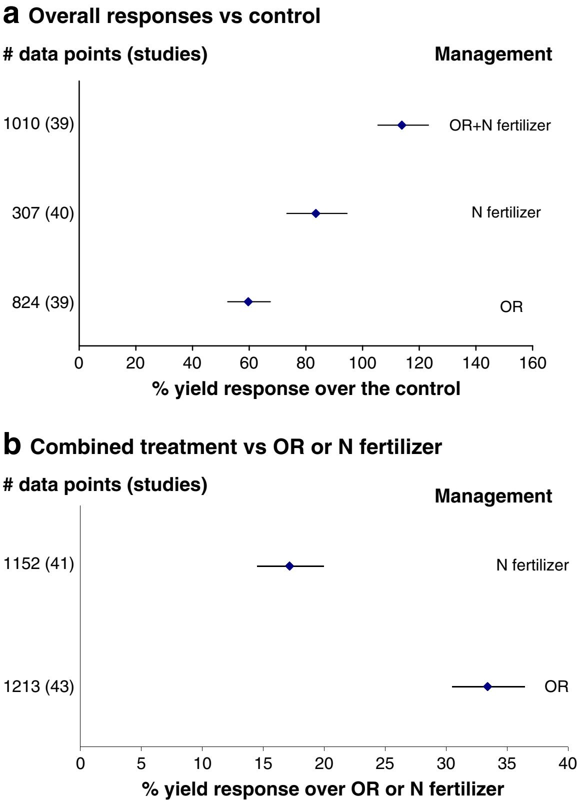


**Fig. 2** Yield responses **a** to the addition of organic resources (OR), mineral N fertilizers and the combined application of the two (OR + N fertilizer) compared to the no input control, and **b** of the combined treatment compared to sole mineral N fertilizers or sole ORs expressed as yield responses. Responses are expressed as weighted average response percentage with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses

### *Organic resources with N fertilizers*

Yield responses increased with increasing OR quality when ORs were applied in combination with N fertilizers, but again there were interactions with soil texture. Across all textures, the greatest yield responses were observed with class II ORs but were not significantly different from class I ORs (Fig. 5a). Similar to sole added ORs, three distinct OR quality classes were recognizable when looking across all soils with classes I and II ORs clustering into one OR class of high quality residues, and class III and IV ORs forming the intermediate and low quality classes, respectively (Fig. 5a). Unlike sole added ORs, yield responses were positive for all OR quality classes in all soils (Fig. 5a). Yield responses also tended to increase with increasing quantities of OR-N added with a yield response of about 215% where >100 kg OR-N$\mathrm{ha}^{-1}$ in sandy and clayey soils (Fig. 5b). The addition of N fertilizers with residual ORs resulted in yield responses that were lower than where fresh ORs were added in the sandy and clayey soils. Again in the loamy soils residual OR effects resulted in greater yield responses but was not different from where >100 kg OR-N$\mathrm{ha}^{-1}$ was added (Fig. 5b).

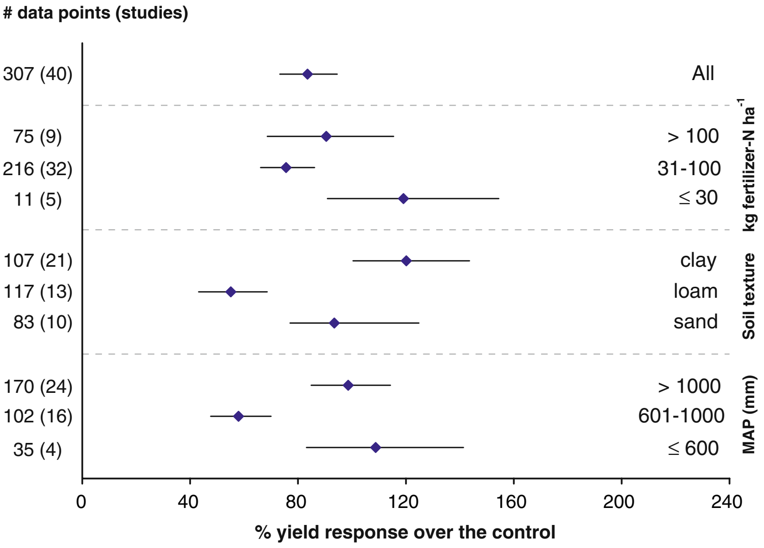
### *Residual effects of ORs*

The residual effects of ORs on yield responses, both when applied alone or in combination with N fertilizers, increased from class IV to class I ORs but there were no significant differences among OR classes I, II and III (Fig. 6). There were no residual effects for sole applied class IV ORs (Fig. 6a), but the addition of N fertilizers in the residual season increased crop yields, and the same was observed with other OR classes (Fig. 6b). In sandy soils and in areas receiving 601–1000 mm MAP, there were also no significant residual OR effects but were increased when N fertilizer was added (Fig. 6). However, the addition of N fertilizers resulted in no differences between sandy soils and the other textures and also between the MAP categories (Fig. 6b).

### *Efficacy of ORs + N fertilizers over sole ORs or N fertilizers*

When the combined treatment was compared to sole ORs, yield responses tended to increase with decreasing OR quality, and were generally positive except in loamy soils where there were no differences between sole class IV OR and the combined treatment (Fig. 7a). Greater yield responses were observed in the sandy soils than finer textured soils; for class IV specifically; crop yield responses for ORs + N fertilizers over sole applied ORs were 249% compared to ≤35% in finer textured soils (Fig. 7a). In contrast, the combined application of class IV ORs with N fertilizers was not different from sole N fertilizer for all soils (Fig. 7b). Additionally, there was a general decline in maize yield responses with decrease in OR quality (Fig. 7b). Contrary to other soils, in the clayey soils yield responses of the combined treatment compared to sole N fertilizer were greatest (25%) with class II ORs compared to 11% observed with classes I and III ORs, respectively (Fig. 7b).

**a** N fertilizer vs control: % Yield response



**b** N fertilizer vs control: Yield difference

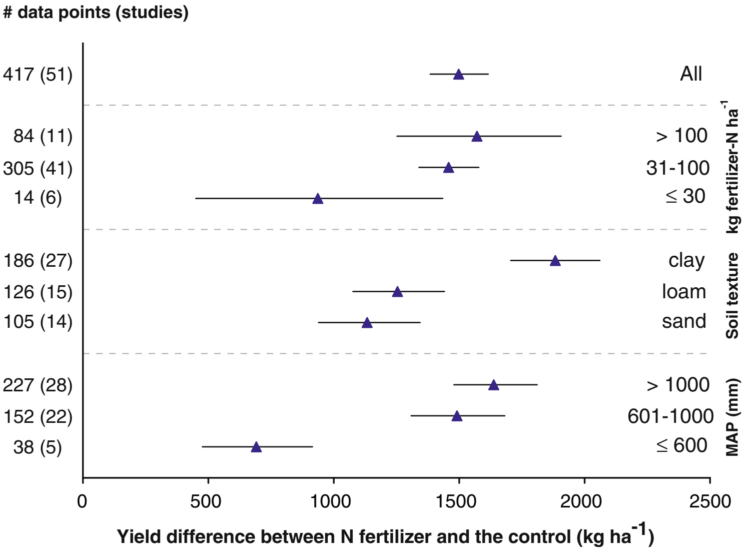


**Fig. 3** Yield response to the addition of mineral N fertilizers compared to the no input control categorized into quantities of fertilizer-N applied (kgNha$^{-1}$), test crop, and mean annual precipitation (MAP) classes. Yield responses are expressed as average **a** response ratio percentage, and **b** absolute yield difference, with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses

### *Interactive effects of the combined application of ORs and N fertilizer on maize yields*

Overall, the addition of ORs + N fertilizers resulted in negative interactive effects on maize yields (−445 kg ha$^{-1}$; Figs. 8 and 9), except in sandy and loamy soils of areas receiving ≤600 mm MAP (Fig. 8). While there was a general decrease in interactive effects with increasing MAP in sandy and clayey soils, there was no clear pattern for loamy soils (Fig. 8). Generally, interactive effects decreased with increasing OR quality with the most negative interactive effects

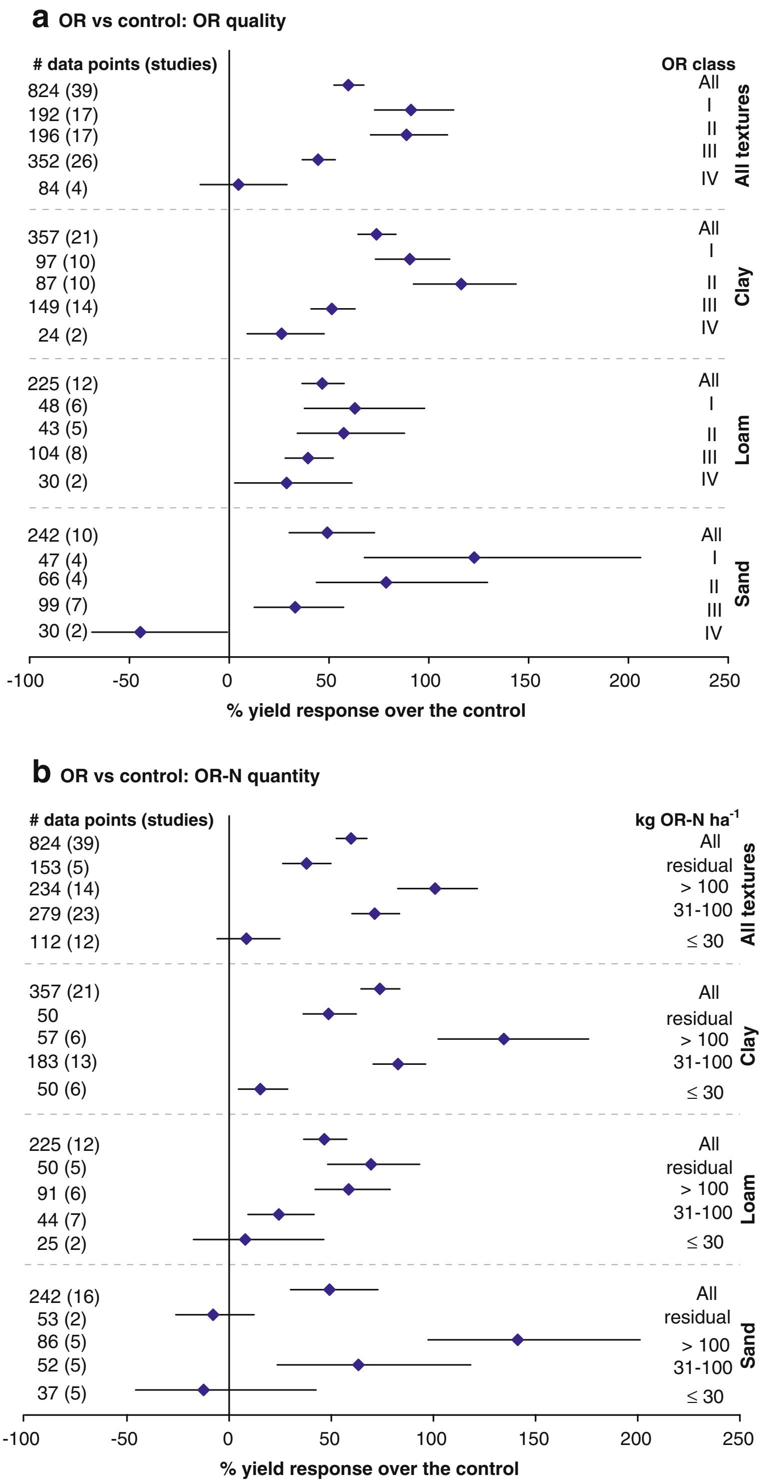


**Fig. 4** Yield response to the addition of organic resources (OR) compared to the no input control categorized into **a** four quality classes (See Table 1), and **b** three OR-N quantities applied. Yields are expressed as weighted average response percentage with 95% confidence intervals represented by the *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses

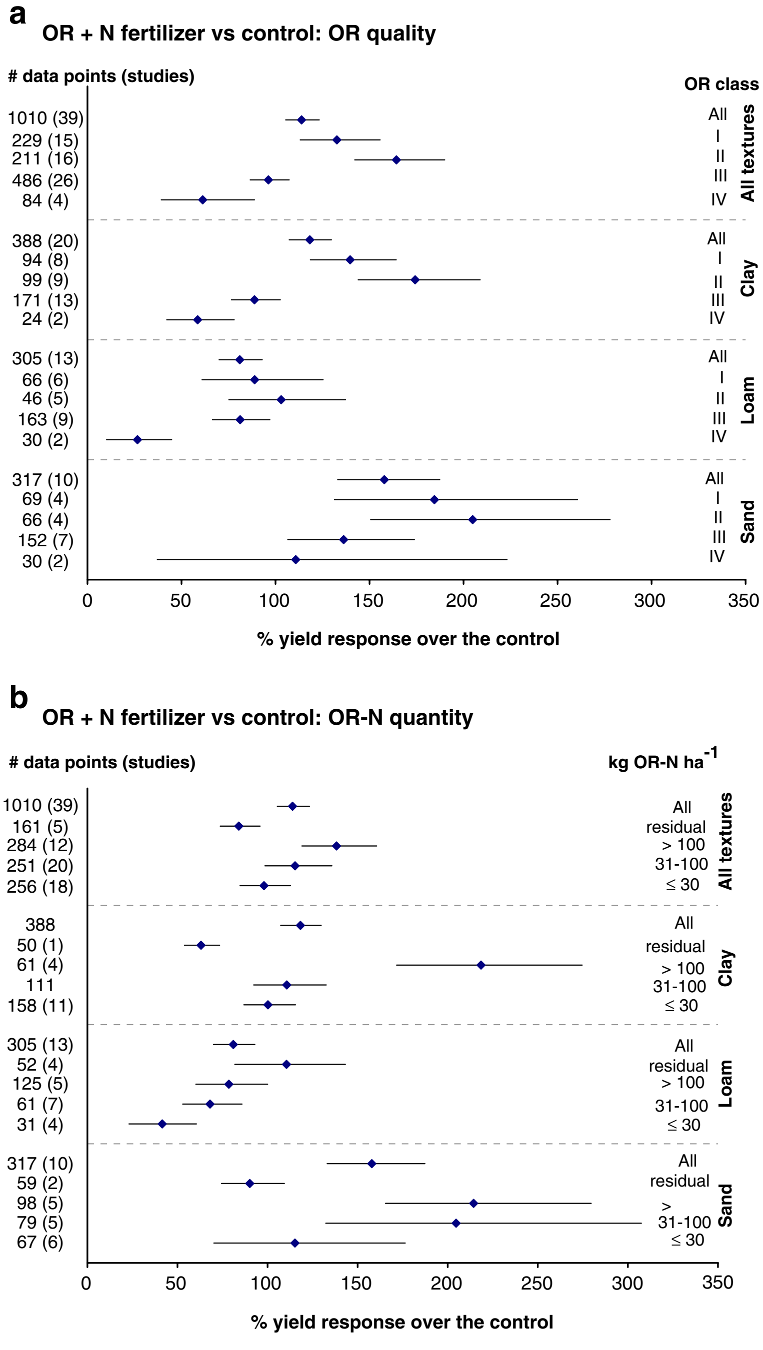
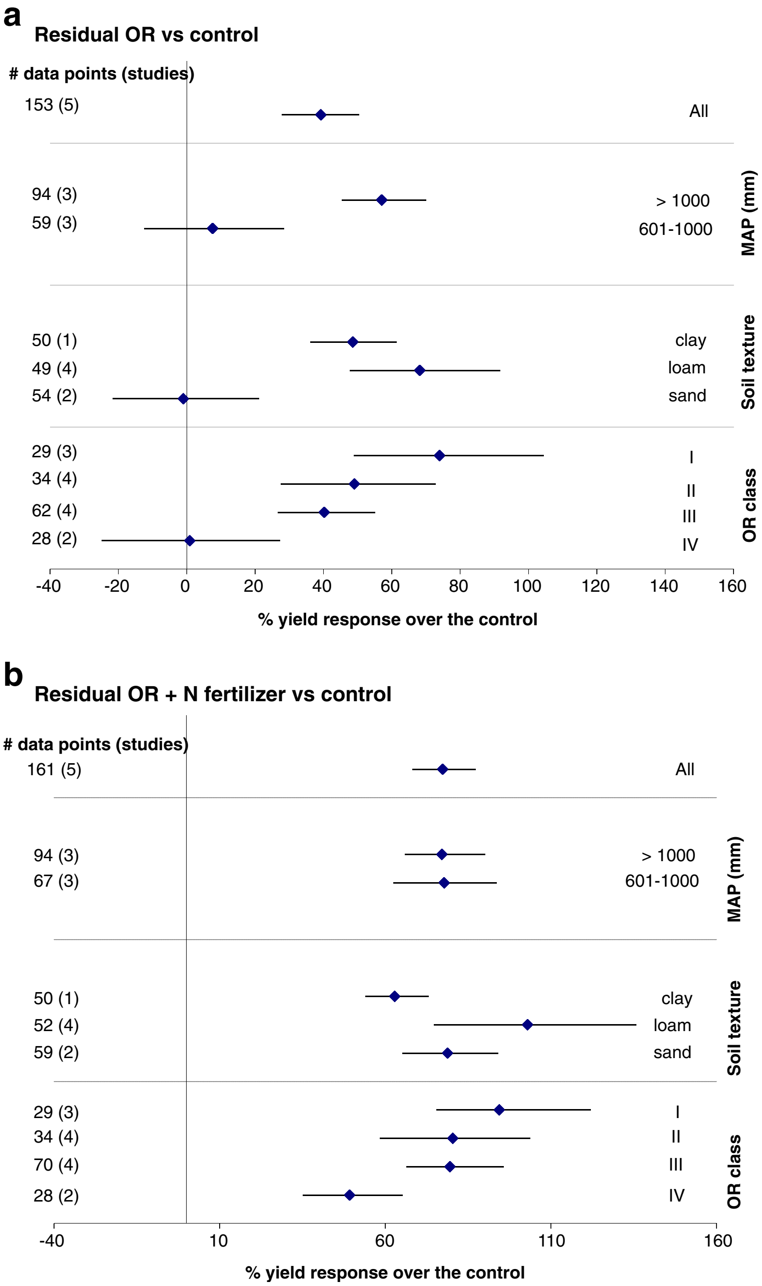


**Fig. 5** Yield response to the combined addition of organic resources (OR) with mineral N fertilizers compared to the no input control categorized into **a** four OR quality classes (See Table 1), and **b** three OR-N quantities applied. Yield responses are expressed as weighted average response percentage with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses

being observed with class I ORs in clayey and sandy soils (Fig. 9a). Although interactive effects were generally negative following the addition of ORs + N fertilizers in sandy soils, the combined application of class IV ORs with N fertilizers resulted in positive interactive effects, 360 kgha$^{-1}$ (Fig. 9a). Interestingly, when ≤30 kg OR-Nha$^{-1}$ was added with N fertilizers in sandy soils, interactive effects tended to be positive (Fig. 9b). Surprisingly however, while interactive effects of residual OR-N effects with N fertilizers were negative or zero in clayey and sandy soils, respectively, in loamy soils they were 224 kgha$^{-1}$ (Fig. 9b).

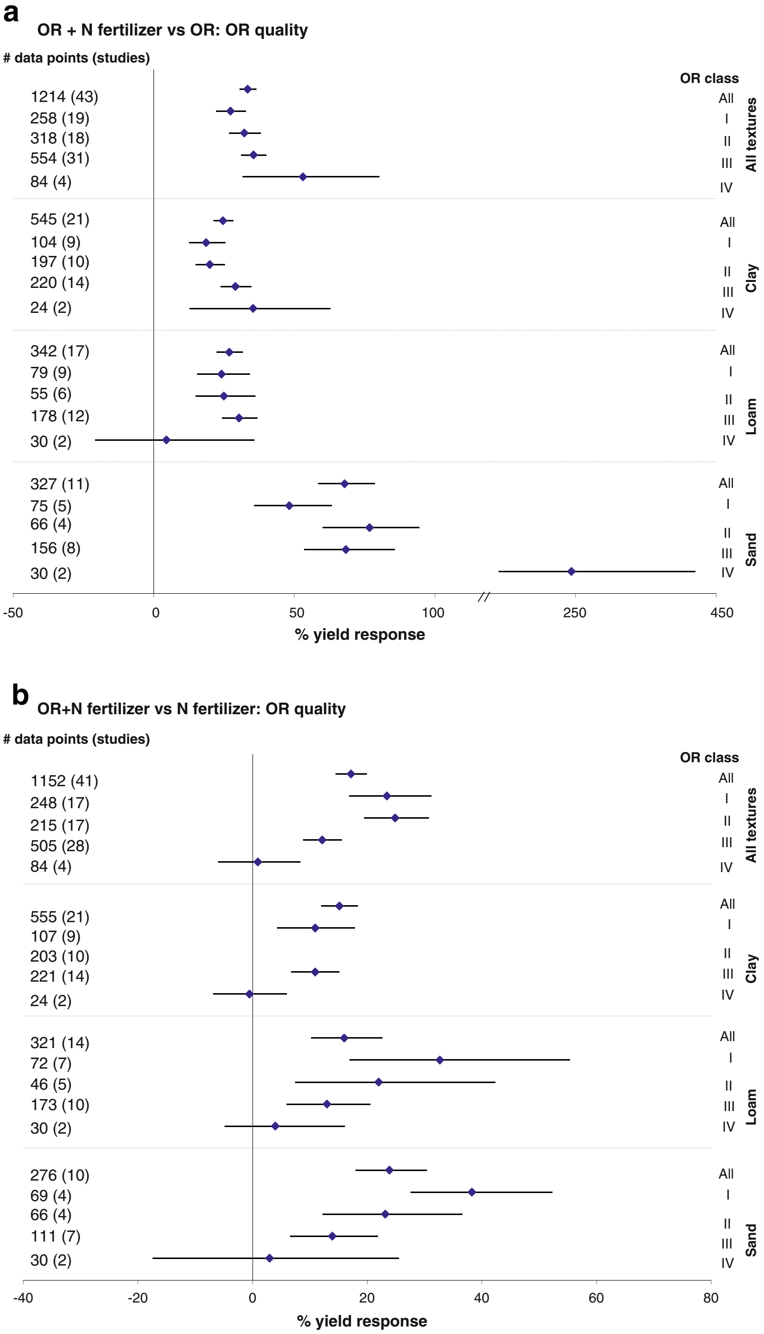
**Fig. 6** Yield responses to residual effects of **a** organic resources (OR), and **b** OR + mineral N fertilizers, compared to the no input control for three categorical variables, mean annual precipitation (MAP), soil texture, and OR quality classes (See Table 1). Responses are average percentages with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses



### *Agronomic N use efficiency*

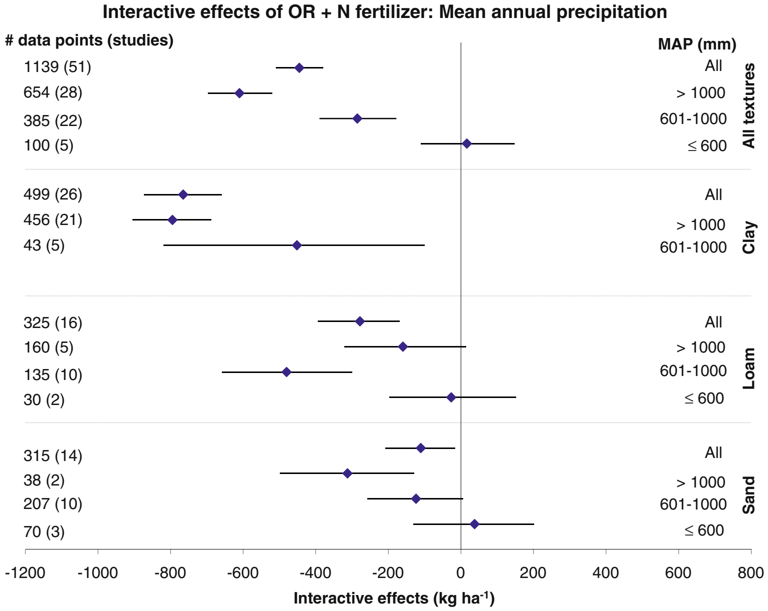
Agronomic N use efficiency was greater following the addition of N fertilizers (22 kg grain increase kg$^{-1}$ N applied) than ORs and ORs + N fertilizers which had agronomic N use efficiencies of 13.1 and 13.6 kg grain increase kg$^{-1}$ N applied, respectively (Fig. 10a). When all soils were combined, agronomic N use efficiency of the combined treatment were lowest with class IV ORs but there were no differences among OR classes I, II and III (Fig. 10b). In sandy soils agronomic N use efficiency was 11.7 kg grain increase kg$^{-1}$ N applied for class III ORs compared to ≤5 kg grain increase kg$^{-1}$ N applied with classes II and IV ORs (Fig. 10b). In loamy soils, on the other hand, class III ORs resulted in agronomic N use efficiency, which was significantly greater than class I and IV ORs (Fig. 10b). Generally, there were no differences

**Fig. 7** Yield response to the combined addition of organic resources (OR) with mineral N fertilizers compared to **a** sole OR and, **b** sole N fertilizer expressed as yield responses, categorized into the four OR quality classes (See Table 1) for clayey, loamy and sandy soils. Yield responses are expressed as weighted average response percentage with 95% confidence intervals represented by the *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses



between OR classes I and II except in sandy soils where agronomic N use efficiency for class I ORs was twice as much that of class II ORs (Fig. 10b). Agronomic N use efficiency of the combined addition of ORs with N fertilizers increased with decreasing quantities of both OR-N and fertilizer-N, except in loamy soils where ≤30 kg OR-N$\,$ha$^{-1}$ was not significantly different from when greater amounts of OR-N were added (Fig. 11a and b). The addition of ≤30 kg$\,$N$\,$ha$^{-1}$ resulted in agronomic N use efficiencies of 20 and 31 kg grain increase kg$^{-1}$ N added as ORs and N fertilizers, respectively across all textures (Fig. 11a and b). The combined addition of ORs and N fertilizers resulted in greater N use

**Fig. 8** Interactive effects of the combined addition of organic resources with N mineral fertilizers categorized into three mean annual precipitation (MAP) classes for clayey, loamy and sandy soils. Interactive effects (kgha$^{-1}$) are expressed as unweighted averages with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses



efficiencies in clayey soils; 20 kg grain increase kg$^{-1}$ N applied compared to 7 and 10 kg grain increase kg$^{-1}$ N applied to loamy and sandy soils, respectively (Figs. 10 and 11). The greatest agronomic N use efficiency of 27 and 37 kg grain increase kg$^{-1}$ N added was observed in clayey soils when ≤30 kgNha$^{-1}$ was added as OR-N and fertilizer-N, respectively (Fig. 11a and b). In comparison, in coarser textured soils agronomic N use efficiency was less than 13 and 20 kg grain increase kg$^{-1}$ N added where ≤30 kgNha$^{-1}$ was added as OR-N and fertilizer-N, respectively (Fig. 11a and b).

### Soil organic carbon

The addition of ORs, both alone and in combination with N fertilizers resulted in SOC contents that were 17% and 12% greater than the no input control, respectively (Fig. 12a). Although, there were no differences in SOC responses over the control between sole ORs and ORs + N fertilizers, the ORs + N fertilizers treatment tended to result in lower SOC than sole ORs (Fig. 12a). The sole addition of N fertilizers resulted in SOC contents that were not significantly different from the control but was significantly less than when ORs were added alone (Fig. 12a). There was a general trend of increasing SOC responses with increasing OR-N quantities; greater SOC responses were observed in treatments where >30 kg OR-Nha$^{-1}$ was added while experiments where ≤30 kg OR-Nha$^{-1}$ was added were not different from the control (Fig. 12b). Soil organic C responses following the application of sole ORs was greater in sandy soils and least in loamy soils (Fig. 12c).

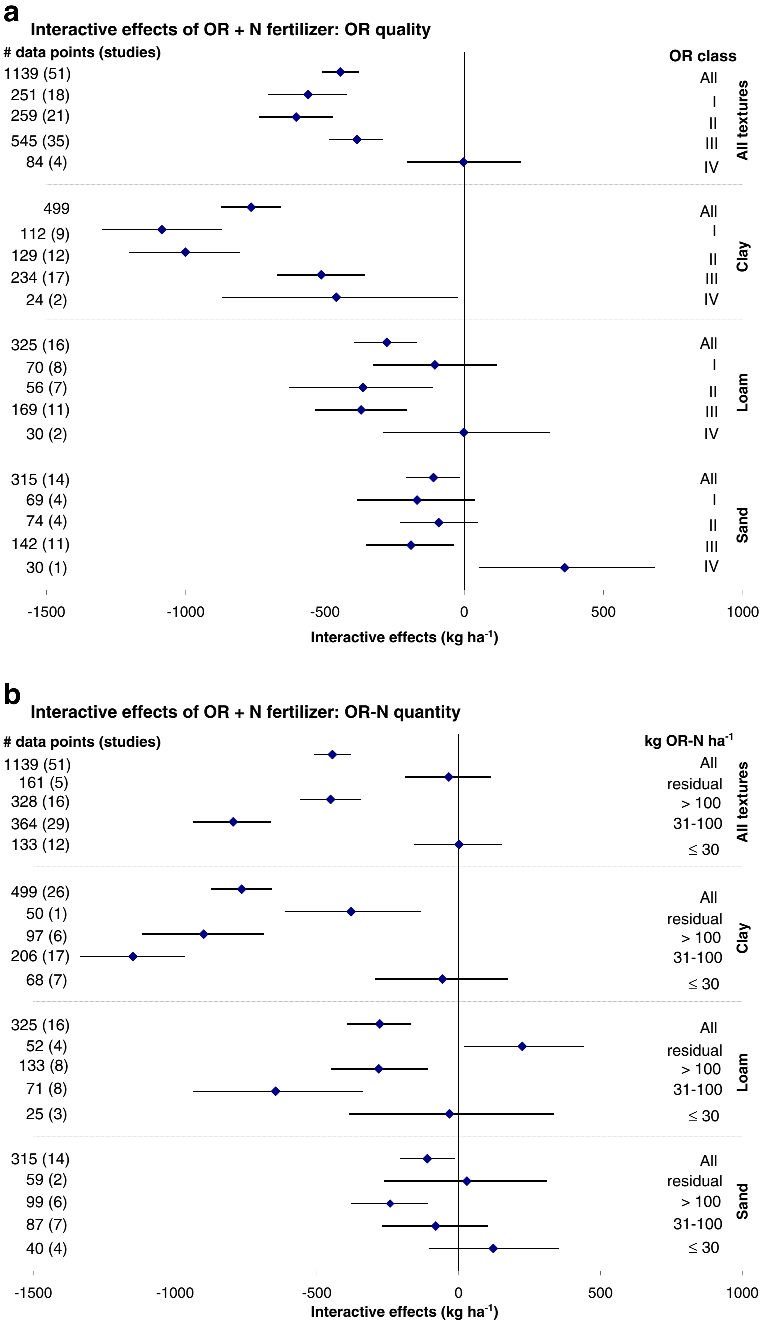
## Discussion

### Maize yield responses

#### *Benefits of external nutrients*

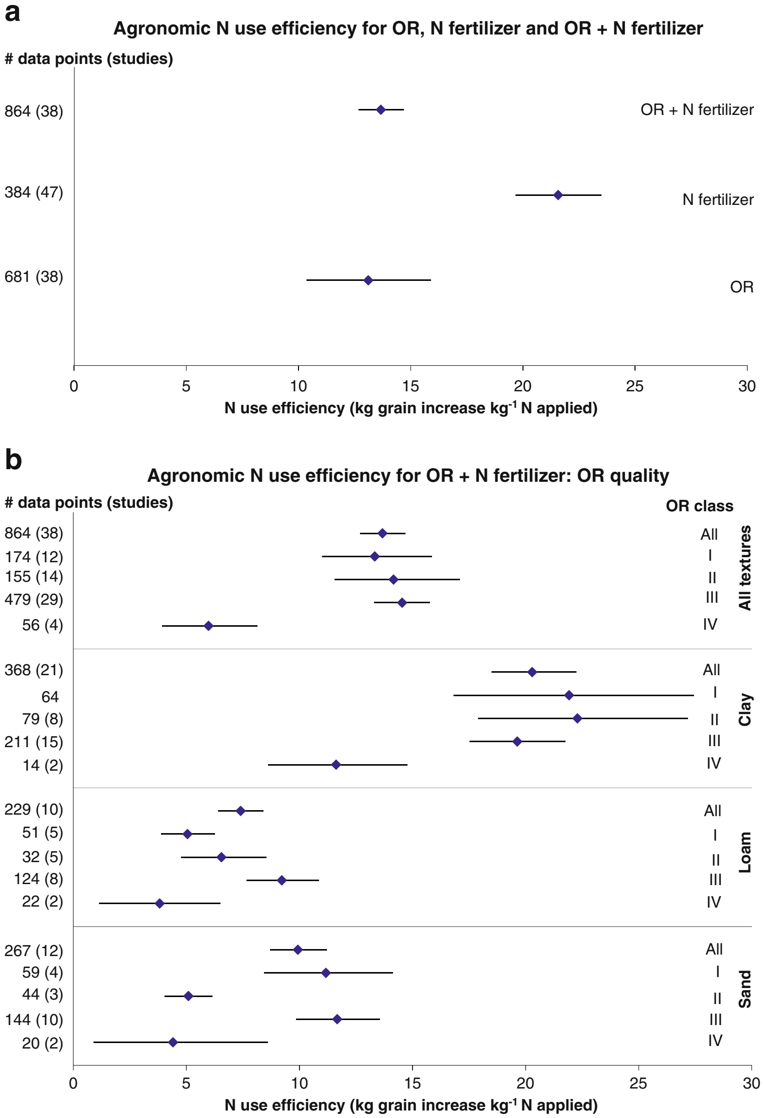
Results from our meta-analysis clearly highlight the positive maize yield benefits realized following the external addition of nutrients in SSA soils in the following decreasing order; ORs + N fertilizers > N fertilizers > ORs (Fig. 2a). While the addition of N fertilizers has been shown to result in greater crop yields than ORs (Baggs et al. 2000; Bremer and van Kessel 1992; Ladd and Amato 1986), greater crop yields have been observed following the combined application of ORs with N fertilizers (Kimani et al. 2007; Kramer et al. 2002; Mtambanengwe et al. 2006). The greater yield benefits with the combined treatment have been mainly attributed to the direct interactions between the two resources where temporary immobilization of N from fertilizers by ORs may result in improved synchrony between supply and

**Fig. 9** Interactive effects of the combined addition of organic resources (OR) with mineral N fertilizers categorized into **a** four OR quality classes (See Table 1), and **b** OR-N quantities for clayey, loamy and sandy soils. Interactive effects (kg ha$^{-1}$) are expressed as unweighted averages with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses



demand of nutrients (Myers et al. 1994; Palm et al. 2001a; Vanlauwe et al. 2001c). This improved synchrony enhances the use efficiency of the two resources, often leading to positive interactive effects on yield, i.e. yields greater than the sum of yields obtained following the sole application of either resource (Vanlauwe et al. 2001a). The positive interactive effects might also be due to the alleviation of other growth limiting factors such as micronutrients (Palm et al. 1997; Zingore et al. 2008). However, in our analysis across all studies, the interactive effects of combining the two resources were, most often, negative (Figs. 8 and 9). Moreover, the agronomic N use efficiency following the combined addition of ORs and N fertilizers was not different from sole applied ORs but was instead lower

**Fig. 10** Nitrogen use efficiency of the combined addition of organic resources (OR) with mineral N fertilizers categorized into four OR quality classes (See Table 1) for the clayey, loamy and sandy soils. Nitrogen use efficiency (kg grain increase over the control kg$^{-1}$ N applied) expressed as unweighted averages with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses



than sole applied N fertilizers (Fig. 10a). This indicates that the extra yields observed with the combined treatment were not caused by improved efficiency of utilization when the two resources are added together, but likely due to the extra N supplied when the two resources were added together. However, excess amounts of N were added in the combined treatment where at least 100 kgNha$^{-1}$ was added in the combined treatment in more than 70% of the studies (data not shown) with sum N added as high as 667 kgNha$^{-1}$. This could have reduced the agronomic N use efficiency (Cassman et al. 2002) and masked the possible positive interactions. Nonetheless, it should be noted that yield responses were variable under different conditions; for example different OR qualities led to different interactive effects in different textured soils while low quantities of N added resulted in greater agronomic N use efficiencies (see sections below).

While results from our meta-analysis imply no improvement in agronomic N use efficiency following the combined addition of ORs with N fertilizers compared to sole applied ORs or N fertilizers, there is a possible shift towards increased N utilization efficiency of the two resources in the long-term. Previous studies have shown lower recoveries of OR

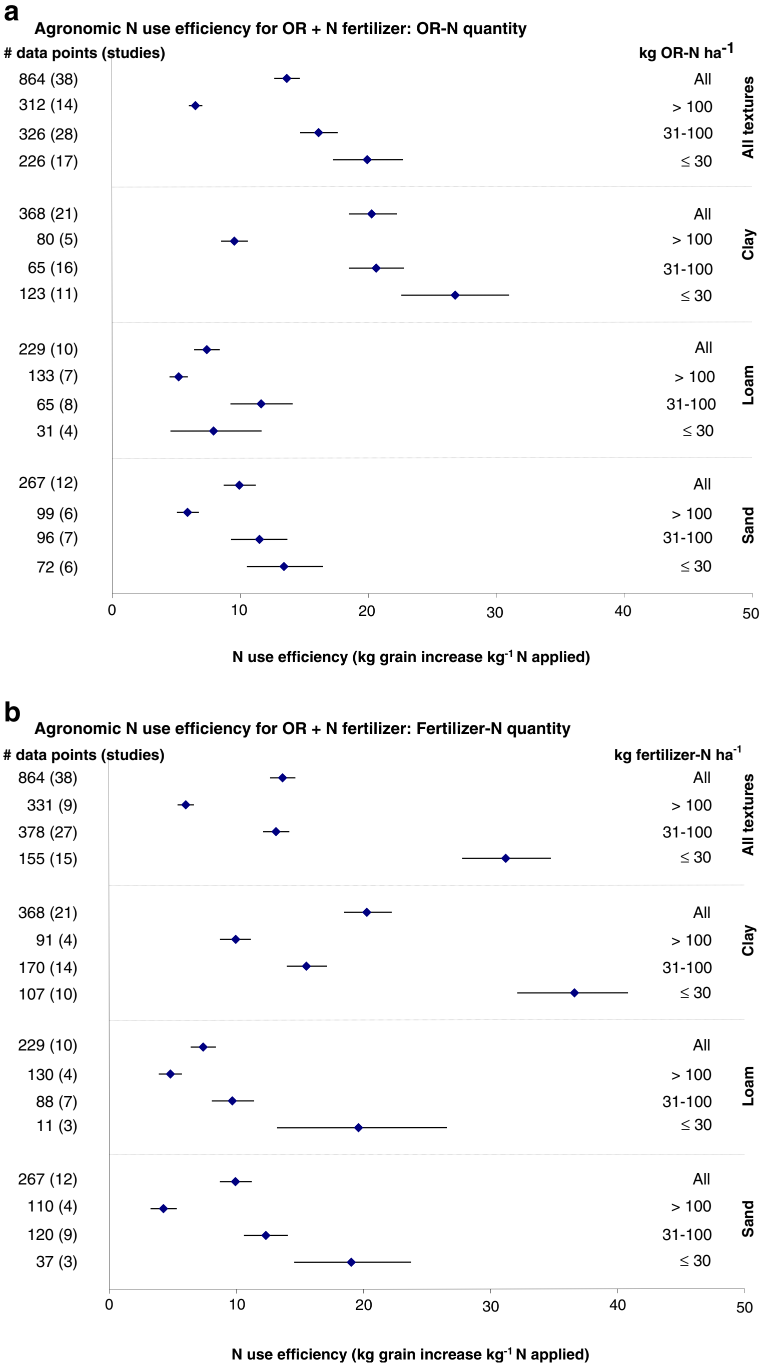


**Fig. 11** Nitrogen use efficiency of the combined addition of organic resources (OR) with mineral N fertilizers categorized into **a** OR-N and, **b** fertilizer-N quantity classes (See Table 1) for the clayey, loamy and sandy soils. Nitrogen use efficiency (kg grain increase over the control kg$^{-1}$ N applied) expressed as unweighted averages with 95% confidence intervals represented by *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses

applied N in the first year of application compared to N fertilizers but with greater residual benefits than N fertilizers in subsequent seasons (Bosshard et al. 2009; Cadisch et al. 1998; Handayanto et al. 1997). We also observed residual OR benefits on average crop yield response of 40% for sole applied ORs compared to the control, implying possible build-up of nutrients in soil following the application of ORs (Fig. 6a). Moreover, the addition of ORs, alone or in combination with N fertilizers resulted in greater SOC increases compared to the control whereas SOC following N fertilizer additions was not different from

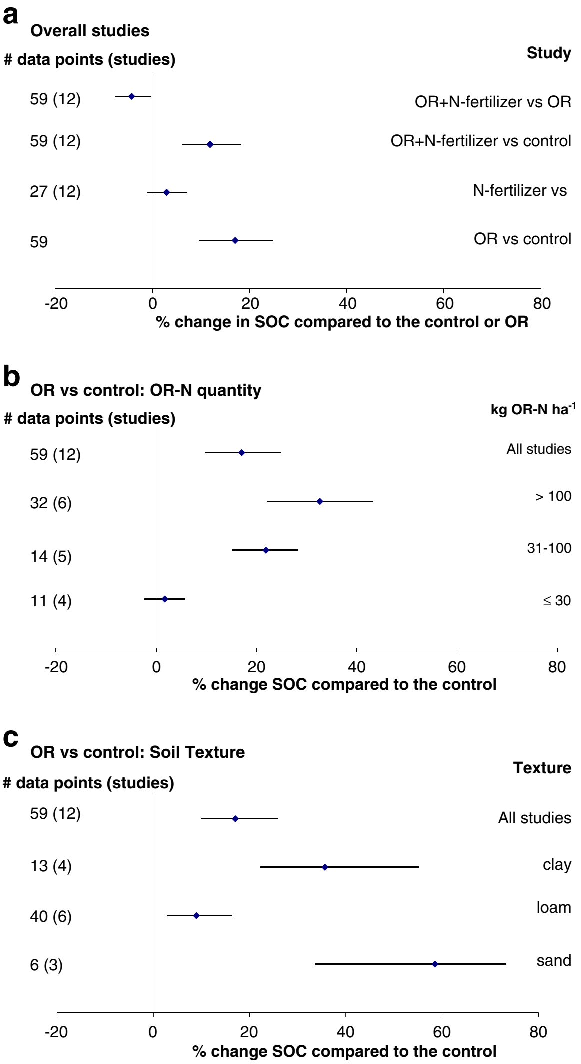


**Fig. 12** **a** Soil organic C (SOC) responses to the addition of organic resources (OR), mineral N fertilizers, or OR + N fertilizer compared to the control. The combined treatment (OR + N fertilizer) is also compared to sole applied OR (OR + N fertilizer vs OR). **b** SOC responses to the addition of OR compared to the no input control, categorized into three OR-N quantities. **c** SOC responses to the addition of OR compared to the no input control, categorized into three soil textural classes. SOC responses are expressed as average response percentage with 95% confidence intervals represented by the *error bars*. Numbers of effect size comparisons are given as # of data points and number of studies from which the points are taken appear in parentheses

the control (Fig. 12a). Greater sustainability and soil organic matter build-up in the long-term following the addition of ORs, alone and in combination with N fertilizers (Bhattacharyya et al. 2007; Bhattacharyya et al. 2008; Bi et al. 2009) also imply greater crop yields may be achieved by these treatments than sole applied N fertilizers over time. Most of the studies (48) included in our meta-analysis were carried out over less than 5 yr, with 16 of them being carried out over one season. Thus, although there were lower agronomic N use efficiencies and negative interactive effects following the combined addition of ORs with N fertilizers in the short-term, there are possible improvements on these in the long-term. This brings a need to invest in long-term evaluations of the combined addition of ORs with N fertilizers in SSA.

### *Organic resource quality and OR-N quantity influences*

Generally, greater OR-N quantities were added with high quality ORs than low quality ORs thus the greater yield responses with high quality ORs were likely due to greater amounts of N added (Figs 4). In support, several studies have observed greater crop yields with high than low rates of OR application (Chivenge et al. 2009; Mtambanengwe and Mapfumo 2006). Similarly, greater yields have been observed with high than low quality ORs (Mtambanengwe et al. 2006; Murwira et al. 2002; Teklay et al. 2006; Vanlauwe et al. 2001c). The addition of high quality ORs, class I, results in a fast release of nutrients, which may be taken up by plants if they are in synchrony with crop demands (Kimetu et al. 2004; Mafongoya et al. 1998a; Palm et al. 2001b). In contrast, the addition of intermediate to low quality ORs, classes III and IV ORs, may cause N immobilization and, therefore, lead to lower yields than the no input control (Kapkiyai et al. 1999; Mugwira and Murwira 1997; Sakala et al. 2000). In our meta-analysis, although low quality ORs, class IV, resulted in lower crop yield responses than other OR quality classes, the decline in crop yields with class IV ORs compared to the control was only observed in sandy soils (Fig. 4a), probably reflecting the inherent infertility of sandy soils (Bationo et al. 2007; Grant 1981). This was supported by the low yields of the control and the greater yield responses following the external addition of nutrients in sandy soils compared to other textures (Fig. 1). Although the addition of low quality ORs would have been anticipated to increase moisture retention and availability (Bationo et al. 2007; Bauer and Black 1992; Tian et al. 2007; Vanlauwe et al. 2002a), nutrient limitations may have been more critical for crop growth (Greenwood et al. 1996; Ouédraogo et al. 2006) and probably more so in sandy soils where the nutrient base is low. Nonetheless, differences among OR quality and OR-N quantity classes were more distinct in the clayey soils (Fig. 4b) and this was probably because of the greater contact between OR and clay particles (Gentile et al. 2008; Mary et al. 1996). Clay particles have a large surface area, enhancing microbial contact with ORs whereas the limited contact in coarse textured soils may limit OR decomposition (Strong et al. 1999). Additionally, coarse textured soils have a lower moisture holding capacity which may also limit decomposition of ORs (Manning et al. 2008), and thus result in less distinct OR quality differences compared to fine textured soils. Moreover, soil aggregate and SOC dynamics in clayey soils are influenced by OR quality and in turn influence OR decomposition and nutrient dynamics whereas in coarser textured soils there are fewer aggregates (Bossuyt et al. 2001; Six et al. 2001).

Although OR quality was clearly important in influencing maize yield, there were generally no differences in maize yield responses, agronomic N use efficiency and interactive effects between OR classes I and II when applied alone or in combination with N fertilizers in all soils (Figs. 4, 5, 6, 9 and 10). This suggests that polyphenol content, which separates the two classes (Mafongoya et al. 1998a; Oglesby and Fownes 1992; Palm et al. 2001a), may not play a significant role in nutrient release under field conditions. While polyphenols have been shown to be biochemically recalcitrant and, therefore reduce N mineralization (Heal et al. 1997; Mafongoya et al. 1998b; Palm and Sanchez 1991), Vanlauwe et al. (2001b) showed that polyphenol contents influenced maize N uptake in a pot trial, but its impact was minimal under field conditions. Similarly, N mineralization (Basamba et al. 2007; Gentile et al. 2008; Teklay and Malmer 2004) and crop yields (Chivenge et al. 2009; Kimetu et al. 2004; Shisanya et al. 2009) have been observed to be similar for the two OR classes, probably because in some instances the polyphenols are leached out of the soil (Vanlauwe et al. 2002b). Additionally, recent studies have shown that biochemical recalcitrance may not be as long lasting as initially thought (Gentile et al. 2008; Grandy and Neff 2008; Marschner et al. 2008) but that OR decomposition is primarily driven by OR-N content (Parton et al. 2007). Thus, contrary to the decision support system proposed by Palm et al. (2001a, 1997) where they separated classes I and II ORs, we conclude that there are no differences in maize yield responses between the two classes. The current meta-analysis suggests three distinct OR classes with classes I and II falling in the high quality class, classes III and IV in the intermediate and low quality classes, respectively (Figs. 4a, 5a and 9a). Similarly, Vanlauwe et al. (2005b) showed three distinct quality classes based on short-term N mineralization assays.

When the ORs + N fertilizer treatment was compared to sole ORs, greater yield responses were observed with low quality ORs than high quality ORs (Fig. 7a). This was probably because greater yields were observed with sole high quality ORs (Fig. 4a) such that the supplementary addition of N fertilizers resulted in a small increase in maize yields. On the contrary, low quality ORs may have induced N limitations that were alleviated by the addition of fertilizer-N resulting in greater yield increases compared to sole ORs. This alleviation was more pronounced in sandy soils where the addition of N fertilizers to class IV ORs resulted in maize yield responses of 249% when compared to sole ORs, whereas in clayey soils it was only 35% with the same OR class (Fig. 7a). Several studies have also observed greater increases with the combined application of low than high quality OR over sole OR (Friesen et al. 2002; Teklay et al. 2006; Vanlauwe et al. 2002a). Similarly, Mtambanengwe et al. (2006) observed a mere 13% yield increase when class I OR, *C. juncea*, was added in combination with N fertilizer compared to sole *C. juncea* in a sandy soil. In contrast, there was a 325% and 800% yield increase with the combined addition of class III and IV ORs with N fertilizers compared to sole ORs, respectively.

Positive interactive effects have been observed when intermediate and low quality ORs are applied in combination with N fertilizers but not with high quality ORs (Vanlauwe et al. 2002a, 2005a). Thus, we expected positive interactive effects with class III and IV ORs but these were only observed with class IV ORs and only in sandy soils (Fig. 9a). However, when class IV ORs + N fertilizers were compared to sole N fertilizers, there were no yield responses for all soil textures (Fig. 7b). In addition, agronomic N use efficiency for the combined addition of class IV ORs with N fertilizers was less than 5 compared to 12 kg grain increase kg$^{-1}$ N added with class III ORs in sandy soils (Fig. 10). Thus, in support of the decision support system (Palm et al. 1997; 2001a), where fertilizers are available, there are no added benefits of combining their application with class IV ORs.

In contrast to comparisons with sole ORs, when the combined treatment was compared to sole N fertilizers, yield responses increased with increasing OR quality (Fig. 7b). While there were no differences between OR classes I and II in sandy and loamy soils, in clayey soils class II ORs + N fertilizers resulted in a yield response of 25% over N fertilizers compared to 11% with class I ORs (Fig. 7b). This suggests that the combined addition of N fertilizers with class II ORs may be more beneficial than with class I ORs, as proposed by Palm et al. (2001a; 1997) but only in clayey soils. However, the interactive effects of combining class II ORs with N fertilizers were generally negative and not different from class I ORs (Fig. 9a). Additionally, the agronomic N use efficiencies were not different for the two classes in clayey soils but were greater with class I ORs than class II ORs in sandy soils (Fig. 10).

Residual effects of ORs were also influenced by OR quality with greater residual effects observed with high quality ORs, both when ORs were applied alone or in combination with N fertilizers (Fig. 6). This contradicts the general consensus that low quality ORs may have greater residual benefits due to the slow decomposition of ORs making nutrients available over longer periods of time (Mafongoya et al. 1998a, 1997; Palm et al. 2001b; Tian et al. 2007). However, given that OR-N added by the low quality ORs was less than that added by high quality ORs, it is possible that there were just not enough nutrients to be used by the following crop. The lack of residual effects in sandy soils indicates the need to continuously add nutrients to these inherently infertile soils (Bationo et al. 2007). However, while there were no residual effects of ORs in sandy soils, the addition of N fertilizers in the residual year resulted in crop yield responses of about 80% over the control whereas in clayey soils residual effects were 49% and 63% over the control for ORs and ORs + N fertilizers. These results stress the need to continuously add nutrients in the inherently infertile sandy soils and suggest that the addition of ORs in sandy soils may lead to improved water use efficiency once nutrients are added.

### *Fertilizer-N and OR-N quantities and soil fertility influences*

The greater yield responses to N fertilizer additions observed in experiments where ≤30 kgNha$^{-1}$ was added (Fig. 3a) were likely because most of the studies with this low fertilizer-N addition rate were in areas receiving ≤600 mm rainfall annually. As shown in the analyses, greater yield responses were observed in studies done in low rainfall areas (Fig. 3a). When considering the yield differences, it was clear that the absolute yield increases due to addition of ≤30 kgNha$^{-1}$ were lowest among the N application classes (Fig. 3b). Furthermore, absolute yield increases were lowest in climates receiving ≤600 mm MAP (Fig. 3b). Thus, similar to previous observations (Vanlauwe et al. 2001c), proportional yield responses to nutrient additions (ORs, N fertilizers, ORs + N fertilizers) were greater when the initial control yields were low and vice versa (Fig. 1).

The efficiency of utilization of applied N fertilizers was greater when lower quantities of N fertilizers were applied and decreased with increasing fertilizer-N quantities (Fig. 11b). Lower agronomic N use efficiencies have been observed with greater quantities of fertilizer-N added (Cassman et al. 2002; Ortiz-Monasterio et al. 1997; Raun et al. 2002). Thus, the lower agronomic N use efficiencies observed with the combined addition of ORs + N fertilizers than sole N fertilizers were likely because of greater quantities of N that were generally added with the combined treatment compared to sole N fertilizers. However, the same was not observed when the combined treatment was compared to sole ORs where generally lower quantities of N were added compared to the combined treatment (Fig. 10a). The lack of differences in agronomic N use efficiencies between sole applied ORs and the combined treatment imply that ORs may reduce the efficiency of N fertilizers, similar to observations by Takahashi et al. (2007) where the agronomic N use efficiencies of N fertilizers were reduced when applied with compost. Although reduced N losses and improved N synchrony have been proposed to lead to increased N use efficiencies following the combined application of ORs + N fertilizers (Giller 2002; Palm et al. 2001a; Vanlauwe et al. 2002a), in the current meta-analysis there was no evidence of increased N use efficiencies when ORs were combined with N fertilizers. It is worth noting that, agronomic N use efficiencies were greater where lower amounts of N were added, both as OR-N and fertilizer-N, but were greater for low fertilizer-N than OR-N. This was particularly more so in clayey soils where agronomic N use efficiency was 27 and 37 kg grain increase $\text{kg}^{-1}$ N added when ≤30 kg $\text{OR-N ha}^{-1}$ was added as OR-N and fertilizer N, respectively (Fig. 11a and b). Thus, while low quantities of N as OR-N and fertilizer-N enhance utilization efficiency of added N, clayey soils tended to also promote greater efficiency of N utilization. Clayey soils are generally more fertile with greater SOC than coarser textured soils, influencing the efficiency of N utilization. In support, greater agronomic N use efficiencies have been observed in fertile soils close the homestead than those that are further from the homestead and less fertile (Vanlauwe et al. 2010b, 2006).

### Soil organic carbon responses

The increases in SOC with ORs and ORs + N fertilizers and not with sole N fertilizers show the need for OR additions to increase SOC (Fig. 12a). Similar to yield responses, greater differences in SOC were observed in sandy soils than in clayey and loamy soils (Fig. 12c). This was most likely because of the low starting SOC contents such that the addition of ORs caused greater proportional increases in SOC, which, in absolute terms may be lower than in finer textured soils. In addition, because of the lower protection of added ORs and faster loss of nutrients in sandy soils than clayey soils, there is a need for continuous addition of C in sandy soils (Mapfumo et al. 2007). Chivenge et al. (2007) observed greater responses in SOC contents following the addition of mulch in a sandy soil while there were insignificant responses in a clayey soil. Although there were greater yield increases with OR + N fertilizer compared to sole OR (Fig. 2a), there were greater C contents with sole OR than OR + N fertilizer (Fig. 12). This is likely because the added N fertilizers enhanced decomposition of the added OR, which likely resulted in greater N supply but also greater losses of added C (Khan et al. 2007; Nardi et al. 2004). In contrast, Bhattacharyya et al. (2007) observed greater SOC with ORs + N fertilizers than ORs, whereas Nayak et al. (2009) found no differences in SOC between sole applied ORs and ORs + N fertilizers. Nevertheless, Nayak et al. (2009) observed greater microbial biomass C and N, and active SOC with ORs + N fertilizers than ORs.

Greater yield responses with sole N fertilizer than OR probably also led to greater belowground C inputs in the sole N fertilizer (Fig. 2), but N fertilizers applied alone did not increase SOC (Fig. 12a). Similarly, Gentile et al. (2010) and Khan et al. (2007) observed greater SOC contents in treatments where OR was added than when N fertilizer was added. In contrast, Goyal et al. (1992) found that the addition of N and P fertilizers resulted in increased SOC contents. In their study, they also observed greater SOC contents following the combined application of OR and N fertilizers and this was mainly attributed to increased root growth associated with greater organic matter inputs. Studies that compared above- versus belowground C input to soil generally find a greater stabilization of root-derived C than residue-derived C (Denef and Six 2006; Gale and Cambardella 2000; Gale et al. 2000; Six et al. 2002). Nevertheless, our results further emphasize the need of adding C inputs in order to build up and/or maintain SOC, especially in sandy soils.

## Conclusions

Given that the studies included in the meta-analysis were carried out across most agro-ecological zones in SSA and across different soil textures using a wide range of OR qualities, we can confidently conclude that yield responses are largely dependent on addition of nutrients, soil texture and MAP. While OR quality clearly influences crop yield responses, the use of polyphenol content to separate classes I and II seems to be of less importance under field conditions. Organic resource N content and total quantities of OR-N added, just like total fertilizer-N added, are more influential on crop yields than polyphenol contents. Yield responses were greater following the combined application of ORs with N fertilizers compared to the addition of either resource alone. However, the dominance of negative interactive effects and lack of differences in agronomic N use efficiencies with ORs applied alone but lower than N fertilizers applied alone imply that the extra increase in grain yield is mostly related to the extra N added and not to an increase in efficiency of utilization by applying the resources together. However, given that total N added in the combined treatment was ≥100 kgNha-1 in 70% of the observations, possible interactive effects could have been masked with reduced resource utilization efficiency. Utilization efficiency of combining ORs with N fertilizers were greater when lower quantities of OR-N and fertilizer-N were added, suggesting that this may be the most appropriate strategy for managing the resources, particularly in sandy soils. Absolute yield responses were greater in finer textured soils and high MAP areas, but the proportional increases to nutrient additions were greater in low MAP areas and coarse textured soils. Therefore, positive interactive effects were observed when low quality OR was incorporated in sandy soils. Furthermore, there were no residual effects of sole ORs in sandy soils on yield, showing the need to continuously add N fertilizers in these soils. In addition, the application of ORs increased SOC, and this was more so in sandy soils, and thus offers, in combination with N fertilizer additions, the potential for the improvement of soil quality, crop productivity and its sustainability in SSA.

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## Appendix 1

**Table 3** List of publications included in the meta-analysis

| Author | Source | Country | Organic resources | # Sites | Seasons |
|---|---|---|---|---|---|
| Akinnifesi et al. (2007) | Plant & Soil 294: 203–207 | Malawi | *Gliricidium sepium* | 1 | 4 |
| Akulumuka et al. (1996) | CIMMYT 5th Maize Conf, 146–148 | Tanzania | Farmyard manure (fym) | 2 | 1 |
| Ayuk and Mafongoya (2001) | SADC/ICRAF 14th S Africa Proc | Zambia | Farmyard manure, *Tephrosia vogelii, Sesbania sesban* | 1 | 2 |
| Bado et al. (2004) | AFNET TSBF-CIAT Proc, 77–87 | Burkina Faso | Fym | 2 | 7 |
| Baijukya et al. (2005) | Nut Cycl 73: 75–87 | Tanzania | Grass fallow, fym, *Crotalaria juncea* | 1 | 1 |
| Carsky et al. (1999) | Nut Cycl 55: 95–105 | Nigeria | *Mucuna pruriens*, *C. juncea*, *lablab*, *Vigna unguiculata* (cowpea), grass fallow | 2 | 1 |
| Chikowo et al. (2003) | DPhil dissertation | Zimbabwe | Fym | 1 | 1 |
| Chikowo et al. (2004) | Plant & Soil 262: 303–315 | Zimbabwe | *Acacia angustisima, S. sesban, Cajanus cajun,* grass fallow | 1 | 2 |
| Chilimba et al. (2004) | CIMMYT Working Paper No. 11 | Malawi | Compost, fym | 2 | 1 |
| Chivenge et al. (2009) | Agron J. 101: 1266–1275 | Kenya | *Tithonia diversifolia, Calliandra calothyrsus, Zea mays* (maize), sawdust, fym | 2 | 10 |
| Delve et al. (2004) | AFNET TSBF-CIAT Proc, 127–136 | Kenya | *T. diversifolia* | 1 | 2 |
| Fofana et al. (2005) | Nut Cycl 71: 227–237 | Togo | *M. pruriens* | 2 | 4 |
| Franke et al. (2008) | Nut Cycl 82: 117–135 | Nigeria | *Pueraria phaseoloides, Stylosanthes guianensis, Glycine max, Aeschynomene histrix,* cowpea | 2 | 3 |
| Gigou et al. (2002) | INM in SSA, CABI, 199–208 | Cote d'Ivoire | Compost | 1 | 20 |
| Gikonyo and Smithson (2004) | AFNET TSBF-CIAT Proc, 137–149 | Kenya | Fym | 1 | 1 |

**Table 3** (continued)

| Author | Source | Country | Organic resources | # Sites | Seasons |
|---|---|---|---|---|---|
| Goma (2003) | Soil Fert. Mgt Africa, CIAT, pp 187–218 | Zambia | *Leucaena leucocephala, G. sepium, Ficus macrophylla*, fym | 1 | 1 |
| Horst and Hardter 1994 | Plant & Soil 160: 171–183 | Ghana | Cowpea | 1 | 2 |
| Ikerra et al. (1998) | CIMMYT 6th Maize Conf Proc, 226–231 | Malawi | *G. sepium* | 1 | 2 |
| Itimu et al. (1998) | CIMMYT Soil Fert Mal & Zim, 203–207 | Malawi | *Senna spectabilis, G. sepium* | 1 | 1 |
| Iwuafor et al. (2002) | INM in SSA, CABI, 185–198 | Nigeria, Benin | Organic matter, *Zea mays*, fym | 3 | 2 |
| Jones et al. (1997) | Driven by Nature, CABI | Malawi | *L. leucocephala, G. sepium* | 1 | 2 |
| Kapkiyai et al. (1999) | Soil Biol Biochem 31: 1773–1782 | Kenya | *Zea mays*, fym | 1 | 1 |
| Kihanda et al. (1998) | CIMMYT 6th Maize Conf Proc, 250–252 | Kenya | Fym | 1 | 1 |
| Kimani and Lekasi (2004) | AFNET TSBF-CIAT Proc, 187–206 | Kenya | Fym | 1 | 1 |
| Kimani et al. (2007) | Advances in ISFM in SSA, 353–358 | Kenya | *T. diversifolia, M. pruriens, C. juncea, lablab,* compost, fym, *Zea mays* | 3 | 1 |
| Kimaro et al. (2009) | Agric Ecosyst Environ 134: 115–125 | Tanzania | *C. Cajun,* fym | 1 | 2 |
| Kimetu et al. (2004) | Nut Cycl 68: 127–135 | Kenya | *T. diversifolia, Senna siamea, C. calothyrsus* | 1 | 2 |
| Kumwenda et al. (1998) | CIMMYT Soil Fert Mal & Zim, 85–86 | Malawi | *C. cajun, C. juncea, M. pruriens* | 1 | 2 |
| Kwesiga et al. (1999) | Agroforest Syst 47: 49–66 | Zambia | *S. sesban* | 1 | 5 |
| Mafongoya and Dzowela (1999) | Agroforest Syst 47: 139–151 | Zimbabwe | *A. anguistisima, C. cajun, S. sesban* | 1 | 2 |
| Mafongoya et al. (2006) | Nutr Cycl 76:137–151 | Zambia | *S. sesban* | 1 | 3 |
| Makumba et al. (2001) | SADC/ICRAF 14th S Africa Proc | Malawi | *G. sepium* | 1 | 2 |
| Mariki et al. (1996) | CIMMYT 5th Maize Conf, 200–201 | Tanzania | *Zea mays* | 1 | 2 |
| Mochoge and Onwonga (1998) | CIMMYT 6th Maize Conf Proc, 267–270 | Kenya | *V. unguiculata* | 6 | 1 |
| Mtambanengwe et al. (2006) | Nut Cycl 76: 271–284 | Zimbabwe | *C. juncea, C. calothyrsus*, *Zea mays*, sawdust, fym | 2 | 5 |
| Mucheru-Muna et al. (2004) | FORMAT OR Mgt in Kenya | Kenya | *C. juncea, M. pruriens, C. calothyrsus, L. leucocephala, T. diversifolia,* fym | 2 | 4 |
| Mugendi et al. (1999) | Agroforest Syst 46: 30–50 | Kenya | *C. calothyrsus, L.leucocephala* | 1 | 1 |
| Mugwe et al. (2007) | African Crop Sci J 15: 111–126 | Kenya | *M. pruriens, C. ochloleuca, T. diversifolia, C. calothyrsus, Leucaena trichandra,* cattle manure | 1 | 4 |
| Mugwira and Murwira (1997) | CIMMYT Soil Fert Net working paper no. 2, 18 pp | Zimbabwe | Fym | 1 | |
| Mungai et al. (1998) | CIMMYT 6th Maize Conf Proc, 253–255 | Kenya | *T. Diversifolia, Zea mays* | 2 | 1 |
| Murwira et al. (1998) | CIMMYT Soil Fert Mal & Zim, 179–182 | Zimbabwe | Fym | 6 | 1 |
| Nhamo (2002) | MPhil thesis | Zimbabwe | Fym | 11 | 2 |
| Nyadzi et al. (2006) | Agric Ecosyst Environ 116: 93–103 | Tanzania | *A. crassicarpa, A. julifera, A. leptocarpa, L. pallida, S. siamea*, grass fallow | 1 | 1 |
| Nyamangara et al. (2003) | African Crop Sci J 11: 289–300 | Zimbabwe | Cattle manure | 1 | 2 |

**Table 3** (continued)

| Author | Source | Country | Organic resources | # Sites | Seasons |
|---|---|---|---|---|---|
| Nyathi et al. (1995) | African Crop Sci J. 3: 451–456 | Zimbabwe | *Brachystegia spiciformis, L. leucocephala,* fym | 1 | 1 |
| Nziguheba et al. (2004) | AFNET TSBF-CIAT Proc, 329–346 | Kenya | *T. diversifolia* | 1 | 4 |
| Nziguheba et al. (2009) | Plant Soil 314: 143–157 | Nigeria, Benin | | | |
| Okalebo et al. (2004) | AFNET TSBF-CIAT Proc, 359–372 | Kenya | *Triticum aestivum, G. max* | 1 | 4 |
| Onyango et al. (1998) | CIMMYT 6th Maize Conf Proc, 242–246 | Kenya | Fym, compost | 4 | 3 |
| Sakala et al. (2000) | DARS Annual Proc | Malawi | *C. juncea, M. pruriens, lablab* | 1 | 1 |
| Snapp et al. (1998) | Ag Ecosyst Environ 71: 185–200 | Zimbabwe | *Arachis hypogea* | 1 | 1 |
| Swift et al. (1994) | Rothamsted Long-term Exp Proc, CABI, 229–251 | Kenya | Farmyard manure | 1 | 15 |
| Teklay et al. (2006) | Nut Cycl 75: 163–173 | Ethiopia | *Albizia, Cordia, Milletia, Crotia* | 1 | 2 |
| Vanlauwe et al. (2005a) | Plant & Soil 273: 337–337–354 | Nigeria | *L. leucocephala, S. siamea* | 1 | 17 |
| Vanlauwe (unpublished) | Unpublished | Kenya | *T. diversifolia, C. calothyrsus, Zea mays*, sawdust, fym | 2 | 1 |
| Workayehu and Kena (1998) | CIMMYT 6th Maize Conf Proc, 271–273 | Ethiopia | *Coffea arabica* (coffee) | 1 | 3 |
| Yeboah (unpublished) | Unpublished | Ghana | *C. juncea, L. leucocephala,* sawdust, *Zea mays*, fym | 2 | 5 |

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