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Grain yield and nitrogen cycling under conservation agriculture and biochar amendment in agroecosystems of sub-Saharan Africa. A meta-analysis

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ABSTRACT

Soil nitrogen (N) is one of the most limiting factors affecting crop production in sub-Saharan Africa (SSA). Here we conducted a meta-analysis on the effect of climate smart agricultural (CSA) practices (conservation agriculture (CA) and/or biochar (BC)) application on: (1) soil nitrate-N (NO_3-N), nitrous oxide (N_2O) emission, biological N_2-fixation, percent of nitrogen derived from the atmosphere (%Ndfa), grain yield and nitrogen use efficiency (NUE), (2) the role of soil properties and regions on grain yield and N cycling under CA and/or BC biochar application; and (3) the relationship between inorganic N fertilizer and NO_3-N, N_2O emissions, NUE and grain yield. We synthesized 87 unique papers, from 15 countries in SSA with 1643 paired observations. On average across all studies, CA and/or BC significantly increased grain yield and NUE, compared to conventional practices. Residue retention resulted in a significant increase in soil NO_3-N and N_2O emission, compared to conventional practices. Our analysis further indicates that BC application significantly increased biological N_2-fixation, grain yield and NUE. Auxiliary soil parameters also affected grain yield and N cycling. Grain yield was significantly influenced by total organic carbon classes (TOC), whereby highest grain yield was recorded under CSA in soils with 0.5–1 % TOC, compared to soils with < 0.5 % TOC and > 1 % TOC. In addition, total nitrogen (TN) significantly affected the response ratio of CSA and conventional agriculture on N_2O emission and biological N_2-fixation. N_2O emission increased significantly in soils with < 0.05 % TN, while biological N_2-fixation increased significantly in soils with > 0.2 % TN. Increasing N fertilizer use significantly increased the response ratio of CSA and conventional agriculture on N_2O and NO_3-N while significantly reducing the response ratio of yield and NUE. The gap in yield and NUE between CSA and conventional agriculture practises was more pronounced at lower N rates of 0 kg ha^{-1} and narrowed as N input increased to 120 kg ha^{-1}; this implies that, CSA offers more benefits compared to conventional agricultural practices under low N rates.

1. Introduction

Average yields of major crops on smallholder farm in sub-Saharan Africa (SSA) are much lower than what could potentially be produced, and the gap between potential yield and actual yield is large compared to other regions (Tittonell and Giller, 2013). Soil inorganic nitrogen (N) is one of the main yield limiting factors in SSA due to low N fertilizer use, which on average is currently 13 kg N ha^{-1} yr^{-1} (FAOSTAT, 2023; Vanlauwe and Dobermann, 2020) compared to 73 and 170 kg N ha^{-1} yr^{-1} in North America and China, respectively (Falconnier et al., 2023). The severe problem of poor soil fertility and nutrient mining has been highlighted by Liu et al. (2010) and Lassaletta et al. (2014).

To ensure the sustainability of agroecosystems in SSA, nitrogen use efficiency (NUE) must improve. NUE is defined as the grain yield achieved per unit of N available to the crop (Grahmann et al., 2013; Javed et al., 2022). Plants absorb N mostly in the form of NO_3-N and NH_4-N; however, mineral N only constitutes 2 % of the total soil N, and is also prone to losses through NO_3-N leaching, and conversion to gaseous forms (dinitrogen (N_2), nitrous oxide (N_2O), nitrogen dioxide (NO_2), nitric oxide (NO) and ammonia (NH3)) (Govindasamy et al., 2023; Khan

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et al., 2023). Agriculture, forestry, and other land use activities account for more than 50 % of N_2O emissions worldwide (Tian et al., 2020) and N_2O emissions are particularly important in low-pH soils (Wang et al., 2018). In SSA, increase in agricultural production is primarily by expansion rather than intensification of the existing agricultural land which is associated with loss of soil organic carbon (Leitner et al., 2020). While shifts in microbial communities and decomposer activity increase N_2O emissions by threefold in croplands compared to natural forest (Keller et al., 1991), it is imperative to note that the main driver behind the disparity in N_2O emissions in croplands is the microbial transformation processes involving N from applied N based fertilizers (Wang et al., 2018). Lack of comprehensive studies or insufficiently collected data on GHG from natural and agricultural lands in SSA hinders progress in understanding GHG (Dittmer et al., 2023; Kim et al., 2016; Tongwane and Moeletsi, 2018). There is a need to reconsider the design and functioning of agro-ecosystems, to resolve a wide array of problems, such as disconnects in supply of nutrients, demand and recycling (Singh et al., 2022).

There is a consensus that productivity on smallholder farms in SSA must increase to achieve millennium development goals (Andriesse and Meijerink, 2007). The concept of climate smart agriculture (CSA) has been proposed as an option that requires site-specific adaptation, to increase soil fertility and to sustainably enhance crop productivity, by producing more food with less external inputs, and with a smaller environmental impact. Conservation agriculture (CA) is one CSA practice that promotes minimum soil disturbance, maintenance of permanent soil cover and diversification of crop species (Pittelkow et al., 2015; Powlson et al., 2011). Since the 1980s when CA was introduced, it continues to polarize the global discourse in the research and development community (Kassam et al., 2011). Partly, this is because CA is not universally effective due to variability of agro-ecosystems; therefore, it requires context-driven approaches tailored to specific circumstances. Most smallholder farmers are not able to adopt all the three principles, due to several reasons. For example, due to crop-livestock competition, farmers opt to feed their livestock with crop residues during the dry periods, rather than mulching their fields (Giller et al., 2009). While incorporating legumes into farming systems as rotations (Franke et al., 2017) or intercrops (Namatsheve et al., 2020) is known to enhance nutrient cycling and N availability, thus improving the performance of CA, land constrains often result in large proportion of farms committed to cereal production every season, thereby forfeiting the ecological benefits of biological N_2-fixation. When CA is implemented together with other CSA practices such as biochar application it can enhance crop and soil performance even if all three CA principles are not fully implemented. For example, addition of biochar to planting basins and/or rip lines is common in CA systems (Johansen et al., 2012), thus allowing for precision application into the rooting zone of crops and reducing the amount of biochar needed for fertility effects (Cornelissen et al., 2013; Munera-Echeverri et al., 2020).

Biochar, a C-rich product made by pyrolysis of any organic waste (Martinsen et al., 2014; Munera-Echeverri et al., 2018), is relatively stable in soil (Kuzyakov, 2010), thus contributing to carbon sequestration (Zhang et al., 2018). Its high surface area, and affinity for charged solutes interact with physical, chemical and biological components of the soil and can have cascading effects throughout the ecosystem such as reducing nutrient loss and enhancing moisture content in the rooting zone (Biederman and Harpole, 2013). Amendment of soils with biochar is attracting much attention and has been suggested as a promising solution to regulate the soil N cycle. Biochar was found to condition and increase soil pH (Obia et al., 2015; Wang et al., 2018), to increase biological N_2-fixation (rhangi-Abriz et al., 2022), and to enhance soil N mineralisation (Nguyen et al., 2017; Munera-Echeverri et al., 2022). Thereby improving grain yield especially in low-input systems where soils are generally acidic and nutrient-poor (Joseph et al., 2021). Accordingly, application of biochar could be considered as a multi-win strategy. Although soil total N may increase with biochar application, this may not enhance the bioavailability of inorganic N (Biederman and Harpole, 2013). The high C:N ratio of biochar may lead to N lockup in the soil due to microbial immobilization of N, making it temporarily unavailable for crop uptake. This affects plant growth and yields especially during the first season after applying biochar in agroecosystems where inorganic fertilizer use is limited (Brtnicky et al., 2021; Gwenzi et al., 2015). The adoption of biochar in smallholder farming communities of SSA is still low due to challenges related to sufficient biomass for feedstock (Leach et al., 2012). There are competing interests for biomass, creating a trade-off between fuel for cooking and feedstock for biochar production. Also, there is lack of clear policy frameworks regarding biochar technologies in SSA.

Several meta-analyses have been conducted and confirmed that CA can effectively enhance grain yield in SSA (Corbeels et al., 2020; Giller et al., 2015; Kichamu-Wachira et al., 2021; Rusinamhodzi et al., 2011; Thierfelder et al., 2017). However, to our knowledge there is no meta-analysis that focuses on how biochar application in combination with one principle of CA, with a combination of two principles, or with a whole CA package affects N cycling and grain yield in SSA. In this study, we demonstrate how three principles of CA and/or biochar application affect N cycling and grain yield in SSA. Specifically, we determined the overall effect of CA and/or biochar amendment on: (1) N_2O emissions, soil NO_3-N, biological N_2-fixation, grain yield and NUE. In addition, we tested (2) the role of soil properties (pH, organic C and total N content, and clay content), and regions on N_2O emissions, biological N_2-fixation, grain yield and NUE under CA and/or biochar amendment in SSA; and (3) we determined the relationship of inorganic N fertilizer with soil NO_3-N, N_2O emissions, NUE and grain yield.

2. Materials and methods

2.1. Data collection

Using online databases, Scopus (Elsevier) and ISI Web of Science (Thomson Reuters), a comprehensive literature search was carried out for peer reviewed journals published between 2000 and early 2023 using the following search string: TITLE-ABS-KEY (biochar OR mulching OR residue retention OR rotation OR incorporating legumes OR reduced tillage) AND (nitrous oxide OR nitrate OR biological nitrogen fixation OR grain yield OR nitrogen use efficiency) AND (sub-Saharan Africa OR any country in SSA). The database searches were augmented with searches of library resources for relevant papers from citations in retrieved papers. The papers were further selected to meet the following criteria: (1) Peer reviewed journal articles only, i.e., book chapters, conference proceedings, theses are excluded; (2) Field experiments must have been conducted in SSA or any country in SSA reporting biochar or conservation farming (reduced tillage, minimum tillage, zero tillage, mulching, rotations, incorporating legumes, residue retention, and/or mulching). In case of laboratory experiments, they must have been carried out using soils from SSA (3) The articles should report at least one of the following: (i) cumulative N_2O emissions, (ii) N_2-fixation (iii) grain yield or (iv) NUE; (4) The articles should also include at least one of the auxiliary parameters (soil pH, soil N, soil TOC, clay content, amount of inorganic N applied and experimental duration); and (5) Only articles with control (reference) and treatments were considered. The control (reference) treatment was considered as a conventional practice if the CSA is CA i.e. residue retention, reduced tillage and/or incorporating legumes. If the CSA is biochar, the treatment without biochar (viz. either conventional or CSA) was considered as the control (reference) treatment. N_2O emissions must have been sampled using static chamber method, and in case where N_2O emissions were reported in g m^{-2} (or any other units) they were converted to kg ha^{-1}. For incubation studies, to convert N_2O emitted to kg ha^{-1}, we assumed that 1 ha has 2,400,000 kg of soil (provided that the soil samples were collected from 0 – 20 cm, the ploughing depth, with a BD of 1.2). During data mining, we collected data on the means, sample size (number of replications) and standard errors/standard deviations. On NUE, articles to be selected should include NUE, amount of N applied and grain yield. However, we did not find articles on how CA and/or biochar affect NUE in SSA; therefore, we used the ratio between grain yield and applied inorganic N fertilizer, as a proxy for NUE.

During data collection, data reported in tables was extracted directly while graphical data was mined using WebPlot Digitizer (https://automeris.io/WebPlotDigitizer/). Data on standard error /standard deviation were obtained from the tables in the reviewed articles. If an eligible study contains multi-year field trials conducted across different sites and/or different seasons, the data was treated separately. Soil pH, total organic carbon, clay, and total N were categorised into three classes. With the above selection criteria, we included 87 papers in our dataset, i.e., 26 papers on soil NO_3-N and N_2O (of which twenty-two are from field studies, three from incubation studies and one from a greenhouse experiment), 12 papers on biological N_2-fixation and %Ndfa (11 papers are from field studies and 1 is from a pot experiment), and 58 papers on grain yield and NUE. Nine of the papers contain both grain yield and N_2O, or grain yield and biological N_2-fixation (Fig S1).

2.2. Response variables

The response variables were categorised into six groups, which included (i) N_2O emission, (ii) soil NO_3-N (iii) biological N_2-fixation, (iv)%Ndfa, (v) grain yield and (vi) NUE.

2.3. Effect size

Response ratio was used to assess the effect of CSA practices on N cycling, in comparison with conventional agriculture. We calculated the natural logarithm (ln(R)) of the response ratio as the effect to quantify the influence of various forms of CSA practices (biochar, residue retention, reduced tillage and incorporating legumes) on a given variable, to increase metric's symmetry:

$$In(R) = In\left(\frac{Xt}{Xc}\right) \tag{1}$$

where *Xt* and *Xc* represent the arithmetic mean value of the treatment (CSA practice) and corresponding control, respectively, for the given variable. For effect sizes involving conservation agriculture, the control treatment was conventional agriculture. For effect sizes involving biochar the control treatment was either CSA without biochar or conventional agriculture. ln(R) is commonly used in meta-analysis to correct the differences in scale and size of response variables between studies and is considered as a robust metric for making statistical comparisons (Hedges et al., 1999). The overall mean effect size and its 95 % confidence interval (CI) was estimated while accounting for random study effects using mixed effect models, as explained in Table S1. The 95 % quantifies the level of confidence that the average effect size (point estimate) falls within the specified range (lower bound, and upper bound).

When describing results, the mean effect size was converted to a percent change (E^+) to represent the impact of different treatments on various response variables, to better express the results:

$$E^+ = (exp^{lnR} - 1) \times 100 \tag{2}$$

where $E^+ > 0$ % if $Xt > Xc$, while $E^+ < 0$ % if $Xt < Xc$.

2.4. Explanatory variables

We used explanatory variables in analyses of CSA practices on grain yield and N cycling: (1) regions (categorical; three levels: East Africa, West Africa and Southern Africa); (2) treatments (categorical; eight levels: reduced tillage + residue retention + incorporating legumes (RT+RR+IL), reduced tillage + residue retention (RT+RR), reduced tillage + incorporating legumes (RT+IL), reduced tillage (RT), residue retention + incorporating legumes (RR+IL), reduced tillage (RR), incorporating legumes (IL), and biochar (BC); (3) soil pH classes (categorical; three levels: < 5.5, 5.5 – 6, > 6); (4) soil total organic carbon (TOC) classes (categorical; < 0.5 %, 0.5 – 1 %, > 1 %); (5) soil total N (TN) classes (categorical; < 0.05 %, 0.05 – 0.2 %, > 0.2 %) and (6) soil clay content classes (categorical; < 20 %, 20 – 50 %, > 50 %). We examined whether these categorical variables could explain the patterns of grain yield and nitrogen cycling. When a value of a variable was missing (e.g., TOC or pH), the observation record was excluded from the analyses requiring that variable.

2.5. Data analysis

Differences between the explanatory variables i.e., region, treatments, soil pH, TOC, TN and clay (fixed effects), for each of the response variables (soil NO_3-N, cumulative N_2O emission, biological N_2-fixation, %Ndfa, grain yield and NUE) were evaluated separately using mixed-effects models (function lme from the nlme package (Pinheiro et al., 2017) as shown in Table S1. Publications and individual experiments therein were included as random effects to account for variations between publications (studies) and between experiments within publications (Fan et al., 2021). The best random effect structure (study ID and experiment ID) and model selection was identified by fitting different models and comparing them using Akaike's information criterion (AIC). We assumed normal error structure and homoscedasticity and validated the model assumptions by checking quantile plots and plots of residuals against fitted values (Zuur et al., 2009). Parameter estimates and 95 % confidence intervals (CI) were retrieved using lsmeans (Lenth, 2016) and differences between levels of the categorical variables (fixed effects) were assessed using multicomp package with p-value adjustments using tukey test. The response ratio of CSA practices on grain yield and N cycling was considered statistically significant ($p < 0.05$) only when 95 % CI did not overlap with zero. Linear mixed-effect regressions (function lme in R package nlme) with random intercepts associated with publications and individual experiments was used to assess associations between N fertilizer applied and response ratios of CSA on N_2O emission, NO_3-N, grain yield and NUE; and associations between N_2O emissions and sampling duration. All analyses were conducted using R version 4.2.3 (R Core Team, 2023).

Similar to previous meta-analysis in agronomy (Li et al., 2020; Martin-Guay et al., 2018; Mudare et al., 2022; Olhnuud et al., 2022; Xu et al., 2020), an unweighted meta-analysis was performed in this study because either standard errors or standard deviations were reported in only 19 out of 87 papers reviewed, i.e., 3 out of 26 papers on N_2O emission and NO_3-N, 2 out of 12 papers on biological N_2-fixation and % Ndfa, and 14 out of 58 papers on grain yield. Unweighted analysis yields valid and unbiased estimates and allows a greater number of papers to be included in the analysis, thus increasing the population of studies that is available to a meta-analysis (Buck et al., 2022), hence there is no problem with unweighted analysis in this context. Excluding those papers without variance would greatly reduce the number of records in the dataset and would be more detrimental to the accuracy of the results than the unweighted data. Results from the unweighted meta-analysis using the lme function were also compared with a mixed model approach using the rma.mv() function from the metafor package (Viechtbauer, 2010), where the variance was calculated according to Nakagawa et al. (2023); (see supporting information). The statistical outcome of the two methods was similar for all analysis except for effect of region on N_2O emission, and effects of treatments on soil NO_3-N, N_2O emission and grain yield (Figures S4 – S7).

2.6. Publication bias

We drew funnel plots (Duval and Tweedie, 2000) for (InR_{N2O}), ($InR_{nitrate}$), ($In(R_{N2\text{-}fixation})$), ($In(R_{Ndfa})$), ($In(R_{grainyield})$) and ($In(R_{NUE})$) to assess the risk of publication bias for N_2O emission, soil NO_3-N, biological N_2-fixation, %Ndfa, grain yield and NUE, separately. A funnel plot is a scatter plot of the treatment effects estimated from individual studies against a measure of study accuracy. Here, we plotted average values of (In (R_{N2O})), (In ($R_{nitrate}$)), (In ($R_{N2\text{-}fixation}$)), (In (R_{Ndfa})), (In ($R_{grainyield}$)) and (In (R_{NUE})) against the total number of experimental units as a proxy for study accuracy (Viechtbauer, 2007) within each study (replicates) across all the studies reporting data on cumulative N_2O emissions, soil NO_3-N, N fixation, %Ndfa, grain yield and NUE. Therefore, each data point represents one study, where study size was calculated by adding up the number of replicates in each study and are the mean effect sizes from each study. In the funnel plot for cumulative N_2O emissions, soil NO_3-N, biological N_2-fixation, %Ndfa, grain yield and NUE there are no asymmetry observed (Fig S3), indicating no publication bias. However, points outside the funnel plots could suggest potential publication bias although they are outliers.

3. Results

This meta-analysis contains 87 studies (Fig. S1) and 1643 paired observations (192 on N_2O emission, 69 on soil NO_3-N, 74 on N_2-fixation, 56 on %Ndfa, 835 on grain yield and 417 on NUE), from 15 countries in sub-Saharan Africa, spanning from 2000 to early 2023. This detailed dataset provides a unique basis for profound understanding of the effect of biochar and/or all the three principles of CA, i.e., reduced tillage, residue retention, and incorporating legumes on grain yield and N cycling, which cannot be drawn from earlier regional meta-analyses. On average across all studies, we found that the effect of CSA practices (biochar and/or CA) was predominantly positive for soil NO_3-N, N_2O emission, grain yield and NUE where the average effect sizes were 0.34 [95 % CI: 0.07, 0.62], 0.45 [95 % CI: 0.08, 0.82], 0.30 [95 % CI: 0.21, 0.40], and 0.36 [95 % CI: 0.18, 0.54], respectively (Fig. 1). These results indicate that, CSA practices significantly ($p < 0.05$) increased soil NO_3-N, N_2O emission, grain yield and NUE by 41, 57, 35 and 43 %

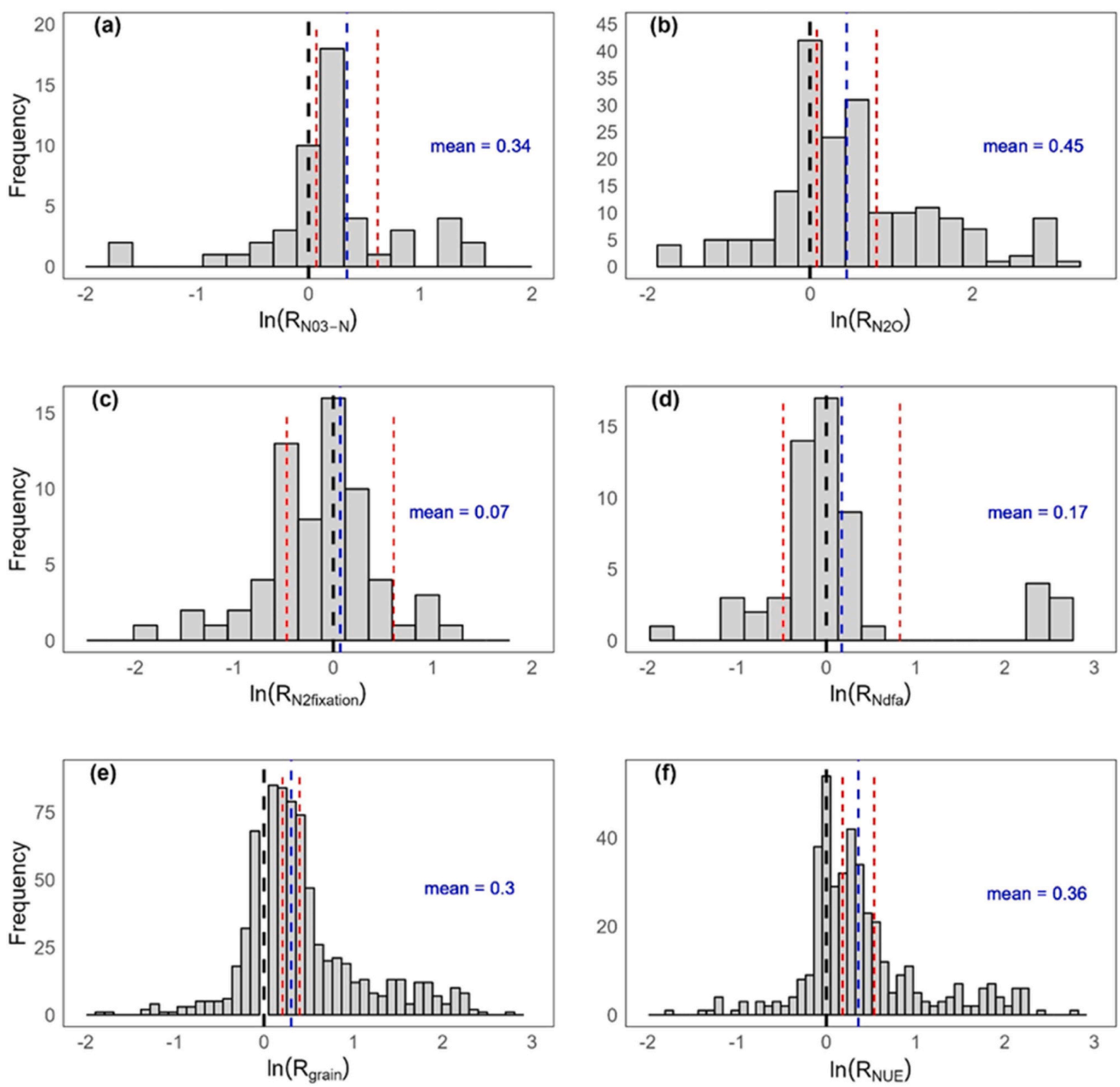

Fig. 1. Frequency distribution of natural log response ratio [In(R)] of (a) N_2O emission (b) soil NO_3-N, (c) biological N_2-fixation, (d) %Ndfa, (e) grain yield and (f) NUE. The dashed black line, dashed blue line and two dashed red lines represent InR = 0, the overall mean of lnR and the 95 % CI, respectively.

respectively, compared to conventional practices. Overall effect sizes of biological N_2-fixation and %Ndfa were positive, but not significant compared with conventional agriculture (0.07 [95 % CI: –0.47, 0.61] and 0.17 [95 % CI: –0.48, 0.83] respectively (Fig. 1, Fig. S3)).

3.1. Effect of regions on N_2O emission, biological N_2-fixation, grain yield and agronomic NUE

The impact of regions in SSA on N cycling, specifically NUE, differed significantly ($p < 0.05$) between climate smart practices and conventional agriculture. Significantly a greater NUE under CSA practices compared to conventional agriculture or CSA without biochar was recorded in East Africa compared to Southern Africa and Western Africa (Fig. 2d). Effect of region was not significant on cumulative N_2O emission, biological N_2-fixation and grain yield. However, significantly ($p < 0.05$) greater N_2O emission was recorded under CSA practices compared to conventional practices in East and Southern Africa (Fig. 2a). In addition, significantly ($p < 0.05$) higher biological N_2-fixation under CSA compared to conventional practices was recorded in East Africa (Fig. 2b). The response ratio of CSA and conventional practises was also significantly ($p < 0.05$) higher for grain yield in East and West Africa.

3.2. Effect of different CSA practices on soil NO_3-N and N_2O emission in SSA

Different CSA practices did not significantly ($p > 0.05$) affect soil NO_3-N and N_2O emission (Fig. 3). However, the response ratio of CSA versus conventional practices was significantly ($p < 0.05$) higher for residue retention (RR) in case of both soil NO_3-N and N_2O emission (Fig. 3). Residue retention [0.55 (95 % CI: 0.23, 0.88)] significantly ($p < 0.05$) increased soil NO_3-N by 74 % compared to conventional practices (Fig. 3a). Cumulative N_2O emission also increased ($p < 0.05$) due to residue retention (RR) [0.77 (95 % CI: 0.05, 1.49)], representing a 116 % increase compared to conventional practices (Fig. 3b). Effect of different treatments on soil NO_3-N and N_2O emission were not significant ($p > 0.05$) (Fig. 3). However, this contradicts the results obtained using the metafor package, where we have shown that residue retention did not affect either NO_3-N or N_2O (Fig. S5, S6).

There was a significant ($p < 0.05$) negative correlation between the response ratio of N_2O and sampling duration (Fig. S8). Increasing sampling duration by 1 day reduced N_2O emissions by 0.13 % under CSA, compared to the conventional practices. However, sampling duration exceeding 600 days resulting in more N_2O being emitted under conventional practices compared to CSA practices.

3.3. Effect of different climate smart practices on biological N_2-fixation and %Ndfa in SSA

Biochar [1.21 (95 % CI: 0.23, 2.20)] significantly ($p < 0.05$) increased biological N_2-fixation by 236 %, compared to conventional practices or CSA without biochar (Fig. 4a). Other climate smart practices did not affect biological N_2-fixation and %Ndfa (Fig. 4). There were no significant differences among treatments on N_2-fixation and %Ndfa (Fig. 4).

3.4. Effect of climate smart practices on grain yield and NUE in SSA

Different CSA practices did not differ significantly with respect to grain yield and NUE. However, most of the CSA practices increased grain yield compared to conventional practices. Specifically, RT+RR+IL [0.47 (95 % CI: 0.17, 0.78)], RT+RR [0.27 (95 % CI: 0.04, 0.50)], RR+IL [0.59 (95 % CI: 0.13, 1.05)], RR [0.41 (95 % CI: 0.13, 0.68)], IL [0.42 (95 % CI: 0.10, 0.73)] and BC [0.44 (95 % CI: 0.18, 0.71)] significantly ($p < 0.05$) increased grain yield by 60, 31, 80, 50, 52 and 56 %, respectively, compared to conventional practices (Fig. 5a). The same trend was observed for NUE where RR+IL, RR, BC and IL significantly increased ($p < 0.05$) NUE by 136, 121, 109 and 77 %, respectively (Fig. 5b). There were no significant differences ($p > 0.05$) among treatments on grain yield and NUE (Fig. 5). However, results on grain yield contradicts the results from the metafor package, where BC significantly increased grain yield compared to conventional practices while RT and RT+IL significantly reduced grain yield compared to conventional practices (Fig. S7).

3.5. Interactive effects of soil properties and CSA practices on N cycling and grain yield

In general, the response ratio of CSA and conventional practices on soil NO_3-N, N_2O emission, biological N_2-fixation and grain yield was not significantly ($p > 0.05$) affected by pH classes (Fig. 6). However, the

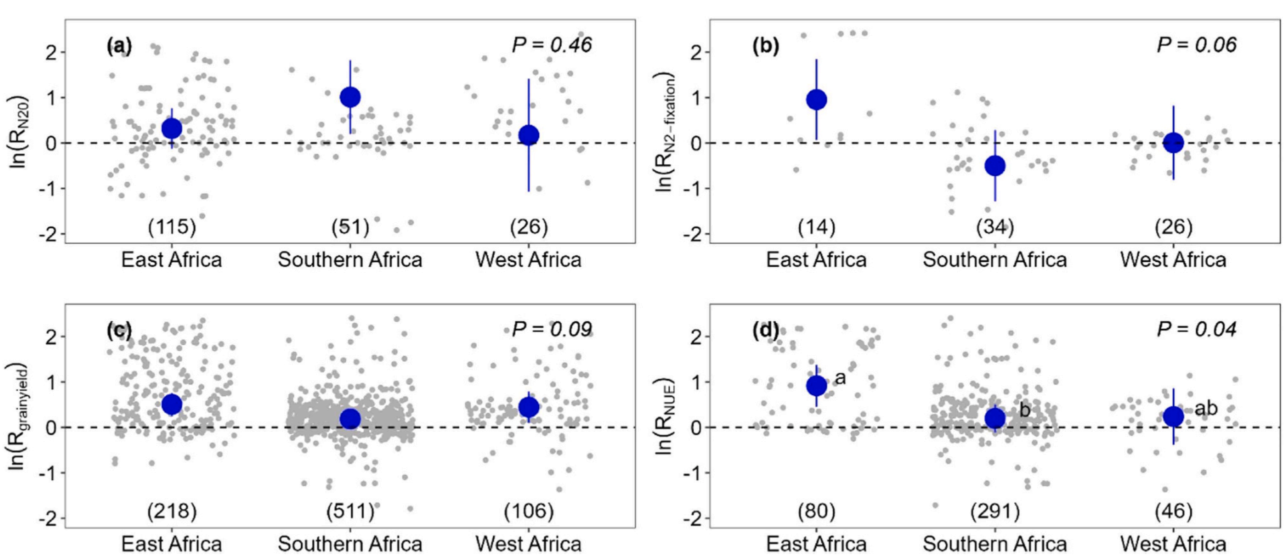

Fig. 2. Effect of regions on (a) emission of N_2O ($\ln(R_{N2O})$), (b) biological N_2-fixation ($\ln(R_{N2fixation})$), (c) grain yield ($\ln(R_{grain})$) and (d) NUE ($\ln(R_{NUE})$) in SSA. Significant differences between categorical variables (regions) are indicated by P-values. Different lowercase letters indicate significant differences between regions ($p < 0.05$). Soil NO_3-N and %Ndfa are not included due to few data points. Blue dots represent estimated means, error bars shows 95 % confidence intervals (95 % CI), and (n) represents the number of data pairs upon which the statistical analysis is based.

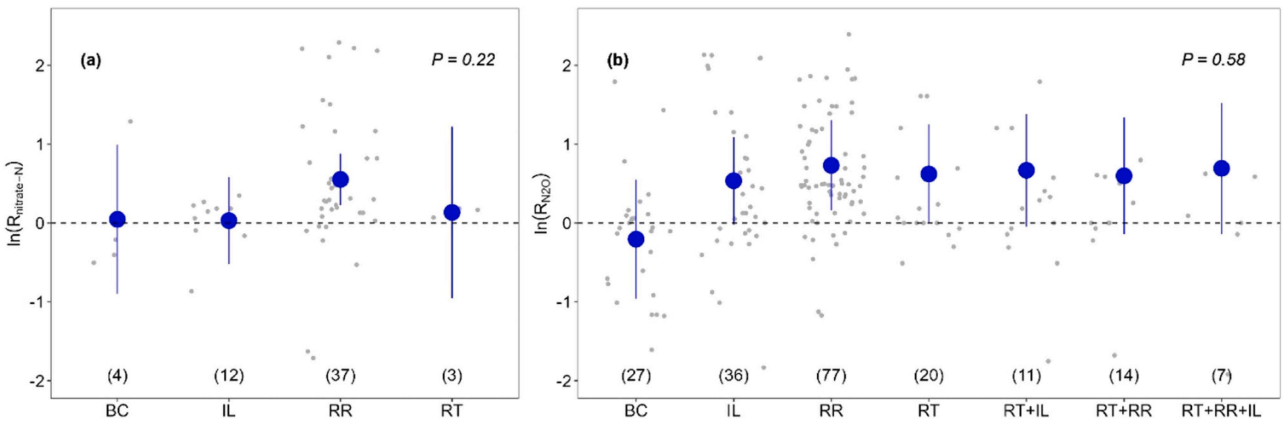

Fig. 3. (a) soil NO_3-N ($\ln(R_{nitrate\text{-}N})$) and (b) N_2O emission ($\ln(R_{N2O})$) under different CSA practices across SSA. Blue dots represent estimated means, error bars show 95 % confidence intervals (95 % CI), and (n) represents the number of data pairs upon which the statistical analysis is based. RT+RR+IL is reduced tillage + residue retention + incorporating legumes, RT+RR is reduced tillage + residue retention, RT+IL is reduced tillage + incorporating legumes, RT is reduced tillage, RR is residue retention, IL is incorporating legumes, and BC is biochar. Significant differences between categories (CSA practices) are indicated by P-values.

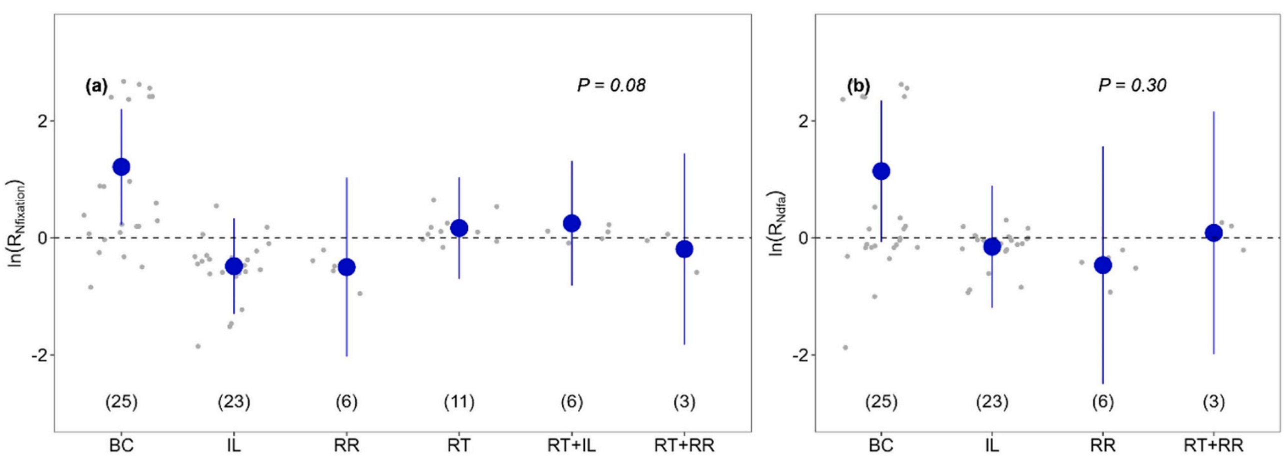

Fig. 4. (a) biological N_2-fixation ($\ln(R_{N2fixation})$) and (b) % of nitrogen derived from the atmosphere ($\ln(R_{Ndfa})$) under different climate smart practices compared with conventional agriculture across SSA. Blue dots represent estimated means, error bars show 95 % confidence intervals (95 % CI), and (n) represents the number of data pairs upon which the statistical analysis is based. RT+RR is reduced tillage + residue retention, RT+IL is reduced tillage + incorporating legumes, RT is reduced tillage, RR is residue retention, IL is incorporating legumes, and BC is biochar. Significant differences between categories (CSA practices) are indicated by P-values.

response ratio on soil NO_3-N was significantly increased by 55 % in soils with pH range of 5.5 – 6 and cumulative N_2O fluxes were significantly increased by 230 % under CSA in soils with pH < 5.5. Regardless of pH ranges, CSA significantly ($p < 0.05$) increased yields by 47, 34 and 57 % in soil with pH < 5.5, 5.5 – 6, and > 6, respectively, compared to conventional practices. Grain yield was significantly ($p < 0.05$) influenced by TOC classes (Fig. 6). The response ratio of CSA to conventional practices was significantly ($p < 0.05$) higher in soils with TOC of 0.5 – 1 % compared to soils with SOC < 0.5 %. In addition, CSA in soils with TOC 0.5 – 1 % and > 1 % significantly increased soil NO_3-N, compared to conventional practices. However, the soil TOC did not affect the differences between CSA and conventional agriculture with respect to N_2O emission and biological N_2-fixation.

Soil total nitrogen (TN) significantly affected the response ratio of CSA compared to conventional practices on N_2O emission and biological N_2-fixation. Soils with < 0.05 % TN had the highest ($p > 0.05$) response ratio of CSA to conventional agriculture with respect to N_2O emission, compared to the soils with TN > 0.2 %. However, CSA had a higher response ratio compared to conventional practices with respect to biological N_2-fixation in soils with TN > 0.2 %, compared to soils in TN classes < 0.05 % and > 0.2 %. CSA in soils with TN < 0.05 % significantly enhanced soil NO_3-N, N_2O emission and grain yield by 189, 109 and 35 % compared to conventional practices. In addition, CSA in soils with 0.05 – 0.2 % TN, as well as those exceeding 0.2 %, significantly increased grain yield by 35 and 69 % respectively, compared to conventional practices. Moreover, CSA in soils with > 0.2 % TN significantly increased biological N_2-fixation compared to conventional practices. CSA significantly increased soil NO_3-N and grain yield in soils with < 20 % clay content; and in soils with 20 – 50 % clay.

3.6. Response to inorganic N fertilizer application of N_2O emission, soil NO_3-N, grain yield and NUE

There was a significant ($p < 0.05$) relationship between the response ratio of N_2O emission, grain yield and NUE, and the amount of inorganic N fertilizer applied under CSA practices in SSA (Fig. 7). However, applied N fertilizer did not significantly ($p > 0.05$) increase the response ratio of CSA and conventional practices on soil NO_3-N. A positive correlation with the response ratio of N_2O indicates that, as the N fertilizer rates increase, N_2O emission increases faster under CSA compared to conventional practices. For example, applying 1 kg N fertilizer under CSA practices increased the response ratio of CSA and conventional practices on soil NO_3-N and N_2O emissions by 0.749 and 0.94 %, respectively. As the N fertilization rate increased to 120 kg, the response ratio of soil NO_3-N and N_2O emissions under CSA practices increased by 59 % and 113 %. In addition, the confidence interval for $\ln(R_{nitrate\text{-}N})$ is

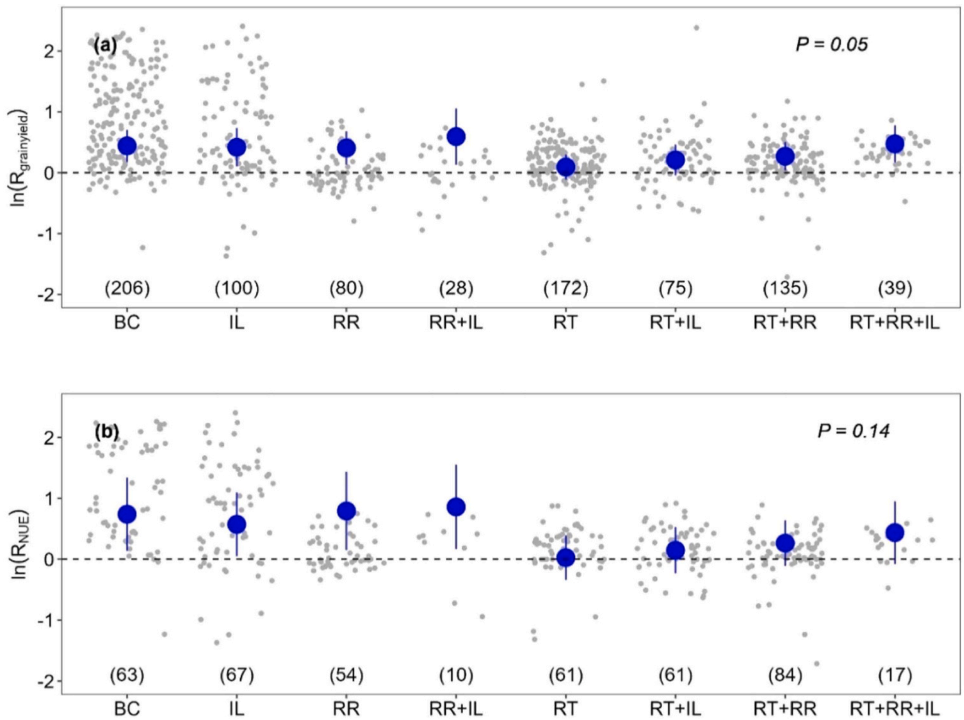

Fig. 5. (a) grain yield (ln($R_{\text{Grainyield}}$)) and (b) NUE (ln(R_{NUE})) under different climate smart practices across SSA. Blue dots represent estimated means, error bars shows 95 % confidence intervals (95 % CI), and (n) represents the number of data pairs upon which the statistical analysis is based RT+RR+IL is reduced tillage + residue retention + incorporating legumes, RT+RR is reduced tillage + residue retention, RT+IL is reduced tillage + incorporating legumes, RT is reduced tillage, RR+IL is residue retention + incorporating legumes, RR is reduced tillage, IL is incorporating legumes and BC is biochar.

relatively large compared to other variables due to few data points (Fig. 7).

There is a highly significant ($p < 0.05$) negative correlation between response ratios of grain yield and NUE with N fertilizer rates under CSA, compared to conventional agriculture practices. However, fertilizer rates exceeding 120 kg N ha^{-1} reduce the response ratio of CSA to conventional practices on grain yield and NUE response under conventional practices, that is, it becomes more beneficial to apply more than 120 kg N ha^{-1} under conventional agriculture compared to CSA (Fig. 7).

4. Discussion

4.1. Grain yield and NUE

In this study, RT+RR+IL, RR+IL, RT+RR, RR, IL and BC resulted in significantly higher grain yield and NUE than conventional practices (Fig. 5). Residue retention adds organic matter to the soil with beneficial effects such as sequestering carbon (Powlson et al., 2011), improving aggregate stability that enhance moisture retention (Rusinamhodzi et al., 2011) and nutrient cycling (Murungu et al., 2011). Improved soil functioning and processes increase grain yield, and this is of paramount importance especially in low-input cropping systems of SSA where external nutrient supplies are generally limited. Effect of crop residues on grain yield and NUE likely result from soil temperature modification and evaporation reduction (Bussiere and Celher, 1994), especially in heat stressed environments in the sub-humid and semi-arid areas of SSA. In Malawi, the use of stress-tolerant maize varieties, legume rotation and residue retention ensured that heat stress due to temperatures exceeding 30 °C did not impact grain yields (Komarek et al., 2021). There is often a larger increase in yield associated with implementation of CSA as compared with conventional practices in low-yielding environments than in high-yielding environments (Porter et al., 1997). Our results indicate that inclusion of crop residues increase grain yield and NUE in SSA. In a meta-analysis by Qin et al. (2015), soil mulching also significantly increased yield and NUE of wheat and maize by 20 and 60 %, respectively. Reduced tillage on its own did not affect grain yield significantly, however, when combined with residue retention (RT+RR) it significantly increased grain yield and NUE. Reduced tillage improves soil moisture thereby providing optimal conditions for N mineralisation from crop residues; ultimately increasing N available for crop uptake, yield and NUE.

Incorporating legumes either as a standalone practice or when combined with other practices, i.e, RR+IL increased grain yield. Crop rotation is regarded as an environmentally friendly strategy for sustainable agriculture which adequately controls weeds by depleting seed banks, (Zhao et al., 2020), and disrupt pests and disease habitats and life cycles (Ball et al., 2005). Rotation effects on the yield of legume-based systems is mainly due to the increased amount of mineralizable N input from leguminous N_2-fixation and N-abundant residues, thereby enhancing subsequent crop yield. Zhao et al. (2022), reported yield advantages of 32 and 7 % in crop rotations in low and high yielding environments respectively.

Our meta-analysis results show that application of biochar significantly increased grain yield and NUE by 67 and 109 %, respectively. Influence of biochar on yield may be linked to improvements in soil properties, particularly TOC, water holding capacity, cation exchange capacity (CEC) and nutrients availability (Martinsen et al., 2014). Application of BC in nutrient deficient soils has been shown to improve plant growth; because BC provides both macro- and micro-nutrients (phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), manganese (Mn), copper (Cu), zinc (Zn), and boron (B)), enhance nutrient use efficiency, and creates a favourable rhizosphere environment; although the element contents differ depending on feedstock and carbonization methods and processes (Agegnehu et al., 2017). In addition, plant roots are better established in biochar amended soils and root growth substantially increases, thereby expand the volume of plant roots in soil for capture of more nutrients and improve plant growth (Abiven et al., 2015; Chen et al., 2022). Biochar reduces nutrient

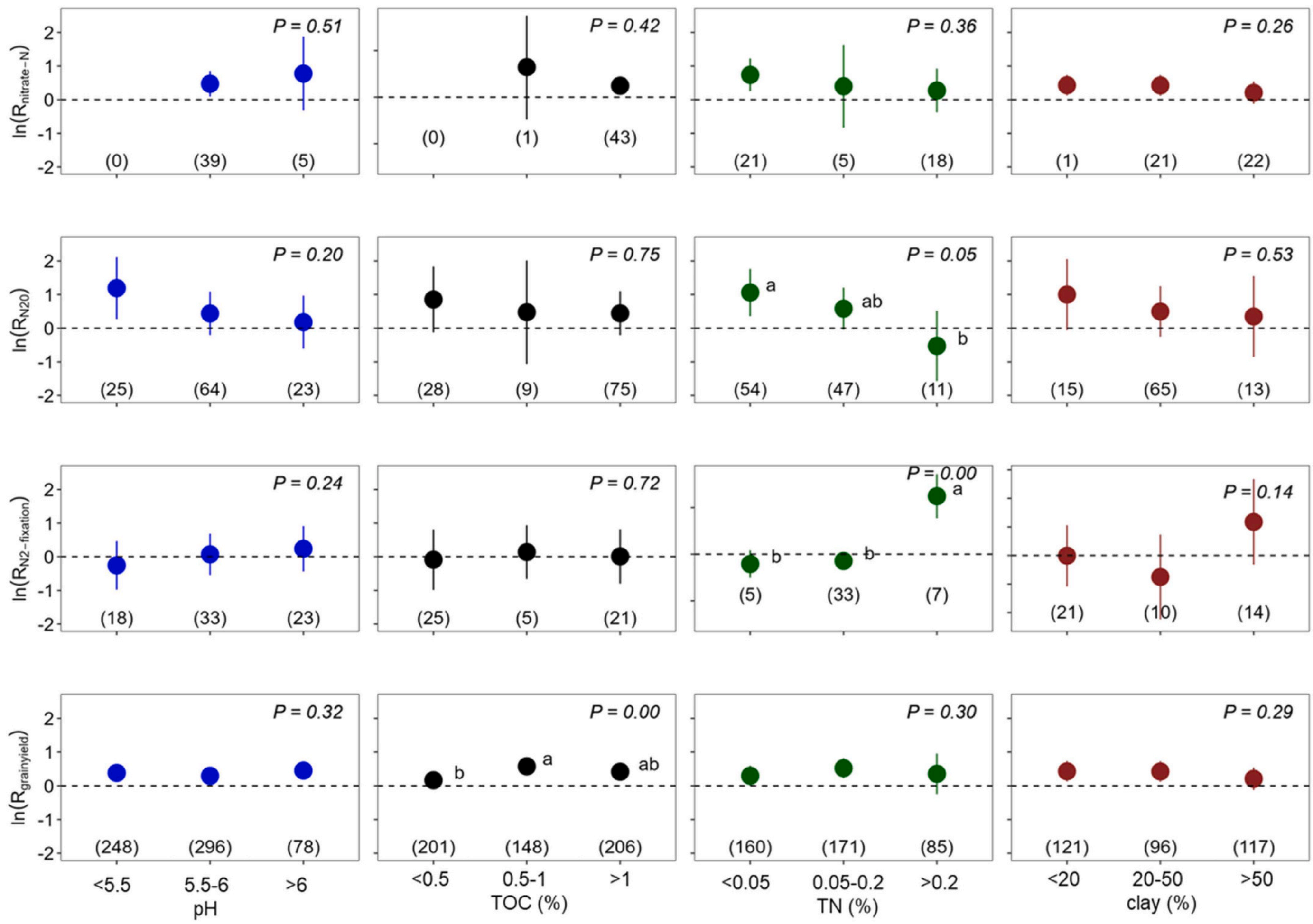

Fig. 6. The effect of soil properties on N cycling and grain yield in SSA under CSA practices relative to conventional agriculture. Dots represent estimated means, error bars shows 95 % confidence intervals (95 % CI), and (n) represents the number of data pairs upon which the statistical analysis is based. Significant differences between categories (pH, TOC, TN and clay) are indicated by P-values and different lowercase letters indicate significant differences ($p < 0.05$).

and moisture loss, hence facilitates their timely supply to the plants (Khan et al., 2023). Our results are in line with Liu et al. (2022) who reported that biochar increased grain yield of rice by 10.73 %. Application of biochar in acidic soils was also shown to increase yield of different crops by 28 – 363 % (Yu et al., 2019). However, Güereña et al. (2013) reported that, applications of biochar up to 30 t ha^{-1} did not significantly improve maize yield, rather it reduced N leaching at high fertilizer rates in temperate soils of Northern America. This might not be feasible in smallholder farms in SSA due to limited feedstock for biochar production. In addition, expecting biochar to increase crop yields in fertile temperate soils may not be practical as the soils already possess high native fertility, adequate CEC, and near-neutral pH.

The response ratio between CSA and conventional agriculture practices on grain yield was significantly increased in soils with clay content of < 20 % and 20 – 50 %. Such soils have low moisture retention capacity, especially those with < 20 % clay (Wei et al., 2023). Low clay content also reduces the ability of soils to retain nutrients, thus making them prone to leaching, and reduced availability of nutrients can negatively impact the growth and functioning of legumes. In such scenarios grain yields respond to CA and/or biochar application more than conventional practices, leading to increase in grain yield, compared to soils with more than 50 % clay. In addition, pH and TOC ranges did not affect response ratio of CSA and conventional practices on grain yield. This could be explained by the resilience and adaptability of CSA across varying soil conditions in SSA.

4.2. *Biological N_2-fixation*

Application of biochar significantly increased biological N_2-fixation by 236 % (Fig. 4). Biochar result in enhanced immobilization of NH_4^+ because a minor fraction of biochar is labile and thus decomposable and is a source of organic C for new microbial biomass. Immobilisation of soil N by biochar reduced available N for absorption by legume roots, thus stimulating N fixation and root nodulation (Nguyen et al., 2017). Nodulation is an indicator used to estimate N_2-fixation, and meta-analysis by Xiang et al. (2017) showed that biochar increases root nodulation. Nodulation requires induction of nodule formation by Nod factors and flavonoids, signal molecules known to be adsorbed by biochar. Although this may interfere with the cell-to-cell communication, and it is necessary to induce nodule formation (Masiello et al., 2013). Biochar activates Nod factors and retains flavonoids longer in soil by adsorption. This may increase the interaction between them and rhizobia, leading to enhanced nodulation. Root nodulation is stimulated by P availability, which is enhanced by the application of biochar (Wu et al., 2022).

Legumes are expected to support the need to increase food production while reducing nitrogen (N) fertilizer input for enhanced agricultural sustainability as they can fix atmospheric N into biologically available forms of N (Ma et al., 2022). However, rhizospheric conditions are important for its potential to be fully exploited. In our meta-analysis, we show that soil N content affect the differences in biological N_2-fixation between CSA and conventional practices. Although biological

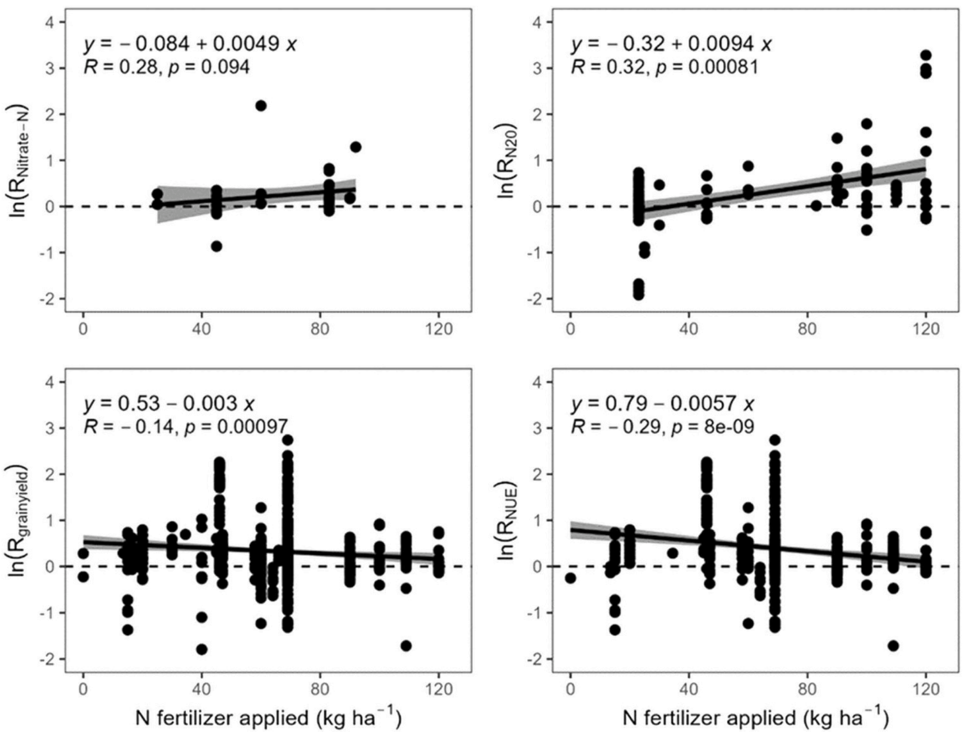

Fig. 7. Regression analysis of (a) In(R_{N2O}), (b) In($_{RNitrate\text{-}N}$), (c) In($R_{grainyield}$), and (d) In(R_{NUE}) vs inorganic N fertilizer applied under CSA practices in SSA. Data points represents the InR of the paired observations from the reviewed papers. Grey area represents the confidence interval (CI) of the fitted model.

N_2-fixation supplies most of the crop's N demand (Peoples et al., 2009), starter N is still necessary to help nodule formation during the early stages of crop growth, i.e., before N_2-fixation occurs (Ghiocel et al., 2013). Moreover, to close the gap between demand for N and N_2-fixation, N must be available for plant uptake through mineralization of soil N or N deposition as basal fertilisation (Mondal et al., 2020). Our study suggests that the difference between CSA and conventional practices on biological N_2-fixation is greatest in soils with N of > 0.2 % (Fig. 6).

4.3. Soil NO_3-N and N_2O emission

Our results showed that relative to conventional agriculture, crop residue retention (RR) significantly increases soil NO_3-N and N_2O emissions (Fig. 3). Adding crop residues to the soil modifies the rhizosphere environment within the ploughing layer (Shang et al., 2016) which tends to become cool and moist (Edwards et al., 2000) thereby increasing the organic N mineralisation (Fang et al., 2007). In SSA, soil temperature exceeding 40 °C is not uncommon (Obia et al., 2020) and may aid faster soil drying, thus restricting mineralisation. Therefore, residue cover is an important influencer of N-cycling in SSA. Organic N mineralisation from crop residues increases soil inorganic N (Shindo and Nishio, 2005), this is typical of a subsistence farming setup in SSA where farmers retain crop residues from leguminous crops that are generally grown in rotations or as intercrops with cereals. Crop residues with a C:N ratio lower than 20 – 30 have been shown to cause a net N mineralization due to their high N (Redin et al., 2014). However, residues from maize and other cereal crops are also common, and they are rich in lignin and have high C:N ratio which might result in N immobilisation (Trinsoutrot et al., 2000).

Our findings indicate that crop residues lead to an increase in both soil NO_3-N and N_2O emissions (Fig. 3). Soil NO_3-N is a precursor for N_2O emissions, especially under anaerobic conditions where denitrifiers reduce NO_3^- to N_2O (Liu et al., 2018). Production and emission of N_2O mainly depends on pH, NO_3-N and moisture. NO_3-N favour denitrification by increasing the abundance of substrate, i.e., nitrogen compounds for denitrifying bacteria to use as electron acceptors (Qiao et al., 2020). N_2O is also produced during nitrification, i.e., NH_4 conversion to NO_3 in aerobic conditions, therefore, high soil NO_3-N may also indicate increased nitrification, and thus producing more N_2O when crop residues are returned to the soil (Munera-Echeverri et al., 2022; Yu et al., 2017). Higher moisture content facilitated by residue retention coupled with high NO_3-N contents promotes denitrification. Localised anaerobic conditions are a result of decomposition of organic matter, producing excess electrons normally taken up by O_2 (Bijay-Singh and Craswell, 2021; Feraud et al., 2023).

Although application of biochar into cropping systems was shown to mitigate N_2O emissions (Liu et al., 2018; Obia et al., 2015; Zhang et al., 2021), in this meta-analysis, biochar did not significantly affect emission of N_2O (Fig. 3). Such discrepancies might be explained by the differences in biochar concentration and experiment duration, for example, in a meta-analysis by Liu et al. (2018), biochar significantly reduced N_2O when more than 10 Mg ha^{-1} were applied. In a study of the interaction between biochar, soil, and land-use, Borchard et al. (2019) highlighted that, low biochar application rates of < 10 Mg ha^{-1} do not affect N_2O emissions. In our meta-analysis, most of the studies on N_2O emission had biochar rates of less than 5 Mg ha^{-1} under field conditions. Low biochar rates are easily diluted due to lateral transport of biochar within the soil profile especially in light-textured tropical soils (Obia et al., 2017), which would lead to decreased effects of biochar on soil properties (Singh et al., 2022).

4.4. Response of NO_3-N, N_2O, grain yield and NUE to inorganic N fertilizer rates

Notable increase in N_2O as N fertilizer rates increases under CSA can be attributed to several factors. Incorporating legumes into farming systems enhance N cycling due to biological N_2-fixation, and if not exported from the field, i.e., when crop residues are incorporated back into the soil, it is a net input to the soil-crop system (Rhangi-Abriz et al., 2022). CSA reduces nutrient loss from the rooting zone, for example, charges on the surface of biochar sorb nutrients thereby reducing nutrient loss (Khan et al., 2023). Adding inorganic N fertilizer in such scenarios further increases N_2O. Reduced tillage and residue retention also improves TOC and soil moisture content (Martinsen et al., 2019; Six et al., 2002), thereby fostering the growth of microbes that actively work on the N substrate supplied by N fertilizers. Therefore, increasing N rates under CSA seems to enhance N_2O emissions due to concurrent increase in TOC, moisture, and availability of N substrate from both inorganic N fertilizers and from legumes, which is not the case under conventional practices.

Our results also highlight the importance of CSA on grain yield and NUE when low N rates are applied (Fig. 7). This implies that high grain yields can be achieved when CSA practices are implemented in low-input farming communities of developing countries where access to fertilizer is generally limited (Xu et al., 2020). Additionally, the gap in yield and NUE between CSA and conventional agriculture practises was more pronounced at lower N rates of 0 kg N ha^{-1} and narrowed as the N inputs increased to 120 kg N ha^{-1}. This could be explained by a relatively higher mineralisation of legume residues at low N compared with that occurring at high N fertilizer rates (Zhao et al., 2022). With more N input, crop utilizes N from the fertilizer, however, when low N rates are applied, N capture and mineralization from residues and soil becomes important for crop performance. High rates of inorganic N fertilizer meet the crop N demand to a greater extent, largely offsetting the N benefits from the CSA effect (incorporating legumes or residue retention).

5. Conclusion

Our study suggests that conservation agriculture and biochar offer a critical pathway for enhancing crop production and regulating N cycle, especially when integrated into low-input and low-diversity agricultural systems of SSA. The assessment of grain yield and N cycling should also receive increased attention because reliable sustainable agricultural practices are key issues considering a growing human population in SSA and enhanced demands for food. In this meta-analysis, distinct trends are apparent on how grain yield and N-cycling responded to various CSA practices relative to conventional methods under a wide range of soils. It is worth noting that residue retention increased soil NO_3-N, N_2O emissions, grain yield and NUE. Therefore, when appraising CSA for resilience, adaptation and mitigation; crop yields, soil NO_3-N and N_2O emissions need to be considered. High N fertilizer rates increased the response ratio of N_2O emissions and soil NO_3-N at the expense of grain yield and NUE under CSA practices; this implies that, under low N fertilizer rates, CSA offers more benefits such as high yield and NUE, and low N_2O emissions, compared to conventional agricultural practices.

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CRediT authorship contribution statement

Alfred Obia: Writing – review & editing, Supervision, Conceptualization. **Jan Mulder:** Writing – review & editing, Supervision, Conceptualization. **Talent Namatsheve:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data mining and curation, Conceptualization. **Vegard Martinsen:** Writing – review & editing, Formal analysis, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Dataset used in this metanalysis is available at NMBU dataverse https://doi.org/10.18710/XF1DFV and the R code is avaialble from the corresponding author upon request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109243.

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