Science of the Total Environment 651 (2019) 2354–2364

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis

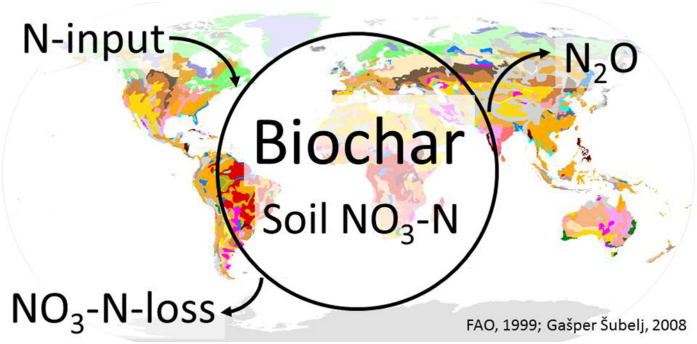
Nils Borchard [a,b,*], Michael Schirrmann [c], Maria Luz Cayuela [d], Claudia Kammann [e], Nicole Wrage-Mönnig [f], Jose M. Estavillo [g], Teresa Fuertes-Mendizábal [g], Gilbert Sigua [h], Kurt Spokas [i], James A. Ippolito [j], Jeff Novak [h]

[a] *Center for International Forestry Research, Jalan CIFOR, Situ Gede, Sindang Barang, Bogor 16115, Indonesia*
[b] *Natural Resources Institute Finland (Luke), Latokartanonkaari 9, 00790 Helsinki, Finland*
[c] *Leibniz Institute for Agricultural Engineering and Bioeconomy, Max-Eyth-Allee 100, 14469 Potsdam, Germany*
[d] *Department of Soil and Water Conservation and Waste Management, CEBAS-CSIC, Campus Universitario de Espinardo, 30100 Murcia, Spain*
[e] *Geisenheim University, Department of Applied Ecology, Von-Lade-Straße 1, 65366 Geisenheim, Germany*
[f] *University of Rostock, Faculty of Agricultural and Environmental Sciences, Grassland and Fodder Sciences, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany*
[g] *University of the Basque Country (UPV/EHU), Department of Plant Biology and Ecology, Apdo. 644, E-48080 Bilbao, Spain*
[h] *United States Department of Agriculture, Agriculture Research Service, Coastal Plains Research Center, 2611 West Lucas Street, Florence, SC 29501, USA*
[i] *United States Department of Agriculture, Agriculture Research Service, Soil & Water Management Research Unit, 439 Borlaug Hall, 1991 Buford Circle, University of Minnesota, St. Paul, MN 55108, USA*
[j] *Department of Soil and Crop Sciences, C127 Plant Sciences Building, Colorado State University, Fort Collins, CO 80523-1170, USA*

HIGHLIGHTS

- N_2O emissions were reduced by 38% with biochar.
- Soil NO_3^- concentrations remained unaffected.
- NO_3^- leaching was reduced by 13% with biochar.
- Biochar strongly reduced N_2O-emission in paddy and sandy soils.

GRAPHICAL ABSTRACT



FAO, 1999; Gašper Šubelj, 2008

ARTICLE INFO

Article history:
Received 31 August 2018
Received in revised form 4 October 2018
Accepted 5 October 2018
Available online 9 October 2018

Editor: Deyi Hou

Keywords:
Land use
Fertilization
Nitrification
Denitrification

ABSTRACT

Biochar can reduce both nitrous oxide (N_2O) emissions and nitrate (NO_3^-) leaching, but refining biochar's use for estimating these types of losses remains elusive. For example, biochar properties such as ash content and labile organic compounds may induce transient effects that alter N-based losses. Thus, the aim of this meta-analysis was to assess interactions between biochar-induced effects on N_2O emissions and NO_3^- retention, regarding the duration of experiments as well as soil and land use properties. Data were compiled from 88 peer-reviewed publications resulting in 608 observations up to May 2016 and corresponding response ratios were used to perform a random effects meta-analysis, testing biochar's impact on cumulative N_2O emissions, soil NO_3^- concentrations and leaching in temperate, semi-arid, sub-tropical, and tropical climate. The overall N_2O emissions reduction was 38%, but N_2O emission reductions tended to be negligible after one year. Overall, soil NO_3^- concentrations remained unaffected while NO_3^- leaching was reduced by 13% with biochar; greater leaching reductions (>26%) occurred over longer experimental times (i.e. >30 days). Biochar had the strongest N_2O-emission reducing effect in paddy soils (Anthrosols) and sandy soils (Arenosols). The use of biochar reduced

---

[*] Corresponding author at: Natural Resources Institute Finland (Luke), Latokartanonkaari 9, 00790 Helsinki, Finland.
E-mail address: nils.borchard@luke.fi (N. Borchard).

https://doi.org/10.1016/j.scitotenv.2018.10.060

Nitrous oxide
Nitrogen
Soil organic carbon

both N_2O emissions and NO_3^- leaching in arable farming and horticulture, but it did not affect these losses in grasslands and perennial crops. In conclusion, the time-dependent impact on N_2O emissions and NO_3^- leaching is a crucial factor that needs to be considered in order to develop and test resilient and sustainable biochar-based N loss mitigation strategies. Our results provide a valuable starting point for future biochar-based N loss mitigation studies.

Contents

1. Introduction

Agriculture accounts for ~60% of global anthropogenic N_2O emissions, largely due to organic and mineral nitrogen (N) fertilizer use and the extended use of legumes either as crops (soy, pea, bean or groundnut) or as green cover (Davidson, 2009; IPCC, 2013; Kammann et al., 2017; Smith et al., 2008). In addition to fertilizer-induced N_2O emissions, excessive N fertilization or inadequate timing of N application not fitting plant demand also leads to N leaching that affects ground and surface water quality, reduces N use efficiency (Ding et al., 2010), and subsequently elevates indirect N_2O emissions (Cooper et al., 2017; Minghua et al., 2017; Tian et al., 2017) e.g. from landscape-draining waterways (Turner et al., 2015).

Soil N_2O emissions and nitrate (NO_3^-) losses are mainly a result of microbial activities affecting inorganic soil N concentrations via nitrification and denitrification processes, and by abiotic processes (Barnard et al., 2005; Bateman and Baggs, 2005; Cayuela et al., 2014; IPCC, 2006). Nitrification is the transformation of ammonium (NH_4^+) to NO_3^- via nitrite (NO_2^-), with N_2O being a by-product. Denitrification reduces NO_3^- or NO_2^- to NO, N_2O, and N_2 (Barnard et al., 2005; Cayuela et al., 2014; Harter et al., 2014; IPCC, 2006; Kammann et al., 2017). Efficiency and productivity of nitrification is mainly affected by availability of N and oxygen while availability of biodegradable organic matter and lack of oxygen govern efficiency and productivity of denitrification (Barnard et al., 2005; Bateman and Baggs, 2005; Linn and Doran, 1984; Granli and Bockman, 1994). Microbes performing nitrification prefer slightly acidic to alkaline soil pH, while soil denitrification is at optimum between pH 4 to 8 (Ahn, 2006; Antoniou et al., 1990; Barnard et al., 2005). Availability of easily biodegradable organic matter stimulates denitrification as it provides energy to maintain microbial metabolism and electrons required to reduce NO_3^- (Ahn, 2006; Barnard et al., 2005). Thus, physico-chemical soil properties regulate and organic matter amendments stimulate N_2O emissions.

Recently, biochar has been proposed as an organic carbon (C) soil amendment for reducing leaching of soil compounds (Abdelrahman et al., 2018; O'Connor et al., 2018a) and for improving soil quality (Crane-Droesch et al., 2013; Liu et al., 2013; Mehmood et al., 2017). Biochar may add both a small mineralizable and a more recalcitrant, less mineralizable C fraction to soils (Wang et al., 2016); additionally, biochar has also been shown to retain NO_3^- within its pores (Kammann et al., 2015; Haider et al., 2016, 2017; Hagemann et al., 2017a; Sumaraj and Padhye, 2017). Therefore, applying biochar to soils may affect conditions that control nitrification, denitrification (Cayuela et al., 2014; Kammann et al., 2017; Liu et al., 2018), and other N transformation and loss pathways. In order to evaluate biochars' overall potential and magnitude for reducing N losses across application locations, agricultural systems, application rates, and time, meta-analyses have been found to be a useful tool (Borenstein et al., 2009).

The first meta-analysis studying biochar impact on soil N_2O emissions showed a mean reduction of 54% (Cayuela et al., 2014); further meta-analyses, particularly those including field studies, have shown lower N_2O reductions ranging between 12 and 32% (Cayuela et al., 2015; Liu et al., 2018; Verhoeven et al., 2017). The meta-analysis published by Liu et al. (2018) was the first study to present biochar impacts on N pools, N fluxes, and the N cycle, but interactions between biochar use and experimental duration, soil types, and land use are still scarcely understood or exclusively assessed for C cycling (Wang et al., 2016; Verhoeven et al., 2017; Duarte-Guardia et al., 2018). Thus, the current meta-analysis differs from previous biochar meta-analyses, because it assesses the impact of biochar on N_2O emissions, NO_3^- leaching and final NO_3^- concentration in soil based on: (i) experimental duration that affects the C and N cycle (Hagemann et al., 2017b; Wang et al., 2016), (ii) relevance of soil and land use types to provide a basis for spatial (global) assessments (Duarte-Guardia et al., 2018; Werner et al., 2018), and (iii) impact of agricultural practices, such as vegetation type and fertilizer use.

2. Material and methods

2.1. Data compilation

A comprehensive survey of literature published between January 1, 2010 and May 31, 2016 was conducted, compiling 608 observations from 88 peer-reviewed publications accessed on the ISI Web of Knowledge. By using the term "biochar" in the "topic" field, 3328 publications appeared, but the number was reduced to 88 publications by abstract and full publication screenings (Table S1). Studies were scrutinized using the following inclusion/exclusion quality criteria: They: (i) were conducted in soil (e.g., horticultural substrates were excluded); (ii) included a minimum of three replicates per treatment; (iii) followed a randomized design; (iv) contained a "treatment" and a "control" such that the treatment was the same as the control in all aspects except for the inclusion of biochar; and (v) reported cumulative net N_2O emissions, cumulative NO_3^- leached and/or final NO_3^- concentrations in soil. Data (i.e. mean values, standard deviation, standard error, number of replicates) on N_2O fluxes, NO_3^- concentration in soil after experiment, and NO_3^- leaching were collected from tables, from figures by using WebPlot Digitizer software (www.automeris.io/WebPlotDigitizer/), or from contacting the authors directly. The final dataset consists of 608 observations, with 120 observations for nitrate leaching, 146 observations for nitrate concentration in soil after the experiment, and 435 observations for cumulative N_2O emissions (Table S2). Factors controlling N_2O emissions, NO_3^- concentration in soil after the experiments, and cumulative NO_3^- leaching were also collected from the publications. Once the dataset was completed, it was subjected to a strict quality check and each observation and related predictor variable was checked by at least two researchers independently. When there was a disagreement between the extracted values, the respective study was checked by an additional third researcher and a final correction was reached. Data were then grouped by study length, biochar properties, soil properties, N fertilization, and land use. Grouping was performed in accordance to previous classifications used by Jeffery et al. (2011) and Cayuela et al. (2014) (Table S3), considering a minimum number of observations per group to process reliable data (Table S4).

2.2. Meta-analysis

The effect of biochar treatment on N_2O emissions, NO_3^- concentration, and NO_3^- leaching was estimated via meta-analysis. As a standardized metric of the effect size, the natural log response ratio (RR) was computed for each experiment (Hedges et al., 1999):

$$\mathrm{RR} = \ln\left(\frac{X_{trt}}{X_{ctr}}\right),$$

which is the ratio between the treatment mean (X_{trt}) and the control mean (X_{ctr}). In the case of N_2O emissions, RR is defined as the ratio between the cumulative N_2O emissions from the biochar treated soil and the N_2O emissions from the non-treated soil in each study. An RR with zero would mean no effect, while a negative or positive RR value would mean a reduction or increase in N_2O emissions through biochar treatment, respectively. The logarithm ensures better statistical properties of the effect size distribution and equal influence of nominator and denominator on the metric. The RR was expressed as a percentage change relative to zero. The variance of RR is given as (Hedges et al., 1999):

$$var(RR) = \frac{SD_{trt}^2}{N_{trt}X_{trt}^2} + \frac{SD_{ctr}^2}{N_{ctr}X_{ctr}^2},$$

where SD_{trt}^2 and SD_{ctr}^2 are the standard deviation and N_{trt} and N_{ctr} are the sample sizes of the treatment or control of the experiment. The parameters for calculating RR and $var(RR)$ were extracted from the studies or recalculated when necessary. Funnel plots were used to detect biases in the traits included in the meta-analyses. The funnel plots were symmetric for N_2O emissions, NO_3^- concentration, and NO_3^- leaching data sets, which indicates absence of publication biases.

The combined effect size over all available studies was estimated with a random effects model. The random effects model was chosen because we did not assume that the underlying true effect size is homogeneous over all included studies due to study conditions and environmental influences, and we further wanted to make generalizations beyond the observed studies (Hedges and Vevea, 1998). The random effects model was estimated with the DerSimonian-Laird estimator (DerSimonian and Laird, 2015). Each study was weighted by the inverse of its sampling error variance (inverse-variance-weighting), which ensures that studies with very small sample sizes do not have a severe influence on the estimates. The overall effect was estimated for cumulative N_2O emissions, final NO_3^- concentration, and cumulative NO_3^- leaching. For assessing the heterogeneity of the meta-analysis, the I^2 index was used. The I^2 index indicates the percentage of the total variability among the effect sizes that can be explained by the between-studies heterogeneity (Huedo-Medina et al., 2006). Furthermore, we explored possible factors and relations influencing the overall effect sizes including study length, biochar properties, soil properties, N fertilization, and land use. These factors were grouped in accordance to previous classifications by Cayuela et al. (2014) and Jeffery et al. (2011) (Tables S3 & S4). Categories with less than two samples were removed from analysis. The subgroup analysis was conducted with a categorical random effects model and summarized in forest plots. All estimates were reported along with 95% confidence intervals. Estimates and confidence intervals were calculated from bootstrapping the random effects models with 1000 bootstrap intervals. Positive publication bias was tested with the Failed Safe N-test that takes into account the tendency of journals to only publish significant results. A fail-safe number was calculated using the Rosenberg method, indicating the number of non-significant or missing studies that one would need to add to the meta-analysis data set to reduce the observed, overall statistically significant results (Rosenberg, 2007).

3. Results

3.1. Percent overall changes and their change over time

Results showed a significant reduction of overall N_2O emissions by 38% ($P < 0.05$; Fig. 1) caused by biochar applications. According to the Failed Safe N-test, the significant N_2O reduction is robust against a possible positive publication bias because a huge number of non-significant observations would need to be furthermore included in the meta-analysis (>650.000) to turn the significant result into a non-significant result (Table S4). However, biochar induced reductions of N_2O emissions were of transient nature with a tendency to be negligible within one year (Fig. S1). In spite of a non-significant overall effect on NO_3^- leaching, biochar significantly and consistently reduced NO_3^- leaching by 26 to 32% in studies with an experimental time of >30 days (Fig. 1). In parallel, available NO_3^- in soils decreased over time with significant reductions for experiments conducted for >120 days (Fig. 1).

3.2. Biochars

Results suggest a dependency of biochar feedstock selection and conversion technology on N dynamics (Fig. 2). Biochars produced of wood and lignocellulosic biomass by gasification, slow pyrolysis, and their combination with steam at each heating temperature, reduced soil N_2O emissions ($P < 0.05$). On the other hand, N_2O emissions remained unaffected after application of i) biochars made of manure and biosolids ($P = 0.095$) and ii) biochar produced by fast pyrolysis (particle residence time a few seconds; Bruun et al. 2012) and iii) hydrochars produced via hydrothermal carbonization (Libra et al.

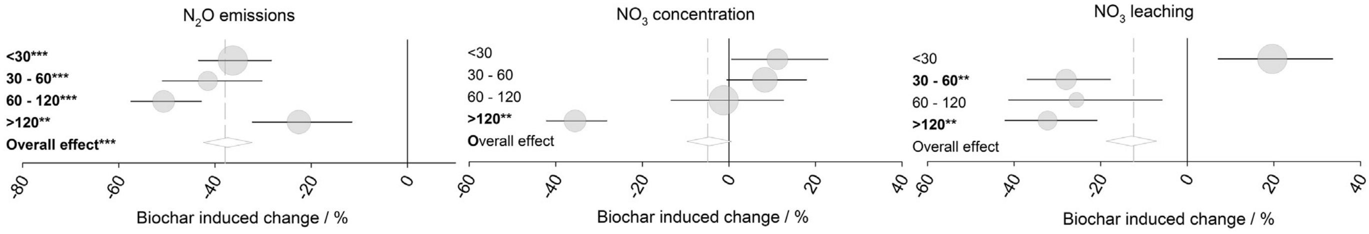


Fig. 1. Impact of study length (days) on soil N_2O emissions, NO_3^- concentration in soil after study, and NO_3^--leaching during study. Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

2011). Concentrations of NO_3^- significantly decreased in soils amended with biochars produced at heating temperatures <500 °C and with those produced by fast pyrolysis. Biochars produced from lignocellulosic biomass and biochars produced at temperatures of >500 °C reduced NO_3^- leaching.

Particle size of biochar particles did not affect N_2O emissions, NO_3^- concentration, and NO_3^- leaching (NO_3^- leaching$_{\text{fine biochar}}$: $P = 0.069$; Fig. 3). N_2O emissions were reduced after biochar application over a broad range of biochar pH, N and C contents, except for biochars consisting of <460 g C kg^{-1}; a relatively small number of biochar types (5.9 to 12.8 g N kg^{-1} and C/N mass ratio of 100 to 200) reduced the NO_3^- concentration in soil. Exclusively wood biochars characterized by pH values ranging between 7.8 and 8.9 increased NO_3^- concentration in soil, while acidic to neutral (pH <7.8) and strongly alkaline (pH >9.6) biochars reduced leaching of NO_3^-. Leaching of NO_3^- was further reduced by biochars consisting of <780 g C kg^{-1}, N ranging between 3.3 and 5.9 g kg^{-1}, and C/N mass ratio of 100 to 200.

3.3. Soils

Soil N_2O emissions were reduced regardless of soil texture (i.e. clay, silt, sand) as reflected by small data variability ($-34 \pm 8\%$; strongest reduction in soil with >70% sand: −47%) (Table S4). The concentration of NO_3^- in soil varied strongly ($-6 \pm 26\%$) among grouped textures (Table S4) and only coarse textured soils (i.e. sand) showed a reduced concentration and leaching of NO_3^- (Fig. 4).

Biochar reduced N_2O emissions at each soil pH and C/N ratio (Fig. 5). However, in soils with SOC concentrations >24 g kg^{-1} and total N concentrations >3 g kg^{-1}, the N_2O emission reduction was smallest and not significant. Furthermore, biochar applications reduced soil NO_3^- concentrations in slightly acidic to neutral soils (pH 5.5 to 7.0), in soils that contained low SOC concentrations (<10 g kg^{-1}), and in low total N soils (<1 g kg^{-1}). Interestingly, soils that were less affected by biochar in terms of soil NO_3^- concentrations actually showed reduced soil NO_3^- leaching (pH <5.5; 10–24 g C kg^{-1}, 0.7–1.7 g N kg^{-1}, C/N mass ratios of >9.3 and >12.4).

3.4. Soil types and soil management

Man-made soils (i.e. Anthrosols represented in this study exclusively by paddy soils), organic soils (i.e. Histosols), sandy soils (i.e. Arenosol), and soils typical for steppe and sub-humid temperate climate (i.e. Luvisol) showed reduced N_2O emissions after biochar applications (Figs. 7 and 8). Biochar applications reduced NO_3^- concentration only in Luvisols (i.e., soils of sub-humid temperate climate). Soil NO_3^- leaching was exclusively reduced in Cambisols (i.e. soils of limited age), and semi-arid soils (e.g. Calcisol, Solonetz) (Figs. 6 and 7).

Low biochar application rates of <10 Mg ha^{-1} neither affected N_2O emissions nor NO_3^- leaching, but increased NO_3^- concentration in soils (Fig. 8). Larger biochar application rates (e.g., >10–20 Mg ha^{-1}) reduced N_2O emissions, and tended to reduce NO_3^- leaching and concentration. N_2O emissions, NO_3^- concentrations in soils, and NO_3^- leaching remained unaffected for soils managed by application of biochar in combination with organic fertilizers. Compared to unfertilized soils, the N_2O emission mitigation potential of biochars was larger for fertilized soils (reduction of −46% for mineral fertilizer [e.g. NH_4NO_3, $(NH_4)_2SO_4$, KNO], −34% for urea, −32% for mixtures of organic and mineral fertilizers, and −27% for unfertilized soils; Fig. 8). The impact of biochar and fertilizers on NO_3^- concentration in soils varied, with reduced NO_3^- concentration for biochar experiments fertilized with mineral N and increased NO_3^- concentration in soils after use of urea in combination with biochar. Additions of organic fertilizer and

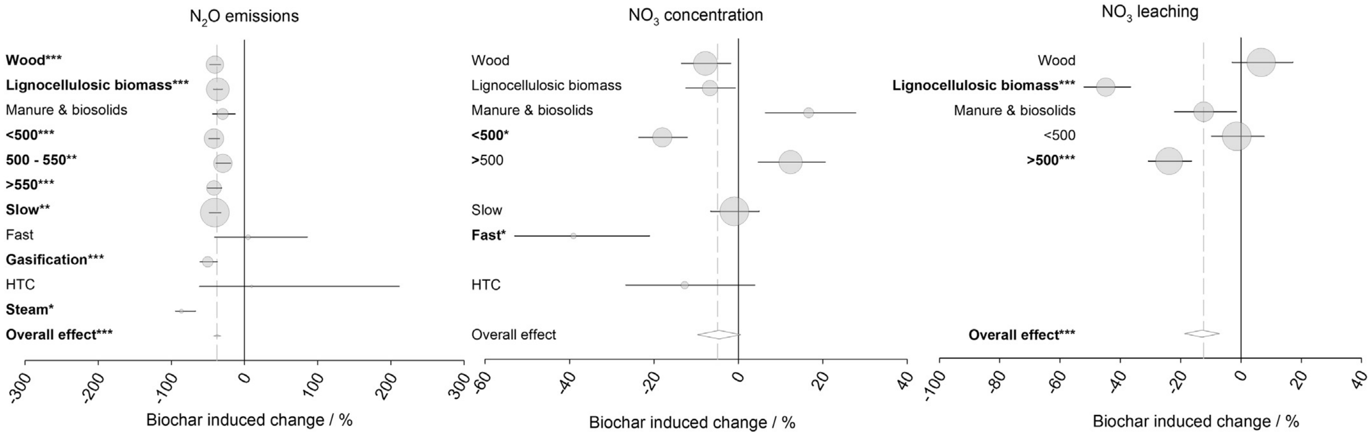


Fig. 2. Impact of feedstock (wood, lignocellulosic [i.e. all other non-woody] biomass, and manure & biosolids), process temperatures (<500 °C, 500 to 550 °C, >550 °C), and production technologies (slow pyrolysis, fast pyrolysis, gasification, hydrothermal carbonization [HTC], and steam) on soil N_2O emissions, NO_3^- concentration in soil after study, and NO_3^--leaching during study. Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

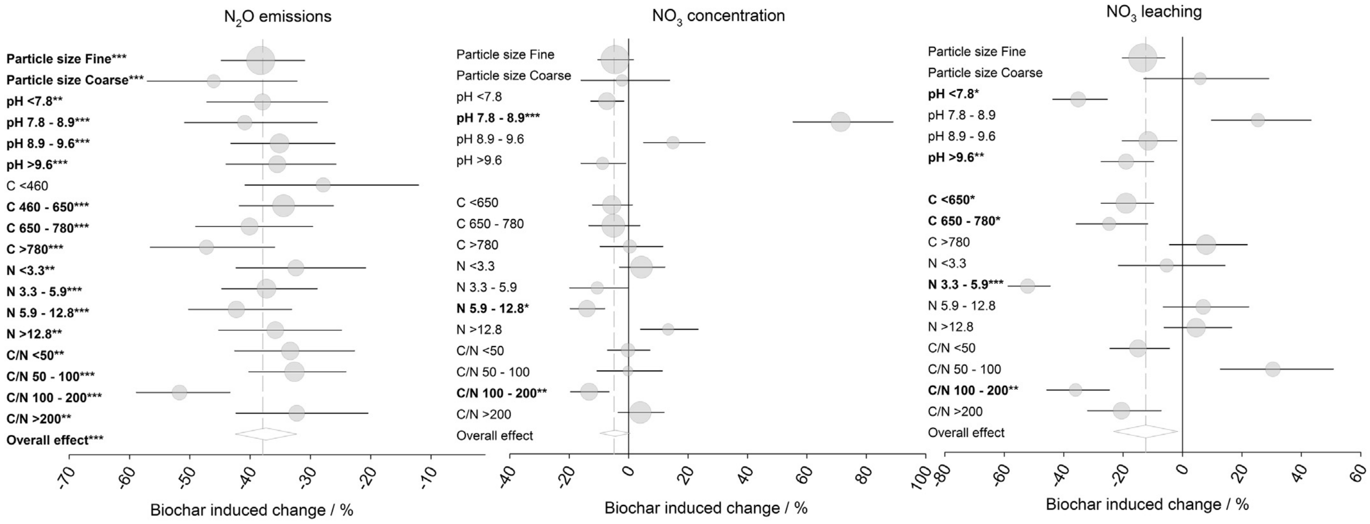


Fig. 3. Impact of various biochar properties (particle size, pH, carbon [C; g kg^{-1}], nitrogen [N; g kg^{-1}], and C/N mass ratio) on soil N_2O emissions, NO_3^- concentration in soil after study, and NO_3^--leaching during study. Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

unfertilized biochar experiments did not affect NO_3^- concentration measured after experiments. Leaching of NO_3^- was reduced by biochar in unfertilized soil and when the fertilizer application rate was below 150 kg N ha^{-1} (Fig. 8). For each N application rate, biochar induced a reduction of N_2O emissions, but leaching of NO_3^- progressively increased in response to increased N application rates (i.e. -26% for <150 kg N ha^{-1}, −7% for 150–300 kg N ha^{-1}, 46% for >300 kg N ha^{-1}). Hence, over all N fertilizer application rates, the NO_3^- leaching reduction was not significant (i.e. +3% with mineral fertilizer, −7% with organic fertilizer, and −35% with organo-mineral fertilizer). In parallel to reduced NO_3^- leaching in soils fertilized with <150 kg N ha^{-1}, concentration of NO_3^- was also reduced. Larger N application rates showed increased concentration of NO_3^- after application of 150 to 300 kg N ha^{-1}, but did not affect NO_3^- concentration after application of >300 kg N ha^{-1}.

Except for perennial crops (e.g. fruit trees), N_2O emissions at least tended to be reduced in all agronomic experiments (i.e. arable crops with −45% and horticultural cultures with −32%) that cultivated cereals (−31%, $P < 0.05$), maize (−31%, $P = 0.17$), rice (−40%, $P < 0.05$), vegetables (−30%, $P = 0.07$), and other crops (−35%, $P = 0.18$) (Fig. 9). Compared to control soils, agricultural soils enriched with biochar were further depleted in NO_3^- while NO_3^- leaching was reduced. Biochar applications to grassland increased NO_3^- concentration in soils, but neither N_2O emissions nor NO_3^- leaching were affected.

4. Discussion

Overall, soil N_2O emissions and NO_3^- leaching were reduced after biochar applications, while soil NO_3^- concentration remained overall unaffected. These findings are in line with meta-analysis results published by Liu et al. (2018) and Nguyen et al. (2017), except that their findings (based on 796 observations) indicated a significant reduction of 12% in soil NO_3^-. In the current study, reasons for reduced NO_3^- leaching and an at least unaffected concentration of NO_3^- in soil were presumably the result of soil processes affected by biochar and the ability of biochar to reversibly take up and release nitrate (Kammann et al. 2015, Haider et al. 2016, 2017; Hagemann et al. 2017a). Soil properties and processes can be modified by biochar in several ways. Biochar increases soil pH due to its "liming effect" (Clough et al., 2013; Hüppi et al., 2015; Nguyen et al., 2017), which induces a shift of the NH_4^+/$NH_{3(g)}$ equilibrium promoting release of NH_3 at elevated pH values, biochar-induced NH_3 volatilization, particularly from acidic soils, may

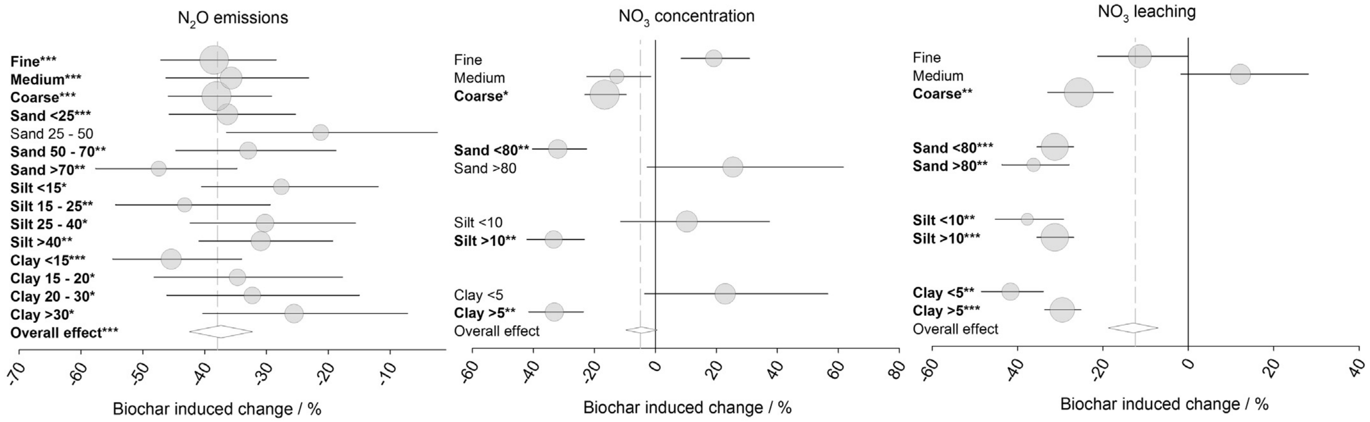


Fig. 4. Biochar effects on soil N_2O emissions, soil NO_3^- concentration post-study, and NO_3^--leaching during study affected by soil texture classes (fine or clay, medium or silt, coarse or sand textured) and proportion (%) of sand, silt, and clay. Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

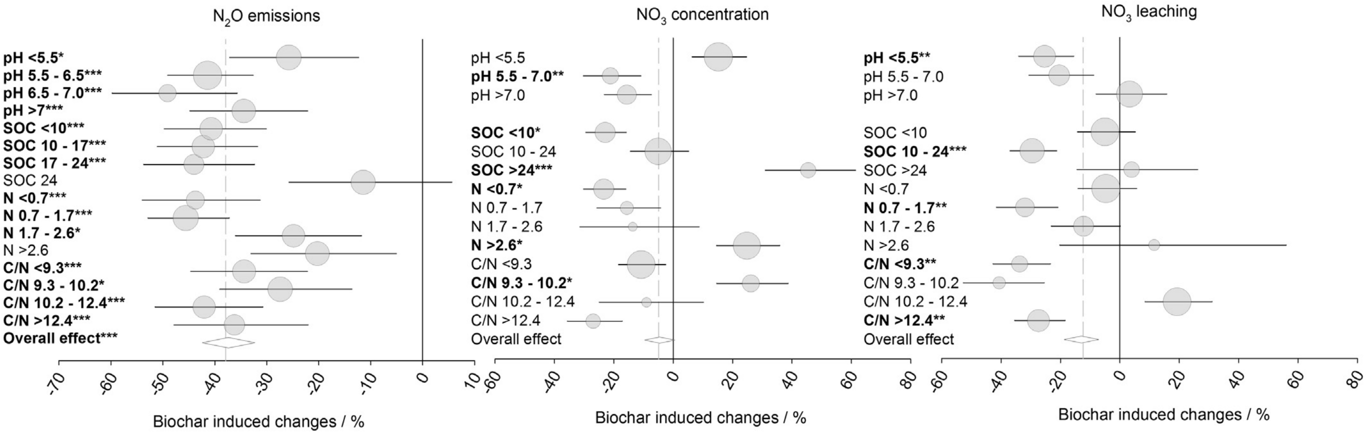


Fig. 5. Biochar effects on N_2O emissions, soil NO_3^- concentration post-study, and NO_3^- leaching during study affected by chemical soil properties (pH, soil organic carbon [SOC; mg kg^{-1}] and nitrogen [N; mg kg^{-1}], C/N mass ratio). Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

have reduced soil NO_3^- concentration and leaching (Liu et al., 2018). Other potential mechanisms explaining NO_3^- concentration and leaching from soil are i) a presumed sorption of NO_3^- on biochar (Nguyen et al., 2017; Sumaraj and Padhye, 2017; Yao et al., 2012), ii) biochar entrapment of NO_2^-/NO_3^- (Kammann et al. 2015; Haider et al., 2016, 2017; Hagemann et al., 2017a, b; Pignatello et al., 2006), and iii) stabilization of NO_3^- in biochar pores and organo-mineral coatings on biochars that hampers release, but promotes nitrate capture (Kammann et al., 2015; Hagemann et al., 2017a, b; Haider et al., 2016; Joseph et al. 2017). Thus, biochar can alter processes controlling NO_3^- formation substantially, but its interaction with pathways of NO_3^- stabilization and retention remain elusive.

The same mechanisms may further explain reduced N_2O emissions, with multiple processes needing to be considered to explain biochar-induced alteration of N_2O emissions. It has been shown that biochar addition can promote the expression of the N_2O reductase genes of denitrifiers (*NosZ*), promoting a complete reduction of NO_3^- to N_2 instead of N_2O (Wang et al., 2013; Harter et al., 2014), thereby shaping microbial communities (Harter et al., 2016a, b; Krause et al., 2018). Theoretically, the effect can be related to a slight pH increase around biochar particles; it is well known that a higher soil pH promotes a more complete denitrification to N_2. On the other hand, a reduction of the nitrate concentration around biochar particles can reduce the concentration of "NO_3^- substrate" for denitrifiers which would be in line with the observation of an increase in the *NosZ* gene expression. Furthermore, one may assume that biochar adds a fraction of readily degradable organic C sources (Lan et al., 2017; Wang et al., 2016), which induces a reduction of N_2O emissions (Barnard et al., 2005; Cayuela et al., 2013; Lan et al., 2017) by microbial growth and N immobilization. These processes impart a complex study matrix upon systems that receive biochar, which may explain the lack of process-based knowledge in the literature.

4.1. Impact of time

Our meta-analysis indicated a transient nature of biochar on N_2O emissions reduction, which needs more research regarding the mechanisms, and which needs to be taken into account as a dynamic factor when assessing biochars' long-term greenhouse gas mitigation potential (Woolf et al., 2010). Factors that affect biochars' long-term ability to reduce soil N_2O emissions includes biochar aging within soil, leading to biochar surface property changes via oxidation and formation of oxygen-containing functional groups (Mia et al., 2017), sorption of natural organic matter leading to clogged biochar pores (Kasozi et al., 2010; Pignatello et al., 2006; Sumaraj and Padhye, 2017; Hagemann et al., 2017b), and formation of organo-mineral complexes coating biochar surfaces (Joseph et al., 2017; Sumaraj and Padhye, 2017). Alteration of surface functional groups will affect electrostatic interactions, reducing the capacity of biochar to sorb NO_3^- (Güereña et al., 2012; Mia et al., 2017; Nguyen et al., 2017) while organo-mineral complexes tend to increase NO_3^- retention by mechanisms still under debate (Hagemann et al., 2017b; Joseph et al., 2017; Nguyen et al., 2017; Sumaraj and Padhye, 2017). Hence, aging of biochar and capturing NO_3^- may explain progressive reduction of NO_3^- concentration in and leaching from soil, which can suppress N_2O emissions from denitrification pathways (Bouwman et al., 2002; Cayuela et al., 2013; Pelster et al., 2011).

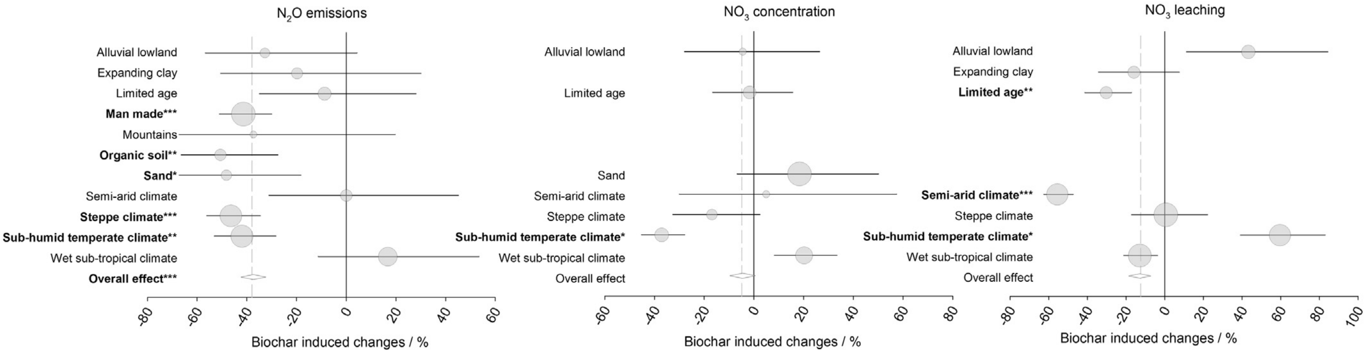


Fig. 6. Biochar effects on N_2O emissions, soil NO_3^- concentration post-study, and NO_3^- leaching during study affected by soil classes (Driessen et al., 2001). Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

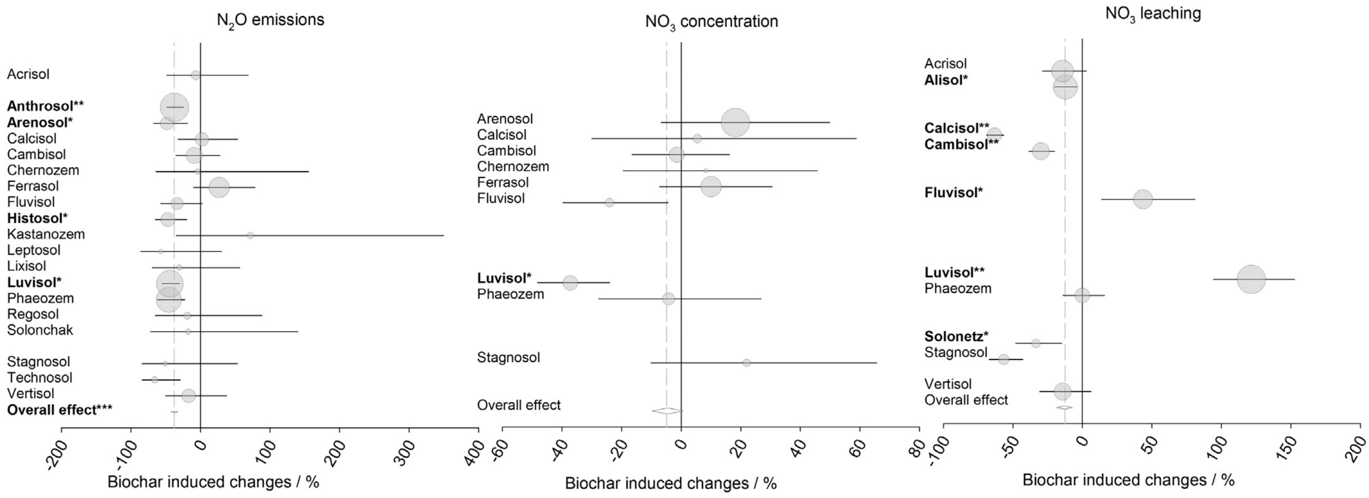


Fig. 7. Biochar effects on N_2O emissions, soil NO_3^- concentration post-study, and NO_3^- leaching during study affected by soil types (IUSS Working Group WRB, 2014; see USDA counterparts below figure). Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$). WRB = USDA: Acrisol = Ultisol; Alisol = all 12 USDA soil orders; Anthrosol = Inceptisol; Arenosol = Inceptisol/Entisol; Calcisol = Aridisol; Cambisol = Inceptisol; Chernozem = Mollisol; Ferrasol = Oxisol; Fluvisol = Entisol; Histosol = Histisol; Kasatanozem = Mollisol; Leptosol = Entisol; Lixisol = Alfisol; Luvisol = Alfisol; Pheaozem = Mollisol; Regosol = Entisol; Solonchak = Aridisol; Solonetz = Aridisol; Stagnosol = Alfisol/Ultisol/Entisol/Mollisol; Technosol = Anthrosol (man-disturbed); Vertisol = Vertisol.

4.2. Impact of biochar production and properties

Results suggested that N_2O emissions remained unaffected after application of N-rich biochars (e.g., manure and biosolids feedstocks) characterized by C/N ratios similar to soil organic matter (C/N: 17 ± 1), while application of N-poor biochars made from wood and lignocellulosic biomass (C/N: 279 ± 13 and 112 ± 5, respectively) reduced N_2O emissions, similar to the findings of Liu et al. (2018). Our results further indicate that NO_3^- concentration remained overall unaffected, but Liu et al. (2018), who utilized a larger number of observations, revealed a significant decrease in soil NO_3^- concentration (12%). Our study revealed that NO_3^- concentrations were reduced at N fertilizing rates (<150 kg N ha^{-1}) typically applied to biochar experiments as also reviewed by O'Connor et al. (2018b), but increased when N fertilization was higher (150–300 kg N ha^{-1}). Similar to previous research (e.g., Clough et al., 2013; Kanthle et al., 2016; Demiraji et al., 2018; Liu et al., 2018), soil NO_3^- leaching was overall reduced by biochar application. Factors that may explain these findings are the availability of easily biodegradable organic C and ash present in biochar, both affecting soil N transformation or nitrate capture by biochar. Biochar produced at temperatures >500 °C are almost free of labile organic C while those produced at temperatures <500 °C can contain labile organic material (Keiluweit et al., 2010; Wang et al., 2016; Zimmerman et al., 2011); biochar-borne labile organic C sources may induce microbial immobilization of N or capture NO_3^- by organic coating found on aged biochars (Borchard et al., 2014c; Clough et al., 2013, Hagemann et al., 2017a, b). Applied biochar particles that contain ash are slightly alkaline (i.e. close to 7.8) and provide a spatially limited, but optimal environment for substantially stimulated nitrifier activity (Antoniou et al., 1990; Barnard et al., 2005; Nguyen et al., 2017), which may explain elevated NO_3^- concentrations in soils amended with biochars having pH between 7.8 and 8.9. Another potential pathway for a stimulated nitrifier activity is the sorption of inhibitory phenolic compounds that can reduce or block nitifier activity e.g. in acidic conifer forest soils (DeLuca et al. 2006).

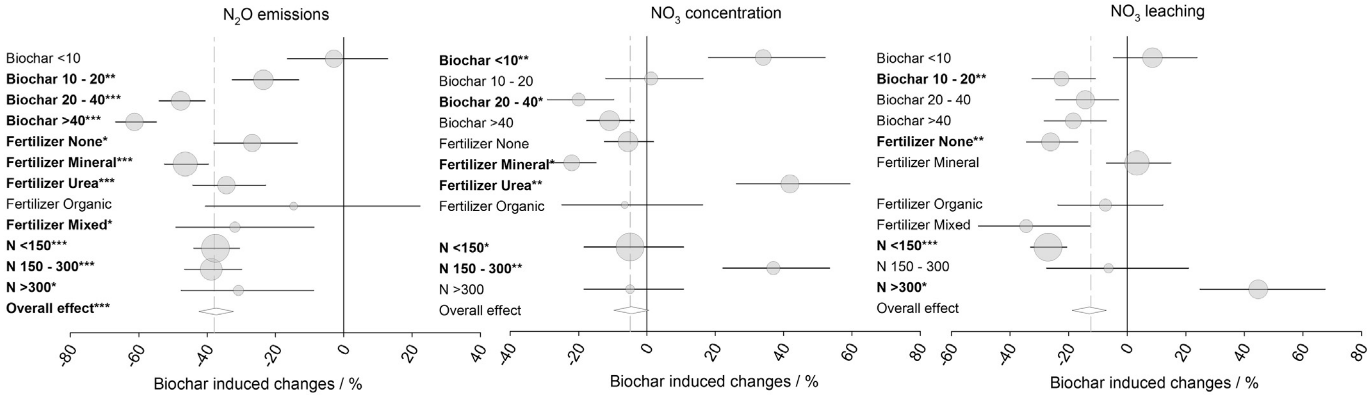


Fig. 8. Biochar effects on N_2O emissions, soil NO_3^- concentration post-study, and NO_3^- leaching during study affected by soil amendments (i.e. biochar application rate [Mg ha^{-1}], fertilizer type and N application rate [kg ha^{-1}]). Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

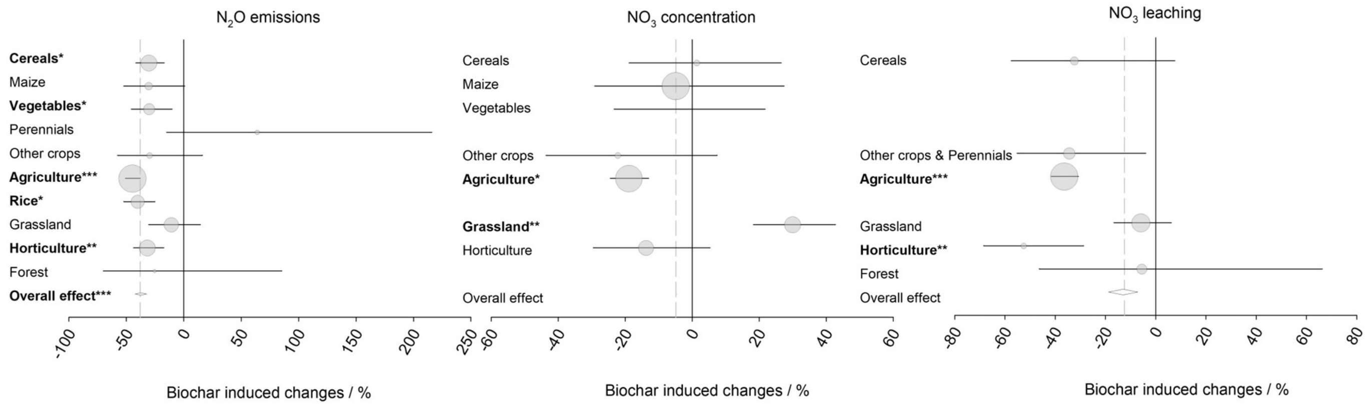


Fig. 9. Biochar effects on N_2O emissions, soil NO_3^- concentration post-study, and NO_3^- leaching during study affected by cultivated crops (cereals, maize, rice, vegetables, perennials, and other) and land use type (agriculture, grassland, horticulture, and forest). Data are shown as estimated mean effects and their lower and upper confidence intervals (95%). Circle size indicates number of observations (see also Supplementary information). Solid vertical line indicates mean of control treatments and dashed vertical line indicates mean of overall effect. Probability levels are indicated by asterisks (*** for $P < 0.001$; ** for $P < 0.01$, and * for $P < 0.05$).

4.3. Impact of soil type and soil properties

Biochar applications increased NO_3^- concentration in very coarse soils (>80% sand) and soils poor in organic C and N. Although the exact mechanisms are unknown, this could be a result of biochar application that increased total soil organic C and a stimulated stabilization of inherent soil C (Borchard et al., 2014a; Hernández-Soriano et al., 2015; Kasozi et al., 2010; Pignatello et al., 2006), a subsequent accelerated N transformation, and sorption and/or retention of NO_3^- (Nelissen et al., 2012; Clough et al., 2013; Liu et al., 2018). Adding biochar to coarse textured soils typically affects water retention and flow (Ajayi and Horn, 2016; Clough et al., 2013; Petersen et al., 2016), which is assumed to reduce NO_3^- leaching as stated by Liu et al. (2018) and this meta-analysis. When applied to acidic soils and soils rich in soil organic matter, biochar may have induced decomposition of native soil organic matter (Ding et al., 2017; Wang et al., 2016), stimulating soil organic matter mineralization, nitrification, and formation of NO_3^- (e.g. Nelissen et al., 2012). In comparison to findings by Liu et al. (2018), our meta-analysis results showed that N_2O emissions remained unaffected in soils rich in organic matter (>24 g kg^{-1}, here exclusively grassland soils as compared to other agricultural soils, see below) at elevated NO_3^- concentration in soil stimulating an incomplete reduction of NO_3^- (Barnard et al., 2005); moreover, the complete reduction of N_2O to N_2 during denitrification was supressed by low pH-values of these soils. Thus, pH, organic matter and texture are controlling factors explaining biochar-induced formation and retention of NO_3^- in soil and corresponding N_2O emissions.

Soils that are well aerated, coarse textured, and typically poor in soil organic matter are Arenosols, while Histosols are rich in organic matter yet may also be anoxic (Driessen et al., 2001). Our results revealed that biochar applications to Arenosols had no effect on NO_3^- concentration and leaching (−14%), but biochar reduced N_2O emissions by −48%. Arenosols are promoting almost complete nitrification of NH_4^+ to NO_3^- (Chapin et al., 2011), which biochar evidently enhances in Arenosols (Meusel et al., 2018; Nguyen et al., 2017). Soils naturally known to be a source of N_2O emissions are Histosols and paddy soils (i.e. man-made soils or Anthrosols) that emit N_2O, especially during transitions of dry-to-flooded or flooded-to-dry soil conditions due to seasonally varying water regimes (Dalal et al., 2003; Kögel-Knabner et al., 2010; Liu et al., 2010; Peng et al., 2011; Schwärzel et al., 2002). Our results revealed that biochar applications to Histosols reduced N_2O emissions by −47%. This N_2O emissions reduction may be improved by biochar through i) alteration in soil moisture regime during non-flooded periods (Ajayi and Horn, 2016; Clough et al., 2013; Petersen et al., 2016), ii) a reduction of redox potentials to levels that promote formation of NH_4^+, or iii) complete denitrification to N_2 (Harter et al., 2014; Barnard et al., 2005; Cayuela et al., 2013; Sumaraj and Padhye, 2017).

4.4. Impact of soil conditioner and land use type

Agricultural land use requires replacement of nutrients by fertilization and can mitigate climate change by sequestering C in soils (Werner et al., 2018; Wollenberg et al., 2016). Biochar is thought to sequester C in soils and stabilize non-charred soil organic C (Abdelrahman et al., 2018; Borchard et al., 2014a; Wollenberg et al., 2016), which may have an impact on nitrification and subsequently on N_2O emissions (Nelissen et al. 2012). Our meta-analysis results showed that typical biochar application rates of >10 Mg ha^{-1} (ranges typically between 5 and 50 Mg ha^{-1}; Liu et al., 2013; Lorenz and Lal, 2014) reduced N_2O emissions, while NO_3^- concentration and leaching tended to be reduced, similar to results of Liu et al. (2018). Our findings confirm that biochar-induced alterations of mineral N transformations are dose-related as also shown for crop yields and soil organic C dynamics (Crane-Droesch et al., 2013; Ding et al., 2017). Moreover, biochar applications significantly suppressed N_2O emissions typically induced by N fertilization (Barnard et al., 2005) indicating biochar could be a valuable mitigation tool to lower emission factors of N fertilizers. Assuming maintained or even increased yields after biochar application (Crane-Droesch et al., 2013), an important factor to consider is that reduced N_2O emissions also reduce greenhouse gas emission equivalents per kg produced agricultural crop.

Based on our meta-analysis results, it appears that a fertilizer dose-related mechanism progressively reduced soil NO_3^- leaching and increased soil NO_3^- concentration; this response, however, dropped to a non-significant response at N fertilizer application rates of >300 kg ha^{-1}. This effect likely may be due to the limited capacity of biochars to immobilize and entrap NO_3^- (Borchard et al., 2014b; Clough et al., 2013; Hagemann et al., 2017b), explaining the reduced or even maintained NO_3^- leaching for experiments that received <300 kg N ha^{-1} compared to those receiving less N fertilization, and increased NO_3^- concentration after application of >150 kg N ha^{-1}. However, biochar could not prevent leaching of NO_3^- after application rates of >300 kg N ha^{1-}. Thus, applying >300 kg N ha^{1-} to biochar amended soils increases the risks associated with N loss by NO_3^- leaching rather than by N_2O emissions; mechanisms controlling this finding remain unclear.

Patterns of reduced N_2O emissions, NO_3^- concentration and leaching suggest that biochar application reduces N losses from agriculture (i.e. cereals, rice), except for grassland, perennial crops (e.g. gapevine and fruit trees), and forest. Compared to other agricultural soils (pH: 6.3 ±

0.1; C: 17 ± 1 g kg^{-1}), grassland soils (pH: 5.3 ± 0.1; C: 34 ± 1 g kg^{-1}) contained larger stocks of soil organic C, which is in line with current knowledge (Guo and Gifford, 2002; Scharlemann et al., 2014). These differences explain unaffected N_2O emissions and NO_3^- leaching, but increased concentration of NO_3^- in these soils as biochar can induce decomposition of soil organic C (Ding et al., 2017, Wang et al. 2016). The mineralization of soil organic matter can accelerate subsequent nitrification and formation of NO_3^- (Nelissen et al., 2012). Simultaneously, biochar elevates soil pH, which alters the $NH_4^+/NH_{3(g)}$ equilibrium and typically stimulates a more complete reduction of N_2O to N_2 (Clough et al., 2013, Hüppi et al., 2015, Obia et al., 2015, Nguyen et al., 2017, Liu et al., 2018), which was assumed to reduce N_2O emissions. Obviously, our knowledge of biochar-induced effects on soil N_2O emissions especially on grassland and perennial crops is incomplete.

5. Conclusion

This meta-analysis revealed that biochar stimulates an overall N_2O emissions reduction of 38% with greater reductions immediately after application. The time dependent impact of biochar application on soil N_2O emissions is a crucial factor requiring consideration in order to develop and test resilient and sustainable biochar-based greenhouse gas mitigation strategies. In terms of land use, biochar can reduce rice paddy soil N_2O emissions (i.e. Anthrosols) by almost 40%; this may significantly mitigate climate change, as ~140 Mha are used as paddy fields globally (Kögel-Knabner et al., 2010), and since methane emissions from paddy soils have been found to be reduced as well (Jeffery et al., 2016). Adding biochar to sandy or coarse textured soils (e.g. Arenosols) reduced both N_2O emissions and NO_3^- leaching, which reduces soil N losses and presumably improves both N use efficiency and mitigates climate change. Considering land use (e.g., paddy soils, grasslands, annual or perennial cropping systems, etc.) in conjunction with soil properties (e.g. texture, soil organic matter, pH) may provide reliable information suitable for up-scaling N_2O emission reduction estimations and potentials, and ultimately the best practical scenarios for environmental biochar use. Our results support the notion of a dose-response relationship of biochar application on N_2O emission reduction and also NO_3^- leaching, which hints towards the interesting possibility of using biochar as a carrier matrix for "carbon-fertilizers" as successfully explored by Qian et al. (2014). Using biochar in this way would greatly reduce the required dose of N per hectare, which would improve N use efficiency and reduce the economic barriers for biochar use in agronomy. However, the eco-physiological mechanisms controlling N uptake by plants in soil-biochar-plant systems require further analyses to ensure sustainable N-management.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.060.

Acknowledgement

This work is also supported by the USDA/NIFA Interagency Climate Change Grant Proposal number 2014-02114 [Project number 6657-12130-002-08I, Accession number 1003011] under the Multi-Partner Call on Agricultural Greenhouse Gas Research of the FACCE-Joint Program Initiative. The German BLE and FACCE-JPI funded the German participants of the "DesignerChar4Food" (D4F) project (CK: Project No. 2814ERA01A; NW-M: Project No. 2814ERA02A), the Spanish colleagues (JME and TFM) were funded by FACCE-CSA no 276610/MIT04-DESIGN-UPVASC and IT-932-16, and US colleagues (JN, JI and KS) were funded by The USDA-National Institute of Food and Agriculture (Project # 2014-35615-21971), USDA-ARS CHARnet and GRACENet programs – D4F greatly stimulated discussions. MLC was supported by a "Ramon y Cajal" research contract from the Spanish Ministry of Economy and Competitiveness and thanks Fundación Séneca for the project # 19281/PI/14. Any opinions, findings, or recommendation expressed in this publication are those of the authors and do not necessarily reflect the view of the USDA. Nils Borchard was appointed as integrated expert at CIFOR by the Centre for International Migration and Development (CIM). CIM is a joint operation of the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (*GIZ*) *GmbH* and the International Placement Services of the German Federal Employment Agency. Many thanks owed to Ines Heyer, Lisa Fitkau, and Andreas Haller for the help with compiling data.

References

Abdelrahman, H., Hofmann, D., Meyer, N., Bol, R., Borchard, N., 2018. Historical charcoal additions alter particulate organic matter fractions and affect soil C composition and stabilization. J. Plant Nutr. Soil Sci. (2011), 1–9 https://doi.org/10.1002/jpln.201800261.

Ahn, Y.-H., 2006. Sustainable nitrogen elimination biotechnologies: a review. Process Biochem. 41, 1709–1721.

Ajayi, A.E., Horn, R., 2016. Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. Soil Tillage Res. 164, 34–44. https://doi.org/10.1016/j.still.2016.01.011.

Antoniou, P., Hamilton, J., Koopman, B., Jain, R., Holloway, B., Lyberatos, G., Svoronos, S.A., 1990. Effect of temperature and ph on the effective maximum specific growth rate of nitrifying bacteria. Water Res. 24, 97–101.

Barnard, R., Leadley, P.W., Hungate, B.A., 2005. Global change, nitrification, and denitrification: a review. Glob. Biogeochem. Cycles 19, GB1007.

Bateman, E.J., Baggs, E.M., 2005. Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. Biol. Fertil. Soils 41, 379–388.

Borchard, N., Ladd, B., Eschemann, S., Hegenberg, D., Möseler, B.M., Amelung, W., 2014a. Black carbon and soil properties at historical charcoal production sites in Germany. Geoderma 232–234, 236–242.

Borchard, N., Siemens, J., Ladd, B., Möller, A., Amelung, W., 2014b. Application of biochars to sandy and silty soil failed to increase maize yield under common agricultural practice. Soil Tillage Res. 144, 184–194.

Borchard, N., Spokas, K., Prost, K., Siemens, J., 2014c. Greenhouse gas production in mixtures of soil with composted and noncomposted biochars is governed by char-associated organic compounds. J. Environ. Qual. 971–979.

Borenstein, M., Hedges, L.V., Higgins, J.P.T., Rothstein, H.R., 2009. Introduction to Meta-analysis. John Wiley & Sons Ltd., Chichester, UK https://doi.org/10.1002/9780470743386.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Modeling global annual N_2O and NO emissions from fertilized fields. Glob. Biogeochem. Cycles 16, 28–29.

Bruun, E.W., Ambus, P., Egsgaard, H., Hauggaard-Nielsen, H., 2012. Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. Soil Biol. Biochem. 46, 73–79. https://doi.org/10.1016/j.soilbio.2011.11.019.

Cayuela, M.L., Sánchez-Monedero, M.A., Roig, A., Hanley, K., Enders, A., Lehmann, J., 2013. Biochar and denitrification in soils: when, how much and why does biochar reduce N_2O emissions? Sci. Rep. 3 (1732).

Cayuela, M.L., van Zwieten, L., Singh, B.P., Jeffery, S., Roig, A., Sánchez-Monedero, M.A., 2014. Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agric. Ecosyst. Environ. 191, 5–16.

Cayuela, M.L., Jeffery, S., van Zwieten, L., 2015. The molar H:Corg ratio of biochar is a key factor in mitigating N_2O emissions from soil. Agric. Ecosyst. Environ. 202, 135–138.

Chapin III, F.S., Matson, P.A., Vitousek, P.M., 2011. Principles of Terrestrial Ecosystem Ecology. 2nd ed. Springer, Heidelberg, Germany.

Clough, T., Condron, L., Kammann, C., Müller, C., 2013. A review of biochar and soil nitrogen dynamics. Agronomy 3, 275–293.

Cooper, R.J., Wexler, S.K., Adams, C.A., Hiscock, K.M., 2017. Hydrogeological controls on regional-scale indirect nitrous oxide emission factors for rivers. Environ. Sci. Technol. 51, 10440–10448.

Crane-Droesch, A., Abiven, S., Jeffery, S., Torn, M.S., 2013. Heterogeneous global crop yield response to biochar: a meta-regression analysis. Environ. Res. Lett. 8.

Dalal, R.C., Wang, W., Robertson, G.P., Parton, W.J., 2003. Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Soil Res. 41, 165–195.

Davidson, E., 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nat. Geosci. Vol 2, 659–662. https://doi.org/10.1038/ngeo608.

DeLuca, T.H., MacKenzie, M.D., Gundale, M.J., Holben, W.E., 2006. Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests. Soil Sci. Soc. Am. J. 70, 448–453.

Demiraj, E., Libutti, A., Malltezi, J., Rroço, E., Brahushi, F., Monteleone, M., Sulçe, S., 2018. Effect of organic amendments on nitrate leaching mitigation in a sandy loam soil of Shkodra district, Albania. Ital. J. Agron. 13, 93–102. https://doi.org/10.4081/ija.2018.1136.

DerSimonian, R., Laird, N., 2015. Meta-analysis in clinical trials revisited. Contemp. Clin. Trials 45, 139–145.

Ding, Y., Liu, Y.-X., Wu, W.-X., Shi, D.-Z., Yang, M., Zhong, Z.-K., 2010. Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water Air Soil Pollut. 213, 47–55.

Ding, F., Van Zwieten, L., Zhang, W., Han Weng, Z., Shi, S., Wang, J., Meng, J., 2017. A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment. J. Soils Sediments. 18 (4), 1507–1517. https://doi.org/10.1007/s11368-017-1899-6.

Driessen, P., Deckers, J., Spaargaren, O., Nachtergaele, F.O., 2001. Lecture notes on the major soils of the world. World Soil Resour. Reports.

Duarte-Guardia, S., Peri, P.L., Amelung, W., Sheil, D., Laffan, S.W., Borchard, N., Bird, M.I., Dieleman, W., Pepper, D.A., Zutta, B., Jobbagy, E., Silva, L.C.R., Bonser, S.P., Berhongaray, G., Piñeiro, G., Martinez, M.-J., Cowie, A.L., Ladd, B., 2018. Better estimates of soil carbon from geographical data: a revised global approach. Mitig. Adapt. Strateg. Glob. Chang. https://doi.org/10.1007/s11027-018-9815-y.

Granli, T., Bockman, O.C., 1994. Nitrous oxide from agriculture. Nor. J. Agric. Sci. Suppl. 0 (12), 1–128.

Güereña, D., Lehmann, J., Hanley, K., Enders, A., Hyland, C., Riha, S., 2012. Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system. Plant Soil 1–16.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Chang. Biol. 8, 345–360.

Hagemann, N., Kammann, C., Schmidt, H.-P., Kappler, A., Behrens, S., 2017a. Nitrate capture and slow release in biochar amended compost and soil. PLoS ONE 12, e0171214.

Hagemann, N., Joseph, S., Schmidt, H.-P., Kammann, C.I., Harter, J., Borch, T., Young, R.B., Varga, K., Taherymoosavi, S., Elliott, K.W., McKenna, A., Albu, M., Mayrhofer, C., Obst, M., Conte, P., Dieguez-Alonso, A., Orsetti, S., Subdiaga, E., Behrens, S., Kappler, A., 2017b. Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. Nat. Commun. 8, 1089.

Haider, G., Steffens, D., Müller, C., Kammann, C.I., 2016. Standard extraction methods may underestimate nitrate stocks captured by field-aged biochar. J. Environ. Qual. 45, 1196–1204.

Haider, G., Steffens, D., Müller, C., Kammann, C., 2017. Biochar May Physically Entrap Nitrate During Field Aging or Co-composting Which Become Plant Available Under Controlled Conditions.

Harter, J., Krause, H.-M., Schuettler, S., Ruser, R., Fromme, M., Scholten, T., Kappler, A., Behrens, S., 2014. Linking N_2O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. ISME J. 8, 660–674.

Harter, J., Guzman-Bustamante, I., Kuehfuss, S., Ruser, R., Well, R., Spott, O., Kappler, A., Behrens, S., 2016a. Gas entrapment and microbial N_2O reduction reduce N_2O emissions from a biochar-amended sandy clay loam soil. Sci. Rep. 6, 1–15. https://doi.org/10.1038/srep39574.

Harter, J., Guzman-Bustamante, I., Kuehfuss, S., Ruser, R., Well, R., Spott, O., Kappler, A., Behrens, S., 2016b. Gas entrapment and microbial N_2O reduction reduce N_2O emissions from a biochar-amended sandy clay loam soil. Sci. Rep. 6, 1–15. https://doi.org/10.1038/srep39574.

Hedges, L., Vevea, J., 1998. Fixed- and random-effects models in meta-analysis. Psychol. Methods Vol 3, 486–504. https://doi.org/10.1037/1082-989X.3.4.486.

Hedges, L., Gurevitch, J., Curtis, S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology Vol. 80, 1150–1156.

Hernández-Soriano, M.C., Kerré, B., Goos, P., Hardy, B., Dufey, J., Smolders, E., 2015. Long-term effect of biochar on the stabilization of recent carbon: soils with historical inputs of charcoal. Glob. Change Biol. Bioenergy. 8, 371–381.

Huedo-Medina, T.B., Sanchez-Meca, J., Marín-Martínez, F., Botella, J., 2006. Assessing heterogeneity in meta-analysis: Q statistic or I 2 index? Psychol. Methods Vol. 11, 193–206. https://doi.org/10.1037/1082-989X.11.2.193.

Hüppi, R., Felber, R., Neftel, A., Six, J., Leifeld, J., 2015. Effect of biochar and liming on soil nitrous oxide emissions from a temperate maize cropping system. Soil 1 (2), 707–717. https://doi.org/10.5194/soil-1-707-2015.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change (IPCC), Cambridge and New York.

IUSS Working Group WRB, 2014. World reference base for soil resources 2014. World Soil Resources Reports. Food and Agriculture Organization of the United Nations, Rome.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144, 175–187.

Jeffery, S., Verheijen, F., Kammann, C., Abalos, D., 2016. Biochar effects on methane emissions from soils: a meta-analysis. Soil Biol. Biochem. Vol. 101, 251–258. https://doi.org/10.1016/j.soilbio.2016.07.021.

Joseph, S., Kammann, C.I., Shepherd, J.G., Conte, P., Schmidt, H.-P., Hagemann, N., Rich, A.M., Marjo, C.E., Allen, J., Munroe, P., Mitchell, D.R.G., Donne, S., Spokas, K., Graber, E.R., 2017. Microstructural and associated chemical changes during the composting of a high temperature biochar: mechanisms for nitrate, phosphate and other nutrient retention and release. Sci. Total Environ. 618, 1210–1223.

Kammann, C.I., Schmidt, H.-P., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C., Koyro, H.-W., Conte, P., Joseph, S., 2015. Plant growth improvement mediated by nitrate capture in co-composted biochar. Sci. Rep. 5. https://doi.org/10.1038/srep11080.

Kammann, C., Ippolito, J., Hagemann, N., Borchard, N., Cayuela, M.L., Estavillo, J.M., Fuertes-Mendizabal, T., Jeffery, S., Kern, J., Novak, J., Rasse, D., Saarnio, S., Schmidt, H.-P., Spokas, K., Wrage-Mönnig, N., 2017. Biochar as a tool to reduce the agricultural greenhouse-gas burden – knowns, unknowns and future research needs. J. Environ. Eng. Landsc. Manag. 25, 114–139.

Kanthle, A.K., Lenka, N.K., Lenka, S., Tedia, K., 2016. Biochar impact on nitrate leaching as influenced by native soil organic carbon in an Inceptisol of central India. Soil Tillage Res. 157, 65–72. https://doi.org/10.1016/j.still.2015.11.009.

Kasozi, G.N., Zimmerman, A.R., Nkedi-Kizza, P., Gao, B., 2010. Catechol and humic acid sorption onto a range of laboratory-produced black carbons (biochars). Environ. Sci. Technol. 44, 6189–6195.

Keiluweit, M., Nico, P.S., Johnson, M.G., Kleber, M., 2010. Dynamic molecular structure of plant biomass-derived black carbon (biochar). Environ. Sci. Technol. 44, 1247–1253.

Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., Kalbitz, K., Kölbl, A., Schloter, M., 2010. Biogeochemistry of paddy soils. Geoderma 157, 1–14.

Krause, H.M., Hüppi, R., Leifeld, J., et al., 2018. Biochar affects community composition of nitrous oxide reducers in a field experiment. Soil Biol. Biochem. 119, 143–151. https://doi.org/10.1016/j.soilbio.2018.01.018 (January).

Lan, Z.M., Chen, C.R., Rashti, M.R., Yang, H., Zhang, D.K., 2017. Stoichiometric ratio of dissolved organic carbon to nitrate regulates nitrous oxide emission from the biochar-amended soils. Sci. Total Environ. 576, 559–571.

Libra, J.A., Ro, K.S., Kammann, C., Funke, A., Berge, N.D., Neubauer, Y., Titirici, M.-M., Fühner, C., Bens, O., Kern, J., Emmerich, K.-H., 2011. Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. Biofuels 2, 71–106.

Linn, D.M., Doran, J.W., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils1. Soil Sci. Soc. Am. J. Vol. 48, 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x.

Liu, S., Qin, Y., Zou, J., Liu, Q., 2010. Effects of water regime during rice-growing season on annual direct N_2O emission in a paddy rice–winter wheat rotation system in southeast China. Sci. Total Environ. 408, 906–913.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G., Paz-Ferreiro, J., 2013. Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. Plant Soil 373, 583–594.

Liu, Q., Zhang, Y., Liu, B., Amonette, J.E., Lin, Z., Liu, G., Ambus, P., Xie, Z., 2018. How does biochar influence soil N cycle? A meta-analysis. Plant Soil 426, 211–225.

Lorenz, K., Lal, R., 2014. Biochar application to soil for climate change mitigation by soil organic carbon sequestration. J. Plant Nutr. Soil Sci. 177, 651–670.

Mehmood, K., Garcia, E.C., Schirrmann, M., Ladd, B., Kammann, C., Wrage-Mönnig, N., Siebe, C., Estavillo, J.M., Fuertes-Mendizabal, T., Cayuela, M., Sigua, G., Spokas, K., Cowie, A.L., Novak, J., Ippolito, J.A., Borchard, N., 2017. Biochar research activities and their relation to development and environmental quality. A meta-analysis. Agron. Sustain. Dev. 37.

Meusel, H., Tamm, A., Kuhn, U., Wu, D., Leifke, A.L., Fiedler, S., Ruckteschler, N., Yordanova, P., Lang-Yona, N., Pöhlker, M., Lelieveld, J., Hoffmann, T., Pöschl, U., Su, H., Weber, B., Cheng, Y., 2018. Emission of nitrous acid from soil and biological soil crusts represents an important source of HONO in the remote atmosphere in Cyprus. Atmos. Chem. Phys. 18, 799–813.

Mia, S., Dijkstra, F., Singh, B., 2017. Long-term aging of biochar: a molecular understanding with agricultural and environmental implications. Adv. Agron. 141, 1–51.

Minghua, Z., Bo, Z., Shijie, W., Xinyu, Z., Harry, V., Nicolas, B., 2017. Stimulation of N_2O emission by manure application to agricultural soils may largely offset carbon benefits: a global meta-analysis. Glob. Chang. Biol. 23, 4068–4083.

Nelissen, V., Rütting, T., Huygens, D., Staelens, J., Ruysschaert, G., Boeckx, P., 2012. Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. Soil Biol. Biochem. 55, 20–27. https://doi.org/10.1016/j.soilbio.2012.05.019.

Nguyen, T.T.N., Xu, C.-Y., Tahmasbian, I., Che, R., Xu, Z., Zhou, X., Wallace, H.M., Bai, S.H., 2017. Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis. Geoderma 288, 79–96.

Obia, A., Cornelissen, G., Mulder, J., Dörsch, P., 2015. Effect of soil pH increase by biochar on NO, N_2O and N_2 production during denitrification in acid soils. PLoS One 10, e0138781.

O'Connor, D., Peng, T., Zhang, J., Tsang, D.C.W., Alessi, D.S., Shen, Z., Bolan, N.S., Hou, D., 2018. Biochar application for the remediation of heavy metal polluted land: a review of in situ field trials. Sci. Total Environ. 619–620, 815–826.

O'Connor, D., Peng, T., Li, G., Wang, S., Duan, L., Mulder, J., Cornelissen, G., Cheng, Z., Yang, S., Hou, D., 2018a. Sulfur-modified rice husk biochar: A green method for the remediation of mercury contaminated soil. Sci. Total Environ. 621, 819–826.

Pelster, D.E., Larouche, F., Rochette, P., Chantigny, M.H., Allaire, S., Angers, D.A., 2011. Nitrogen fertilization but not soil tillage affects nitrous oxide emissions from a clay loam soil under a maize–soybean rotation. Soil Tillage Res. 115–116, 16–26.

Peng, S., Hou, H., Xu, J., Mao, Z., Abudu, S., Luo, Y., 2011. Nitrous oxide emissions from paddy fields under different water managements in southeast China. Paddy Water Environ. 9, 403–411.

Petersen, C.T., Hansen, E., Larsen, H.H., Hansen, L.V., Ahrenfeldt, J., Hauggaard-Nielsen, H., 2016. Pore-size distribution and compressibility of coarse sandy subsoil with added biochar. Eur. J. Soil Sci. 67, 726–736.

Pignatello, J.J., Kwon, S., Lu, Y., 2006. Effect of natural organic substances on the surface and adsorptive properties of environmental black carbon (char): Attenuation of surface activity by humic and fulvic acids. Environ. Sci. Technol. 40, 7757–7763.

Qian, L., Chen, L., Joseph, S., Pan, G., Li, L., Zheng, J., Zhang, X., Zheng, J., Yu, X., Wang, J., 2014. Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. Carbon Manage. 5, 145–154.

Rosenberg, M.S., 2007. The file-drawer problem revisited: a general weighted method for calculating fail-safe numbers in meta-analysis. Evolution 59, 464–468.

Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manage. 5, 81–91.

Schwärzel, K., Renger, M., Sauerbrey, R., Wessolek, G., 2002. Soil physical characteristics of peat soils. J. Plant Nutr. Soil Sci. 165, 479–486.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 363, 789–813.

Sumaraj, Padhye, L.P., 2017. Influence of surface chemistry of carbon materials on their interactions with inorganic nitrogen contaminants in soil and water. Chemosphere 184, 532–547.

Tian, L., Zhu, B., Akiyama, H., 2017. Seasonal variations in indirect N_2O emissions from an agricultural headwater ditch. Biol. Fertil. Soils 53, 651–662.

Turner, P.A., Griffis, T.J., Lee, X., Baker, J.M., Venterea, R.T., Wood, JD., 2015. Indirect nitrous oxide emissions from streams within the US Corn Belt scale with stream order. Proc. Natl. Acad. Sci. 112 (32), 9839–9843. https://doi.org/10.1073/pnas.1503598112.

Verhoeven, E., Pereira, E., Decock, C., Suddick, E., Angst, T., Six, J., 2017. Toward a better assessment of biochar–nitrous oxide mitigation potential at the field scale. J. Environ. Qual. Vol. 46, 237–246. https://doi.org/10.2134/jeq2016.10.0396.

Wang, C., Lu, H., Dong, D., Deng, H., Strong, P.J., Wang, H., Wu, W., 2013. Insight into the effects of biochar on manure composting: evidence supporting the relationship between N_2O emission and denitrifying community. Environ. Sci. Technol. 47, 7341–7349. https://doi.org/10.1021/es305293h.

Wang, J., Xiong, Z., Kuzyakov, Y., 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8, 512–523.

Werner, C., Schmidt, H.-P., Gerten, D., Lucht, W., Kammann, C., 2018. Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °C. Environ. Res. Lett. Vol. 13, 044036. https://doi.org/10.1088/1748-9326/aabb0e.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander, B.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F.F., Baedeker, T., Sadler, M., Vermeulen, S., Campbell, B.M., 2016. Reducing emissions from agriculture to meet the 2 °C target. Glob. Chang. Biol. 22, 3859–3864.

Woolf, D., Amonette, J., Street-Perrott, A., Lehmann, J., Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nat. Commun. 1 (5), 1–9 doi:citeulike-article-id: 7694581.

Yao, Y., Gao, B., Zhang, M., Inyang, M., Zimmerman, A.R., 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere 89, 1467–1471.

Zimmerman, A.R., Gao, B., Ahn, M.-Y., 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol. Biochem. 43, 1169–1179.