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Meta-Analysis of N2O Emissions from Chinese Cropland Soils Under Biochar Application: Postprint

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Abstract

To clarify the effects of biochar application on N2O emissions from Chinese cropland soils and identify the main controlling factors, published experimental data were collected and analyzed using meta-analysis to quantitatively evaluate the impacts of climate, soil properties, field management practices, biochar characteristics, and application rate on soil N2O emissions under biochar amendment, with path analysis performed for each influencing factor. The results showed that when annual rainfall $ 600*mm*, *biocharsignificantlyreducedsoilN*2*Oemissions*(*P* < 0.05), *andthismitigationeffectstrengthenedwithincreasingannualrainfall*; *whenannualsunshinehours* > 1000*h*, *theN*2*Oemissionreductioneffectofbiocharweakenedwithincreasingsunshinehours*.*WhensoilpH* $6.5 the N2O mitigation effect of biochar exhibited a trend of initially increasing then decreasing with rising soil pH; biochar application in loam soil produced a significant N2O emission reduction (P<0.05), whereas the effects in sandy and clay soils were not significant (P>0.05). The N2O emission reduction effect of biochar was superior in mulched soils compared to non-mulched soils; the mitigation effect weakened with increasing nitrogen fertilizer application rate but strengthened with increasing biochar specific surface area. When biochar C/N ratio ranged from 30~500, soil N2O emissions under biochar application were significantly reduced (P<0.05); when biochar application rate ranged from 20~160 t hm 2, the N2O emission reduction effect of biochar strengthened with increasing application rate. The effect of biochar on soil N2O emission reduction displayed significant regional characteristics, with significant effects observed in South China, East China, Central China, and Northeast China (P<0.05), but not in Northwest China (P>0.05). Nitrogen fertilizer application rate, biochar application rate, mean annual temperature, and annual rainfall were the most critical factors influencing the emission reduction effectiveness of biochar, with interactions among these factors jointly affecting the N2O mitigation effect of biochar. This study can provide a reference for the

promotion and application of biochar in agricultural regions of China and for cropland N2O emission reduction.

Full Text

Abstract

To clarify the effects of biochar application on soil N_2O emissions and identify the main controlling factors in Chinese farmland, this study employed Meta-analysis to quantitatively analyze the impacts of climate, soil properties, field management practices, and biochar characteristics (including application rate) on soil N_2O emissions. Path analysis was subsequently used to determine the dominant influencing factors. The results demonstrated that biochar application significantly reduced soil N_2O emissions when annual precipitation was \$ $600mm(P <$
$0.05), withthemitigationeffectstrengtheningasprecipitationincreased.Whenannualsunshinehoursexceeded$
$0.05)butnotinsandyorclaysoils(P > 0.05).Themitigationeffectwasmorepronouncedinmulchedsoilsthaninno$
$mulchedsoilsanddiminishedwithincreasingnitrogenapplicationratewhilestrengtheningwithincreasingbioch$
$0.05).Atapplicationratesof20–160t·hm^{-2},themitigationeffectintensifiedwithincreasingbiocharapplicati$
$0.05)butnosignificanteffectinNorthwestChina(P > 0.05).Nitrogenfertilizerinput,biocharapplicationamou$
emissions.

1.1 Data Sources

Literature published before December 2016 was systematically searched from Chinese and English databases including CNKI, VIP, Wanfang, Web of Science, and Google Scholar using keywords such as "biochar," "black carbon," "nitrous oxide," "N_2O," "charcoal," and related terms. The screening criteria were: (1) studies conducted on Chinese farmland soils; (2) field, plot, or pot experiments; (3) at least one paired treatment of biochar application and control with identical field conditions; (4) clear documentation of experimental location, duration, and basic properties of soil and biochar; (5) provision of soil N_2O emission data or N_2O-N equivalents; (6) minimum of three replicates per treatment; and (7) selection of the longest-duration study when multiple publications reported identical experimental sites, years, and crop types. Based on these criteria, 41 valid publications were obtained, yielding 132 datasets.

1.2 Data Classification

Data were grouped according to factors influencing soil N_2O emissions, including experimental region, climatic factors (annual precipitation, mean temperature, sunshine hours), soil properties (pH and texture), field management practices (nitrogen application rate and mulching), and biochar characteristics (production temperature, specific surface area, C/N ratio) and application rate. Classification standards followed reference [15]. Using China' s regional classification method [16], study sites were divided into five regions: East China (Jiangsu, Zhejiang, Jiangxi, Anhui), Central China (Hunan, Henan), South China (Guangdong), Northwest China (Xinjiang, Shaanxi, Ningxia), and Northeast China (Liaoning). Annual precipitation thresholds were set at 400 mm and 600 mm [17], and mean annual temperature at 10 °C [18]. Data categories are summarized in .

1.3 Meta-analysis

Since some studies reported N_2O emissions as CO_2 equivalents or N_2O-N, data conversion was necessary. For CO_2 equivalents, values were divided by 298 to obtain N_2O emissions [19]. For N_2O-N values, conversion used a molecular weight factor of 28/44 [15]. Standard deviation, a critical parameter in Meta-analysis representing study weights, was obtained either directly from publications or by digitizing graphical data using Origin 9.0. When standard deviations were not reported, MetaWin 2.1 software' s resampling function was used to generate unweighted variance estimates [21-22].

Meta-analysis was performed using MetaWin 2.1, requiring mean N_2O emissions, standard deviations, and sample sizes for both biochar and control treatments. Effect size was quantified using a random-effects model to calculate the response ratio (lnR) [23]:

$$\ln R = \ln\left(\frac{X_e}{X_c}\right)$$

where R is the response ratio (N_2O emissions with biochar, X , divided by emissions without biochar, X). To express the direction and magnitude of biochar effects, the percentage change in N_2O emissions was calculated as:

$$\text{Change rate} = (R - 1) \times 100\%$$

The 95% confidence intervals were calculated following reference [24]. If the interval included 0, biochar had no significant effect ($P>0.05$). If entirely above 0, biochar significantly promoted emissions ($P<0.05$). If entirely below 0, biochar significantly reduced emissions ($P<0.05$) [25].

1.4 Path Analysis

Path analysis is a multivariate statistical method that reveals relationships among variables by partitioning direct, indirect, and total effects. Direct path coefficients represent a factor' s immediate influence on soil N_2O emissions, indirect coefficients show effects mediated through other variables, and total coefficients indicate overall impact [26]. Computational procedures followed reference [27].

1.5 Data Processing

Microsoft Excel 2010 was used for database construction, Origin 9.0 for figure preparation and digitization, MetaWin 2.1 for Meta-analysis, and SPSS 19.0 for path analysis.

2.1 Effects of Climatic Factors on Soil N_2O Emissions

Analysis of 41 publications revealed that biochar' s mitigation effect on soil N_2O emissions was closely related to climatic conditions [Figure 1: see original paper].

2.1.1 Effects of Annual Precipitation

Meta-analysis showed that annual precipitation attenuated soil N_2O emissions in Chinese farmland. When precipitation was <600 mm, biochar had no significant mitigation effect (P>0.05). However, at $ $600 mm, biochar significantly reduced emissions (P<0.05). The reduction rates were 10.7% (95% CI: 1.1% to -22.5%), 19.2% (95% CI: 2.4% to -40.8%), and 25.3% (95% CI: -6.6% to -43.4%) for precipitation levels of <400 mm, 400-600 mm, and $ 600*mm*, *respectively*, *indicatingthatmitigationstrengthenedwithincreasingprecipitation*.*Higherprecipitat* reductase [28]. Additionally, N_2O diffusion from deep soil to the atmosphere decreases with higher water content, while nitrifier activity declines, limiting substrates for denitrification. Biochar adsorbs ammonium, reducing energy substrates for nitrifiers, and its aromatic carbon structure adsorbs substrates for denitrifiers, thereby inhibiting both microbial groups and enhancing N_2O mitigation [29].

2.1.2 Effects of Annual Mean Temperature and Sunshine Hours

The 10 °C threshold represents the temperature at which warm-season plants begin accumulating organic matter [30]. At temperatures <10 °C and $ 10°*C*, *biocharsignificantlyreducedN{2}$O emissions by 27.3% and 17.9%, respectively, showing that mitigation effectiveness decreased with rising temperature. For sunshine hours of 1,000-2,000 h, the reduction rate was 21.3%, while at $* 2, 000*hitwas*16.7{2}$O mitigation.

Overall, biochar' s mitigation effect diminished with increasing temperature and sunshine hours. Both factors influence soil organic matter decomposition, microbial enzyme activity, and crop growth [31]. Higher temperatures enhance microbial and enzyme activities, strengthening substrate uptake by nitrifiers and denitrifiers and promoting organic matter mineralization [32]. Sunshine duration affects both soil temperature and crop growth, influencing N_2O emissions. Extended sunshine enhances root water and nutrient uptake, root oxygen consumption, and organic exudation, promoting denitrification [33]. Roots also absorb dissolved N_2O that cannot diffuse to the atmosphere, releasing it via transpiration [34]. Although biochar reduces N_2O emissions, its adsorption capacity is limited, so mitigation effectiveness declines as temperature and sunshine increase.

2.2 Effects of Soil Properties

2.2.1 Effects of Soil pH

Soil pH affects nitrifier and denitrifier activities, altering rates and end products of nitrification and denitrification [35]. At pH<6.5, biochar reduced N_2O emissions by 31.5%, but not significantly (P>0.05). At pH 6.5-7.5 and \$ $7.5, reductionsweresignificant(P < 0.05)at52.3\{2\}Oemissions[36].Inacidicsoils, microbialmetabolismisre$
$containingfunctionalgroupsshowreducedheavymetaladsorption, impairingmicrobialhabitat, andweakenedco$
adsorption [31,38].

2.2.2 Effects of Soil Texture

Biochar significantly reduced N_2O emissions in loam soils (P<0.05) but not in sandy or clay soils (P>0.05). Reduction rates were 2.8%, 22.6%, and 13.7% for sandy, loam, and clay soils, respectively, with loam showing the best mitigation. Soil texture influences nitrification, denitrification, N_2O diffusion, and organic matter decomposition [39-40]. Gas diffusion coefficients vary with texture, and loam' s balanced pore structure facilitates N_2O emission pathways, resulting in higher baseline emissions than sandy or clay soils [41].

2.3 Effects of Field Management Practices

2.3.1 Effects of Nitrogen Fertilizer Application Rate

Nitrogen application increases soil nitrogen content and substrates for nitrification ($NH_4{}^+$ and $NO_3{}^-$) while stimulating root growth and exudation, affecting N_2O emissions [42]. At application rates \$ $60kg \cdot hm$^{-
$2\}, biocharreducedemissionsbutnotsignificantly(P > 0.05).Themitigationeffectdecreasedwithincreasingni$
ratio in denitrification products [30]. Although biochar improves soil microenvironment and reduces nitrogen-related microbial abundance [44], its adsorption capacity is limited, causing mitigation effectiveness to decline at high nitrogen rates.

2.3.2 Effects of Plastic Film Mulching

Mulching alters soil temperature and moisture, affecting N_2O production, transport, and emissions. Biochar significantly reduced N_2O emissions under both mulched and non-mulched conditions (P<0.05), with a 25.3% reduction in mulched soils–6.2% greater than in non-mulched soils. Plastic film physically blocks water evaporation, increasing soil moisture [45] and promoting organic matter mineralization and denitrification. Film also absorbs solar radiation, reducing heat exchange and increasing soil temperature, which enhances microbial activity and organic matter decomposition [46]. Mulching concentrates

N_2O in a confined humid space, increasing its concentration and biochar adsorption efficiency, thereby improving mitigation effectiveness.

2.4 Effects of Biochar Properties and Application Rate

2.4.1 Effects of Biochar Production Temperature, Specific Surface Area, and C/N Ratio

Biochar production temperature, specific surface area, and C/N ratio all influence N_2O emissions. Production temperature significantly reduced emissions ($P<0.05$), with reduction rates of 32.6%, 43.9%, 35.6%, and 51.3% for temperatures of <400 °C, 400-500 °C, 500-600 °C, and \$ \$600 °C, respectively. This aligns with Cayuela et al. [47] because surface functional groups change with temperature; higher temperatures increase aromaticity, reduce polarity, and enhance stability [48]. Low-temperature biochar has uniform micropores, while elevated temperatures cause irregular distribution and pore wall collapse, increasing surface roughness [49], consistent with observed emission patterns.

Specific surface area showed no significant overall effect ($P>0.05$), but reduction rates were 15.5% and 35.1% for areas <100 and \$ $100m^{\{2\}\cdot g}$\{-1\}, $respectively, indicatingthatmitigationimproveswithincreasingsurfacearea. Largersurfaceareaenhances$ adsorption capacity [50].

When biochar C/N ratio was 10-30, the effect was not significant ($P>0.05$), but at 30-500 it became significant ($P<0.05$). Mitigation increased then stabilized with higher C/N ratios because elevated C/N intensifies microbial activity while limiting nitrogen supply for nitrification and denitrification, promoting microbial immobilization of mineral nitrogen and interspecies competition, thereby reducing N_2O emissions [51].

2.4.2 Effects of Biochar Application Rate

Higher biochar rates increase adsorption area for ammonium and alter electron acceptors and redox potential [52], affecting N_2O emissions. At application rates of 20-160 $t \cdot hm^{-2}$, biochar significantly reduced emissions ($P<0.05$), with mitigation strengthening as application rate increased. Rates below 20 $t \cdot hm^{-2}$ showed no significant effect ($P>0.05$). Increased biochar application enhances adsorption of nitrification and denitrification substrates, reducing microbial N_2O production [53]. New porosity created by biochar improves anaerobic microbial community function and diversity, reducing denitrifier populations and soil denitrification potential [54], consistent with findings by Li et al. [55] and Jia et al. [56].

2.5 Regional Characteristics of Biochar Effects on Soil N_2O Emissions

Biochar effects varied significantly across China [Figure 5: see original paper]. In South, East, Central, and Northeast China, biochar significantly reduced

N_2O emissions ($P<0.05$) by 31.4%, 27.2%, 26.7%, and 21.5%, respectively. In Northwest China, emissions decreased by 17.2%, but not significantly ($P>0.5$). Biochar showed the best mitigation in South China and the worst in Northwest China, correlating with regional climate, soil properties, and management practices. Annual precipitation decreases from southeast to northwest, with South China receiving the most rainfall [57]; since mitigation strengthens with precipitation, South China showed the greatest effect. Spatial patterns of sunshine hours (more in north and west) and temperature variations also influenced regional effectiveness. Soil property variability and different cropping systems further contributed to these regional patterns [59-60], as did management practices affecting soil hydrothermal conditions and microbial communities [61].

2.6 Path Analysis of Biochar Effects on Soil N_2O Emissions

Since biochar mitigation is influenced by multiple interacting factors, path analysis was conducted using quantitative parameters: annual precipitation (X_1), mean temperature (X_2), sunshine hours (X_3), soil pH (X_4), texture (X_5), nitrogen rate (X_6), biochar production temperature (X_7), specific surface area (X_8), C/N ratio (X_9), application rate (X_{10}), and N_2O emission reduction rate (I) .

Direct path coefficients ranked as: $X_6 > X_{10} > X_2 > X_1 > X_3 > X_9 > X_4 > X_5 > X_8 > X_7$, indicating that nitrogen fertilizer input, biochar application rate, and mean temperature were the three dominant factors. Annual precipitation and sunshine hours had similar direct effects, while biochar production temperature and specific surface area had smaller direct impacts. All factors showed positive direct effects on mitigation.

Indirect effects revealed that temperature and precipitation most strongly influenced mitigation indirectly through soil pH, while sunshine hours acted primarily through precipitation. Among soil properties, pH and texture interacted strongly, with each influencing mitigation primarily through the other. Nitrogen rate affected mitigation mainly through soil pH. Among biochar properties, production temperature acted primarily through specific surface area, while specific surface area, C/N ratio, and application rate all influenced mitigation mainly through soil pH. Total path coefficients showed that nitrogen fertilizer input, biochar application rate, mean temperature, and precipitation were the most important factors overall, with pH’ s indirect contributions being substantial. Therefore, optimizing nitrogen and biochar application while managing soil pH is crucial for effective N_2O mitigation in Chinese farmland.

Conclusions

1) Biochar application reduces soil N_2O emissions in Chinese farmland, but the magnitude depends on external factors including precipitation, temperature, sunshine hours, soil pH and texture, nitrogen application rate, and plastic film mulching.

2) Biochar properties including production temperature, specific surface area, C/N ratio, and application rate also affect emissions, with C/N ratio and application rate being particularly influential.

3) Biochar significantly reduced N_2O emissions in South, East, Central, and Northeast China, but not in Northwest China.

Therefore, achieving effective N_2O mitigation through biochar application requires integrated consideration of climate, soil properties, field management, and biochar characteristics.

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