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Effect of Biochar on N_2O Emission in a Vegetable Field

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Abstract

Biochar application to croplands has been proposed as a potential strategy to decrease losses of soil-reactive nitrogen (N) to the air and water. However, the extent and spatial variability of biochar function at the global level are still unclear. A field experiment was conducted in a Shanghai suburb in 2021. The experiment included 4 treatments in a randomized complete block design with 3 replicates: biochar (CK); biochar at rates of 10t/ha (C1), 20t/ha (C2), and 40t/ha (C3), both as basal and two topdressings. Soil N_2O emissions and the properties of soil and infiltration water samples were investigated. The soil N_2O emissions (6.5-38.0%) decreased after biochar amendment. The lowest N_2O emission was achieved when the biochar application rate was 40 t/ha. The soil N_2O emission was correlated with soil pH, soil water content, and dissolved nitrogen content. A straw biochar application rate of 40 t/ha could serve as an appropriate amendment for mitigating N_2O emission in the plastic shed cultivated with vegetables.

Keywords

Biochar, N_2O emission, Greenhouse gas, Soil, Vegetable

1. Introduction

Anthropogenic activities of rapid industrial development based on fossil-fuel combustion and intensive agricultural production with heavy nitrogen (N) fertilization are driving excessive releases of carbon (CO_2 and CH4) and reactive N (NH3, N_2O, and aqueous leached N) to the atmosphere and hydrosphere. This leads to global warming, ecosystem acidification, waterway eutrophication, and biodiversity loss. As the earth becomes warmer and warmer, the planet will soon no longer be habitable. August 12, 2022, is the day which China Meteorological Administration launched a red alert for extremely high temperatures (≥40ºC) for the first time in history. It is actually an alert from the planet that reminds human beings to reach Carbon Neutrality as soon as possible. As we all know, economic crops such as vegetables, corns, and wheat all produce mass amounts of CO_2, CH4, and also N_2O when farming, especially when too much N fertilizer is added to the soil.

N_2O is the third most important greenhouse gas globally, with emissions at 6%, after CO_2 and CH4. Although the N_2O emission level is relatively low, its warming potential is 300 times that of CO_2, and it can exist in the atmosphere for 114 years, which will seriously damage the stratosphere and ozone layer. N_2O emission sources are divided into natural sources and man-made sources. Anthropogenic sources include arable land, fossil fuels, livestock farms, and industrial production. About two-thirds of the nitrous oxide released into the atmosphere each year comes from soil. Over the past 40 years, the concentration of nitrous oxide emissions has increased by 1.83 parts per million per year, to about 330 ppb in the atmosphere today.

Biochar (a recalcitrant carbonaceous biomass product generated by anaerobic pyrolysis) research, as with any other line of research, should be based on a well-defined scientific question. As the number of researchers conducting and publishing biochar-related research is large, it is essential that authors are up-to-date with the literature. In addition, they can demonstrate the novelty of the research in the paper being submitted for publication, rather than repeating research that has already been conducted. Biochar research needs to move from descriptive to mechanistic. Linking the effects of

biochar on N_2O emissions to changes in the composition of bacteria communities responsible for denitrification to the composition of functional groups of biochar, or to variations in N_2O-producing processes and related functional microbes, provides an understanding of the mechanisms involved in changes in N_2O emissions. The mechanistic understanding gained from biochar research will allow us to extrapolate findings from one site to another. Lack of novelty is the single most frequently used reason to reject a biochar research-related manuscript with or without review.

In recent years, the use of biochar in cropland management has attracted great attention due to its high potential to sequester carbon and regulate soil N cycling. A global biochar strategy has been estimated to be capable of mitigating as much as 12% of the annual anthropogenic CO_2-C equivalent emissions. However, the impact of biochar on soil N emissions is still under debate and warrants further investigation. If a proper biochar strategy could effectively reduce soil reactive N emissions, multiple benefits would be achieved to cope with the changing global environment.

The effect of biochar on soil N emissions is highly variable, depending on biochar types, biochar addition rates, soil characteristics, and environmental conditions. To illustrate whether biochar holds promise as a sustainable strategy for improving soil N conservation, several research groups have conducted meta-analyses. These analyses explored the linkage between the soil N emissions and each individual factor separately. However, they were less adequate to combine multiple parameters to predict how a specific type of biochar at a specific addition level influences a certain soil. The diverse interaction of biochar with soil properties illustrates the need for a spatially resolved assessment of biochar impacts across landscapes. To the authors' knowledge, they explored the spatial changes in crop yield as affected by biochar; however, no studies have mapped the role of biochar in the soil N emissions, and as a result, the overall capacity of biochar to regulate N fluxes at regional and global levels remains uncertain. This information is critically needed to judge whether and how biochar application to croplands could achieve sustainable benefits to both crop production and soil N conservation. The impact of biochar on cropland N emissions involves complex nonlinear processes that integrate biochar, soil, and environmental properties. Previous studies investigating the effects of biocharaging on soil properties show changes in biochar surface chemistry, which could potentially affect C and N cycling and therefore affect the fluxes of N_2O. However, experimentation under carefully controlled incubation conditions or for short periods does not represent well the aging processes in field soils. An experiment of soil inorganic N dynamics under biochar amendment for a long time linked to N_2O emissions was needed.

1.1 Research question

The benefits of biochar application are well-described in agricultural soils, however, there is a dearth of information on its effects in agricultural temperate soils. An interesting and little-explored interaction may occur in an intensive agriculture setting; biochar addition may modify the effect of commonplace N fertilization. At what ratio of biochar with N fertilizer will decrease the amount of N_2O emissions in the plastic shed cultivated by the vegetable field?

1.2 Literature review

Biochar contains stable carbon which exists as aromatic hydrocarbon and graphite. They have a large surface area due to their porous structure, which also brings characteristics such as having a good ability to absorb heavy metals and other pollutants in the soil. They also reduce the production of greenhouse gases especially N_2O when added to farmlands for vegetables by allowing fewer microbes that produce this gas alive [1]. As a new amendment used on agriculture in order to reduce carbon emission, its effect on reducing nitrates emission is also great [5, 6]. The N_2O emission amount is a linear positive correlation with the amount of nitrate nitrogen content in the soil, which is shown in multiple researches [2-4]. Adding biochar into soil under dry conditions will decrease the emission of nitrogen oxide on a big scale but increase when soil is wet and moist, on the other hand, biochar also decreases the amount of nitrates turning into N_2O [7-9]. On the other hand, N_2O is also a big deal since nitrous oxide is 250 times more responsible for global warming than the same mass of carbon dioxide. The major way of nitrous oxide formation is caused by heavy irrigation where nitrogen ions in soil react with water which forms a lot of gaseous nitrous oxide escaping into the air [10]. Fertilizers and irrigation measurements may increase the emission of N_2O [11]. Biochar may decrease the emission of N_2O by approximately 38% in the experiment of Nils Borchard [12]. The data shown might be biased by multiple factors including the type of biochar used, climate, etc. [13]. Under different environments, the usage of biochar can be different [14].

This research is based on previous research focusing majorly on wheat, corn, rice, and potatoes. However, there is nearly no research focusing on vegetables like lettuce and tomatoes, which are also widely planted. There are actually many differences between vegetables and staple foods on how to use biochar in an efficient way. Staple foods usually produce N_2O in the vegetable field. So, this research will mainly focus on how to use biochar in the most efficient way in order to decrease the amount of greenhouse gases produced. This research is important for the goal of reaching Carbon Neutrality since agriculture is responsible for about 16% of total carbon emissions in China. It is much higher than the average ratio of the world which is 12%. This research is about how to decrease greenhouse gases produced by vegetables, which will help to decrease the total carbon emission from agriculture. This is needed in order to reach the goal of Carbon Neutrality.

2. Materials and Methods

The experiments were conducted in a field in Shanghai. The wheat straw biochar was purchased from Sanli Co., Henan Province, China. The experimental biochar (0.1-1.0 mm) was pyrolyzed at 350-400°C with low oxygen. Each plot (5 m length × 2 m width) had straw biochar incorporated at three different rates: 10, 20 and 40 t/ha. The treatments were designated CK (control without biochar), C1, C2, and C3. The control without biochar amendment was also set for reference. Each of the four treatments had three replicates. Altogether, the 12 plots were randomized in the greenhouse and each plot was isolated from surrounding plots by PVC baffles.

The field study lasted for 90 days. The tomato was cultivated. The gas samples were collected using a static transparent chamber. The N_2O samples from all the plots were collected at the same time to avoid sampling time influences on greenhouse gas concentrations, and then immediately taken to the laboratory. The sampling frequency was once a week. The N_2O concentrations were determined by a gas chromatograph (7820A, Agilent Technologies Inc., Santa Clara, CA, USA).

Soil samples were collected using a steel auger of 2.0 cm diameter before transplanting and after harvesting. The sampling depth was 20 cm. Soil samples were collected before and after tomato planting. The pH with a digital pH meter (pH meter 6250, Jenco Co. Ltd, USA). For the determination of soil carbon (TC), soil samples were ground to a fine powder (<75 μm) and were analyzed using an elemental analyzer (Vario EL cube, Elementar Co. Ltd, Germany).

3. Results

3.1 Soil pH

Soil pH is a measure of the acidity or alkalinity of the soil. Most soils have pH values between 3.5 and 10. In higher rainfall areas, the natural pH of soils typically ranges from 5 to 7. While in drier areas, the range is 6.5 to 9. Soils can be classified according to their pH value: 6.5 to 7.5—neutral; over 7.5—alkaline; less than 6.5—acidic, and soils with pH less than 5.5 are considered strongly acidic. Soil pH affects the amount of nutrients and chemicals that are soluble in soil water, and therefore the amount of nutrients available to plants. Some nutrients are more available under acid conditions while others are more available under alkaline conditions.

The soil pH is in the range of 6.66-7.08. The pH level increased with the amount of biochar application was found. The initial soil pH was about 6.66 in all the treatments. After the vegetable cultivation, the soil pH increased to 6.78, 6.88, and 7.08 in C1, C2, and C3 treatments, respectively. This indicated the fact that a higher presence of biochar applied into the soil may make soil basic. Under this experiment, the highest ratio of biochar added to soil is 40 t/ha which raises the pH value to 7.08. compared with the CK, the pH was increased by 0.42 units.

3.2 Soil TN

Soil TN refers to the sum of various forms of nitrogen content in the soil. It includes organic and inorganic nitrogen but does not include molecular nitrogen in soil air. The soil TN content decreased sharply with the increase in soil depth. Soil TN content is in dynamic change. Its fluctuation depends on the relative amount of N accumulation and consumption, especially on the bioaccumulation and hydrolysis of soil organic matter. For natural soils, the equilibrium value of TN content at stable levels is a function of climate, topography or landform, vegetation and organisms, parent material, and age or time of soil formation. The soil TN content was in the range of 2.4-2.6 g/kg. The TN contents increased a bit with the amount of biochar application in the current study.

3.3 Soil DN

Soil DN refers to N compounds with different structures and molecular weights that can be dissolved in water through 0.45 μm filter pores. It is one of the most active nitrogen components in terrestrial ecosystems. On the one hand, DN can be absorbed by plants and microorganisms, which is of great significance in improving soil biological activity and soil fertility. On the other hand, it can be lost with water and will cause environmental pollution.

The soil DN was in the range of 235.68-263.34 mg/kg. The DN level decreased with the amount of biochar application was found. The initial soil pH was 263.34 mg/kg in the CK treatment. After the biochar application and vegetable cultivation, the soil DN content decreased to 256.5 mg/kg, 247.1 mg/kg, and 235.7 mg/kg in C1, C2, and C3 treatments, respectively. The soil DN content decreased by 2.6-10.5%.

3.4 Soil water content

The water in the soil is constantly exchanged with the water in the surrounding medium, and the water inside the soil is also in motion. This water exchange and change is not only restricted by soil physical properties but also affected by rainfall, infiltration, evapotranspiration, and other water movements. In order to describe the dynamic changes of soil

moisture with time and space, soil water content is usually used to represent the size of soil moisture. The soil water content under some characteristic conditions is used to reflect the characteristics of their change. This study was conducted in a plastic shed with only irrigation water and no rain received. Water-filled pore space (WFPS) content was calculated by the soil water content.

The soil WFPS was in the range of 45.5-50.4%. The WFPS increased with the amount of biochar application was found. The soil WFPS content increased by 0.4-10.8%.

3.5 Soil N_2O emission

The cumulative soil N_2O emission was in the range of 5.8-3.6kg N/ha. The cumulative soil N_2O emission decreased with the amount of biochar application was found. The soil N_2O emission decreased by 6.5-38.0%.

4. Discussions

Soil pH will affect N_2O emission amount by influencing the amount, kind, and activity of microbes in the soil. As pH value is set as the major independent variable, the N_2O tends to show an inversely proportional relationship with pH value between a range of pH 5.5-7.5 for the reason of NOS (nitric oxide synthase). NOS will be the most active under a pH level of 8, while acidic soil will depress its activity. Its effect is to depress the formation of N_2O and make it back to N. Meanwhile, a lower pH level may also encourage the escalation of N_2O from soil.

Soil moisture will impact the effect of biochar decreasing soil N_2O emission. The diffusion routine becomes meandering due to low soil moisture. However, the presence of biochar makes it even more meandering, providing more absorbing binds and more time before N_2O is emitted. It means more N_2O would be absorbed instead of emitted. A wet soil will make the cracks less meandering, which increases the emission. As observed in a drier field, N_2O emission will actually increase as the WFPS increases. This proves the theory that under certain situations, wetter soil does increase the emission of N_2O.

Biochar is a kind of basic material that can make the soil environment less acidic through the liming effect which already proved effective in decreasing the soil emission of N_2O. Adding lime to agricultural soil will raise the pH level which suppresses the nitrification action which produces N_2O. Among all the ways of decreasing the emission of N_2O based on suppressing nitrification action, raising the soil pH may also increase the soil's total nitrogen as nitrous oxide is turned into nitrogen. Adding biochar to agricultural soil in order to make the soil more basic has been connected to the reduction of nitrous oxide emissions. It is clear that using biochar can decrease N_2O emission through changing the properties of soil which causes impacts on nitrification action caused by microbes and soil. This is also caused by another factor of biochar, porous, which lets air be more able to blow into the soil and make soil full of oxygen. This may suppress the nitrification process of microbes.

Biochar, in general, has a mitigation potential for soil N_2O emissions. Biochar type, biochar addition rate, and climatic zone are significant controlling factors that influence the effect of biochar on soil N_2O emissions. A significantly larger potential of biochar for N_2O mitigation is observed in laboratory experiments relative to that in field trials. The possible reasons for biochar to decrease soil N_2O emissions in denitrification-dominated soils include the following: (a) The N_2O reductase was found to be less active at low pH, and therefore, the liming effect of biochar may benefit N_2O reductase activity, which in turn facilitates further N_2O reduction towards N2; (b) The “electronic conductor” of the biochar matrix itself, together with the “electron shuttle” derived from the quinone-hydroquinone functional groups on the surface of the biochar, might act as catalytic active sites favoring the transfer of electrons towards soil denitrifying microorganisms, thus promoting N_2O consumption; (c) Biochar may increase the abundance of N_2O-reducing bacteria in certain cases, providing more biochemical reaction basis. (d) The hydrophilic property of biochar and its interaction with soil microaggregates may protect soil microsites from exposure to oxygen, creating further reduced conditions prone to N_2O conversion. Biochar made from manure has a smaller impact on mitigating soil N_2O emissions. This may be ascribed to the lower surface area, weaker aromatic structure, and fewer functional groups of this biochar, which is less reactive in interacting with N_2O turnover. In addition, manure biochar usually has a high N concentration, which has been demonstrated to mineralize in soil to a certain extent. This may be due to the additive function of the biochar properties. A relatively higher reduction in soil N_2O emissions by biochar tends to occur in finely textured loam soils, which are more prone to denitrification and thus could assist with biochar's role in reducing soil N_2O emissions by regulating the denitrification process. In comparison with Soil Organic Content-rich soils, biochar is less effective in decreasing N_2O emissions in soils with low Soil Organic Content. How to use biochar in order to decrease N_2O emission is still a topic needing further exploration about the mechanism between biochar, N_2O formation, and microbes.

5. Data analyze

Multi-factor repeated measures analysis of variance (ANOVA) was used to investigate the main effect of biochar

application on soil properties. Each data point in Figures represents an average value, vertical bars standard error of the means. All significant levels were set at $p < 0.05$.

6. Conclusions

This report is focused on the research question of at what dose of biochar with N fertilizer will decrease the amount of N_2O and it produced by the kind of vegetable planted, with experimental data that gives the maximum efficiency and limitations about the presence of different amounts of biochar applied into the soil. It is proved that adding biochar into the soil helps in reducing the emission of N_2O in agricultural soil where the balance of the reversible reaction nitrification, and also made the soil moisture at a high level. The soil with biochar will become more permeable so more air may enter the soil increasing the yield of amoA and other microbes.

This research is conducted based on former researches on biochar. It justified the effect of biochar on reducing N_2O emissions in agricultural soil. Furthermore, it finds the efficiency pattern curve which indicates that overdose biochar not only could be wasted but also increase N_2O emission if the soil is dry with a WFPS under 40%. This research points out that the maximum efficiency of biochar reaches between 20 t/ha and 40 t/ha. Compared to former researches, this research determines the most efficient dose of wheat straw biochar pyrolyzed at 350-400°C with low oxygen is 20 t/ha or 40 t/ha depending on the soil moisture in an environment with similar temperature and soil pH in Shanghai suburb.

7. Future outlook

The biochar effects synthesized in this paper are, in many cases, derived from experiments characterized by single-dose designs and at relatively short-term time scales. Therefore, the current global simulations may well reflect the biochar first-year effects after a single-dose application. In the long term, the physically mediated effects of biochar (such as improvements to soil porosity, water holding capacity, and CEC) may be maintained or even increased via biochar weathering. In contrast, the chemically mediated effects (such as soil pH increase and mineral nutrient supplement) may fade due to mineral nutrient uptake, ion exchange, and leaching reactions. Therefore, the introduction of biochar in the soil may provide a long support for reduced N_2O emission as time goes by. However, the long-term impacts of biochar on soil N_2O emissions and crop production remain controversial. The biochar application in the soil still requires further investigation.

There are also unsolved problems and deficiencies within this research. There are too few samples and trials done within this research so the accurate amount of the most efficient dose of wheat stem biochar is not clear. The following research conduct trials at doses between 20 t/ha and 40 t/ha, based on the data of this research. Also, the limitation of this data is very large since only soil with similar particle size, acidity, and contents and under similar climates may use this data directly. A little difference may cause a large difference in consequences. Also, only tomatoes are cultivated which also means that different kinds of crops may lead to completely different data and trends. This problem may be solved by planting different kinds of crops, which produce different possibilities such as wheat and rice.

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