Effects of Biochar and Basalt Additions on Carbon Sequestration and Fluxes of Greenhouse Gases in Soils

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Abstract

Inspired by soil as a major terrestrial stock of greenhouse gases, the overuse of agricultural fertilizers, and the adoption of geoengineering as a scientific strategy to curtail the onset of climate change, this investigation focuses on the range of potential of different soil additives to enhance sequestration and storage of greenhouse gases while increasing soil health. Research centered on the sequestration- and health-enhancing abilities of two soil additives—biochar and basalt powder—when mixed at different magnitudes and combinations within agricultural soil. Analyses included comparisons of soil pH, moisture content, total carbon and nitrogen stocks, ammonium and nitrate stocks, microbial biomass, and fluxes of carbon dioxide and nitrous oxide across 24 plots of soil mixed with different magnitudes and combinations of biochar and basalt powder. The goal behind this investigation was to potentially highlight key combinations that could be used in agroecosystems to increase global sequestration and storage of greenhouse gases, while naturally improving soil health. Results of this investigation show that soils treated with different levels and combinations of biochar and basalt can lead to changes in pH, moisture, stocks of carbon, nitrogen, ammonium, and nitrate, and microbial biomass, and provide a unique structure, substrate, porosity, and/or sorption capacity, that affect the ability of soil to store and sequester carbon dioxide and nitrous oxide.


Introduction

Of late, climate change has gained widespread prominence as one of the greatest human-induced threats of the natural world. Largely stimulated by a global increase in greenhouse gas emissions, humankind faces boosts in temperatures, rising sea levels, and extreme weather. In light of an apparent global failure to mitigate these emissions, many scientists have developed geoengineering strategies, wherein the current state of the planet could be altered to curtail the onset of climate change. One such tactic involves using soil in agroecosystems as a method of sequestering and storing greenhouse gases from the atmosphere.

Soils function as both sinks and sources of carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) (Zwieten et al 2009). Although roughly 20 percent of global emissions of greenhouse gases originates in agricultural activities, soil contains approximately 2,500 gigatons of carbon globally—3.3 times the amount stored in the atmosphere, and 4.5 times the amount stored in terrestrial biota (Lokupitiya and Paustian 2006; Lal 2004). In light of the Green Revolution, agricultural cultivation in temperate zones has caused the release of 60 percent of its stored carbon into the atmosphere (Lal 2004). In 2004 alone, agricultural sources released 3 giga tonnes CO₂e (carbon dioxide equivalents)—approximately 8 percent of global greenhouse gas emissions (Zwieten et al 2009). Of the 16 Tg of nitrous oxide released per year in the 1990s, almost half originated from human alterations to agricultural soil (Reay et al 2012).

As human-created-and-managed arrangements, agroecosystems can be easily manipulated, and they provide a direct, widespread method of sequestering and storing atmospheric carbon dioxide and nitrous oxide that humans have unnaturally released through unsustainable tilling and the overuse of fertilizers. Soil sequestration and storage of greenhouse
gases is a naturally functioning, cost-effective, and environmentally friendly biological tool. This investigation explores the range of potential of different soil characteristics to sequester and contain greenhouse gases from the atmosphere through the lens of two productivity-enhancing organic soil additives—biochar biomass and basalt powder—mixed at different magnitudes and combinations within agricultural soil. Biochar, produced by pyrolysis, stores carbon sequestered in plant biomass with an extremely slow, stable decomposition rate; and it enhances soil structure, fertility, biomass production, and nutrient retention and efficiency (Lehmann 2007). Basalt provides nutrients in the form of base cations that enhance plant processes (short term), combines with carbon dioxide to form carbonate minerals (long term), and improves soil infiltration, runoff, and retention (Gislason et al 2010; Rudd 2012). The goal of this investigation was to assess the abilities of biochar and basalt additives to naturally enhance soil health while simultaneously decreasing and sequestering greenhouse gas emissions. Assessments were made through a comparison of soil pH, moisture, carbon and nitrogen stocks and ratios, concentrations of ammonium and nitrate, microbial biomass, and fluxes of carbon dioxide and nitrous oxide gases.

**Methods**

**Study Site and Experimental Design:** Soil samples were collected at New Harmony Farm in West Newbury, Massachusetts—home to a layout of twenty-four 2.0 m by 2.0 m plots of agricultural soils (two control plots and twenty-two experimental plots), each of which were manipulated with different magnitudes and combinations of basalt and biochar in July of 2012 (Figure 1). Basalt gradients included no basalt, low basalt, medium basalt, and high basalt; biochar gradients included no biochar, low biochar, and high biochar. Soils were left undisturbed for five months, aside from the planting and harvesting of *Raphanus sativus* (radishes)—the latter of which took place days before the third round of sampling. A total of 72 soil cores were taken at random locations within each plot—three replicates from each plot on three separate trips to the field—using a bulk density soil corer (3.03 cm radius, 10.15 cm height). These soil cores were placed in plastic zip-lock bags, put on ice, and transported back to the Marine Biological Laboratory in Woods Hole, Massachusetts, where they were homogenized and refrigerated for later testing. Soil temperatures were measured at each plot using an analog soil thermometer.

**Soil pH:** Soil pH was observed through a direct measurement in the laboratory. For each plot replicate, 10.0 grams of soil were added to 50.0 ml of deionized water, whereafter its pH was measured using an Accumet pH/conductivity meter.

**Soil Moisture:** Soil moisture content was measured through a comparison of wet to dry weight in each soil core collected. In the lab, 10.0 grams of soil from each plot replicate was heated in a drying oven at 60°C for 24 hours and remassed. The difference in final and initial mass was used with bulk density to extrapolate the amount of water content in each soil plot. This information was then used in a comparison of wet and dry weights using a wet-to-dry ratio.

**Carbon and Nitrogen Content:** Total soil carbon and nitrogen content was measured through a calculation of bulk density and an elemental analysis. For each plot replicate, homogenized soil was massed and dried for 24 hours to calculate bulk density. 3.0 grams of each replicate were crushed and mixed with its replicate counterparts to create a composite sample, from which 15.0-20.0 mg of soil were packed and placed in a PerkinElmer Series II CHNS/O Analyzer to measure the percentage of carbon and nitrogen in the soil at each plot. This data was combined with bulk density to obtain the amount of carbon and nitrogen in each soil plot.
Storage of Ammonium and Nitrate: Organic nitrogen storage was measured through an observation of ammonium ($\text{NH}_4^+$) and nitrate ($\text{NO}_3^-$) stocks at each plot. For each plot replicate, 15.0 grams of homogenized soil were added to 50.0 ml of 1.0 M KCl and shaken at 150 rpm for one hour. After settling for 12 hours, the supernatant from each mixture was then pressure-filtered through one glass fiber Whatman GF/F filter and frozen for later analysis. To measure ammonium concentrations in each plot, filtered supernatants were unfrozen at room temperature and mixed for one hour with phenol, nitropusside, and hypochlorite oxidizing solutions, respectively, after which absorbance was measured at a wavelength of 640.0 nm with a UV-1600 spectrophotometer, and translated into concentration values. To measure nitrate concentrations in each plot, filtered supernatant was measured untreated with a LACHAT QuickChem 8000. Three KCl blanks were prepared and analyzed for ammonium and nitrate for each round of sampling.

Microbial Biomass: Organic carbon storage and microbial life were observed through a measure of microbial biomass within each soil plot, a value that was obtained by counting bacterial cells through a method of direct epifluorescence. For each plot, 1.0 gram of soil were placed in 15.0 mL falcon tubes, which were then filled to the brim with 1.0x phosphate-buffered saline (PBS) solution and placed on a Thermolyne MAXIMIX Plus vortexer for 10 minutes to shake the microbes loose. The shaken falcon tubes were then placed upright for 2.0 minute to settle the soil out, whereafter the suspended solution was pressure-filtered through one glass fiber Whatman GF/F filter. 4.0 mL of the remaining liquid was then stained with a 200.0 uL DAPI (4', 6 diamidino-2-phenylindole) working solution of 200.0 ug/ml for 5 minutes, and then filtered through a 0.22 um pore-size black polycarbonate Millipore GS filter (an additional 2.0 mL of PBS was filtered to collect remaining sample). Each filter was then placed on a glass microscope slide over a drop of immersion oil and under a cover slip that also contained a drop of oil, and viewed under a Zeiss epifluorescence microscope for counting. Three controls of 4.0 mL of PBS were also stained and filtered for viewing. Only organisms less than 5.0 um were included in counts.

Greenhouse Gas Fluxes: Fluxes of carbon dioxide ($\text{CO}_2$) and nitrous oxide ($\text{N}_2\text{O}$) from each plot were measured in the field on two separate days using a Mobile Greenhouse Gas Measurement System that included LGR, LMA, LNC, and Li-Cor 7000 gas analyzers. Soil on each plot was covered with a gas chamber, from which fluxes were measured for a total of 5 minutes, with a 1-minute ambient atmospheric measurement in between. Calculations of these fluxes were inclusive of only minutes 2-4 to improve accuracy.

Results

Soil pH: Average pH in each treatment showed a general trend of increasing acidity across increasing gradients of biochar and basalt (Figure 2). In the absence of biochar, pH increased from approximately 5.75 to about 6.1 with increasing levels of basalt, despite a drop back to 5.7 at medium basalt levels. At low levels of biochar, pH increased from about 5.75 to approximately 6.2, although medium basalt exhibited the highest pH at about 6.3. At high levels of biochar, pH increased from about 6.1 to 6.35 from no to low basalt levels, followed by a decrease in medium and high basalt levels to about 6.2. In the absence of basalt, pH increased from approximately 5.75 without biochar and with low biochar levels to roughly 6.2 at high biochar levels. At low levels of basalt, pH increased from about 5.9 in the absence of biochar to approximately 6.4 at high levels of biochar. At medium levels of basalt, pH increased from about 5.7 to roughly 6.25 at low and high levels of biochar. At high levels of basalt, pH increased from about 6.1 to roughly 6.2, although this increase was not significant. pH was highest in soils
Soil Moisture: Average wet-to-dry ratios in each treatment revealed two noticeable trends (Figure 3). For one, at each level of biochar, moisture was greatest when basalt was absent or at low levels, and noticeably lower at levels of medium and high basalt. At each level of biochar, average wet-to-dry ratios remained relatively constant at about 1.31-1.34 when basalt was absent or at low levels, but dropped to between around 1.29-1.30 at medium and high levels of basalt. In addition, as levels of biochar increase, the gap between wet-to-dry ratios between soils with no and low basalt and medium and high basalt increases. Soil moisture was greatest in soils with low biochar and no basalt, at a wet-to-dry ratio of approximately 1.34, and lowest in soils with high biochar and high basalt at about 1.28.

Carbon and Nitrogen Content: Average carbon content in each treatment revealed no distinct overall trends, with all soils holding between roughly 210.0-260.0 g C/m² (Figure 4). In soils treated with low basalt, soils treated with high biochar exhibited the highest levels of carbon at roughly 260.0 g C/m², distinctly higher than in soils with no biochar at 225.0 g C/m². In soils treated with high basalt, soils treated with high biochar exhibited the highest levels of carbon at roughly 240.0 g C/m², noticeably higher than in soils with both no and low biochar at roughly 210.0 g C/m². No distinct changes were exhibited in soils treated with no basalt and medium basalt. Soils treated with low levels of basalt and high levels of biochar contained roughly 264.0 g C/m², a value noticeably higher than in all soils treated with no basalt, those treated with low basalt but no biochar, and high basalt and no biochar. Carbon content was the lowest in soils treated with both medium and high basalt levels and no and low biochar at approximately 215.0 g C/m².

Average nitrogen content in each treatment revealed no distinct overall trends as well, with all soils holding between approximately 15.0-18.0 g N/m² (Figure 5). In soils treated with no biochar, soils treated with low basalt exhibited the greatest amount of nitrogen at approximately 16.5 g N/m², roughly 1.5 g N/m² more than any other soil treated with no biochar. In soils treated with low biochar, soils with no basalt exhibited the highest amount of nitrogen at about 17.5 g N/m², after which nitrogen content decreases by roughly 1.5 g N/m² until it returns to its original level of about 17.0 g N/m² when treated with high levels of basalt. Soils treated with high levels of biochar showed no distinct pattern, with only medium basalt containing noticeably lower nitrogen at about 15.0 g N/m². Trends across biochar treatments were only exhibited in soils treated with no basalt, in which those treated with low biochar contained the most nitrogen at roughly 17.5 g N/m², compared to 15.0 and 16.5 g N/m², and in soils treated with high basalt, in which those treated with low biochar contained the most nitrogen at about 17.4 g N/m², compared to 16.5 and 15.0 g N/m². Soil nitrogen was greatest in soils treated with low biochar and high basalt at roughly 17.5 g N/m², and lowest in soils treated with low biochar and low medium basalt at approximately 15.0 g N/m².

Average carbon-to-nitrogen ratios in each treatment also revealed no distinct overall trends, with all soils exhibiting ratios between approximately 13.0-15.5 (Figure 6). In soils treated with no biochar, soils treated without basalt exhibited the greatest C:N ratio at approximately 15.1, higher than in those treated with low, medium, and high levels of basalt, all of which exhibited ratios about 1.0 lower. In soils treated with low biochar, soils treated with low and medium levels exhibited the greatest C:N ratio at roughly 15.0, higher than in soils without basalt and with high basalt, at 13.5 and 12.0, respectively. Soils treated with high levels of biochar showed no distinct pattern. Trends across increasing levels of biochar were exhibited only in soils treated with no basalt, in which soils treated with no biochar displayed a noticeably higher C:N
ratio at about 15.0 than with low and high levels of biochar, both of which exhibited ratios of about 14.0. Soil carbon-to-nitrogen ratios were highest in soils at low biochar and low basalt, and at high biochar and medium basalt, both of which exhibited ratios at around 15.1, and lowest in soils with low biochar and high basalt at approximately 12.5.

**Stocks of Ammonium and Nitrate:** Average ammonium concentrations in each treatment displayed no noticeable trends across both biochar and basalt gradients, and no treatment exhibited a distinctly higher or lower concentration of ammonium (Figure 7). Individual concentrations were extremely variable across each sampling, and they showed a noticeable increase in the third round of sampling, following the removal of radishes from the plots.

Average nitrate concentrations in each treatment showed a general increase across biochar gradients in each level of basalt treatment, with the exception of high basalt (Figure 8). Soils with no and low basalt both exhibited their highest concentrations in soils treated with high biochar at approximately 1.7 ug NO₃/g soil, roughly 1.5 times as large as concentrations in soils treated with low biochar and 3.0 times as large than concentrations in soils treated with no biochar. Soils treated with medium basalt also contained the highest concentrations of nitrate in soils treated with high biochar at roughly 2.6 ug NO₃/g soil, about 1.7 times as large as that exhibited in soils treated with low biochar and 5.0 times as large as that exhibited in soils treated with no biochar. Soils treated with high basalt exhibited relatively similar concentrations of nitrate in soils with low and high biochar at about 1.3 ug NO₃/g soil, roughly 2.5 times as large as that exhibited in soils treated with no biochar. Aside from soils with high basalt, soils treated with high biochar revealed the highest levels of nitrate, the highest of which was exhibited at 2.6 ug NO₃/g soil in medium biochar, a value about 1.5 times as large as that found in soils treated with no and low basalt and almost 2.0 times as large as in soils treated with high basalt. Soils treated with increasing levels of basalt in the absence of biochar and with low biochar did not reveal noticeable changes. Soils treated with no biochar exhibited the smallest concentrations of nitrate, all of which were measured at about 0.6 ug NO₃/g soil.

**Microbial Biomass:** Average counts of microbes in each treatment exhibited a general increase in population size across biochar gradients in almost all levels of basalt treatment (Figure 9). In soils treated with no basalt, the greatest microbial populations were found in soils treated with high biochar at about 1.0*10⁶ cells/g soil, a value roughly 1.25 times as large as that found in low biochar, and twice as large as that without biochar. In soils treated with low basalt, the greatest microbial populations were found in soils treated with high biochar as well at about 1.1*10⁶ cells/g soil, a value roughly 1.4 times as large as that found in low biochar, and 2.2 times as large as that found in soils treated with no biochar. No noticeable trend was displayed within each layer of biochar. Soils treated with medium basalt exhibited equally high microbial populations in soils treated with low and high biochar at approximately 9.0*10⁵ cells/g soil, a value about 1.3 times as large as that found in soils treated with no biochar. Soils treated with high basalt exhibited their greatest population sizes in soils treated with low biochar at approximately 1.0*10⁶ cells/g soil, a value roughly 1.7 times as large as that found in soils treated with both no and high amounts of biochar. Soils treated with no biochar showed a general increase in populations from roughly 5.0*10⁵ cells/g soil in soils without basalt to about 7.0*10⁵ cells/g soil in soils with medium basalt, whereafter populations decreased to the size of those in low basalt at roughly 6.0*10⁵ cells/g soil. Soils treated with low biochar showed a general increase in populations from approximately 8.0*10⁵ cells/g soil in soils with no and low basalt to approximately 1.0*10⁶ in soils treated with medium and high levels of basalt. Soils treated with high amounts of biochar exhibited their highest populations in soils treated with no and low basalt, at 1.0*10⁶ cells/g soil and 1.1*10⁶ cells/g soil, respectively, whereafter populations
noticeably dropped with medium and high levels of basalt to approximately $6.0 \times 10^5$ cells/g soil. The greatest populations were found in soils treated with high biochar and low basalt at $1.1 \times 10^6$. The smallest populations were found in soils treated with high and low levels of biochar and high basalt, at roughly $6.0 \times 10^5$ cells/g soil.

**Greenhouse Gas Fluxes:** Average fluxes of carbon dioxide in each treatment did not reveal noticeable trend across the biochar gradient with each level of basalt (Figure 10). Soils treated with low basalt exhibited their smallest fluxes of carbon dioxide in soils treated with low biochar at 0.4 umol m$^{-2}$ s$^{-1}$, a flux almost 1.5 times as small as that exhibited in soils treated with no biochar and 2.75 times as small as that exhibited in soils with high biochar. Soils treated with medium basalt also exhibited their smallest fluxes of carbon dioxide in soils treated with low biochar at 0.5 umol m$^{-2}$ s$^{-1}$, a flux almost 1.6 times as small as that exhibited in soils treated with no biochar, and roughly 1.8 times as small as that exhibited in soils treated with high biochar. No noticeable trend or differences were exhibited in soils treated with no basalt and high basalt across biochar gradients. No clear trend or differences were revealed in soils treated with no biochar across the basalt gradient. Within soils treated with medium basalt, the smallest fluxes were exhibited in soils treated with no and high basalt. In soils treated with high biochar, soils treated with high basalt exhibited the smallest fluxes at roughly 0.6 umol m$^{-2}$ s$^{-1}$, a flux roughly 1.3 times as small as that exhibited in soils treated with no basalt, about 1.5 times as small as that exhibited in soils treated with medium basalt, and 1.8 times as small as that in soils treated with low basalt. The greatest flux of carbon dioxide was exhibited in soils treated with high biochar and low basalt at about 1.1 umol m$^{-2}$ s$^{-1}$. The smallest flux of carbon dioxide was exhibited in soils treated with low biochar and low basalt at approximately 0.4 umol m$^{-2}$ s$^{-1}$.

Average fluxes of nitrous oxide in each treatment revealed varying trends at each level of basalt with each level of biochar (Figure 11). Soils treated with no biochar exhibited a noticeable decrease in fluxes with increasing levels of basalt, exhibiting the smallest fluxes in soils treated with high levels of basalt at approximately -0.02 nmol m$^{-2}$ s$^{-1}$, a flux not only about 1.5 times as large as that exhibited in soils treated with medium and low basalt and roughly 1.5 times as small as that exhibited in soils treated with no basalt, but also uniquely negative. Soils treated with low biochar exhibited the lowest fluxes in soils treated with medium and high basalt at approximately -0.002 nmol m$^{-2}$ s$^{-1}$, a flux roughly 10.0 times smaller than soils treated with no and low levels of basalt and also uniquely negative. Soils treated with high biochar exhibited smallest fluxes at 0.0025 nmol m$^{-2}$ s$^{-1}$, a flux roughly 14.0 times as small as that exhibited in soils treated with no and low basalt and about 6.0 times as small as that exhibited in soils treated with high basalt. Within soils treated with no basalt, soils with low biochar exhibited the lowest fluxes at roughly 0.02 nmol m$^{-2}$ s$^{-1}$, a flux roughly 1.5 times as small as those exhibited in soils treated with no and high biochar. Within soils treated with low basalt, soils treated with no biochar exhibited the smallest fluxes at about 0.017 nmol m$^{-2}$ s$^{-1}$, a flux about 1.1 times as small as those exhibited in soils treated with low biochar and 2.0 times as small as those exhibited in soils treated with high biochar. Within soils treated with medium basalt, the smallest fluxes were exhibited in soils treated with low and high biochar at approximately 0.002 nmol m$^{-2}$ s$^{-1}$, fluxes about 10.0 times smaller than those displayed in soils treated with no biochar and uniquely negative. Within soils treated with high basalt, soils treated with no biochar exhibited the smallest fluxes at about -0.02 nmol m$^{-2}$ s$^{-1}$, a flux about 2.0 times as large as those exhibited in soils treated with high biochar, about 10.0 times as large as those exhibit in soils with low biochar; both soils treated with low and no biochar displayed negative fluxes. The greatest fluxes were exhibited in soils treated with
no basalt but with no and high basalt, and low basalt but high biochar, all of which were displayed at about 0.075 nmol m$^{-2}$ s$^{-1}$. The smallest fluxes were exhibited in soils treated with medium basalt and high biochar at roughly 0.002 nmol m$^{-2}$ s$^{-1}$. Fluxes of nitrous oxide show a relatively strong correlation with soil moisture across the treatments (Figure 12).

**Discussion**

*Soil pH:* The general increase in soil pH with increasing additions of both biochar and basalt were largely expected. Previous studies of biochar have shown that mixing biochar into soils increases pH and improves base cation availability due to its natural liming potential and increased ability to adsorb organic molecules such as ammonium, both of which are a function of its high surface area and porous nature (Clough and Condron 2010; Nigussie et al 2012). The use of basalt in soils has been known to increase the overall negative charge of soil, increasing soil pH and augmenting cation exchange capacity (Shamshuddin and Anda 2008). Results of this investigation show that additions of biochar and basalt alone increase pH with increasing magnitudes, and that mixing them also generally enhances these increases.

*Soil Moisture:* The general increase in soil moisture with increasing additions of biochar alone was largely expected. Biochar is known to have a high porosity, allowing it to provide soil with a higher water holding capacity (WHC) and the ability to move water to lower layers through larger pores after the onset of rain (Karhu et al 2011). The addition of crushed basalt was thought to provide similar WHC-enhancing effects as a vesicular, extrusive, igneous rock (Al-Harthi et al 1990). However, results show that soils with no basalt and low basalt both increased moisture at similar levels across an increasing biochar gradient, but that the addition of basalt at medium and high levels negates the porosity enhancement provided by increased amounts of biochar. It is quite possible that 1) the pores of the basalt used in these plots are not as large or connected as planned; 2) the basalt pieces are so small that they can fit in the pores provided by the biochar, thus blocking water; or 3) that the basalt and biochar combined add too much porosity, preventing less water from staying within the soil.

*Carbon and Nitrogen Content:* While results of total carbon content displayed no distinct differences among the soil treatments, it was hypothesized that both biochar and basalt would increase the total content of the soil. Soil mixed with biochar was thought to have greater amounts of carbon because of its carbon-rich composition and tendency to enhance microbial biomass (Nigussie et al 2012; Kolb et al 2008). The amount of carbon stored in biochar is dependent on the temperature at which the biochar underwent pyrolysis, so it is possible that the temperature at which this biochar was heated was not high enough to produce the high carbon stocks that were predicted (Lehmann et al. 2006). Soil mixed with basalt was hypothesized to hold greater amounts of carbon because of the ability of the calcium within it to combine with free carbon dioxide to form calcium carbonate (Gislason et al 2010); however it is possible that this geological process is too slow to be detected after only five months. Soil was also predicted to have more total nitrogen with increasing levels of biochar due to biochar’s ability to prevent nutrient leaching of ammonium and nitrate, although results of total nitrogen also reveal no distinct patterns (Hyland et al 2010). Insignificant differences in carbon-to-nitrogen ratios among the plots were thus produced, although it was expected that soils mixed with more biochar and basalt would contain more carbon and thus produce larger ratios.

*Stocks of Ammonium and Nitrate:* Average stocks of ammonium displayed no distinct differences among the soil treatments, although it was expected that ammonium stocks would increase with the increasing biochar gradient due to the increased adsorption capacity of biochar.
to contain ammonium molecules and prevent leaching, largely the result of its large surface area, negative surface charge, and charge density (Lehmann 2007; Singh et al 2010). It was predicted that the added surface area provided by the basalt would enhance this adsorption power, although no distinct trends were observed. It is important to note that the results of ammonium stocks may not be accurately represented due to the uncontrolled harvesting of radishes from the plots before the third round of sampling, which may have disrupted trends that were previously apparent. Despite a distinct increase in nitrate stocks across the biochar gradient with no, low, and medium basalt, it was expected that biochar’s negatively charged surfaces would not be able to retain nitrate well; however, it is possible that the increased adsorption of ammonium in these soils could have reduced the rate of N mineralization, thus causing the rate of nitrate leaching to decrease (Laird et al 2010). Leaching may also have been minimized because these basalt-biochar combinations encourage nitrification. Furthermore, the increasing moisture found in soils treated with no and low basalt at each level of biochar treatment could signify that water, and thus the negative nitrate, is being retained. Regardless of the reason, it is important to note that soils with increased basalt and biochar appear to hold nutrients for use by plants and microbes more efficiently and effectively.

**Microbial Biomass:** With the exception of soils treated with high levels of basalt, all soils showed an increase in microbial population size with increasing levels of basalt across the biochar gradient, a trend that can be directly translated into additional stored carbon in microbial biomass. This growth is likely due to the increased surface area, carbon substrate availability provided by the increasing biochar, creating a larger, more nutritious habitat for microbial life to thrive (Kolb et al 2008). The addition of basalt may have added additional base cation nutrients and surface area at low and medium levels that promoted additional microbial growth, although at high levels it appears to interfere with the biochar’s benefits.

**Greenhouse Gas Fluxes:** Fluxes of carbon dioxide exhibited minimally significant trends across biochar and basalt gradients. While it was expected that increasing amounts of biochar would cause decreasing fluxes of carbon dioxide, it is possible that the soil type and the amount of time that the biochar has been in the soil currently negate this potential (more time may be needed for fluxes to decrease) (Singh et al 2010). The distinct increase in fluxes from low to high biochar in soils with low and medium basalt may be a result of an increased organic carbon substrate provided by the biochar that enhances microbial productivity—although this change is not apparent between soils treated with no biochar and low biochar (Singh et al 2010). In terms of basalt, it is possible that the formation of calcium carbonate is too slow of a process to produce noticeable flux changes, although it was predicted that the additional basalt would augment this process. Minimally significant trends may also have resulted from minimal differences in carbon content, as increased total carbon can lead to increased carbon dioxide emissions (Singh et al 2010).

The dramatic decrease in fluxes of nitrous oxide in soils treated with medium and high basalt across the biochar gradient signals that this combination is significantly enhancing the greenhouse gas storage capacity of the soil. It is important to note that the negative values of these fluxes imply that the nitrous oxide produced during microbial processes (i.e. nitrification) is being readily contained by the soil. It is possible that the additional biochar likely provides a nutritious carbon substrate for microbes that increased their populations and productivity, creating an anoxic soil environment and triggering the activity of N₂O-reductase in the soil to obtain more oxygen by converting nitrous oxide to pure nitrogen gas (Singh et al 2010). Fluxes of nitrous oxide are often found to be lower in soils with less moisture, so it is possible that the
noticeably lower moisture exhibited in soils with medium and high basalt is also contributing to these decreased fluxes (Singh et al 2010).

Conclusions

Results of this investigation show that soils treated with different levels and combinations of biochar and basalt can lead to changes in pH, moisture, stocks of carbon, nitrogen, ammonium and nitrate, and microbial biomass, as well as a unique structure, substrate, porosity, and sorption capacity all of which affect the ability of that soil to store and sequester carbon dioxide and nitrous oxide. It is also evident that biochar and basalt affect these factors in different ways, and their interaction in soil poses a complicated relationship that can either enhance or negate the effects of each. As such further research on the use of biochar and basalt should further address the effects of their combination in soils at different magnitudes, and should emphasize structure, rates of net mineralization, nitrification, and microbial productivity. Studies could also be performed over longer time periods to further assess soil health and greenhouse gas storage potential.

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References


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Figure 6. Soil carbon-to-nitrogen ratios across gradients of increasing additions of biochar and basalt.
Figure 7. Soil ammonium concentrations across gradients of increasing additions of biochar and basalt.
Figure 8. Soil nitrate concentrations across gradients of increasing additions of biochar and basalt.
Figure 9. Soil microbial population sizes across gradients of increasing additions of biochar and basalt.
Figure 10. Soil fluxes of carbon dioxide across gradients of increasing additions of biochar and basalt.
Figure 11. Soil fluxes of nitrous oxide across gradients of increasing additions of biochar and basalt.
Figure 12. Soil fluxes of nitrous oxide as a function of soil moisture in wet-to-dry ratios across gradients of increasing additions of biochar and basalt.