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Research paper

Greenhouse gas emissions from soil amended with agricultural residue biochars: Effects of feedstock type, production temperature and soil moisture

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ABSTRACT

The conversion of agricultural residues into biochar produces a material with agronomic and environmental benefits. Biochars have been found to positively or negatively affect soil greenhouse gas (GHG) emissions, with the variability being explained by differences in biochar properties and environmental conditions. This study evaluated the effect of soil moisture conditions on the emissions of GHGs from soils amended with different types of biochar. For that, we added biochars to a sandy soil and incubated the samples at 23 °C for 90 days under two moisture conditions. While CH_4 fluxes remained not significantly different from zero in all treatments, CO_2 effluxes were stimulated at higher soil moisture contents, though the stimulating effect varied with biochar type. Soils amended with biochars with a narrow C:N ratio showed a higher CO_2 efflux than soils amended with biochars with a wide C:N ratio. There were significant main effects of pyrolysis temperature and soil moisture conditions on the N_2O fluxes from the treatments, however total N_2O fluxes from biochar amended soils were overall not significantly different from the control due to treatment interactions. Our study indicates that the main effect of biochars on the GHG balances of soils is related to an increase in soil C stocks, with little short-term changes in soil CH_4 and N_2O fluxes. Nevertheless, short-term increases in GHG emissions due to biochar addition to soils can be easily mitigated by use of biochars with high C:N ratios produced under high temperatures and by avoiding application to moist soils.

1. Introduction

Biochar is the solid product from the pyrolysis of biomass, intentionally produced to be applied to soils [1] for improving both soil fertility and soil physical properties [2]. Biochar has also been proposed as an effective way to reduce greenhouse gas (GHG) emissions from waste management [3], and mitigate GHG emissions from agricultural systems [4], as additions increases soil C contents. Moreover, additions of biochar can affect soil emissions of CO_2 and CH_4 as well as N_2O, as a result of its impact on soil C and N cycles [5,6]. However, results are contradictory with some studies reporting stimulating [7] effects, while others report inhibiting or no significant effects on soil N_2O and CH_4 fluxes [8,9]. This variable responses of soil GHG emissions to biochar amendments has been attributed to differences in biochar properties as well as in environmental conditions in the individual studies [10].

Among the various biomass feedstocks used to produce biochar, agro-industrial residues are the preferred option as those are highly available, have a low market value and often pose a potential environmental risk if deposited without treatment. Being aware of the benefits and potentials of the use of agro-industrial residues, Brazil launched the National Solid Waste Policy in 2012; a policy that intends to reduce the volume of agricultural waste produced nationally and increases the sustainability of solid waste management. In Brazil, the agro-industrial activities generate about 290.8 million tons of residues

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yearly [11]. Thereby, sugarcane bagasse and sugarcane filter cake contribute 69% of all agricultural residues produced per year [11]. Swine production and the wood industry are the other two activities that also produce large quantities of residues. In 2009, swine production produced 20 million tons of manure, while wood log processing generated 51 million m^3 of lingo-cellulosic residues [12]. Inadequate handling/disposal of these wastes might result in environmental degradation of surface and groundwaters. Thus, the conversion of agro-industrial residues into biochar offers the opportunity to reduce the quantity of solid agricultural waste and increase the sustainability of the agricultural sector [13].

Both biomass type and the charring process used to produce biochar affect its chemical-physical properties. Plant-derived biochars have higher aromatic C content than biochars produced from animal manures, so that plant-biochars have a higher stability and resistance to microbial decomposition [14]. Biochars produced from manure are rich in N compounds and labile C, often decompose rapidly after addition to soils and, thus, are not expected to increase C storage in soils at longer time scales [14]. The temperature used to produce biochar also affects its properties. Biochar produced at low temperatures are rich in volatile matter contents, high in O:C ratio and low in aromaticity, so that the produced biochar is less stable than biochar produced at higher temperatures [15,16]. Thus, origin of the biomass and biochar production conditions result in a wide variety of biochars with different chemical and physical properties that are likely to influence GHG emissions from biochar amended soils.

On the short-term, biochar amended soils show higher soil respiration [17,18], and this effect is more pronounced for biochar produced at low temperatures [10,19]. Increased soil respiration, which often lasts for a few weeks only, has been attributed to the decomposition of the labile fraction of biochar, or to increased rates of decomposition of autochthonous soil organic C due to priming effects [19]. The fraction of biochar that does not decompose within weeks is thought to persist in the soil for decades or even centuries, very slowly releasing C back to the atmosphere as CO_2. The addition of biochar to soil can also affect the production and consumption of N_2O and CH_4. The addition of biochar with low N contents (< 1.5%) to soils have been found to generally decrease soil N_2O production [20]. This decrease has been attributed to different mechanisms such as: (i) retention and immobilization of ammonium and nitrate at biochar surfaces [21,22]; (ii) facilitation of the terminal step of denitrification (N_2O to N_2), thereby reducing the $N_2O/(N_2+N_2O)$ ratio [23]; (iii) decreasing of soil bulk density in biochar amended soils, which favors soil aeration and thus hampers anaerobic processes such as denitrification [24]. However, studies applying biochars with high N content (> 1.5%) to soils show that biochar might increase soil N_2O emissions [25], as some of the biochar nitrogen might be mineralized to finally fuel microbial N_2O production. High N_2O emissions were observed e.g., from rice paddy soils amended with biochar made from swine manure [26]. However, the effect of biochar additions to soils is also depending on the soil water content. At soil moisture contents close to saturation, biochar amended soils showed higher N_2O emissions compared to non-amended control soils, while at soil moisture conditions < 75% WFPS N_2O emissions were reduced [27].

Biochar alters the physical properties of the soil because it has a low bulk density and a large surface area. Thus, biochar-amended soils show an improved soil aeration, which in predominantly aerobic soils has been found to increase the net sink strength of soils for atmospheric CH_4 while for predominantly water-saturated and, thus, anaerobic soils, a decrease in net CH_4 emission due to increased gross CH_4 oxidation was found [6,28]. On the other hand, biochar also retains water in its porous structure, thereby creating anoxic micro-sites within the soil, thereby increasing CH_4 production. However, a recent meta-analysis found that biochar additions decrease or have no effect on the uptake potential of soils for atmospheric CH_4 [8].

In summary, the effect of soil biochar amendments on GHG fluxes might highly be dependent on the source of the organic material, the production condition of biochar as well as on soil moisture conditions. In our study, we therefore investigated the effect of biochar type, production condition, and soil moisture level on GHG fluxes from biochar amended tropical soils. For this a laboratory scale incubation experiment with various biochars, produced either at 400 °C or 600 °C, was designed and soils were incubated under two soil water levels. As controls we used on the one hand un-amended soils and on the other hand soils amended with N-poor biochar produced from *Miscanthus* at 450 °C, as this is a biochar type often used in other studies [29–33]. We hypothesized that: (i) addition of agricultural residue biochars into soil would stimulate emissions of CO_2, CH_4 and N_2O under high soil moisture conditions; (ii) soils amended with N rich biochars would have higher CO_2 and N_2O emissions as those soils amended with N poor biochars; and (iii) that soils amended with agricultural residue biochars pyrolyzed at high temperatures would have lowest emission potentials for GHG emissions.

2. Materials & methods

2.1. Biochars and soil characteristics

In our study we included four commercially produced biochars (SPPT Ltd., Mogi Morim, São Paulo, Brazil) with biomass coming from agricultural residues relevant for Brazil (Table 1): (i) swine manure (SM), (ii) eucalyptus sawdust (ES), (iii) sugarcane filter cake (SFC), and

Table 1
Origin of biomass feedstocks used, pyrolysis temperatures for biochar production, biochar yield and physical and chemical properties of biochars (*n* = *1*).

Biomass	Origin of biomass	Pyrolysis temperature	Biochar code	Biochar yield	Surface area	C	N	C:N	pH	CEC
		(°C)		(%)	(m^2 g^1)	—— % ——			(H_2O)	(pH7)
Sugarcane filter cake	São Paulo, Brazil	400	SFC400	43[a]	13.5	39.5	1.8	21.7	8.6	3.9
		600	SFC600	35[a]	41.3	35.0	1.5	23.7	8.4	10.8
Swine manure	São Paulo, Brazil	400	SM400	57[a]	7.2	49.6	2.7	18.5	9.2	28.9
		600	SM600	44[a]	36.9	47.0	1.8	25.0	10.7	45.4
Cotton husk	Mato Grosso, Brazil	400	CH400	38[a]	0.2	69.8	2.0	35.0	10.0	49.0
		600	CH600	33[a]	1.9	65.6	1.8	36.8	10.0	56.8
Eucalyptus (*E. saligna*) sawdust	São Paulo, Brazil	400	ES400	41[a]	0.3	78.5	0.7	109.6	7.7	3.7
		600	ES600	33[a]	132.0	84.0	0.8	107.5	9.6	19.8
Miscanthus (M. *giganteus*)	Groningen, Netherlands	450	MG450	31[b]	371.9	64.4	0.8	78.4	5.9	20.1
Entisol subsoil	–	–	–	–	–	0.6	0.1	9.3	4.6[c]	33

CEC: cation exchange capacity.
[a] Expressed as mass fraction of the original dry biomass.
[b] Expressed as mass fraction of the original wet biomass.
[c] pH determined in $CaCl_2$.